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GEOINFORMATIC METHODS FOR THE DETECTION OF FORMER WASTE DISPOSAL SITES IN KARSTIC AND NONKARSTIC REGIONS (CASE STUDY OF DOLINES AND GRAVEL PITS)

DISSERTATION

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DECLARATION

I hereby state that the present dissertation “**GEOINFORMATIC METHODS FOR THE DETECTION OF FORMER WASTE DISPOSAL SITES IN KARSTIC AND NONKARSTIC REGIONS (CASE STUDY OF DOLINES AND GRAVEL PITS)**” is the result of my own research work. The results, generated in the scope of joint research with other researchers, or contributed by other researchers (experts), are explicitly stated and quoted in the dissertation.

Mateja Breg Valjavec

Nova Gorica, 18. October 2012

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ABSTRACT

Geoinformatic Methods for the Detection of Former Waste Disposal Sites in Karstic and Nonkarstic Regions (Case Study of Dolines and Gravel pits)

***Key words**:* former waste disposal site (FWDS), geoinformatics, doline, gravel pit, remote sensing, relief, soil, vegetation.

Geoinformacijske metode za odkrivanje nekdanjih odlagališč odpadkov v kraških in nekraških pokrajinah (na primeru vrtač in gramoznic)

Ključne besede: nekdanja odlagališča odpadkov, geoinformatika, vrtača, gramoznica, daljinsko zaznavanje, relief, prst, rastje.

The main research objects are former waste disposal sites (FWDS), hidden in dolines and gravel pits. The potential locations of the FWDS in dolines and gravel pits could be determined using geoinformatic methods, which are based on the analysis and comparison of various spatial data (aerial photographs, satellite images, cartographic data, digital elevation models) from different periods (past and recent) by determining physical changes within the following landscape elements: relief, soil, vegetation. The research limited itself on two case study sample areas, which represent two different flat landscape types (Logaško karst polje, Ljubljansko polje plain), for which different relief basins are typical. Within the chosen karstic landscape type, dolines were mainly exposed to disintegration. On non-karstic gravel plains, waste was mainly deposed into abandoned and non-rehabilitated gravel pits. Considering the characteristics of the studied object the research must focus on the past and recent landscape as well as on the comparison of both. The natural and socio-economic factors for the appearance of FDWS existed in the past landscape, while the impacts can be recognized in the recent landscape. Regarding this, the research concept divides into five phases. The first includes studying the relevant socio-economic and spatial factors in the past landscape. The second focuses in determination and presentation of the ZERO STATE (the state before land filling), based on archive aerial photograph analyses. The third phase includes locating of filled dolines and gravel pits by studying data of the recent landscape by applying geoinformatic methods that enable defining the impacts of past waste disposal on three environmental elements: relief, soil, vegetation. The validations of the results in phase four is based on the application of laboratory methods by comparing existing waste disposal sites registers with the study results and extensive field survey by applying the relevant methods (soil sounding; electrical resistivity tomography, mapping the relief and vegetation anomalies). Synthesis of the results and a digital cadaster of all the potential locations

according to risk assessment is made in phase five. The basic research concept was called 2TL/3E. It consists of methods for studying the past landscape and methods for studying the environmental consequences on all three landscape elements: relief, soil and vegetation in the recent landscape, which gave the methodological concept its name. The concept represents a framework and action plan for the research. It is the basis for generating a general FWDS model that will be executable in identical and similar landscape types in Slovenia.

The main goal of studying the past landscape was to determine zero state of dolines and gravel pits. In Logaško polje the initial number of dolines is around 1,300 objects while in Ljubljansko polje around 300 gravel pits were determined. Determination of dolines is based on analysis of archive aerial photographs from initial year while the locations of gravel pits must be studied in more sequential years.

FWDS can be determined using geoinformatic methods, which enable relief analyses and determining relief changes. This hypothesis, posed at the beginning of the research, was proved with relief analyses of the past and recent landscape and also with quantitive comparisons of both surfaces on Logaško polje. Soil and vegetation analyses are based on recent landscape data (multispectral CIR images), while relief analyses are possible in both landscapes and also with a comparison of the past and recent relief. The use and success of the selected methods differ according to the geological characteristics of the studied area, land use and type of filled waste or cover layer.

Determination of the anthropogenic relief elements that were formed by dumping waste in nature is based on a geomorphological knowledge and understanding of the natural landforms and processes. Each studied area is very specific from that aspect. The relief changes resulting from improper waste dumping in the past remain in both studied relief types; the only difference being that this anthropogenic process has caused the karst relief today to be much more altered and degraded as a landscape element than the fluvial one. In the case of filling dolines on Logaško polje, this is namely a permanent degradation of a large number of natural karstic landforms, while Ljubljansko polje and filling gravel pits is a case of actual relief returning to its original shape. Of course, the consequences are more visible on other landscape elements, most visibly in the presence of anthropogenous soils called deposols and the ruderal surface vegetation, as well as in the pollution of underground water.

The multispectral analysis of both landscapes was based on the aerial photograph analysis (aerial photographs from 2006, ©GURS), where the entire area of Slovenia was recorded in four radiometrical bands (red, green, blue, NIR). The data is available free of charge for research purposes at the GURS. The radiometric bands are mosaicked in the RGB and CIR files; as a consequence, they need to be processed to generate a four-band image for automatic image processing. The multispectral analysis consists of unsupervised image classification (ISODATA) and of the detection of vegetation stress via the calculated vegetation indexes (NDVI, IR/R) of the vegetated surface. The method cannot be used as an independent method to successfully determine FWDS on Ljubljansko polje, while it gives very good results on Logaško polje, predominantly the alluvial part of studied area (cover dolines). The method enables to exclude the areas with warm / dry vegetation (automatic analysis) and areas with sparser vegetation above the waste (visual analysis) that are typical for FWDS dolines. The method of locating FWDS using soil anomalies is not usable on the areas that are densely overgrown with forest. On such areas, it is necessary to analyze especially the density and height of the vegetation. Data from the laser scans of the surface are of use here, as the vegetation layer is eliminated. The use of the method is also limited on built-up and partly built-up surfaces.

Some new conclusions were made about the direct and indirect impacts of waste disposal on landforms, soil and vegetation, mostly through detailed laboratory and field research. It is almost impossible to find a completely natural doline in the studied area, starting with the traditionally cultivated dolines that are ranked as partially preserved. The filled dolines on Logaško polje differ from one another according to the type of filled waste material, which is often different as the covering layer that was used for the covering of the waste and “remediation” of place. The vegetation that developed on the covering layer is a reflection of both. The amount of soil moisture available to the plants depends on characteristics of top layer, while the underlying waste can be a source of nutrients (decaying organic waste – nitrogen) or of toxic substances.

In comparison to past researches of waste disposal sites and FWDS, the present research is innovative in different ways. The application of different relief data and selected geomorphometric analyses in the determination of FWDS that enable relatively good results; The combination of laboratory (multispectral) and field results (soil sampling); Some new pedogeographical findings about the characteristics of deposols that should be the input for further research; Some basic findings about vegetation on FWDS; The application of different field methods.

CONTENTS

1 INTRODUCTION

1.1 The Background

Former waste disposal sites represent **old environmental burdens** that have been inherited from past generations, in addition to the positive goods. The task and moral obligation of recent generation, mandated by the paradigm of sustainable development, is to establish a register, to build a monitoring network and to start with the rehabilitation of the worst cases. According to the *Decree of dealing with waste* in Slovenia, we have made an official obligation to solve the problem of old burdens: "*… the formation of an efficient system of dealing with waste and gradual abolition of old environmental burdens…"* (UL RS 84/1998). Former waste disposal sites were generally not subject to the regulations governing modern landfills without underlying protection layers. The results of earlier Slovene field studies (Bricelj 1988; Knez and Regent 1993; Šebenik 1994; Šebenik 1995a; Šebenik 1995b; Kušar 2000; Kušar 2001; Kušar 2001a; Breg and Urbanc 2005; Smrekar et al 2005; Požar 2006; Breg 2007; Smrekar 2007 etc.) show that former waste disposal sites are often located in natural (dolines, dried river branches) and anthropogenic landforms (gravel pits or other open mining pits) without protection layers. The landscape types in Slovenia with such landforms that have been exposed to waste-filling are Dinaric plateaus, Alpine plains and Panonian plains.

The general assumption that an aftercare period of a few decades is adequate to allow for the degradation of waste to an inert state is now being questioned, with recent studies (Rathje 1991, Hjelmar et al. 1995; Wall and Zeiss 1995; Kruempelbeck et al. 1999; Röhrs et al. 2000; Fourie et al. 2003, Allgaier and Stegmann 2005) suggesting that waste may remain active for many decades and even hundreds of years, depending on the physical conditions. Because the majority of waste dumps did not have protective waterlogged layers, they still represent a danger to the quality of the environment and to people's health, seeing that excretion of various degraded substances into the atmosphere, soil and groundwater has a rather lasting effect (Allgaier and Stegmann 2005). The problem is that landfills are not vast composters; there is biodegradation, but its pace is measured in centuries, not decades. Even organic materials, such as food scraps, remain unchanged after 30 or 40 years (Rathje 1991).

1.2 The Definition of the Research Object

The main research objects are waste disposal sites that mostly emerged in the post-war period (World War II; in continuation WWII) as a product of socio-economic development, increased industrial production and an increased amount of different waste types. Their locations are unknown or can be only imprecisely situated in recent landscape. This makes any further evaluation of the impacts on the environment impossible. Not being able to determine the amount and the elements of the waste also presents an unpredictable problem. The research will focus on waste disposal sites in the dolines and gravel pits with the following characteristics:

1. Are **non-functioning** from the perspective of disposing waste;
2. Are **unregulated** seeing that environmental standards regarding the dumping of waste and the regulations (which came into use in the late nineties when dealing with active waste dumps, for example, Regulations of waste dumping, 2000), were not met so the waste was disposed on natural geologic layers (gravel in gravel pits, loamy sediment in dolines) without any use of protective waterlogged layers on the bottom as well as on the top and there is consequently no drainage and cleaning of the landfill leachate, etc;
3. Can be divided into waste disposal sites which had a permit given by the authorities (municipal, industrial, etc.) and those that did not have this permit (illegal waste dumps);
4. Waste disposal sites that **store waste of various types and ages** with their quantity and structure being unknown or just determined as an estimation;
5. Waste disposal sites that are nowadays more or less **hidden** as a result of the time and conditions for an ‘automatic’ renaturation; with regard to the type of remediation and their current state they can be divided as follows:
    A. Waste disposal sites that were not rehabilitated and are overgrowing without any earlier filling in with earth or other materials today;
    B. Waste disposal sites that were rehabilitated with a cover layer (with earth or building materials) and are non-overgrowing today;
    C. Waste disposal sites that were rehabilitated with a cover layer and are partly or completely overgrowing today.

The term **Former Waste Disposal Site** as well as the abbreviation **FWDS** will be used in this research for the studied type of waste disposal sites.

1.3 Goals and Objectives

The main research goals involve **the identification** of former unregulated and illegal, currently abandoned waste disposal sites, which represent an old environmental burden. The purpose of this research is to test and determine the most suitable geoinformatic methods or a methodological concept (model) for determining the potential locations of FWDS, evolved over decades in dolines and gravel pits. Different geoinformatic methods based on remote sensing data (aerial and satellite images) were tried out. The method / model should guarantee the best results in the case study areas as well as in similar landscape types (Alpine plains, Dinaric plateaus, Pannonia plains). The field methods have been selected to control the results of the geoinformatic analyses. The primary objectives are:

1. Testing the chosen geoinformatic methods and choosing the most suitable one with best results from the point of view of determining the locations of the FWDS in other, the same or similar, landscape types as well.
2. The formation of a cadaster of FWDS dolines and gravel pits, formed in the second half of the 20th century (1945–1991).
3. Determining the representative year for establishing the starting point of the dolines in the studied karst area, (Logaško polje in 1944). Determining a few other comparable reference years for a spatial and time study of the gravel pit features in gravel plains (Ljubljansko polje in 1959, 1964, 1975, 1985).
4. Determining the **location, size, shape and area** of the dolines and gravel pits, estimating their **number, depth and volume** in the starting year (doline) or reference years (gravel pits), determining the **land use** in the dolines and their immediate vicinity.
5. Determining the location, extent, surface and the period of formation / activity of the FWDS. Estimating and evaluating the characteristics of a specific FWDS: the amount of waste, the depth of filling in, the age of the disposed waste, the time and manner of the remediation, if it was performed at all (for example covered with excavated materials, with soil).
6. The classification of the FWDS depending on their environmental risk.
7. The validation of the results with field methods and comparison to old registers of waste disposal sites.

1.4 Hypothesis

The potential locations of the FWDS in dolines and gravel pits could be determined using **geoinformatic methods**, which are based on the analysis and comparison of **various spatial data** (aerial photographs and satellite images, cartographic data, digital elevation models) from **different periods (past and recent)** by determining and locating **physical changes** within the following landscape elements:

- **relief,**
- **soil,**
- **vegetation.**

The success of a specific geoinformatic method varies according to **the type** and **the quality of data used** the **landscape type of the studied area** and **the former and current land cover type** (forest, bushes, meadow, field, built-up area) in the area of a former waste disposal site. The results gathered with the geoinformatic methods are ascertainable in the recent landscape to some extent using **field methods**.

2 WASTE DISPOSAL IN GENERAL

2.1 The History of Waste Disposal

The history of garbage is as old as human kind itself. For most of the past two and a half million years, human beings have left their garbage where it fell. The garbage was organic and decomposed over time without polluting the environment. This disposal method functioned adequately because throughout prehistory we were hunter-gatherers who frequently abandoned their campsites to follow game or find new stands of plants. We remained hunter-gatherers until about 10,000 years ago (Williams et al. 1993).

Within the next 5,000 years, virtually the entire human population became farmers or herders and we domesticated more plants and animals (Rathje 1991). In rural areas waste did not cause any special problems as it started to emerge with the establishment of the first bigger settlements (cities) and the increase in the population density. These factors contributed to the growth of waste production per land-unit and to the decrease of the percentage of land, suitable for waste dumping (Internet 6). In the time of the early civilizations in the region of today's Palestine, people usually buried their waste. Waste at that time consisted mainly of household waste and some waste as the result of the arms, tools and useful as well as ornamental items manufacturing (Rathje 1991).

Archaeological digs into the Bronze Age Troy found that the floors had been so littered that a fresh supply of earth had been periodically brought in to cover up the refuse. Over time, the ancient cities of the Middle East rose high above the landscape on massive mounds called tells. The uplift was calculated to be about 1.2 meters per century during the Bronze Age (Rathje 1991). In the time of the Minoan civilization (from 3,000 to 1,000 BC) people in the Cretan capital of Knossos dumped solid waste into deeper karst gorges, which were later filled with layers of earth. Ancient Romans did not know this type of disposing waste, as they disposed of their waste by simply dropping them along their roads, causing various infections, diseases and quite unnerving aromas. Nevertheless, this way of disposing waste existed in this area until the 19th century (Internet 6). Rathje (1991) cites an account of an excavation of an ancient Roman garbage dump, in which the smell of putrefaction remained unbearable even after 2,000 years. Archaeological excavations in northern

Europe showed that in many cities people disposed of their waste by simply putting them into the cellars of their houses. The ground was sometimes covered with as much as half a meter of waste, which was then covered with reeds, consequently leading to fires at times, when entire city quarters would burn down to the ground (Williams et al. 1993).

As early as 1387, Londoners started collective gatherings and dumping waste in waste dumps. Up to then, the prevailing method of waste disposal was simply dropping the waste into the Thames or the canals and sewers running into the Thames, causing an almost unbearable odor. London got the law of the distribution of waste collectors and waste dumps as early as in the 15th century, with their locations remaining the same to the present time.

The first organized state regulated and financed waste collection occurred in the USA in 1856. It was based on the Ordinance of dealing with waste from 1798, when the authorities in the city of Georgetown (today's part of Washington) prohibited the expansion of waste dumps over private property or dropping waste along roads. In 1874, the first waste burning factory was built in England, which was quickly followed by an incinerator in the USA in 1885. In 1914, Hamburg had three incinerators, whereas there were already around 200 in England, with 65 of them producing electricity (Internet 6).

The relationship towards dealing with waste changed drastically before the Industrial revolution, namely for the first time in the 16th century, when waste, rich with nitric compounds, was used to obtain nitrates, which were used for the production of gunpowder. An interesting story pertains to Edinburgh, the capital of Scotland, where city records from the 18th and 19th century note that the city waste dump remained the same size for almost a century, due to the fact that the majority of waste was sorted through and mainly sold to craftsmen and farmers (Internet 6). Dumping, slopping and scavenging were the norm in Europe and the United States until the late 1800s, and sadly in most Third World countries, a slopping-and-scavenging system remains in place today (Rathje 1991).

We encountered our first garbage crisis when, rather than move ourselves, we decided to move our garbage. We moved it into dumps, which has been the favored means of disposal everywhere, including cities since prehistory right through to the present day (Williams et al. 1993). In the very old days waste was often recycled, simply because people could use it again. Ancient landfills are now archeological sites. Waste problems on a regional and national scale started in the era of industrialization and urbanization and are a reflection of the industrial history of the specific region (Glover 1995).

Dumping garbage on the outskirts of a town or into natural depressions or valleys has long been the favoured practice. Sometimes the garbage was covered with some dirt, or burnt slowly onsite, but generally in many cases it was simply left in the open. It attracted vermin and scavengers, litter and odours were scattered by the wind, which created a whole range of health and environmental problems. But it was cheap and health and environmental issues were not a priority. In the 1950s and 60s, liquid waste and industrial waste containing toxic chemicals and hazardous materials were also carelessly dumped into landfills causing extreme environmental and public health damage (Glover 1995).

In the 70s of the last century, environmental awareness became a public issue in many countries. People protested against leaking landfills in their neighbourhood and national environmental laws were made. In the 90s EU directives, modeled on the experience of the frontrunners, set the rule for the new countries that joined the EU in the beginning of this century (Internet 5).

2.2 Waste Disposal Sites in Europe and in Slovenia

Waste disposal sites in general are a widespread problem in Slovenia as well as in European countries. Roughly estimated, Europe counts over 150,000 landfills. These waste disposal sites as a group are a footprint of the way people in Europe lived in the previous centuries (Sufalnet 2009). Many countries tried to solve the problem starting with a detailed inventory, the classification of individual sites regarding appropriate remediation and in some cases physical remediation took place. The final tep after site remediation is the prevention of further disposal waste disposal by raising general public awareness. Approximately 2,000 waste disposal sites exist in Ireland which may be contaminated because of the current or historical activities associated with them; of these, as many as 487 may be contaminated due to hazardous and non-hazardous waste disposal activities – of which 84 are operating sites (Moran et al. 2003). Compared to biger Germany, more than 100,000 waste disposal sites were registered in 2005. However, this number was expected to grow due to the continuous enhancement of the Brownfield site register. Collected data showed that approximately 80% of them are smaller than 50,000 m^3 and approximately 60% are even smaller than 10,000 m^3 (Allgaier and Stegmann 2005). More than 11,000 illegal waste disposal sites were identified in Slovenia in 2010 within the frame of the voluntary action Let's clean Slovenia 2010 (Petrovič 2011).

An irrefutable consequence of the polycentric settlement system (that installed industrial companys in every town) in Slovenia in the socialistic period is a bigger number of smmaler illegal waste dumps in Slovenia (Figure 1). It is worth mentioning that research on the occurrence of illegal waste disposal sites was pioneered by geographers, with this issue still being in the domain of geographers' interests. In 1970, Orožen Adamič wrote about the preservation of caves and areas in karst regions and condemned waste dumping in karst hollow depressions. The same author published two scientific articles in 1975 and 1979 about the issue of dealing with waste in Ljubljana. Geographer Plut (1981) researched illegal waste disposal sites in the area of Blejski Kot and in Bela Krajina (Plut 1985). One of the first field registers of illegal waste disposal sites was made in the municipality of Logatec in 1988 (Bricelj 1988). Although some municipal landfills got an official permit from the authorities, the waste dumping was inadequate and uncontrolled. Hazardous industrial waste has been dumped in municipal landfills together with non-dangerous municipal waste (Orožen Adamič et al. 1978). A whole series of smaller illegal waste disposal sites that were filling up quite quickly were found as early as at the beginning of the 1970s in the vicinity of all the major Slovene cities (Šebenik 1994).

In Slovenia, different authors studied the topic of illegal waste dumping and they have used different terms for illegal waste dumping sites: "wild dumping site" / "illegal dumping site" (*divje odlagališče odpadkov*) by Smrekar et al. (2005), Smrekar et al. (2006) and Smrekar (2007), "black waste dump" (*črno odlagališče odpadkov*) by Špes, "illegal waste dumps" (*nedovoljeno odlagališče odpadkov*) by Šebenik (1994, 1995a, 1995b) and others. In continuation, we will use the general term *illegal waste disposal site* for all the mentioned names in this research.

In 1990s the first comprehensive study of illegal waste disposal sites in Slovenia was made by Šebenik (1994). An important novelty of Šebenik's approach, in comparison to research up to then was a far more precise study of the quantity parameters of illegal waste disposal sites. Šebenik analyzed 3,501 sample illegal waste disposal sites comprising of sizes from 1 to 10,000 m³. The collective quantity of waste in these disposal site amounted to 163,282 m³, with the collective surface of these areas amounting to 471,235 m². The average disposal site was 135 m² in size and 47 m³ in the volume of waste. The average thickness layer of the waste was 0.35 m and grew from 0.2 m for illegal waste disposal sites with only 1 m³ to more than 1 m in categories above 500 m³. Almost all the waste disposal sites (99%) were smaller than 1,000 m³, with 74% being smaller than 10 m³, although the amount of waste in them was not negligible. 39% of all the waste was in the smallest waste disposal site category (size up to 1,000 m³). It may be stated with certainty that smaller waste disposal sites were important with regard to the amount of waste and not just the number of such smaller waste disposal sites.

Šebenik tried to give an estimation of the dispersion and the characteristics of this occurrence for the entire country of Slovenia. Due to the dynamics of illegal waste disposal sites, the results of his study are recently outdated, whereas the methodological content can be regarded as the basis for further research work on FWDS. The estimated values of the collective number of illegal waste disposal sites, the disposed amounts and the areas of disposing waste in the case of Slovenia are shown in the Figure 1, taking the landscape types and morphological categories into account.

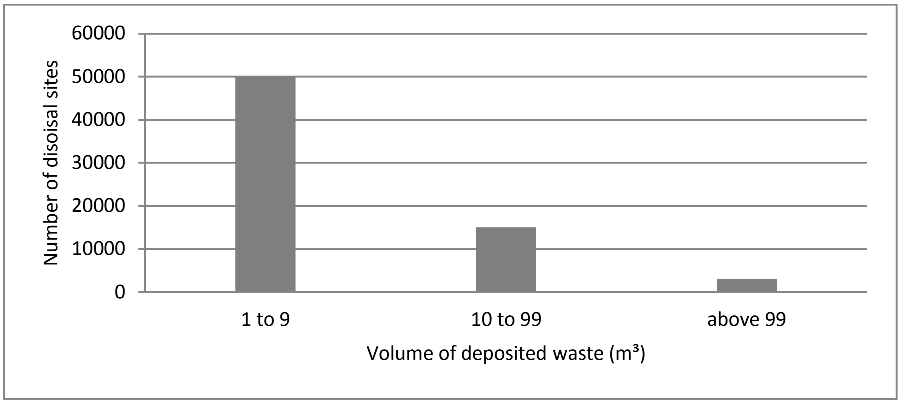


***Figure 1**: Projected values of waste disposal sites regarding their size, for Slovenia (Šebenik 1994).*

The projection showed that the total volume of waste amounted to approximately 2 million m³ on a surface of 6 km² (the area of disposing waste). The study also evaluated spatial indicators of illegal waste disposal sites in various landscape types of Slovenia (Table 1).

indicator	Slovenia	**accessible areas***	**plains**
illegal waste disposal sites density (No. dumps/km^2)	**2.3**	7.5	**2.0**
share of disposal area	**0.4**	1.3	**1.5**
waste volume per area (m^3/km^2)	176	590	**1,059**

Table 1: *Spatial indicators of illegal waste disposal sites (Šebenik 1994).*
**About 30% of the surface, excluding steep, remote and inaccessible areas.*

A more detailed research on the entire surface of Slovenia would undoubtedly show many unrevealed burdens in gravel pits, clay pits and also karst dolines, gorges, caves and other landforms. Alongside industrial and construction waste, illegal dumping of houshold waste was one of the main factors of the formation of illegal waste disposal sites in the past. The waste disposal was best regulated in more urbanized plains and valleys, in the vicinity of municipal centers and other major cities, or better said, in areas where the density of the population is the highest and the accessibility the best (Šebenik 1994).

Waste disposal sites, in general, are spatially very dispersed, differently sized (many smaller areas), with waste of different levels of toxicity and diversified environmental effects. From the landscape-ecological perspective, illegal waste disposal sites are the most important environmental consequence of unsustainable dealing with waste (Šebenik 1994). Previous researches in Slovenia have been mainly based on field registers and have dealt with visible illegal waste disposal sites (can be seen on the surface). Knowledge of such researches on waste disposal sites is important from the perspective of this research, due to the fact that active visible illegal waste disposal sites noted down thirty years ago are completely filled in today and are regarded as FWDS.

2.3 Legislative Provisions

The normative disposition of dealing with waste was one of the least regulated areas of environment protection in Slovenia for several years, although waste represents an enormous source of pollution and threat for every environmental element. The reasons for such non-regulation stem from the past attitude of the society when dealing with waste and the manner of disposing waste, the lack of municipal and expert harmonization and organization, the economic measures and natural characteristics of Slovenia as a country (Viler Kovačič 2001 cited in: Smrekar et al. 2005). The knowledge of regulations is necessary for including the studied issue into a broader context of dealing with an endangered environment.

The **Act of dealing with waste** (UL SRS 8/1978) has been the foundation for dealing with waste since 1978. With this act we bound ourselves to preventing and reducing any further formation of waste and to try and recycle waste and deal with waste with caution in a suitable and harmless manner for the environment. This act was supplemented with the **Decree of dealing with waste**, **which includes dangerous elements** (UL SRS 20/1986). When the **Act of environment protection (ZVO-1),** (UL RS 32/1993 with anexes) came into effect in 1993, started the issue of environment protection and dealing with waste stated being dealt with in a completely new manner. The act followed some modern trends and acquired important solutions from international acts and laws of developed countries. The Act was valid till 2004 when the new **Act on environment protection (ZVO-2**) was introduced and accepted (UL RS 41/2004 with anexes).

Slovenia becoming a member of the EU contributed to better ways of managing and dealing with waste, mainly regarding waste separation and transportation. A great issue still exists from the point of illegal waste disposal concerning construction waste, which represents the biggest part of waste in active wild dumps (Smrekar 2007). The EU has passed many directives on dealing with waste in the past decades. Based on the Strategy of dealing with waste (Communicatin to…1989) and the **Fifth environmental action program** (Resolution on…1993), the EU dealt with the issue of waste on the level of systematic directives on waste. In the late 80's and during the 90's, the European Union passed some directives regulating the following: (1) special types of waste (accumulators, batteries, mineral oils, PCB) and (2) ways of disposing waste (incarceration and dumping).

The **Landfill Directive 1999/31/EC** of 26th April 1999 on the landfill of waste entered into force 16 July 1999. The deadline for the implementation of the legislation in the Member States was 16 July 2001. The objective of the Directive is to prevent or reduce the negative effects on the environment caused by the landfilling of waste as far as possible by introducing stringent technical requirements for waste and landfills. The Directive is intended to prevent or reduce the adverse effects of the landfill of waste on the environment, in particular on surface water, groundwater, soil, air and human health. It defines the different categories of waste (municipal waste, hazardous waste, non-hazardous waste and inert waste) and applies to all landfills, defined as waste disposal sites for the deposit of waste onto or into the soil. The landfills are divided into three classes:

- landfills for hazardous waste,
- landfills for non-hazardous waste,
- landfills for inert waste.

The Directive sets up a system of operating permits for landfill sites. The member States must ensure that existing landfill sites may not continue to operate unless they comply with the provisions of the Directive as soon as possible.

Normative regulation on dealing with waste in Slovenia started evolving as late as in 1998, when the **Decree of dealing with waste** (UL RS 84/1998 with annexes) was accepted as the basic regulation for dealing with waste and not represents the basis for new regulation. It was followed by various regulations focusing on dealing with waste:

- the decrease of potentially dangerous waste already at their core,
- the increase of elemental and energetic use of waste and the reduction of emissions of greenhouse gases,
- the formation of an effective system for dealing with waste and a gradual abolition of old burdens.

The **EU legislation** was taken into account, as Slovenia obliged itself to acquire and establish the EU legislation on the matter of dealing with waste upon becoming a member of the EU. The new **Act of environment protection (ZVO-2)** (UL RS 41/2004 with anexes) follows the EU directives and pays much attention to dealing with waste, as it has anticipated further ways of dealing with waste with a whole array of executive acts.

This decree was the **Statute of waste disposal** (UL RS 5/2000 with annexes, UL RS, 41/2004-ZVO-1, 43/2004, 32/2006). Until March of 2006, it determined all the necessary actions and other conditions for the disposal of waste, as well as all the conditions and measures in connection with planning, building, managing and even closing down waste dumps. The statute was subject to changes in 2004 (UL RS 43/2004), with new limit values for the disposal of waste as well as various categories of waste dumps, enabling the use of new European criteria for the collection of waste on waste dumps. Instead of the aforementioned statute, the **Ordinance of disposing waste onto landfills** (UL RS 32/2006) came into use with various annexes, not significantly altering the statute.

The key act to more comprehensive knowledge and solutions of this issue was the **Statute of burdening the soil with waste** (UL RS 3/2003), which defines the conditions on burdening the soil with waste and the necessary actions when planning and realizing the input of dredging spoil or artificially prepared soil due to the improvement of the ecological state of the soil. The latter is currently especially interesting for the rehabilitation of gravel pits; the empty ones, as well as those filled with waste. **The operative program for dealing with construction waste for the period between 2004 and 2008** directed the quantities of construction waste, which was allowed to be disposed onto dumps with non-dangerous (mostly communal) waste or with uncontrolled disposing from wild dumps, to registered centers for the modification of the construction waste. An effective system of dealing with construction waste would help to achieve the following solution, among other goals "…the use of the remainder of the waste by modifying the construction waste (around 10%) and using construction waste from earth excavations (around 40%) in order to input it into or onto the ground as a process of modifying waste in order to ecologically improve the soil and to fill in natural depressions or areas of strip mining within their rehabilitation" (Operative program… , 9-10).

The **Ordinance about limit values of the input of hazardous elements and fertilizers into the soil** (UL RS 84/2005) determines the limit values of hazardous substances and fertilizers for the soil during the input of mud from waste water treatment plants, or compost or silt from riverbeds and lakes as well as the limit values during the processes of irrigation and fertilization.

The ordinance about the changes and the completion of the Ordinance of disposing waste onto landfills (UL RS 53/2009) came into use on 9 July 2009 and drastically changed the current system of disposing waste onto waste communal dumps in Slovenia. This ordinance brings the provisions of the 1999/31/EC Landfill

Directive into Slovene legislation. The inability to achieve certain goals with disposing biologically decomposing waste caused some waste dumps to become inactive. The needed values are noted in the following table. The new regional centers for dealing with communal waste were determined within the ordinance.

Waste management in Slovenia has improved since having entered into the European Union, especially in the field of waste separation, collection and carting off. However, the illegal and non-controlled waste disposal into nature remains one of the crucial issues of the Slovene waste management system. Construction waste is inert and mostly non-dangerous or toxic and represents the biggest problem; however, it has a big recycling potential. Construction waste has the highest portion among the other waste types in today's active illegal waste disposal sites (Smrekar 2007).

The predominant way of dealing with waste in Slovenia is still removing waste from their point of origin and putting it in more or less regulated waste disposal sites which can be also called landfills. Society puts the main emphasis on the need to remove waste from their point of origin on one hand, while on the other it has a negative relationship towards objects which handle waste in different environments.

3 LANDFORMS – ‘ATTRACTIVE’ FOR WASTE DISPOSAL

3.1 The Doline (Sinkhole) - Representative Karst Landform

Dolines or sinkholes are closed relief depressions with internal drainage that are characteristic features of karst landscapes (Figure 2). They display a wide range of morphologies (cylindrical, conical, bowl or pan-shaped) and are up to several hundred meters across and tens of meters deep (Gams 2003; Ford and Williams 2007). The term dolina (slo. *vrtača)* is widely used and derived from *dolina,* an everyday Slovenian expression for a valley (Gams 1994). The word doline is used in European literature while dolines are called sinkholes in engineering and North American literature (Sowers 1996; Beck 2003; Fookes 200; Waltham et al. 2005 cited in: Ford and Williams 2007). The mental picture of word doline is a subcircular bowl or funnel-like depression while of sinkhole is a form which has originated through a gradual or sudden lowering of a portion of the topographical surface (Sauro 2003).

Figure 2*: One of the last perfectly preserved dolines on Pusto polje (Logaško polje) is approximately 6 m deep. All the dolines around it are filled.*

There are several genetic types of dolines developed by different processes and in different materials, rocks: solid carbonate karst rocks (limestone, dolomite), residual soil material or allogenic unconsolidated deposits (clay, loam etc.) and non-karst rocks (Williams 2003; Beck 2003; Waltham et al. 2005; Gautierrez et al. 2008). Several genetic classifications of dolines have been published (Williams 2003; Beck

2003; Waltham et al. 2005; Gautierrez 2008) and used in theory and practice. These classifications distinguish two main categories of dolines—those resulting from dissolutional lowering of the surface and those created by internal Erosion and deformational processes caused by subsurface karstification (Gautierrez et al. 2008). The main doline types, regarding the most cited categorizations (Williams 2003; Sauro 2003; Beck 2003; Waltham et al. 2005; Gautierrez et al. 2008) are listed and shown (Figures 3 and 4) in continuation.

The **solution dolines** are mostly bowl-shaped forms. They are formed by solution of carbonate bedrock, where the greater mass of rock has been removed from their centers than from around their sides into karst underground (Gams 2003; Ford and Williams 2007). The main factor in removing of rock is water that infiltrates and percolates through cracks in the carbonate rock into karst underground. The bottom of dolines is covered by loamy or clay deposits (sediments).

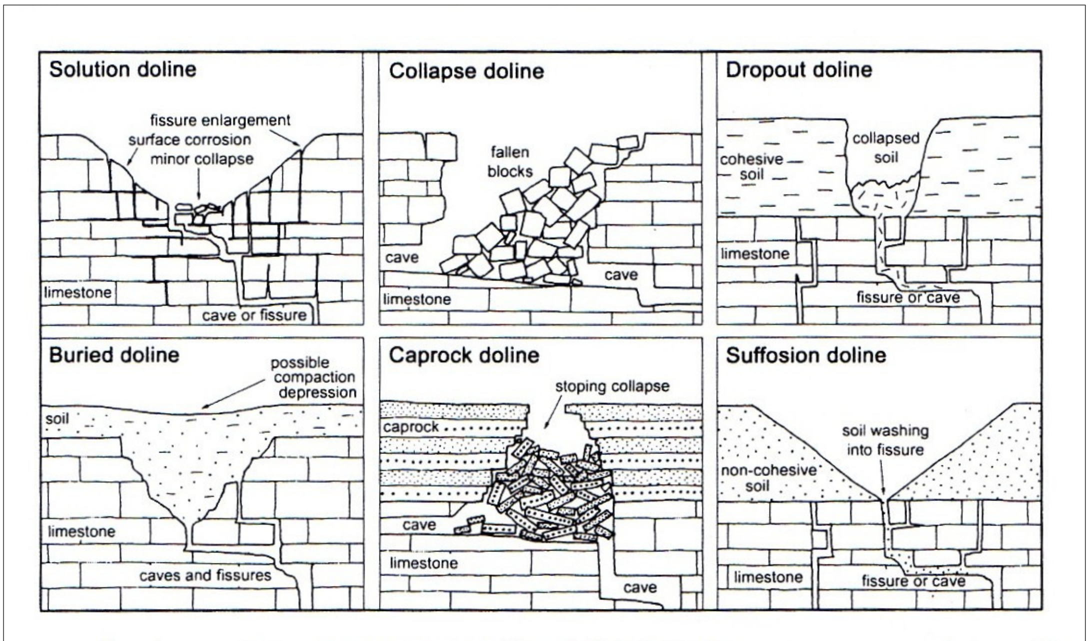


***Figure 3**: The main doline categories according to Ford & Williams categorization (2007).*

The **collapse dolines** are formed by the collapse of the roof of a cave. In Slovenia they were studied in detail by geographer Stepišnik (2006).

The **Cover collapse (dropout) dolines** form by the upward propagation of breakdown cavities through cohesive and brittle but unconsolidated cover above dissolutional voids (Ford and Williams 2007). Such dolines frequently develop with catastrophic rapidity and have cliffed or overhanging sides. Old cover collapse dolines may be difficult to differentiate from suffosion dolines since they tend to degrade into conical or bowl shapes (Gautierrez et al. 2008).

The **cover dolines** (Sauro 2003; Gautierrez et al. 2008; Beck 2012) or **suffosion dolines** (Ford and Williams 2007) and also called **alluvial dolines** (Gams 2003) result from the downward migration (suffosion, collapse, raveling) of cover material through dissolutional voids and its ductile settling (Sauro 2003; Gautierrez et al. 2008). These dolines are commonly funnel or bowl-shaped depressions and may reach more than 10 m in diameter

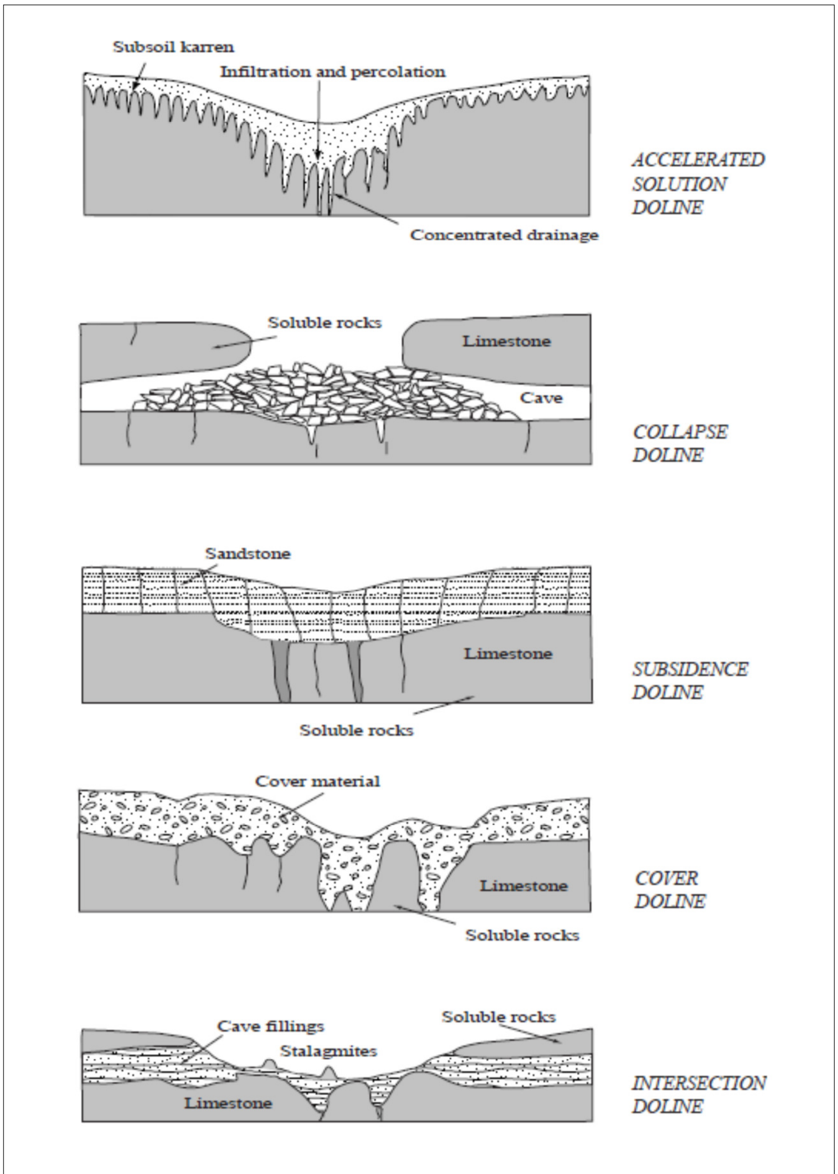


Figure 4*: The main categories of dolines (Sauro 2003).*

The **subsidence dolines** are closed depressions which originate from the settling down of a surface area of an insoluble rock such as sandstone, following the mass wasting by solution of an underlying soluble rock (Sauro 2003).

Among all listed doline types Mihevc (2001) exposed also the speleologic point of view on doline genesis by exposing another type of doline form called "**roofless caves**" or "**unroofed caves**" or by Sauro (2003) **intersection dolines** (Figure 4). This type of doline forms following the intersection of empty or filled caves by the topographical surface and evolves by the weathering and hydrological processe triggered by such an event (Sauro 2003).

3.2 Natural and Anthropogenic Landforms of Alluvial Gravel Plain

The important natural landforms that have formed in alluvial plains are **relict (dry) riverbeds** through which the rivers do not flow through anymore in the present. These are longitudinal concave relief shapes that can be identified in the relief as lowerings in altitude, which is clearly visible on very precise Lidar relief models. Dry relict riverbeds are the remains of past hydrogeological and geomorphological processes and could be recognized in recent landscape in different ways, for example in geomorphology, vegetation and soil moisture and even visualy on aerial photographs (Figure 5).

Figure 5*: Relict river beds in the landscape of Ljubljansko polje. The photography was taken from the balloon (Photography: Aleš Smrekar).*

The most important landforms in alluvial plain regarding waste dumping are of anthropogenic origin – different extraction pits (gravel pit, sand pit, clay pit). Biger and smaller excavations occurred in the past periods (often in the shape of a land lot) in all Slovene alluvial plains (Ljubljansko polje alluvial plain, Dravsko polje alluvial plain, Ptujsko polje alluvial plain, Krško-Brežiška ravan alluvial plain, Kamiško-bistriška ravan alluvial plain, Kranjsko-sorško polje alluvial plain etc.). Some have been preserved to this day as concave landforms, some have been overgrown with vegetation (Figure 6), some overflown by groundwater and many filled with waste.

Figure 6*: The abandoned gravel pit is already overgrowing with pioneer plants.*

Several scientific studies and publications showed that the issue of gravel pits in Slovenia is not a new phenomenon. It was mainly dealt with by experts from different technical fields, mostly in combination with solving individual cases or the possibility of the excavation of gravel. Gravel pits in general were studied by Hanjže (2001), Jakič (1995), Konjar (2001) and Vogrin (1994), while Kosmač (1988), Kušar (2000, 2001a, 2001b), Breg and Urbanc (2005) concentrated mainly on the illegal waste dumping in gravel pits. Large amounts of easily accessible gravel along the main rivers after WWII (post-war reconstruction, the development and expanding of cities) enabled digging up gravel and the formation of numerous gravel pits. After digging up was abandoned, these gravel pits became a "suitable place" for disposing waste, with which these gravel pits were subjected to "remediation" (Breg and Urbanc 2005).

In Slovenia, estimations point to several thousand non-active gravel pits of sizes between 10 m² and 10,000 m². In the area of Ljubljansko polje alluvial plain alone, several hundred gravel pits were registered with a total surface of over 200 ha, amounting to more than 3% of the plain. Most of the gravel pits are left to the forces of nature after the production of waste stops. However, they are more often given over to the dumping of different types of waste (Radinja 1951 cited in: Konjar 2001).

***Figure 7**: The abandoned gravel pit is in the phase of fillilg with waste.*

Gravel pit is an anthropogenic landform that is very dynamic in its spatial development. In the excavation period, their shape is concave, changing and growing in size during the time of excavations. The anthropogenic relief re-shaping is most expressed in distinct concave (basins of unfilled gravel pits) and convex (embankments) landforms. After the excavations cease, the relief shape remains concave and is swiftly overgrown by pioneer vegetation. The gravel pits that had been filled with waste may be partly (Figure 7) or completely filled. The partly filled gravel pits retain a concave shape, while most of the filled gravel pits have only a slightly convex or concave ridged surface.The waste-filled gravel pits do not particularly stand out in the recent relief, as they were leveled with the surrounding relief when they were filled.

4 THE SELECTION AND PRESENTATION OF STUDIED AREAS

4.1 Sampling Criteria

The selection of studied areas is based on non-contingent sampling. "… *Units become part of the sample after a subjective estimation and a possible preliminary analysis. We limit ourselves only to those units, which are most representative for the entire population. Such sampling of units is also known as choosing the typical units. Seeing that our unit sampling is intentional, with the purpose of adequate representation of the population, we acknowledge such observation as an intentional sample …* (Košmelj and Rovan 1997, p. 37)*."* Sample areas, which were subjectively chosen, represent typical units from the perspective of forming FWDS over several years in natural and anthropogeneous relief basins. On the basis of preliminary studies in Slovenia (Šebenik 1994; Bricelj 1988; Kušar 2000; Smrekar 2007 etc.), the landscape types that are most exposed to illegal waste dumping are the Alpine and Pannonian plains, Dinaric valleys and plateaus, Pannonian hills and Mediterranean flysch highlands. These landscape types have already been densely populated in the past and have been exposed to various production-modification activities, which resulted in larger waste quantities.

The research limited itself on two case study sample areas (Figure 8), which represent two different flat landscape types (Dinaric plateau, Alpine plain (Perko 2008)), for which different relief basins are typical. Within the chosen karstic landscape type, dolines were mainly exposed to disintegration. On non-karstic gravel plains, waste was mainly deposed into abandoned and non-rehabilitated gravel pits:

- **Case study area 1** (Dinaric plateau): the karstic area that includes **Logaško karst polje and surrounding karst plateau**;
- **Case study area 2** (Alpine plain): the non-karstic area that includes the**Ljubljansko Polje gravel plain**.

The two chosen landscape types are traditionally densely populated landscape types. In both areas many industrial plants operated after WWII. Due to illegal waste management and a lack of environmental legislation, various dangerous industrial waste (galvanic sludges, organic industrial waste, chemical waste, etc.) were dropped in areas of smaller legal communal waste dumps and into natural or anthropogenous landforms.

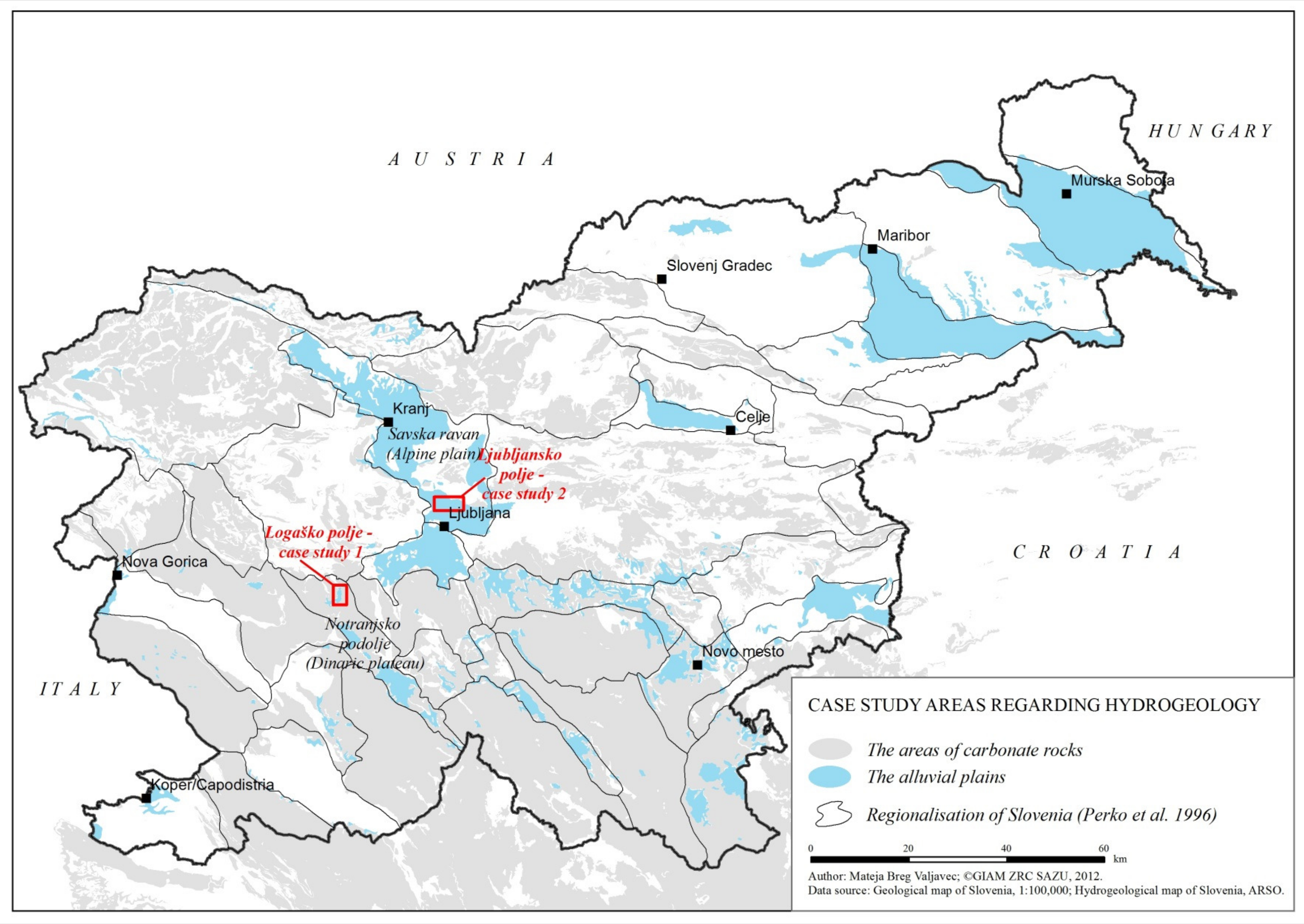


Figure 8: *The research limited itself on two case study sample areas, which represent two different flat landscape types.*

4.2 Presentation of Doline Case Study Area – Logaško Karst Polje

4.2.1 Karst Polje and Dolines

Logaško karst polje is an example of long-term human intervention onto karst geomorphology, where degradation processes of dolines have been very intense during the last fifty years. The previous analyses showed that 78% of dolines have completely disappeared mostly by being filled up with different waste materials (excavation material, municipal, industrial and building waste, etc.) or they were built up, while 22 % of dolines have been entirely or partly preserved (Breg 2007). The preliminary studies (Smrekar et al. 2005) indicate that active illegal waste disposal sites contain the highest percentage of construction waste (more than 70%), while the percentage of municipal waste is decreasing. Considering these facts in combination with a growing migration and an increased interest for new or better lodging facilities on the Logaško polje, the filling up of dolines with construction waste will most likely continue in the future.

The intensity of anthropogenic processes in bigger centers in the karst regions along major transport corridors is on the rise. It should be pointed out the urban and agricultural karstic areas with a higher population density (the area of Logaško Polje) is still topical where there were and still are some anthropogenous sources and natural characteristics for the formation of illegal waste disposal sites and where filling in of dolines with construction waste occurs. On the surface there are basins, in which people have been dumping communal waste from near-by towns and industry for decades (Šebenik 1994; Bricelj 1988). The characteristics of karstic study area 1 have attracted past waste disposal, which is mainly located in dolines (Šebenik 1994).

The characteristics of dolines on the studied area are basically a result of hydrogeological conditions and processes that are still shaping Logaško polje. Logaško polje is a part of Logaški ravnik (Logatec plateau) (in Slovene *Logaški ravnik*). It is an overflowing ponor karst polje (29 km^2) and is deepened on the far north-west part of the Logatec plateau on the contact point between dolomite and limestone. A large portion of the karst polje lies on dolomite, while limestone at the altitude of the plateau represents a 10 to 15 m higher rock cut terrace (Mihevc 1979).

The northern and western parts of the polje consist of **Early Triassic layered dolomite**, with layers from 0.5 to 1 meter thick. Permian deposits of **flint sandstone** and **clay slate** appear on the far north edge of Logaško polje. Lower Cretaceous and Cenomanian deposits can be found on the south-east and east part of Logaško polje and consist of a range of **grey and dark grey platy limestone**, intermitted with **grainy bituminous dolomite** a few centimeters in thickness. The contact between the Upper Triassic and Lower Cretaceous limestone runs along the Logatec fault on the east side of the polje. On the bottom of the polje, located at an altitude between 470 and 480 meters, lie **Quaternary river and stream deposits** (Figure 9) of an average thickness of 3 to 4 meters (Geological Map of SFRY, 1963).

The southern part of Logaško polje near Gorenji Logatec is a widened fluvial valley, formed at the confluence of Reka and Črni potok, continuing into a fossil blind valley towards the south (Mihevc 1979). The Reka and Črni potok streams, which spring in the surrounding dolomite hill regions west of Logaško polje, merge into Logaščica in Gorenji Logatec, which sink into a ponor after three kilometers of surface flow on the eastern edge of Logaško polje in Dolenji Logatec. In the last few hundred meters of the surface flow, where the thrust of the dolomite to limestone ends, Logaščica has carved a 30 meter deep canyon. Logaščica sinks into the Jačke ponors, merging with the waters running from Planinsko polje underground and then reappears on the surface at Vrhnika in the karst springs of the Ljubljanica River to the west of Retovje springs. The Logaščica River is an expressed torrent stream, as its catchment area runs on a poorly porous dolomite surface, which is the reason why most of the water runs on the surface (Nagode 2002). The capacity of the Jačke ponors in which Logaščica sinks is limited to 15 to 20 m^3/s; consequently, floods occur (Mihevc 1979). The water rises from 410 m of altitude at the ponor to the height of 474 meters. However, such floods are rare and occur every 10 years on average (Mihevc 1979). There is 20 km^2 of flooding surface on Logaško polje (Šušteršič 1994).

The spatial distribution of the dolines on Logaško karst polje and the surrounding Logatec plateau is conditioned by the lithological characteristics of the hosting rock. Regarding this, basic doline zones (Figure 10) with different doline types may be distinguished:

1. Dolines on limestone are represented by **solution dolines** and **collapse dolines**;

2. Dolines on dolomite are represented by a **solution type of doline,** beside this, some dells can be found here**. Dell** (Komac 2006) is a trough-shaped valley or a flat

floored valley, typical on dolomite areas. Komac (2006) studied in detail the morphological and genetic characteristics of dells at the Logatec plateau.

3. Dolines in alluvial (Quaternary deposits) parts of the karst polje are formed by suffosion processes and are called by some authors as **suffosion dolines** (Ford and Williams 2007) by some authors as **cover dolines** (Sauro 2003, Beck 2003) and also **alluvial dolines** (Gams 2003). In the present research the term cover doline was selected.

Figure 9*: The collapse cover doline (dropout doline) on Pusto polje near Valkarton company. It was formed by anthropogenic water runoff from the roof of the company building (Gams 2003, p.171).*

Dolines on limestone and dolomite are larger than those appearing on Quaternary deposits (cover dolines); their density is lowest on dolomite and highest on limestone, while dolines do not appear on Permian rocks. Cover dolines are the smallest. In addition to the lithological base, the general morphometric characteristics of the surface (incline and exposition) also influence the density, shape, and size of the dolines (Ravbar and Zorn 2003).

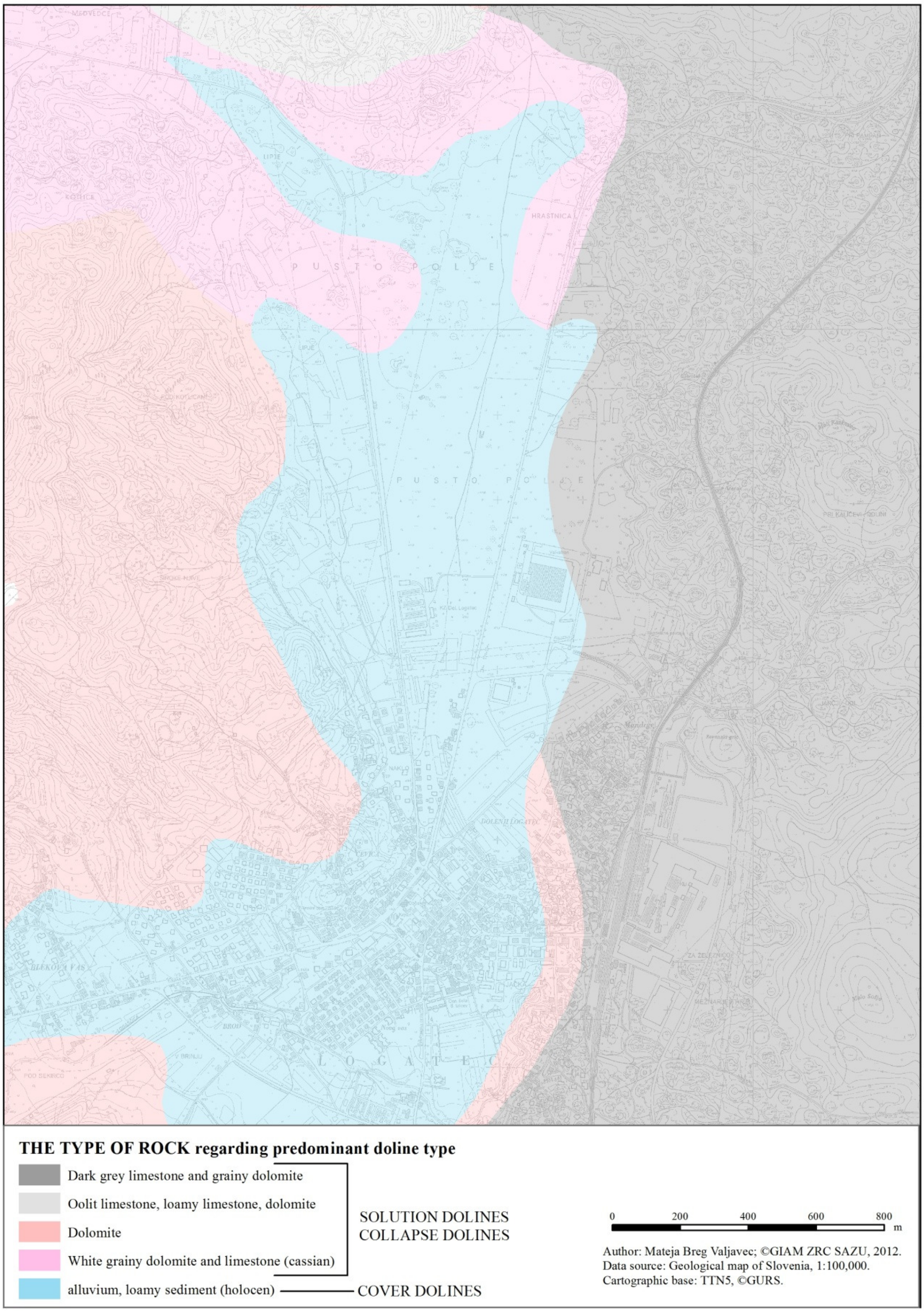


***Figure 10**: The areas of dolines in relation to the type of hosting rock material.*

4.2.2 Socio-economic Factors for Waste Disposal

The first anthropogenous interference into the landscape of Logaško polje and the beginning of degradation of the dolines were **traditional agricultural activities**. In the majority of cases, this involved filling smaller karst depressions, mostly cover dolines (alluvial subsidences) in the alluvial part of the karst polje, with allogenic material (rocks and soil) with the intent to create a field or a meadow on the more flattened surface; in some places with the intent to enlarge the house's yard or enable easier access to the house. Simple, mostly harmless, household waste was disposed in dolines in that period.

The formation of the first dumps with non-communal waste was a result of the **railway transport** in the period after the establishment of the Southern Railway through Logatec (in 1850s). At that time, cinders from steam locomotives were dropped in near-by dolines. Many dolines were intentionally filled in and leveled with the surrounding surface with material from railway mounds of the former Logatec – Idrija railway connection (WWI). After WWII, when the quantity of communal waste from households started to rise, the authorities in the area of Logatec started with the organized gathering and disposal of waste into dolines, which were intended for just that.

Extensive **agromeliorations** were launched in 1986; at first along the Logaščica River and later on Pusto polje in 1987 and 1988. 12,000 m^3 of material was used for the purpose, which initially served as material for building the railway embankment from WWI. Even today, farmers in the area of Lipje and Pusto polje still fill the areas where alluvial subsidence in Quaternary alluviums occurs.

In the period of **industrialization and urbanization**, karst depressions were filled with different waste, the largest share of which was houshold waste along with industrial and agricultural waste, while construction and demolition material were used only for the final covering. After WWII, the number of inhabitants in Logatec grew rapidly and amounted to 7,600 inhabitants in 2002. Especially after 1970, this growth was accompanied by the construction of apartment buildings and individual houses. After WWII, the construction of industrial complexes began in Logatec as well. The KLI wooden furniture factory was opened along the railway in Dolenji Logatec in 1953. Today it is almost impossible to determine the composition and the amount of the KLI Logatec waste, with which the dolines were filled. In addition to the industrial waste that was used to fill the majority of the near-by dolines on very porous Lower Cretaceous strata, they were also filled with environmentally dangerous galvanic sludges, which were generated as a by-product of the galvan operation for three decades (up to 1982) (Bricelj 1988). In 1971, the Valkatron (paperboard production) and Konfekcija factories (textile industry) were opened in Pusto polje and a smaller substation in the vicinity. A larger agricultural plant was built along the road toward Rovte on Pusto polje (Pagon 2008).

With the handicraft and industrial workshops, new forms of hazardous waste products arrived that were dumped under no control until the introduction of adequate legislation and the setup of regulated waste disposal sites. Different waste materials were used for the fill-up depending on their availability. With the growth of transport (railway), handicraft (blacksmith, charcoal-burning) and industrial activities (timber, cardboard-box and metal industry), hazardous waste was produced. Several FWDS that are already covered and overgrown contain heterogeneous and dangerous waste (sawdust, bark, industrial oils, galvanic sediment etc.) deposited thirty years ago or even earlier.

In the study of illegal waste disposal sites on the area of Logaško Polje, Bricelj (1988) concluded that the majority of industrial waste disposal sites of the aforementioned timber company was already at that time filled in. *"…The structure of waste, with which the dolines were filled in, is impossible to determine today, only guesses can be made about their structure on the basis of water analyses in the mouth of the Ljubljanica River …"* (Bricelj 1988). The mentioned study was based on the field inventory of the current state at that time and did not take into account the past state. "…*Taking Into account the fact,that within the combine of timber industry the galvans functioned for three decades (till 1982), we could make a conclusion about the substantial quantities of galvanic sludges, which were disposed into dolines along with other industrial waste. Residuals from paint rooms, as for example trichloroethylene, were also disposed into near-by dolines without any problems …"* (Bricelj 1988). According to Bricelj, the mentioned company still used five locations in their immediate vicinity in 1988, which raises an additional question about the quantity, structure and potential level of danger of waste after the 1988.

4.2.3 Environmental Impacts of Filling the Dolines

Over a few decades after WWII, waste disposal sites in dolines became an irrefutable anthropogenous landscape element. Illegal waste disposal sites in dolines were studied in detail by Igor Šebenik (1994) in the scope of a research on illegal waste disposal sites in Slovenia. The author ascertains that areas with "suitable" locations for illegal dumping have several characteristics: they are accessible, less visible (relief depressions), covered by vegetation, remote, non-functioning and uninhabited. The two thirds of dolines filled with waste are located in the forest or are covered with a bushy-vegetation. Less than 15% of waste-dolines are in the form of meadows or abandoned pastures (Šebenik 1994).

Dumps in dolines are most commonly unspecific (these represent 84% of the waste), some are periodical or private. On both, larger and smaller dumps, mixed waste materials (including waste from households) prevail. A large part is in the form of dug material and tailings as a residue of different activities (e.g. house-construction), which are being transported to illegal waste disposal sites together with the rest of the waste. This kind of unusable material is very common in karst areas and in many cases represents the majority of waste materials. 75% of waste disposal sites are accessible through roads and only 10% of the waste is dumped beyond. Dolines are furthermore favorable dump locations due to their steep slopes that make depositing simple. In karst areas it is common to believe that dolines need to be filled up since they are only pointless and limiting holes (Šebenik 1994).

Filling in dolines does not only affect the rise in the danger of chemical burdening of the environment, but also permanently transforms the natural relief forms as well as entire areas, where these forms can be found. The environmental effects change with the intensity of interferences regarding dolines. "…*Waste dropped in nature in greater amounts forms a new habitat for flora and fauna – a secondary habitat ...*" (Geister 1999). A waste disposal site has specific growing conditions, which are like ecological niches for vegetation (Maurice 1998). In the area of an illegal waste disposal site such vegetation can be found, which can take advantage of these aforementioned niches, formed due to specific micro-factors, while the surrounding vegetation is represented in smaller numbers.

The effects of waste dropping are also seen in the karst groundwater system. "… *How the karst water system responds to pollution can clearly be seen from the Berlin* *and Graz cases. After WWII, when the city ruins were mainly dropped in a big gravel pit, they noticed that the groundwater, which was there and streamed through gravel or conglomerate (or limestone) became so hard that it was not even suitable for washing clothes …"* (Gams 2003 p. 240). Due to the fact, that construction waste is mostly inert, they are usually found in illegal waste dumps. As such they are ideal for filling in different depression forms and as such physically transform the relief.

Karst is a chemical laboratory (Gams 2003 p. 65). The most significant chemical reaction happens among various types of limestone ($CaCO_3$), water (H_2O) and carbon dioxide (CO_2). The reaction is reversible with its balance changing regarding changes in temperature and the partial pressure of carbon dioxide. Waste disposal sites are a source of polluted landfill leachate, gases and solid waste, which influence the reaction and the speed of limestone dissolving (Medved 2005). Decomposing gases stay in dolines longer due to their concave form and as such have a great influence on the corrosion intensity. During the anaerobic decomposition of biologically decomposing waste, biogas is formed due to the presence of microorganisms. Biogas is an energetically useful gas mix, consisting of methane and carbon dioxide (Medved 2005).

Waste dropped in nature in greater amounts forms a new habitat for flora and fauna. The waste site is often a "floristic Babylon", as seeds and other forms of cultivated pot plants are introduced in addition to the waste. Alongside stray dogs, cats, and rats, several species of neighboring birds are among the waste site visitors that nest there. Such initially uncovered waste disposal sites and dolines were often "remediated" by filling it with construction and demolition material or excavation material. However, filling the doline creates the conditions for a new habitat to form, which generally lasts a short amount of time. With time, they grow over and change the character of the barren land, which also happens when the habitats are built-up. This shortness of habitation upon settling the filling is taken into account as the flora and fauna adapt their life cycles to those short-termed "favorable" living conditions (Geister 1999). At first, pioneer plants, mostly weeds, mosses, and lichens appear and with time, other species start to flourish as well. With the intensity of interferences in the dolines, the environmental effects change as well. Filling the dolines has not only increased the danger of chemically straining the environment, but has also permanently changed the natural relief shape and area, of which it is an element. The reasons for such intensive degradation lie in decades of illegal waste management and especially the inhabitants' irresponsible attitude to nature in the present. A further reason is also the inappropriate and lacking legislation that would shield the space as a non-renewable natural source.

4.2.4 Ecological Awareness about Waste Disposal Sites

Logatec is and old carrier business town with an agrarian tradition and wood processing production, enabled by a strategic geographical location throughout its history and local natural resources (forest). The number of inhabitants in Logatec increased after WWII due to immigration, in accordance with the political introduction of industrial plants and social agriculture. The vicinity to Ljubljana and the easy access to the freeway and railway has resulted in a wave of new migrators. The relation of "native" inhabitants and the newcomers has therefore been tipped in favor of the latter.

With the population growth and production-activities, built-up surfaces and garbage quantities have increased. The municipality of Logatec produces around 4,000 tons of waste yearly (SURS 2005). Until the 90s, the public collecting of municipal waste was gradually introduced in Slovene settlements that until then had to dump their increasing amount of waste somewhere nearby. Later it was taken over by public companies that continued to dispose the waste in dolines.

In 2007, a survey was carried out among the Logatec inhabitants (No 200) on waste handling, which also included questions about illegal waste disposal sites. In addition to answering questions, the people were asked to mark all the FWDS they remembered on an aerial image from 2006. The locations were included in the evaluation of the geoinformatic analyses (Figure 12).

The results differ greatly depending on the individual. Some are not familiar with any, while some were familiar with quite a number of filled dolines. It mostly depends on their age and how long they have been living in Logatec as well as their interests and connection to the local environment. In accordance, the questionnaire sample was aimed to the older inhabitants, retirees who were most likely to be "natives" and was also willing to cooperate in the survey. 40% of the people who filled out the questionnaire have lived in Logatec for over 30 years and an additional 18% have lived here for more than 20 years.

Illegal waste sites are still a very common occurrence in Logatec in the present. This mostly involves filling dolines with construction and demolition waste, which is a consequence of a disorganized handling of construction and demolition waste on a national level, not sanctioning illegal waste disposal and the locals' interest to fill unnecessary basins. 28% believe that there are no illegal waste disposal sites in Logatec, 29% are not sure whether any exist, while 48% are more or less certain that illegal waste disposal sites do exist in Logatec (Figure 11).

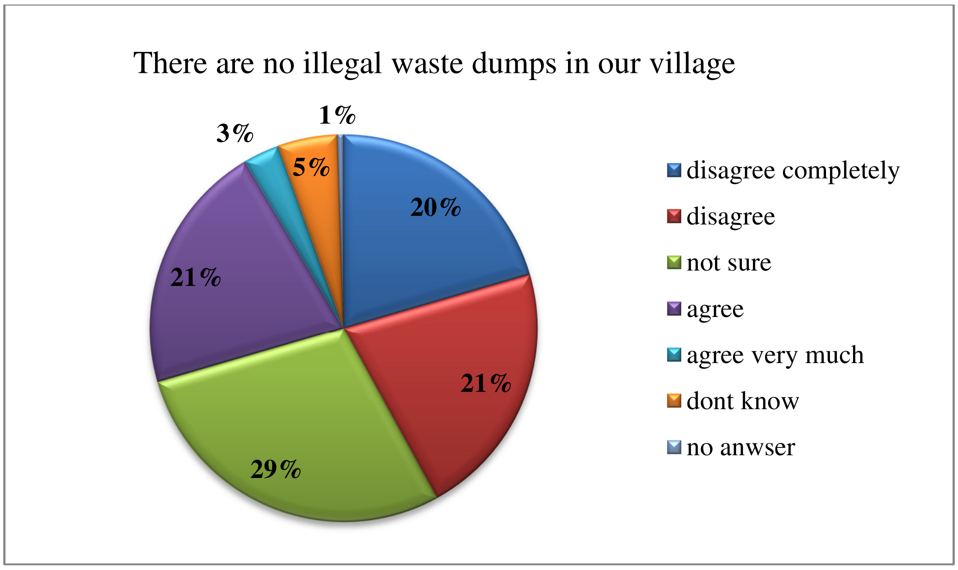


Figure 11*: Knowledge of illegal waste disposal sites among the locals.*

In line with this, it is interesting to note that almost half of the people participating in the survey do not notice illegal waste disposal sites in their surroundings or do not know about them and the other half do notice them. The results are directly proportional to the number of marked locations of illegal waste disposal sites on the aerial photographs of the recent landscape.

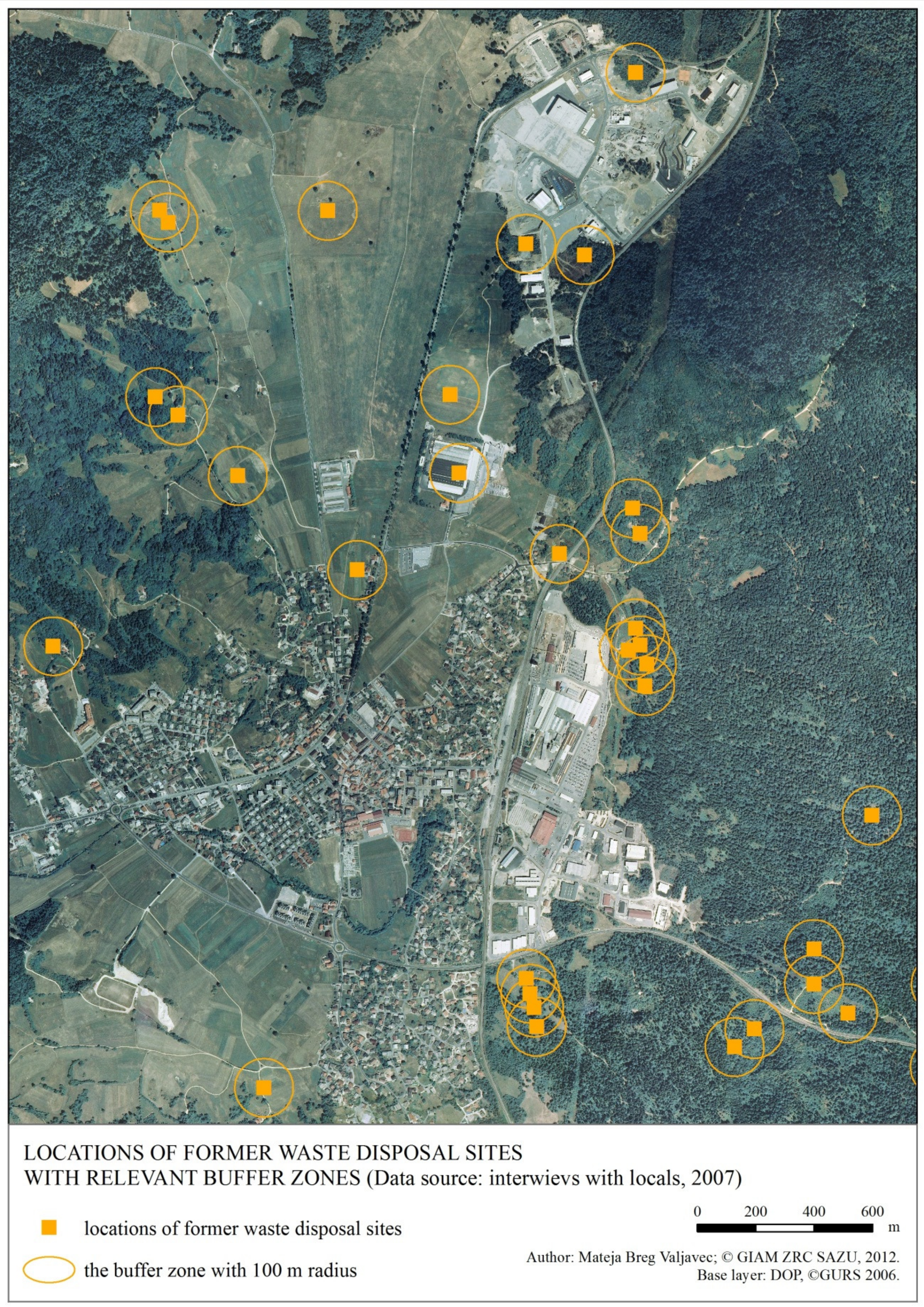


***Figure 12**: Locations of FWDS that people marked on the aerial photographs were used as a basis to determine potential dumping areas - buffer zones.*

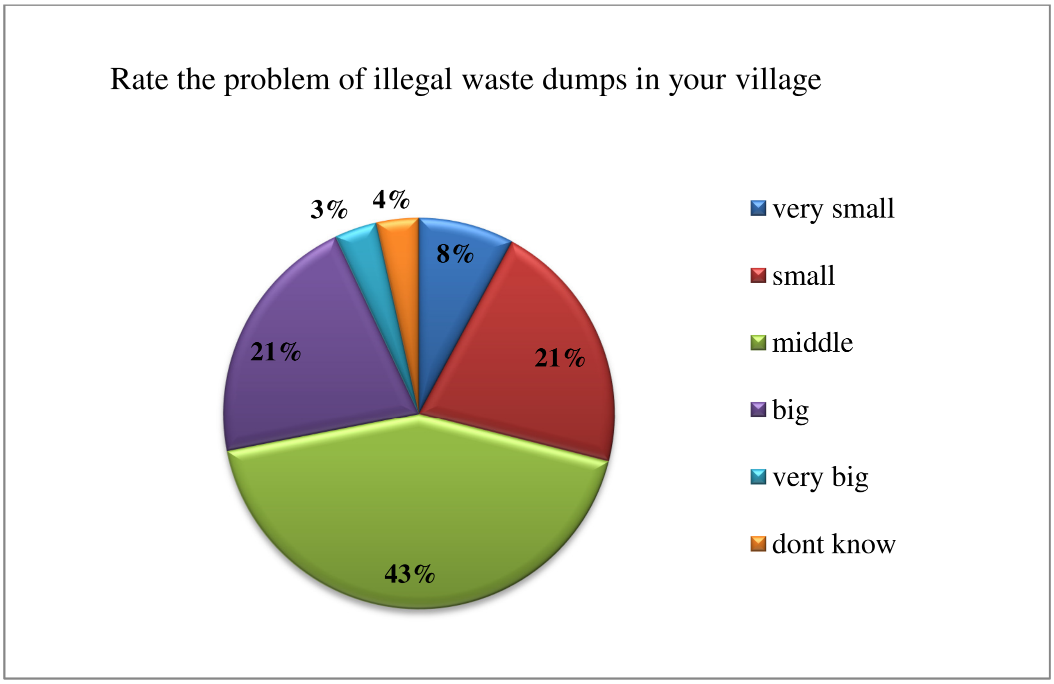


***Figure 13**: The problem of illegal waste disposal sites in the local surroundings.*

Half of the people believe that illegal waste disposal sites present a problem of moderate proportion to the town, about a quarter (21%) believe they pose a large problem and the same per cent believe they pose a small problem to the town (Figure 13). Only 14% believe that the number of illegal waste disposal sites in Logatec and its surroundings has increased in the last 10 years, while 12% notice the same amount of them and 63% believe the number as decreased. The number of newly-created illegal waste disposal sites with communal and industrial waste has drastically decreased with the introduction of organized separated collection and disposal of the mentioned waste, while we may once again stress the newly-created landfills of construction and demolition material and bulk waste in some places. Some locals (42%) are still not familiar with the fact that the local waste treatment center is obliged to receive waste without a payment demand, so they still take their waste to the illegal waste disposal sites in a doline (8%), as was the custom and the rule before 1979, when the Ostri vrh communal landfill in Logatec started operations.

In Logatec, as well as in many towns around Slovenia, there are several smaller privately owned filled dolines that served as local landfills for communal and other waste during the period of organized waste pickup (by the public services). The Slovenian legislation binds the lot owners to remove the waste and rehabilitate the area of the illegal waste disposal site. Rehabilitating such old environmental burdens is undoubtedly an excessive financial burden for the individual and should be taken over by the local community or the country. The inhabitants of Logatec are principally in favor of removing the illegal waste disposal sites (97%), where 72% think the local community (municipality) or the country should be responsible for this, 17% are not sure of it and 8% do not agree with this (Figure 14).

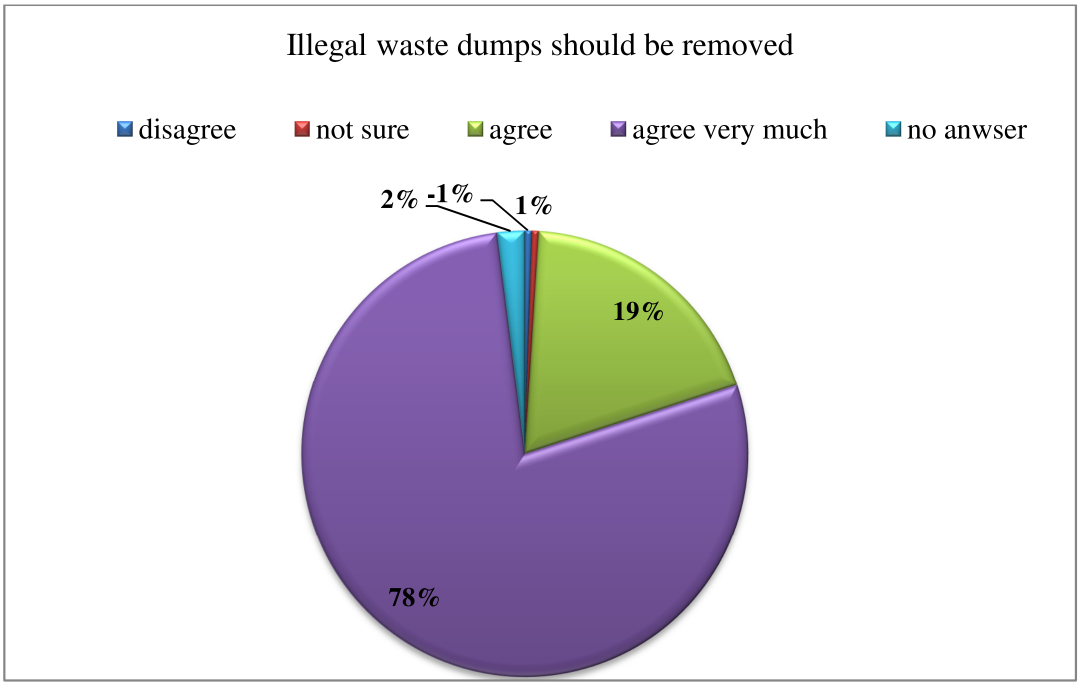


***Figure 14**: What to do with illegal waste disposal sites?*

54% are also prepared to pay 0.5 € to a special fond for the rehabilitation of illegal waste disposal sites if it were added to, for instance, the monthly bill for electricity. Some would be prepared to pay higher sums, although most remain under €2.

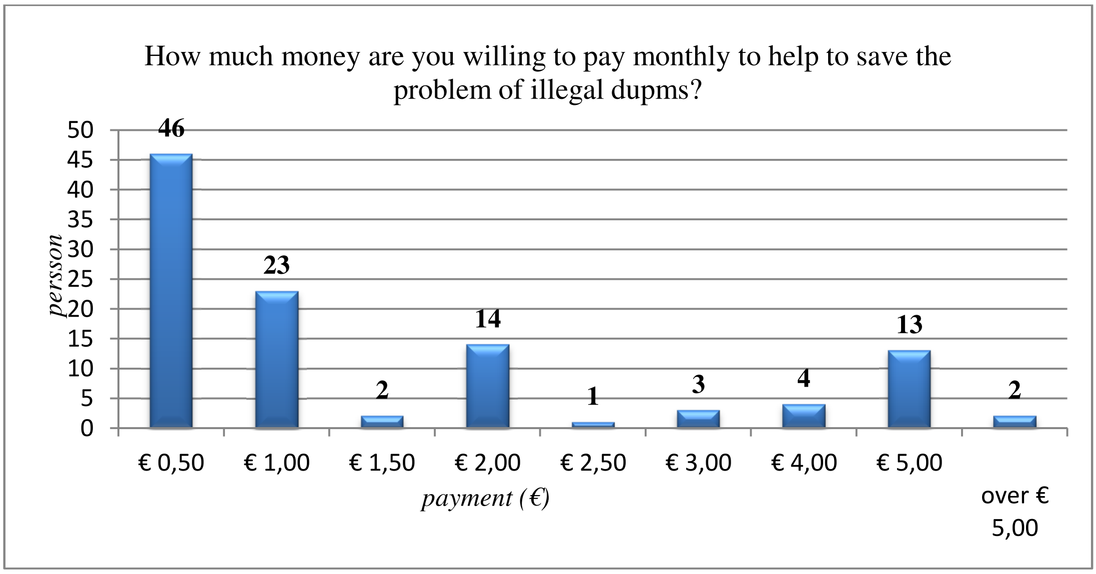


***Figure 15**: Willingness to cooperate in solving the problem.*

There are 2,460 registered households in the Logatec municipality. If half of them, in accordance to the percent of people participating in the survey, were willing to pay €0.5 in the rehabilitation fund, that would amount to €615 monthly, €7,380 annually. Quite a few years, even decades would be necessary to gather a sufficient amount to rehabilitate the waste-filled dolines. However, the locals believe that plenty of the filled dolines have been properly "rehabilitated" with extensive agromeliorations, when they simply covered the waste with a thick layer of soil and leveled the surface to a level that enables machine cultivation (e.g. mowing).

4.3 Presentation of Gravel pit Case Study Area – Ljubljansko Polje Gravel Plain

4.3.1 The Resources of Gravel Plain – Water and Gravel

Ljubljansko polje is a tectonic depression composed of rocks of a Permo-Carbon age that is clay slate with layers of flint sandstone (Bračič Železnik et al. 2005). The depression has been filled by rivers and streams for millions of years, the Sava River being among the most important, bringing gravel material from its upper stream. Several terraces on all sides accompany Sava: the highest Pleistocene and the lower Holocene terraces. During extreme floods in the past, the Sava riverbed could move by as much as 100 m. The riverbed shift is not the same along the entire length of the stream; it is most prominent on the Gameljški and Tomačevski prod ("*prod*" in Slovene means gravel). The entire area on Ljubljansko polje amounts to 430 ha. This gravel plain was called Prod, also Pesek ("*pesek*" in Slovene means sand) near Tomačevo and Roje near Obrije and represents the studied area for this research.

By shifting its riverbed, Sava caused damage by flooding, breaking its banks and preventing crossing the river. The first hydroregulation on the Sava River occurred as early as the mid-nineteenth century, with more extensive interventions starting at the end of the century. In 1895, works began in Tacen that were finished by 1908. They straightened the riverbed, moved it towards the south and increased the water slope (Radinja 1951). Increasing the water slope caused greater erosion, destroying the ground thresholds and the riverbed being deepened, which also decreased the groundwater level. (Radinja 1951). The expensive and demanding project needed regular maintenance, which subsided along with the downfall of the Austro-

Hungarian Empire. By 1935, Sava had created roughly the same conditions and water slope as before the regulation and destroyed most of the work done by man (Radinja 1951).

The Ljubljansko polje groundwater is still the most important source of drinking water for Ljubljana, as it provides 90% of the necessary water supply. Drinking water from Ljubljansko polje is pumped at four water plants: Kleče, Šentvid, Hrastje and Jarški prod. The first two are located on the western part of Ljubljansko polje, the Hrastje water plant on the eastern part and Jarški prod on the left bank of the Sava River.

The amount of the groundwater in the gravel sediments of Ljubljansko polje is estimated at 100 million m^3 (Rismal 1993). The normal flux exceeds $3m^3/s$ and the high one is said to exceed even $4m^3/s$. The thickness of the water-bearing gravel-conglomerate layer is of great importance with respect to the self-filtering abilities of the groundwater. The thickness of this layer increases from the west towards the central area, where it exceeds 70 m and then gradually decreases. The groundwater surface runs deepest on the western part of Ljubljansko polje at a depth of 20 to 30 m, approximately 20 m deep on the middle part of the polje and 15 m deep on the eastern part. On the left bank of the Sava River, where Jarški prod lies, the groundwater runs at a depth of 4 to 8m at a high water level and 8 to 11m deep at a low one (Analysis ... 1995 cited in: Smrekar et al. 2006). The groundwater gets even closer to the surface in gravel pits due to the removed covering surface and a complete removal of the covering lid (soil and vegetation).

The groundwater direction is parallel to the stream of the Sava River. Due to depression funnels forming around active aquifers, a large changeable area is established where the groundwater is concentrically directed (re-directed) towards the pumping area; in such cases, the water flow is re-directed back towards the water plant on its draining side. Upon increasing the amount of pumped water, the area is consequently spread in all directions. At high waters and a strong current, the Sava River current can be redirected up towards the Jarški prod water plant due to the connectedness of the river stream with the groundwater. In such cases, the waste disposal sites south of the water plants become potentially dangerous and a threat to the water source.

Groundwater renewal occurs reasonably quickly, which is a consequence of the good porousness of the covering layer and the sandy gravel part that connects the aquifer to the Sava River. In this way, the water from the Sava River, which contributes 50% of the flow, can intensely seep through the non-mudded riverbed ground; the rainfall infiltration is also considerable, as it contributes 42% of the flux (Brečko 1998). The direct rainfall infiltration is estimated at 740 mm (according to some measurements as much as 1,000 mm), which is almost half of the average rainfall in Ljubljana. The remaining 8% of the groundwater is contributed by the water inflows from the surroundings, sunken streams and sinking water from the water distribution system, which is lost on the way to the consumers.

Due to the gravel alluviums of the Sava River, the wider area of Ljubljansko polje has always been interesting for gathering gravel. The older inhabitants of the neighboring areas (Črnuče, Ježa, Nadgorica, Kleče) testify that gravel was already being dug for in the early twentieth century. During WWII, material from the Sava terrace edge near the villages Ježa and Nadgorica was used to build the German railway and Zasavska cesta road. Since the 50s, gravel was also acquired to the south, near the Sava riverbed (Krušec 2011).

Until the mid-sixties, the inhabitants of the area around Jarški prod had the right to dig on active gravel sites for gravel and sell it as construction material. Fine sand is especially interesting as it is still swiftly (and, of course, illegally) dug up in places sometimes from under a terrace edge. The south bank of the Sava River was probably most used for collecting gravel when they stopped using the gravel pits that lay nearer to the city, mostly near Bežigrad. These were mostly excavations for the market, because the settlements on the south bank lie on gravel, so the farmers had gravel at their disposal on their own land. There are no settlements on the north bank that would lie on gravel – except for Brod and Ježica and a part of Šentjakob. They are mostly clustered on the edge of Taborsko gričevje and Soteski hrib. These are composed of Permo-Carbon slate clay, which is useless as a construction material. For this reason, the inhabitants had to dig for gravel for home use as well. These were small excavations of gravel, a few carts under smaller, not yet balanced terrace edges. As the area has always been quite overgrown (grassland is renewed a few years after the river subsides and willows do not need more than 5 years) such digs, which are usually small and dispersed, are not simple to locate on the aerial photographs.

There have not been any serious regulations on the area of Jarški prod since the Austrian regulation in 1963, when they started directing the riverbed north of

Šmartno. The roads recognizable on the older aerial photographs served to transport the gravel. A large-scale gravel excavation began on the northern bank of the Sava River only after the intervention regulations in the spring of 1962 (Sava undercut a part of Jarše in a matter of a few days), when taking gravel became physically impossible at least on the south bank, regardless of any permits. The increased possibility of truck transport contributed to this as well. Until they had to transport the gravel in horse-drawn carts, this commercial endeavor on the north bank would be nonsensical. The oscillation of Sava's riverbed on active gravel sites is mostly a consequence of fast accumulation right after the height of a flood. However, by removing it with diggers on the critical spots, the Sava riverbed could be conditioned to man's will. The power plant constructions on the Sava River and consequential gravel accumulation have drastically changed the parameters of sedimentation, erosion, and riverbed placement. The accompanying prohibition of digging for gravel on active gravel sites, which were practically excluded by the regulation, also contributed to the situation. The chain of events was also heavily influenced by the never finished land arondation (combining of smaller parcels into bigger) in the late sixties, when entire areas were planned to be planted by aspen trees. The wood was going to be used to supply the local paper plants. When the plan was brought to a standstill, this "no man's land" saw the introduction of semi-legal business. (France Šušteršič, PhD., 2012).

4.3.2 The Characteristics of Waste Production in 1945 – 1991

The past socialist period up to the nineties was marked by ineffective legislation enforcement and **industriocracy**. The latter term describes how the industry in Slovenia had such a powerful influence over the politics and administration that it was able to pollute the environment for years with no consequence. This was a result of a general ideological desire for the largest possible number of industrial workers. The industry exploited this role with guiltless handling of waste matters. There were documents of great pollutions in the seventies and eighties (Breznik 1990). Sava, the main water vain of the Ljubljansko polje underground (in addition to direct rainfall), has an important role with pollution as well as the self-filtering abilities of the groundwater. Many hazardous matters, in liquid, solid, condensed physical form, were stored in metal barrels, containers at the factory locations or were brought to a waste disposal site. In many cases, these barrels got mixed up with communal waste and may still be in the same state today. If there is a crack in the barrel and the matter starts leaking, the surrounding waste is the first to be contaminated, reactions occur with the surrounding substances and the leaking into the groundwater is smaller. There is a line of possible combinations and all of them are speculation until a thorough analysis of the waste site location (georadar measurements, chemical analyses, waste excavation, etc.) is performed.

1950s and 1960s

After WWII, in 1955, the city authorities started with the mechanisation and the use of waste bins and stopped disposing waste on many locations. Parallel to the de-agrarisation, this also lowered people's care for the land and demand for waste. Waste was disposed in a far lesser extent in abandoned gravel pits in **the northern suburbs** (near River Sava) of the city (Orožen Adamič and Pleskovič 1975). Dumping was one of the most common ways of dealing with waste and is still prevalent today, which is why industrial waste was often dumped mixed together with communal waste. There are no precise estimates for the 50s on the amount of waste generated by the individual companies' production processes and their treatment; however, waste was most certainly generated, with hazardous waste being among them. The oldest information, from which the amount and type of industrial waste may be estimated, is the statistical data on the number of employees in a specific industrial field from 1953/55, with given data for the areas Ljubljana-city, Ljubljana-surroundings separated by industrial and craft sectors. Former companies were divided into the following industrial branches, in accordance with the data categorization from 1955 (SURS 1955).

Figure 16 shows the majority of the workers in Ljubljana (Ljubljana city) in 1955 were employed by the metal industry (6,000), with a big share of employees at Litostroj. There were over 1,000 employees in each of the textile, food-processing, electro industry, paper, printing, wood, and construction industries. The number of employees is an indicator, with which it is possible to determine the intensity level of a field. In accordance, it may be assumed that a large number of employees results in more waste; however, this is not always true and depends on the type of production process. Individual industrial processes can be more or less likely to produce waste. When dealing with former industrial companies, the characteristics of the former producing plants need to be taken into account, which differ from today with regard to technology, so the information on the number of employees in only usable as an estimate.

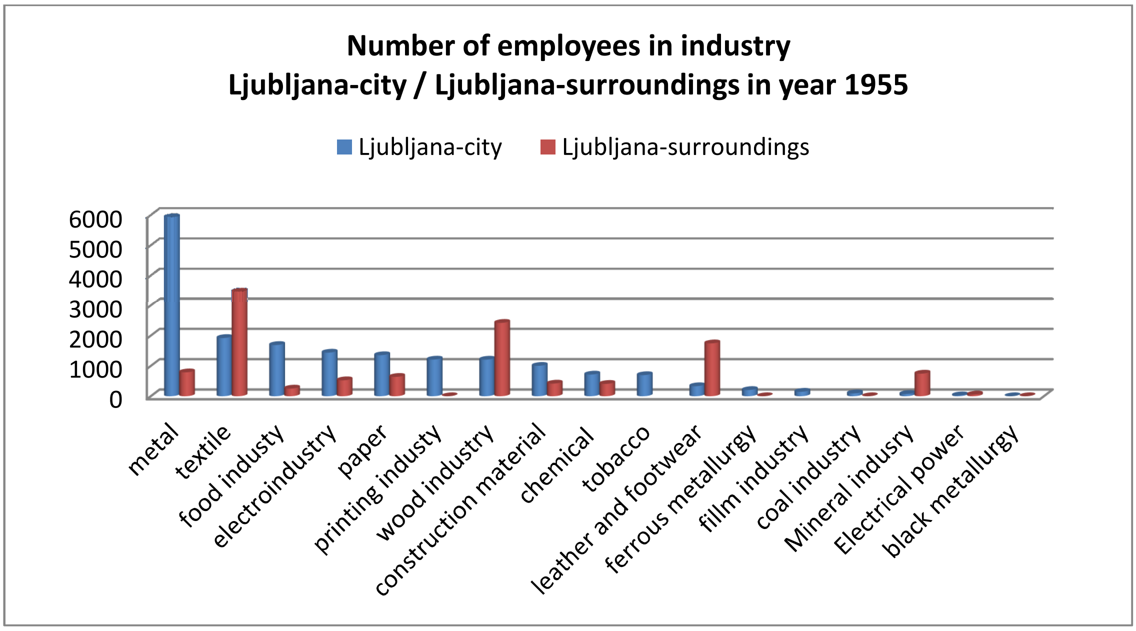


Figure 16*: Predominant industry in Ljubljana and surroundings in the 50s.*

Parallel to the city expansion, the amount of waste started to grow and its structure begn to change. The prevalent factor before was the organic waste, whereas in the 70s the amounts of inorganic (also dangerous) waste, as well as the quantity of waste per person, started to rise (Orožen Adamič and Pleskovič 1975). The disposed waste from the 50s up to the early 70s is characterized by high portions of (fine) inert materials like ashes, slags, soil and construction waste. Starting from the 70s, industrial waste was increasingly disposed of at the larger, supra regional-/ and company owned “landfills” (Allagaier and Stegmann 2005). Gravel excavation and the formation of new gravel pits up to the 70s are undoubtedly linked to the growth of the construction industry. A number of new companies produced waste that differed in amount, type, dangerousness, aggregate state, way of storage and disposal site. The location of the companies’ waste sites cannot be determined with certainty in the present without reliable written historical sources, which mostly do not exist, since this area was not legislated, or without oral sources (oral sources that were indirect or direct witnesses to the action).

1970s and 1980s

In 1975, the entire city of Ljubljana (excluding the suburbs of Gameljne, Medno, and Medvode) had a regulated collecting and disposal of waste. Waste was dumped onto three municipality dumps: along the Cesta dveh cesarjev street, near Šmartno and in Zajčja Dobrava. These dumps were already completely filled in the 70s and relatively unregulated without permanent rehabilitation safety. The quantity of waste transported onto waste disposal sites in 1973 amounted to approximately 440,000 m³ or 120,000 tons with the average mound weight of 273 kg/m³. The quantity of waste per person amounted to 1.43 kg per day. It was estimated that approximately 1 kg of industrial waste per person was formed in the early seventies (Orožen Adamič and Pleskovič 1975). From the perspective of studying FWDS, an important fact is the following script from 1975 *"… the problematic of industrial waste still has not been researched, with the majority of substances being disposed in illegal waste dumps…"* (Orožen Adamič and Pleskovič 1975)… and the fact that the problem of FWDS (filled in) still remains unsolved, despite the fact, that many registers of wild dumps in the area of Ljubljana exist.

The industry in Ljubljana saw its height in the 80s. According to the created value of the gross domestic product, the metal industry was in first place in Ljubljana with (21.9%), the food-processing industry in second place (17.6%), and the chemical industry with new plants (Lek, Bayer Pharma, Belinka) was the third most powerful field (14.1%). A completely new field that only developed in the post-war period was the electro industry, which took ninth place on the scale of the gross domestic product (10.5%). Some other influential fields were the printing, paper, and textile industry (Cerkvenik 1977 in Šulin 2007).

In the first half of the eighties, a detailed registry was made at the present-day Slovenian Chemical Institute under the leadership of Viktor Grilc, PhD., which represents a comprehensive study on dangerous substance producers in the former industrial plants on the Ljubljana area (Grilc and Husić 1984). The study that remained on the level of a cadaster was thoroughly analyzed using contemporary methods. The analogue data was formulated into digital form (the cadaster included data on the location) and an information layer with all the existing data was generated with the most attention paid to the amount of waste, type of hazardous waste and ways of waste management and disposal. The data was adjusted to the Ljubljansko polje aquifer; then 35 companies (covering the study area) were

analyzed, within which 65 producing plants operate. An example of the metal industry is the **Tovarna kovinske galanterije** factory, which had 4 producing plants at the time that used different production processes and generated different types of industrial waste. These were the galvane, paint plant, metal heat treatment plant and a montage plant. 45 tons of very toxic solid waste was generated yearly in the galvane (metal hydroxides (Cu^{2+}, Ni^{2+}, Cr^{3+}, Cr^{6+}), cyanides, phosphates, nitrites) that had been stored in 200 liter barrels and dumped on the communal waste disposal site. The metal heat treatment plant generated 2.25 tons of slightly less hazardous waste of rapeseed oil in 1982, which was deposited at a communal waste disposal site. The paint plant produced 0.3 tons of highly toxic waste material (resines, lead chromates, Zn-chromate, Ti02, butanol, xylen) in a solid state, which was also deposited on a communal waste disposal site.
The other plants produced about a ton and a half of motor oils and greases in the form of sludge, stored in 200 liter metal barrels. In the direct vicinity of the Kleče water plant, only 700 m upstream towards the north-east, the Unis-TOS company operated with a paint plant and a metal heat treatment plant. They produced about 5t of highly hazardous waste a year (resins, lead chromates, Zn-chromate, TiO_2, butanol, xylen, cyanides, nitrates, nitrites), which was deposited in a sediment pool; the rest of the solid matter, less hazardous material after the trichlorethylene distillation, was stored in 200l barrels (4t). On the north-west side upstream of the drinking water pump in Kleče, there were condensed Iskra plants (Iskra Industrija baterij Zmaj Ljubljana), IMP Ljubljana DO - IKO Ljubljana TOZD Trata Ljubljana and Dekorativa, TOZD Surova tkanina Ljubljana. It was not possible to acquire data on the amount of generated hazardous waste from Iskra, while data for the hazardous material stored (potassium hydroxide, chromate, amalgam, mercury (II) oxide, magnesium dioxide, rapeseed oil, etc.) in barrels that were dumped at an unknown location was available.

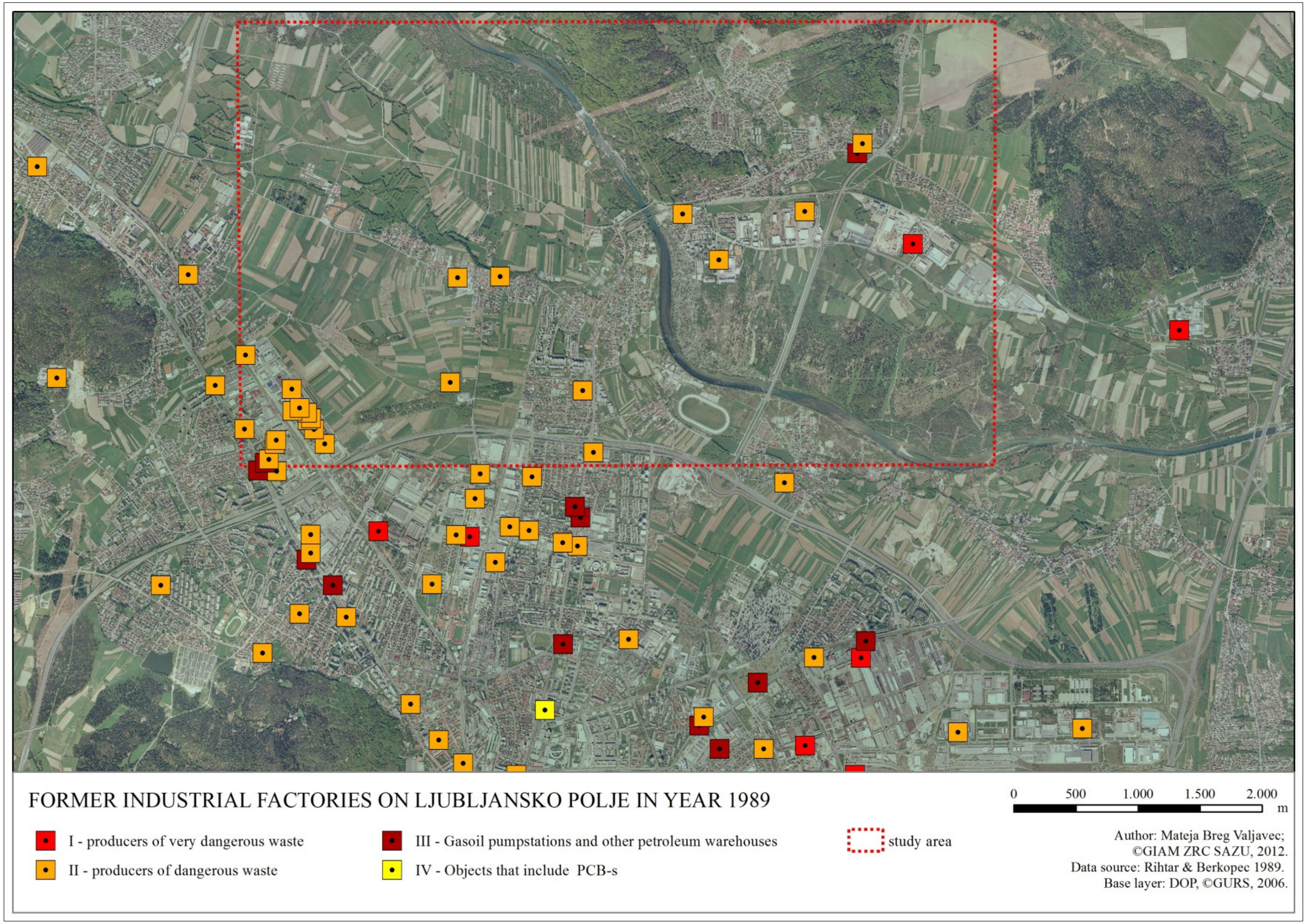


Figure 17: *The spatial distribution of dangerous industrial waste producers in 1980s, regarding their proximity to the study area.*

On the left bank of the Sava River in the direction of the stream towards the Jarški prod water plant, four companies operated during the 1980s generating hazardous waste: Elma Črnuče (galvane), Inkop Kočevje (paint), Energoinvest Sarajevo, Tovarna transformatorjev Ljubljana – Črnuče (paint), MP TOZD Dvigalo Ljubljana – Črnuče (paint plant and an emulsion cooling and cutting plant). Together, they generated 25t of extremely hazardous material in a solid state (resins, lead chromates, Zn-chromate, TiO_2, butanol, xylene, Zn^{2+}, Fe^{3+}, Ni^{2+}, Cu^{2+}, Cr^{6+}, Cr^{3+}) and regularly deposited some waste on the communal waste site, with no data being available for part of the waste (Grilc and Husić 1984).

The locations which were determined within past research and field registers of illegal waste disposal sites (today some of the formerly active waste dumps are filled in) will be gathered and evaluated. The determination of former industrial plants locations is based on an analysis and synthesis of old studies from the 80s (Grilc and Husić 1984; Planning department of Socialistic Republic of Slovenia 1989 etc.) and is partially represented on Figure 18.

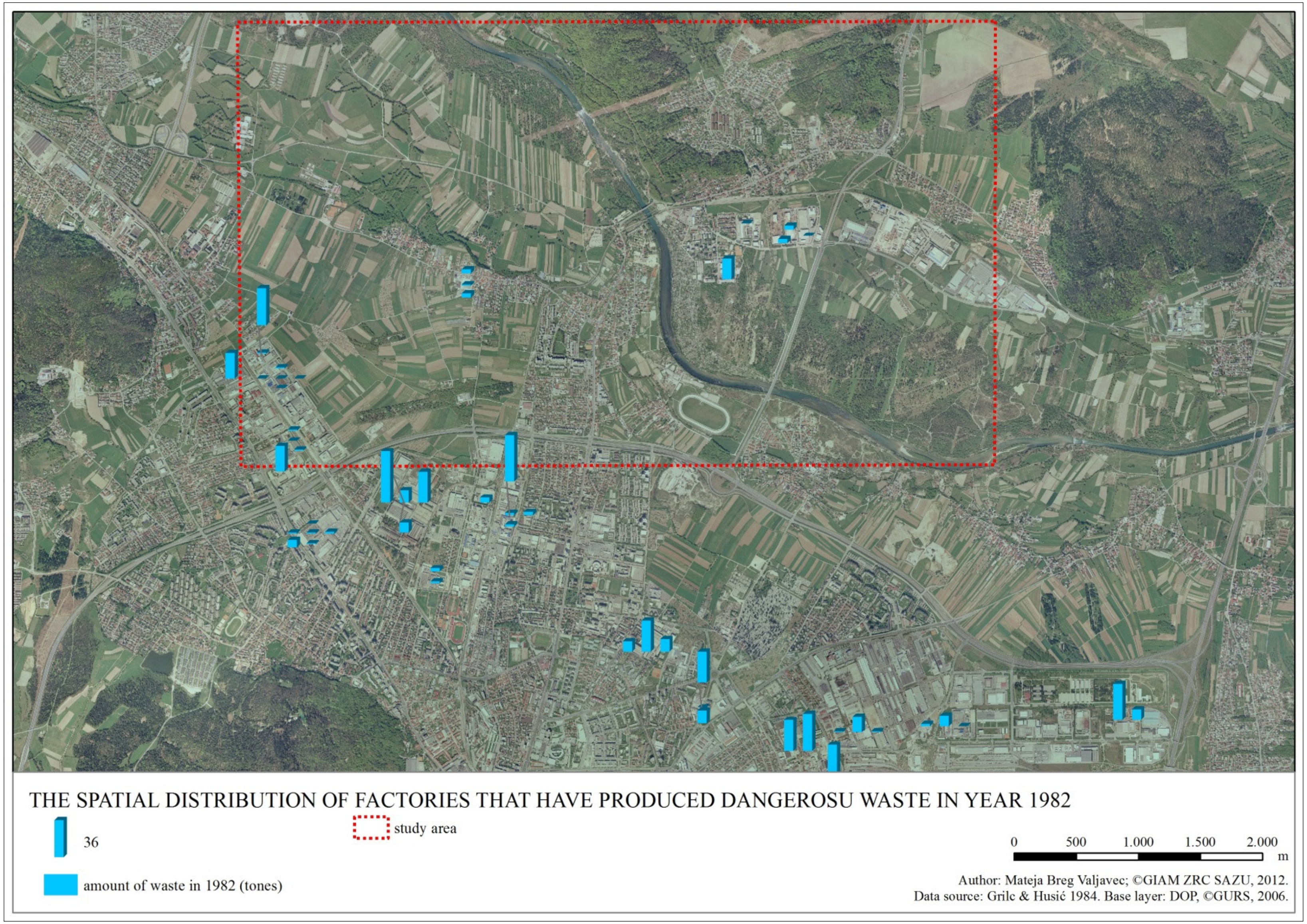


***Figure 18**: Spatial distribution and the amount of produced dangerous industrial waste in the 1980s regarding the proximity to the study area.*

4.3.3 Recent Waste Dumping in Gravel Pits

Dumps in abandoned pits (gravel, clay) are frequent on gravel and impermeable plains on the edges of urban settlements, where they also tend to expand to their largest size. They are typically used for dumping construction material and are quite a "popular site" for waste disposal due to their concave form. Usually individuals or construction companies who fill the pit with construction material and other types of waste are the ones who have previously used the gravel and sand from it. Since waste material is being dumped without proper control and in inappropriate quantities, their effects on groundwater can be extremely harmful. Construction material may also contain toxic waste (asbestos, remains of paint, varnish and others) while due to the removal of the primary material above, the groundwater is closer to the surface than usually (Breg and Urbanc 2005).

Studies on the presence of illegal waste disposal sites (Kušar 2000; Smrekar et al. 2005), which were often carried out on the level of individual municipalities, show their focus on non-active gravel and other open pits (e.g. 75% or 30,000 m^2 in the area of Jarški Prod), even if they are in water protection areas. In 2006 Smrekar et al. registered 87 gravel pits in the water protection zones of Ljubljansko polje. It is concerning that only 15 of them are completely empty and another 15 of them, which have been recently excavated, are already completely filled up with different waste (Smrekar et al. 2006). With the analysis of illegal waste disposal sites regarding strip mining in the Veneto plain (Italy), Silvestri et al. (2005) concluded similarly. 30% of the illegal waste disposal sites and 62% of official waste disposal sites were located in abandoned minings and open pits.

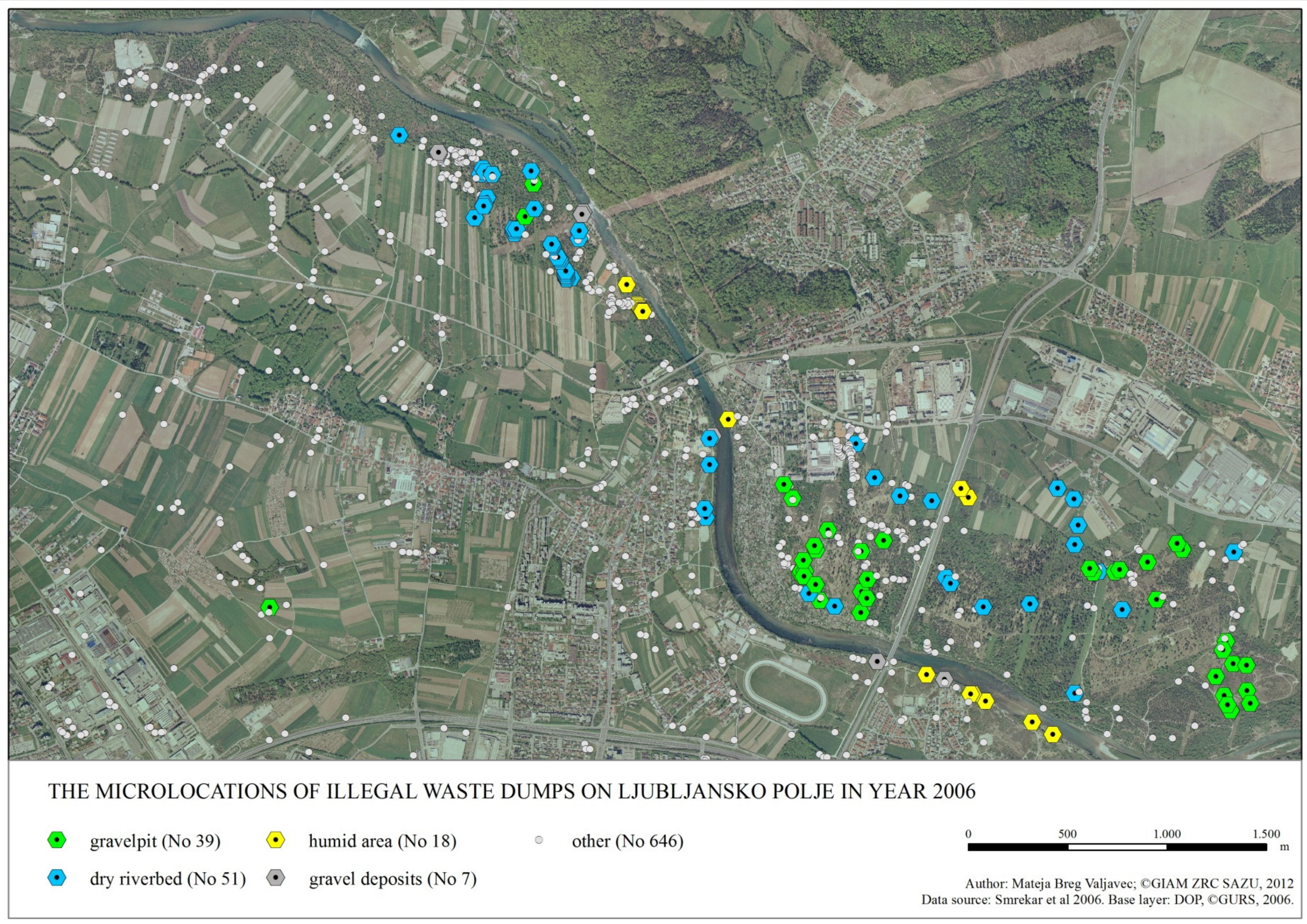


Figure 19: *Illegal waste disposal sites in the studied area of ljubljansko polje are represented depending on the microlocation.*

4.3.4 Ecological Awareness about Waste Disposal Sites

Like in Logatec, a survey was also carried out in Ljubljana on the topic of handling waste and on the familiarity with the illegal waste disposal sites in the local area. The survey was executed in the spring of 2007 in residential neighborhoods in Ljubljana on a sample of 1000 people. We asked the people filling out the questionnaire to mark the locations of FWDS on the aerial photograph from 2006. The results were very poor, so we were unable to use them as a control layer, like we did for Logaško polje. The people did better at answering questions on active waste disposal sites. The question analysis aims to present only whether the topic of illegal waste disposal sites is prominent in society, whether it represents a problem and if it does, how it should be resolved. More than half the people who filled out the questionnaire did not notice any illegal disposal sites in their vicinity or their settlement. They estimate that the number of disposal sites has decreased in the last ten years.

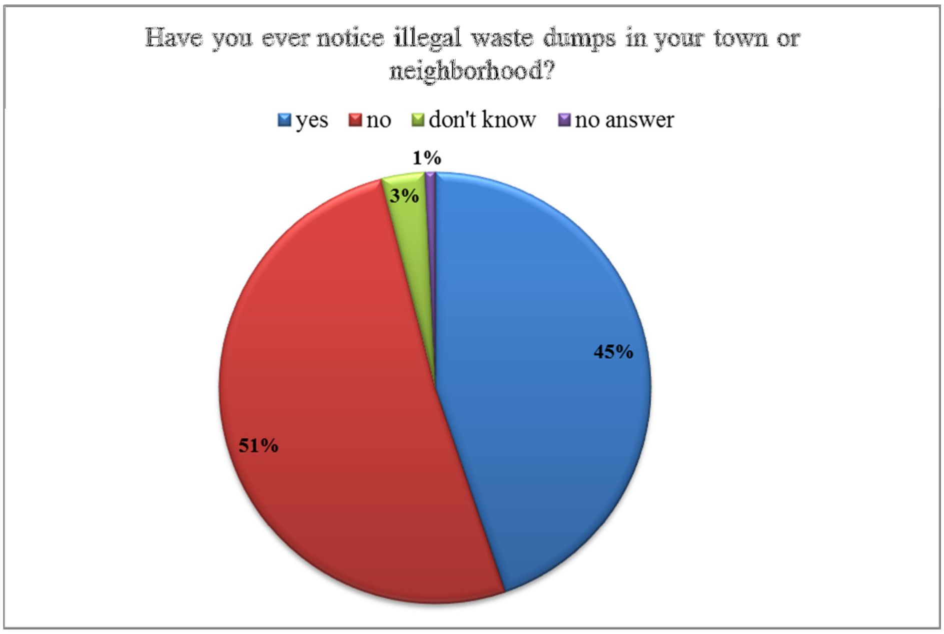


***Figure 20**: Detecting illegal waste disposal sites in Ljubljana by locals.*

Detecting illegal waste disposal sites in the immediate vicinity depends mainly on the lifestyle of the individual, whether they frequent going into nature or to the areas on the edge of the settlement where illegal waste disposal sites are most common. People in the city, especially the city center, are the most far away from the green surfaces on the edge of the city (Jarški prod) and are probably not familiar with them in comparison to the inhabitants of Logatec, which is a small town. 84% agree that the illegal waste disposal sites need to be removed and a similar percent believe that the local community or the country is responsible for removing them. 72% of the people are prepared to be actively involved in solving the issue and contribute €0.5 a month in a thus far hypothetical fund for solving the problem of illegal waste disposal sites.

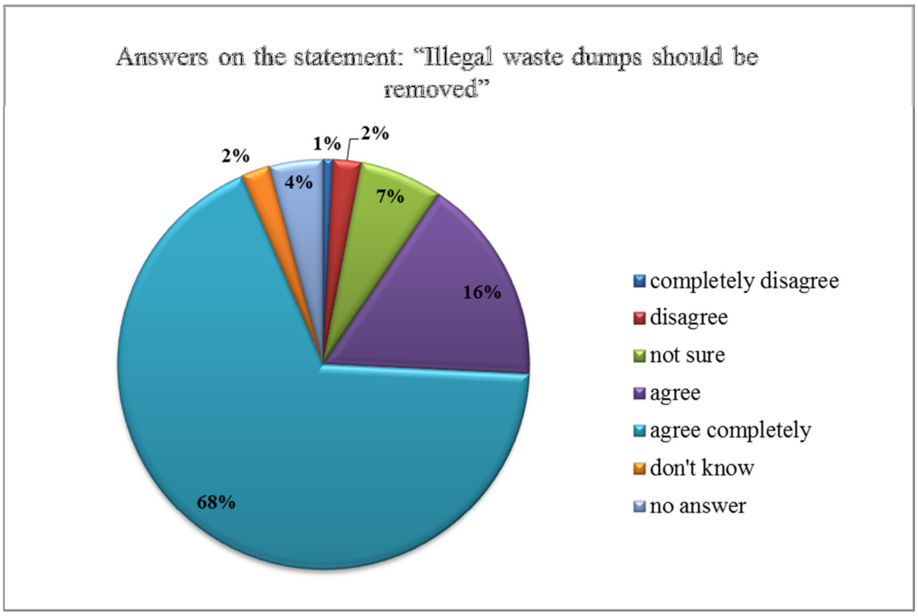


Figure 21*: According to the survey in Ljubljana, illegal waste sites should be removed*

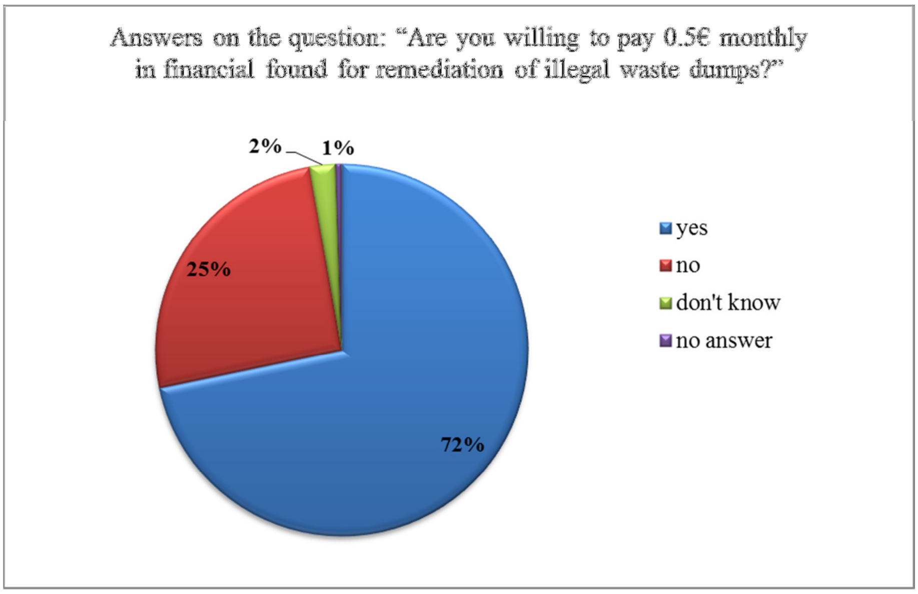


Figure 22*: The people in the survey are willing to actively participate in solving the issue.*

The survey was carried out before the influential action **Let's Clean up Slovenia in a Day!**, where 270,000 citizens cleaned up about 15,000 tons of waste. In addition to removing waste, the action is important for raising Slovenians' awareness on proper waste disposal. After the action, waste disposal sites once again became a trending topic, which would have been reflected in the survey results if it had been repeated in 2012.

5 DETECTION OF FORMER WASTE DISPOSAL SITES

This chapter is intended to represent and explain the general concept of research while the sixth chapter represents the general overview of relevant geoinformatic methods and spatial data that were applied and tested on two study areas (Logaško karst polje and Ljubljansko polje gravel plain). The procedures as well as gained results are represented together in the same chapter in order to improve the transparency of present research. This is in accordance to the primary research purpose, which is the testing of geoinformatic methods.

In chapter eight is represented the application of methods and results on Logaško karst polje. The thematic maps were selected as the most appropriate tool to represent spatial distribution of results. In ninth chapter are represented the methods tested on Ljubljansko polje gravel plain and gained results.

5.1 The "2TL / 3E" Concept of Studying the FWDS

Dumping waste into nature has caused many changes in the natural landscape: from mild to complete disintegration. All of these changes can be quantitatively measured in the recent landscape in various ways, while the reasons for it can be found in the past.

The modern concept of determining anthropogeneous impacts must include innovative geo-information concepts, methods and techniques as well as all the available types of spatial data – geodata. *"… With the use of various types of spatial data, as for example maps, aerial photographs, satellite photographs and high quality digital terrain models (DTM), it became clear that the effects of human activities on the Earth's surface have been present for centuries and even millennia. With such data we can acquire direct information about the geometry of the surface (location, size, the change in height) or indirect information about the temperature (with thermal infra-red scanners), about bio-activity (near infra-red photographs) and the diversity of the terrain (source: DTM). Useful information can be acquired and visualized through the spatial analysis with the help of geographic information systems (GIS)…"* (Podobnikar et al 2008).

The concept of the research assignment foresees three main actions:

1. Detecting the FWDS locations by testing some relevant geoinformatic methods, evaluating the methods and selecting the most suitable methods to build a **final FWDS model**.
2. Forming a digital registry of FWDS.
3. Testing the applicability of the selected geoinformatic methods and acquired results using field methods.

Considering the characteristics of the studied object – **former waste disposal sites – FWDS,** the research must focus on the **past and recent landscape** as well as on the comparison of both. The natural and socio-economic factors for the appearance of FDWS existed in the past landscape, while the impacts can be still recognized in the recent landscape. Regarding this, the research divides into five phases (see Table 2).

PHASE 1 – studying the relevant socio-economic and spatial factors in the past landscape. Geoinformatic methods are used to determine the state before the filling. From the viewpoint of filling landforms, it is important to know what occurred in society in the specific time period that resulted in the waste that gravel pits, dolines, and numerous other natural or artificial landforms are still filled with today. In accordance to that, we composed a comprehensive study of the socio-economic conditions in two studied areas (Logaško karst polje, Ljubljansko polje alluvial plain) for the period from 1945 onward. We determined the producers of hazardous waste, analyzed the organization of waste disposal in the past for the industry as well as for the inhabitants, estimated the amount of produced waste, evaluated the structure of the waste, etc.

PHASE 2 – determination and presentation of the **ZERO STATE** (the state before Land filling), based on archive aerial photograph analyses:

- The **location** of dolines and gravel pits;
- The **shape**, **border** of the landform;
- Disposal site estimates, based on the physical characteristics of the original landforms: for example, **depth** in the starting year (doline) or reference years (gravel pits).

PHASE 3 – Determination of waste-filled dolines and gravel pits by studying data of the recent landscape by applying geoinformatic methods that enable defining the impacts of past waste disposal on three environmental elements: **relief, soil, vegetation** (see Table 3).

PHASE 4 – The two-level validations of the results

The application of laboratory methods by comparing existing waste disposal sites registers with the study results and field survey by applying the relevant methods:

A. Mapping the relief and vegetation anomalies;

B. Soil sampling – sounding;

C. Measuring the electrical resistance of the ground

PHASE 5 – Synthesis of the results and a digital cadaster of all the potential locations and a risk assessment.

The data on the past and recent landscape are needed to determine locations of FWDS with the two presented approaches. Furthermore, the geodata must enable the study of the relief, the soil and the vegetation changes. The relevant mostly remote sensing data is listed in tables 2 and 3in the columns 'input geodata' in correlation to the desired goals and methods. The past landscape methods are based on historical b/w aerial images that enable a two-dimensional (2D in continuation) as well as three-dimensional (3D in continuation) presentation of the landscape. The 3D component (in geometric sense the relief is actually 2.5 D) is very important for studying relief changes of the past landscape up to the present. For this reason, some new digital surface models of the past landscape were produced and existing digital elevation models of the recent landscape were applied for comparison in order to detect relief changes.

By analyzing the table 3 it is obvious that the research concept, named 3E concept after three natural elements, could be also called a 2.5 E concepts, since the vegetation and soil are in the same box. Namely, multispectral remote sensing data, which are in this case the basic data, enable separate soil and vegetation studies in vegetated areas. FWDS are usually overgrown with vegetation that reflexes the conditions of the underlying soil.

<table>
<tr><th>2TL</th><th>INPUT GEODATA</th><th>METHOD</th><th>GOAL</th><th>RESULT</th></tr>
<tr><td rowspan="6">PAST LANDSCAPE ANALYSIS</td><td colspan="4">PHASE 1 – analysis and synthesis of existing data</td></tr>
<tr><td>Industry data, waste management data</td><td>Socio-economic spatial analysis</td><td rowspan="2">- characteristics of studied areas;
- waste management;
- waste disposal</td><td rowspan="2">Risk maps</td></tr>
<tr><td>Geolocated data of existing waste dump registers</td><td>Multicriteria analysis</td></tr>
<tr><td colspan="4">PHASE 2 – locating objects – zero state</td></tr>
<tr><td rowspan="2">Archive aerial photographs, old maps, digital elevation models of past landscape</td><td>Photogrammetric methods to generate 3D surface models of past landscape:
• aerotriangulation of archive aerophotographs,
• generation of DSM and DOP</td><td>3D data for the geometric analysis of past landscape</td><td rowspan="2">Zero state map</td></tr>
<tr><td>Methods for objects locating
• visual photointerpretation
• stereoscopic interpretation
• 3D analysis of past landscape / geo-morphometric methods</td><td>- location,
- shape,
- area,
- depth</td></tr>
<tr><td colspan="5">PHASE 3 – determination of former waste disposal sites - FWDS</td></tr>
<tr><td colspan="2">COMPARISON OF PAST AND RECENT LANDSCAPE</td><td>Qualitative and quantitative comparison of past and recent landscape data</td><td>Determination of waste-filled areas</td><td>Probability map</td></tr>
<tr><td rowspan="4">RECENT LANDSCAPE ANALYSIS</td><td>High-resolution multispectral satellite and aerial images</td><td>• visual interpretation ,
• unsupervised classification,
• vegetation index (NDVI, IR/R)</td><td>Areas of vegetation anomalies or stress and soil anomalies</td><td>Probability map</td></tr>
<tr><td>Existing DEM /DTM of recent landscape</td><td>• visualization of relief data,
• hydro-morphometric modeling</td><td>Areas of anthropogenic relief landforms</td><td>Probability map</td></tr>
<tr><td colspan="4">PHASE 4 – control</td></tr>
<tr><td>Existing registers
Field data</td><td>• soil sounding,
• electrical resistivity,
• mapping relief and vegetation</td><td>Control of results
Gathering ground truth data for GIS analysis</td><td>Control maps</td></tr>
<tr><td colspan="5">PHASE 5 – synthesis and cadaster of potential FWDS</td></tr>
</table>

***Table 2**: Schematic presentation of the research concept – also called two times landscape – 2TL concept.*

3E	INPUT GEODATA	METHOD	RESULTS
RELIEF	Archive aerial photographs	Visual analysis of archive aerial photographs	Identifying locations of presently unknown dolines and gravel pits
	Archive aerial photographs (stereo pars that enable aero-triangulation)	Digital photogrammetric methods for production of DSM	DSMs of studied areas for different time periods (1950-1990)
	DSM of past surface (i.e. 1972) and DEM of recent surface (2006)	Comparative analyses of past and recent surface	Identifying locations of presently unknown filled dolines and gravel pits; Depth of original unfilled landform; Volume of deposited waste.
		Geo-morphometric / hydro-morphometric analysis	
	Field measurements	Field mapping; Electrical resistivity imaging	Ground truth data to control the results of geometric analyses
VEGETATION & SOIL	Multispectral satellite and (Landsat, GeoEye-1) and airborne data RGB and near IR aerial photographs	Unsupervised and supervised image classification;	Identifying the environmental dangerousness of deposited waste; Detection of vegetation or soil anomalies.
		Visual aerophoto-interpretation;	
	Georeferenced field measurements	Pedological sounding; Vegetation mapping	Ground truth data to control the results of multispectral image analyses

Table 3:*The scheme represents the concept of studying recent environmental impacts with regard to three environmental elements (relief, soil, vegetation) concept – 3E concept.*

6 GEOINFORMATICS

6.1 Introduction to Geoinformatics, GIS and Geomatics

"*… **Geoinformatics** represents a coherent integrated approach to the acquisition, storage, analysis, modeling, presentation, and dissemination of geo-processes and not a patchwork solution of unconnected fields of activity. Geoinformatics is as such not a part of Geography, Surveying, or Computer Science, but a new self-contained scientific discipline…*" (Ehlers 2008). Geoinformatics is a relatively new science offering a wide range of methods and tools for research in various scientific fields. The beginnings of geoinformatics are connected with the development of computer science (hardware and software) and remote sensing technology. **GIS (Geographic Information Systems)** is a proven technology and today the basic operations of GIS provide secure and established foundations for the measurement, mapping and analysis of the real world. GIScience provides us with the ability to devise a GIS-based analysis that is robust and defensible (Longley et al 2005). '*Basic Readings in Geographic Information Systems*' (Marble et al 1984) was a collection of papers that represented the first accessible source of information about GIS until Borough P. published the first book on GIS principles in 1986. '*Principles of Geographical Information Systems for Land resources Assessment*' (Borough 1986) quickly became a worldwide reference text for GIS students (Longley et al 2005).

A related term that is sometimes used synonymously with geoinformatics is **geomatics**, however, geomatics focuses more so on surveying (Ehlers 2008). The first Slovene author who wrote about geomatics was Joc Triglav (1996). The piece was published in a special edition of the "*Življenje in Tehnika*" magazine (Life and Technic), entitled "Geomatics – a mosaic of measuring methods" ("*Geomatika – mozaik merskih metod*"). In the article, geomatics is represented as science combining expert fields of different sciences such as geodesy, cartography, photogrammetry, remote sensing and information technology. Computer technology has become the common denominator that is slowly, but surely erasing borders between them. The term geomatics was introduced by French geodesist Dr. Bernard Dubuisson and was later on officially acknowledged by the Terminology Bank of Quebec (Fr. Quebec Banque de Terminologie). Since it was originally introduced in Canada, it has become very popular in French speaking countries. The term geomatics, however, was never fully accepted in the United States, where the term geographical information science is preferred (Raju 2003). There is no exact definition of the term, seeing that the field of geomatics is constantly expanding with new scientific discoveries and a rapid technological development (Triglav 1996). Geomatics enables and at the same time demands a systematic and interdisciplinary approach for the formation and management of the entire spectrum of spatial information in order to acknowledge the development within the environment as well as for future interferences regarding the environment. Geomatics is often defined as the science and the technology for managing geographically based information, including their acquiring, saving, studying and distribution (Triglav 1996).

The term geoinformatics established itself within the Slovene geographical expert field as "*… Geoinformatics, which is regarded as the science and the technology of acquiring, processing, analyzing and representing geographical information, can, in general, draw parallels with the scientific-research, as well as the pedagogic and applicative geography…"*(Krevs 2002, p. 416). The use of geo-information methods has undoubtedly risen quite drastically in the last decade, especially within the geographical science, where the prevailing role is played by **geographic information systems**, **cartography** and even **remote sensing** and **photogrammetry**.

6.2 Remote Sensing

In the 1960s, satellites started sending the first visual and quantitative data about our planet from space. Such an indirect way of data acquisition was defined as remote sensing (Slovene as '*daljinsko zaznavanje*') in the USA. Although this term found its place in acquiring data from space with the help of satellites and other spacecraft, it also started being used for acquiring data with the help of aerial photographs. As a consequence, remote sensing is regarded as any kind of data acquisition about the shape and the characteristics of remote objects (Triglav 1996). Remote sensing encompasses a body of non-contact monitoring techniques that measure energy-matter interactions to determine the characteristics of a target surface or medium. Although remote sensing includes a wide variety of instruments and methods, such as Light Detection and Ranging (Lidar), radar, X-ray technology and acoustic instruments, it is most often associated with overhead imaging techniques, such as aerial photography and satellite imagery that record energy in the solar-reflected part of the electromagnetic spectrum (EMS in continuation) between 400 and 2,500 nm wavelengths (Slonecker et al. 2010). Oštir (2006) mentions the following seven elements in the process of remote sensing:

1. **The source of the electromagnetic waves**: the first condition for remote sensing is the source of the electromagnetic waves, which sheds light on the observed objects, or they themselves emit light. The most frequent source of these waves is the Sun, but some artificial sources (radars) may also be used and the thermal radiation of objects may be utilized.
2. **The path through the atmosphere**: when the electromagnetic waves travel through the atmosphere, they "interact" with it, but can cross the layers of the atmosphere only once (from the surface to the sensor) or twice (from the source of energy – the Sun or any kind of active instrument – to the surface and back).
3. **Interaction with the surface**: when the electromagnetic waves reach the Earth's surface, they interagirate with it. The manner of connecting depends on the surface characteristics and on the wave characteristics themselves.
4. **Registering the electromagnetic waves with a sensor**: when the waves reach the surface or when the surface radiates them, they are registered with a sensor (which is remote and not in direct contact with the object). Sensors detect the electromagnetic waves and transform them into a characteristic record photographic or digital data.
5. **The transfer, acquisition and processing**: signals that are noted by the sensors have to be transferred in the electronic form with radio wavelengths to the reception station on Earth. The transmission operators process the data and form an image that may be printed or, in the majority of cases, digital.
6. **The interpretation and analysis**: the processed image must be interpreted, which can be done visually or digitally, while as much data as possible on the observed object is acquired.
7. **Use**: the last, but the most important element of the process of remote sensing is the use of information that was acquired by the interpretation in a specific study or when dealing with a distinct problem.

Chronologically, aerial photography must be listed as the first product of remote sensing. Wilbur Wright has been identified as the first person to obtain aerial imagery from an airplane. He took movies of his flight in Centoci, Italy on 24 April 1909. The first aerial photography captured from a plane for mapping purposes was done by Captain Cesare Tardivo for a 1:4,000 mosaic of Benghazi, Italy. He presented this survey in a paper delivered at the International Society of Photogrammetry meeting in Vienna on 25 September 1913 (Birdseye, 1940). Aerial photography experienced some important development during WWII. An aerial survey basically resulted from the huge number of individual images taken in the scope of the British Royal Air Force (RAF in continuation), and the German Air Force (Luftwaffe). Most of them are stored in European aerial archives, among them the important National Collection of Aerial Photography (NCAP), where the oldest known aerial images of some parts of Slovenia (1943-1945) are stored. In 2008, after almost fifty years, they were relocated from Keele University and became part of the Royal Commission on the Ancient and Historical Monuments of Scotland (in continuation RCAHMS). After WWII, the USA also saw an improvement in satellite technology in addition to aerial surveys. The United States created the National Aeronautics and Space Administration (in continuation NASA) on 1 October 1958. NASA's birth was directly related to the pressures of national defense. After WWII, the United States and the Soviet Union were engaged in the Cold War, a broad contest over the ideologies and allegiances of the nonaligned nations. During this period, space exploration emerged as a major area of contest and became known as the space race. On 4 October 1957, the Soviets launched the Sputnik 1 satellite; the United States launched its first Earth satellite on 31 January 1958, when Explorer 1 documented the existence of radiation zones encircling the Earth (Internet 12).

6.3 Multispectral Image Applications in FWDS Research

Remote sensing has a long history of providing critical information to the process of identifying, characterizing and remediating hazardous waste problems (Slonecker et al. 2011). It offers a wide range of methods for determining the consequences of waste dumping.

Due to waste dumping three natural geographic factors have changed and are put in focus in the present research:

- relief,
- soil,
- vegetation.

Changes in these factors can cause short-term or long-term positive or negative impacts. Various satellite systems can be used depending on the size of the studied area as well as the goals of the research. For studying the biggest waste disposal sites (for example, municipal or regional waste disposal sites of a few hectares), the satellites of low spatial resolution are sufficient (Landsat TM – 30 m, Landsat MSS, Spot – 20 m) in combination with basic spectral channels (pan-chromatic, red, blue, green, near infrared, thermal infrared). For a more detailed study of the environmental impacts of FWDS, photographs from hyper spectral satellites of high spatial resolutions are required. Satellite images, acquired by Ikonos or GeoEye1 sensors are very precise as the sensors have a high spatial resolution (around 2 m). Unfortunately, they cover only four spectral bands (red, green, blue and infrared). Since these are commercial satellites, the acquired images are quite expensive (for example, the GeoEye1 scene that covers 10 x 10 km costs about €1,500).

Many objects can be identified merely on the basis of their spectral values, especially if the multi-spectral sample is known. A multi-spectral sample is a sample of the spectral reflectance of the same object in different spectral stripes. This basic principle of identifying objects on the basis of spectral samples is not generally valid, as spectral samples may vary for the same object. For example, the spectral sample of a grain field changes drastically from the time of the sowing to the time of the harvest. The same goes for forests, which change the spectral sample in an area due to changes in their structure and the mixture of tree species. The analysis of spectral samples is usually supplemented with the interpretation of structural elements of the picture or with the use of additional data (geographic information layers). The various factors that change through time and space and influence the spectral sample are (Matko 1996):

- vegetation type (forest, grass, corn, bushes, etc.),
- the phenologic and physiologic state of the vegetation (age, exposedness to dangerous substances),

- the reflectance characteristics of assimilation organs (leaves, needle leaves),
- the setting-up and the distribution of assimilation organs,
- the vertical structure of the vegetation (the height) and the ratio between the leaves or needle leaves in the light and in the shadows.

The laws of reflectance of the Sun's radiation from **clear ground/soil** are rather simple in comparison to the vegetation. The characteristics of the upper ground layers mainly influence the course of the spectral curve without any extreme ups and downs within the visible and infra-red specter. These are predominantly presented by the following characteristics of the ground (Matko 1996):

- soil moisture,
- the mineral structure of the ground, meaning the type and size of the particles,
- the type and the amount of hummus substances,
- the graininess of the ground and the surface structure,
- structures formed due to land cultivation.

Several foreign researchers from the past attempted to identify illegal waste disposal sites on smaller sample areas by using various techniques of remote sensing (Erb et al. 1981; Stohr et al. 1987; Zilioli et al. 1992; Del Pero et al. 1995; Gomarasaca and Strobelt 1995; Pitea et al. 1997; Cenedese et al. 2003 and others). Many authors established that determining waste disposal sites with remote sensing requires the development of ad hoc techniques, based on defining indirect occurrences and the consequences of waste dumping, which are seen in the polluted soil, in the effects on the vegetation (vegetation stress) and in unusually high temperatures of the soil as a result of the biological disintegration of waste and the correlating formation of biogas (Zilioli et al. 1992). Remote sensing was successfully used in past research mainly to determine vegetation stress (Carter 1993; Kumar et al. 2001). The methods were used to determine potentially polluted locations of soil on waste disposal sites (Vincent 1994; Del Pero et al. 1995; Gomarasca and Strobelt 1995; Cenedese et al. 2003; Silvestri and Omri 2008). Data gathered with remote sensing is useful for visual photointerpretation of waste material, as well as for determining indirect results that emerge due to dumped waste within natural landscape-ecologic elements (relief, soil, vegetation, air, etc.), like contaminated soil, vegetation damages (vegetation stress) and as peculiarly high soil temperatures, which are a consequence of the organic fermentation during the production of biogas (Silvestri et al. 2005).

Dangerous and toxic materials disposed of underground without any impervious layer may be identified through phenomena connected to the consequences of soil contamination. Toxic materials may greatly influence the development of vegetation growing on contaminated soils and hence **vegetation stress may be used as an indicator of the presence of toxic and dangerous dumps hidden underground** (Cenedese et al. 2003; Pitea et al. 1997). Remote sensing has often been successfully used to identify stressed vegetation (e.g. Carter 1993; Kumar et al. 2001), and this potential has been used to identify possible contaminated soils and dumps (Cenedese et al. 2003; Del Pero et al. 1995; Gomarasca and Strobelt 1995). A detailed overview of visible and infrared remote imaging of hazardous waste was made by Slonecker (Slonecker et al. 2010). Slonecker reviews the literature of remote sensing and overhead imaging in relation to hazardous waste and discusses future monitoring needs and emerging scientific research areas. Aerial photography has a long and effective record in waste site evaluations. Aerial photographic archives allow for a temporal evaluation and change the detection by visual interpretation. Multispectral aircraft and satellite systems have been successfully employed in both spectral and morphological analyses of hazardous waste in the landscape. Emerging hyperspectral sensors have made it possible for the specific contaminants to be identified with the processing strategies that use the tens or hundreds of acquired wavelengths in the solar reflected and/or thermal infrared parts of the electromagnetic spectrum (Slonecker et al 2010). Herman et al. (1994) obtained CIR (color infrared, in continuation CIR) aerial photography for five dates to interpret the intensity and extent of the vegetation stress on the edge of a superfund site in Michigan and found improvements in vegetation health that corresponded to groundwater remediation.

Organic waste materials may be successfully recognized through the analysis of the **thermal infrared data** (Zilioli et al. 1992). In fact, organic materials disposed of underground lay in anaerobic conditions and bacteria produce biogas (mainly composed of methane-CH_4, carbone-dioxide-CO_2 and H_2S) and liquid characterized by a relatively high temperature through the fermentation processes. The analysis of remote sensing data collected in the thermal infrared part of the spectrum from satellite (e.g. Landsat 5 TM and Landsat 7 ETM+, ASTER satellite, etc.) or airborne (e.g. MIVIS or DAEDALUS) spectroradiometers can successfully identify soils that are presenting unusually high temperatures or warm percolating waters (Tesser 2002; Del Pero et al. 1995; Zilioli et al. 1992).

Sensor	Format	Spectral Resolution	Spectral Range	Analysis Methods	Comment
Aerial Photos	Film, digital	Broadband	VIS-NIR 400-900 nm	Manual interpretation	Can be analysed digitally also
Satellite Imagery	Digital	Broadband Multispectral	VIS-NIR 400-2.200 nm	Image processing	Can be analysed manually also
Thermal infrared Imagery	Film, digital	Broadband	Thermal Infrared 8.000-14.000 nm	Manual and digital methods	
Solar reflected Hyperspectral	Digital	Narrow	Solar-reflected 400-2.500 nm	Spectroscopic	
Thermal Hyperspectral	digital	Narrow	Thermal IR 8.000-14.000 nm	Spectroscopic	

Table 4*: Imaging sensors and methods used for hazardous waste analyses (Slonecker et al. 2010).*

The most appropriate season for collecting satellite data is the summer, when the high air temperature and the direct solar radiation favour fermentation processes and a great quantity of biogases and liquids is produced during the day. However, the long summer days may also naturally reach very high temperatures and the discrimination among surfaces simply heated by solar radiation and those heated by biogases may be difficult.

When the Sun sets, the soil temperature naturally decreases. Just before dawn, the uniformity of the air and ground temperatures is high and the influence of solar radiation is negligible and hence it becomes easier to identify soils heated by biochemical processes with respect to surrounding colder areas. Zilioli et al. (1992) found that the highest contrast between waste disposal areas where the processes of methane conversion were active and the surrounding areas is observed just before dawn, when the maximum temperature difference between the water affected by wasting agents and uncontaminated outcropping water table is observed. Some meteorological components are also important for accurate data acquisition (Zilioli et al. 1992):

a) the absence of rainfall before and during measurements, since rain and humidity greatly influence the emissivity of the surfaces;
b) an uniform cover of clouds or the complete absence of them, to avoid irregular irradiation coming from surfaces;
c) the absence of wind to limit the energy transfer by convection.

Non-dangerous waste materials hidden underground are probably the most difficult to identify, because they do not produce phenomena connected to soil contamination, such as vegetation stress or unusually high soil temperatures. Luckily, these materials are inert, as they mainly come from building activities. They can be recognized through the ML classification of high-resolution multispectral images (GeoEye1, IKONOS), since vegetation does not grow well on these areas and the reflectance properties of the soil are modified by the presence of the surface materials.

The automated image processing methods focus mainly on the multispectral analyses of photographs. From the information acquired in several parts of the electromagnetic spectrum, it is possible to draw conclusions about the Earth's surface, the type of clouds, etc. The differences in the intensity of the radiation of different objects are the basis for their differentiation in an aerial or satellite photograph. Each object in nature has its characteristic distribution of reflected, emitted, absorbed and permeable radiation. The differences depend on the amount and the spectral distribution of the reflected, permeable and absorbed radiation. They are the basis for various copying of objects from the mentioned aerial or satellite photographs. At a certain wavelength, the established spectral value for a specific object is only an average value, changing through time and space. For example, the spectral distribution of the reflectance of a leaf changes constantly through its vegetation period. The spectral distribution of reflectance is also different if the leaf is affected due to drought or illness. The reflectance or self-radiation of a leaf of the same type can be quite different on various sites, as these may differ in quality and soil moisture. The spectral values are also relatively dependent on the circumstances in the atmosphere at the time of the recording (Matko 1996).
The method of automated aerophoto-interpretation (unsupervised classification) will be utilized for indirect determining of the waste disposal consequences, which may be observed on the vegetation and the soil as well as on the forms of the surface

acquired with remote sensing. The automatic analysis of the electromagnetic reflectance values noted with an aerial or satellite photograph will represent the basis for determining the location of an illegal waste disposal site and its influence on the vegetation and the soil.

The most often method is a K-means unsupervised classification. It is a multistatistical cluster analysis that calculates initial class means that are evenly distributed in the data space. Then it iteratively clusters the pixels into the nearest class using a minimum distance measure. In the next step, all the pixels are classified to the nearest class after a specified number of iterations. This process continues until the number of pixels in each class changes by less than the selected pixel change threshold or until the maximum number of iteration is reached (Mather 1999).

6.4 Photogrammetry and Related Methods

6.4.1 The Development of Photogrammetry

Photogrammetry is based on the processing of images (photographs). The main products are digital terrain models, digital surface models, orthoimages, 2D and 3D reconstruction and classification of real world objects and visualization. The quality assessment of photogrammetric products is well established and the overall possibilities and limits of photogrammetric methods are commonly known (Baltsavias 1999a).

Photogrammetry has been defined by the American Society for Photogrammetry and Remote Sensing (ASPRS) as the art, science, and technology of obtaining reliable information about physical objects and the environment through the processes of recording, measuring and interpreting photographic images and patterns of the recorded radiant electromagnetic energy and other phenomena.

The developments in photogrammetry from around 1850 have followed four development cycles (Konecny, 1985). Each of these periods extended for approximately fifty years:

1. plane table photogrammetry, from about 1850 to 1900,
2. analogue photogrammetry, from about 1900 to 1960,
3. analytical photogrammetry, from about 1960 to 1980,
4. digital photogrammetry, from about 1990 on.

Although many photogrammetric theories date back more than a century, the use of digital photogrammetry in extracting information has only undergone development during the last 20 years. The degree of automatization and digitalization of the processing work is now quite high (Baltsavias 1999a).

Photogrammetry is a science, which has developed under the reign of the geodetic discipline in Slovenia, seeing that the classical, analogue photogrammetry, required special technical knowledge, as well as using mathematical algorithms and rather expensive technical equipment. In accordance with this, other disciplines, like geography, have not taken advantage of photogrammetric methods to the fullest in their research. With the formation of **digital photogrammetry** this science has become more accessible and amiable for users of other disciplines or sciences as a contemporary software tool. The development of digital photogrammetry and digital orto-photo-processing brought together technologies of satellite remote sensing and photogrammetry, especially regarding saving, processing and cartographic representation, as well as their use within GIS systems. It may be stated that this field is growing stronger and is slowly erasing the borders between both technologies (Triglav 1996).

During the development of the geoinformation science in 1980, the digital photogrammetry methods had appeared on the basis of verified analogue and analytical photogrammetry. Digital photogrammetry makes it possible to acquire exact 3D information from 2D aerial photographs, where the sensor characteristics (the internal and external sensor orientation), the image and the photographed area must be provided.

6.4.2 Visual Aerophoto Interpretation of Aerial Photographs

The most basic use of aerophoto involves the visual interpretation of the morphological characteristics of the production, storage, disposal, transport and effects on the natural environment. Aerial photographs have been used in numerous applications to detect and analyse the presence of hazardous waste, waste-disposal sites and landfills (Slonecker et al. 2010). Visual aerophoto interpretation of aerial photography is the first geoinformation method used in studying visible illegal waste disposal sites in Slovenia. By attempting to determine gravel pits, it has extended into the methodology of determining hidden illegal waste disposal sites.

In 1988, aerophoto-interpretation was used in searching for gravel pits and illegal waste disposal sites in the City Municipality of Ptuj (Rejec-Brancelj et al. 1988). The authors do not mention any problems in acquiring data in this way, which is probably the result of the visibility of gravel pits within the clear and cultivated landscape and the studying of larger illegal waste disposal sites. Šebenik and Stritih (1991) compared the results of the aerophoto-interpretation with the results of a systematic survey and concluded that the aerophoto-interpretation of aerial photographs had not yet been perfected at that time, seeing that it resulted in a loss of some data. Only 31% of the illegal waste disposal sites that were distinguished with a complete field survey of the land are captured within the aerophoto-interpretation. As many as 69% of the locations that were regarded as possible waste disposal sites were marked as false by aerophoto-interpretation (Šebenik and Stritih 1991). Modern spatial aerial photographs of high spatial resolutions (25 cm, 50 cm,) guarantee far better results in distinguishing visible illegal waste disposal sites, which was established in Matos' research (Matos 2007).

Aerial photo interpretations of waste disposal sites could be conducted as site specific studies, as regional studies to systematically produce an inventory of existing and potential waste disposal sites within a certain boundary. The interpretation of waste sites from aerial photographs can be performed using different equipment and techniques, such as a stereoscope or in a digital format depending on the needs of the project or the experience of the interpreter (Slonecker et al. 2010). The method of **aerophoto interpretation** is a completely non-automated method when determining the recorded objects or the 2D characteristics on the aerial photograph. It is based on the human visual senses, with which it is possible to recognize picture elements and real objects mainly in the visible part of the electromagnetic spectre. The third dimension (depth, height) could be visually recognized by stereoscopic viewing (with stereoscopic glasses) of two consequential overlapping stereo-pars; this process is called stereo-interpretation.

6.4.3 DEM or DTM and DSM

There is no common usage of the terms digital elevation model (**digital elevation model** (in continuation **DEM,** in Slovene '*digitalni model višin*' – *DMV*), **digital terrain model** (in continuation **DTM,** in Slovene '*digitalni model reliefa*' - *DMR*) and **digital surface model** (in continuation **DSM,** in Slovene '*digitalni model površja' – DMP)* in scientific literature.

A DTM is a continuous surface that, besides the values of height as a grid (known as a digital elevation model—DEM), also consists of other elements that describe the topographic surface, such as slope or skeleton (Podobnikar 2005). In the most cases, the term digital surface model represents the Earth's surface and includes all objects on it. A DSM in contrast to the DTM, represents the ground, covered with many objects like plants and buildings (Zhu and Gold 2005) (Figure 23). Some Slovene authors (Perko 2001a; Podobnikar 2002b and Perko 2007) as well as foreign authors (Longley et al. 2005) also distinguish the **digital landscape model** (in continuation **DLM,** in slovene *digitalni pokrajinski model*), which includes data about the **natural and social characteristics** of a specific region and is basically equivalent to digital surface model. A somewhat more general and technically oriented definition is as follows: "*... A digital elevation model is a computer database, with which it is possible to, for example, show a virtual image of the landscape, a virtual relief with the geographic information system ...*"(Perko 2007, p. 15).

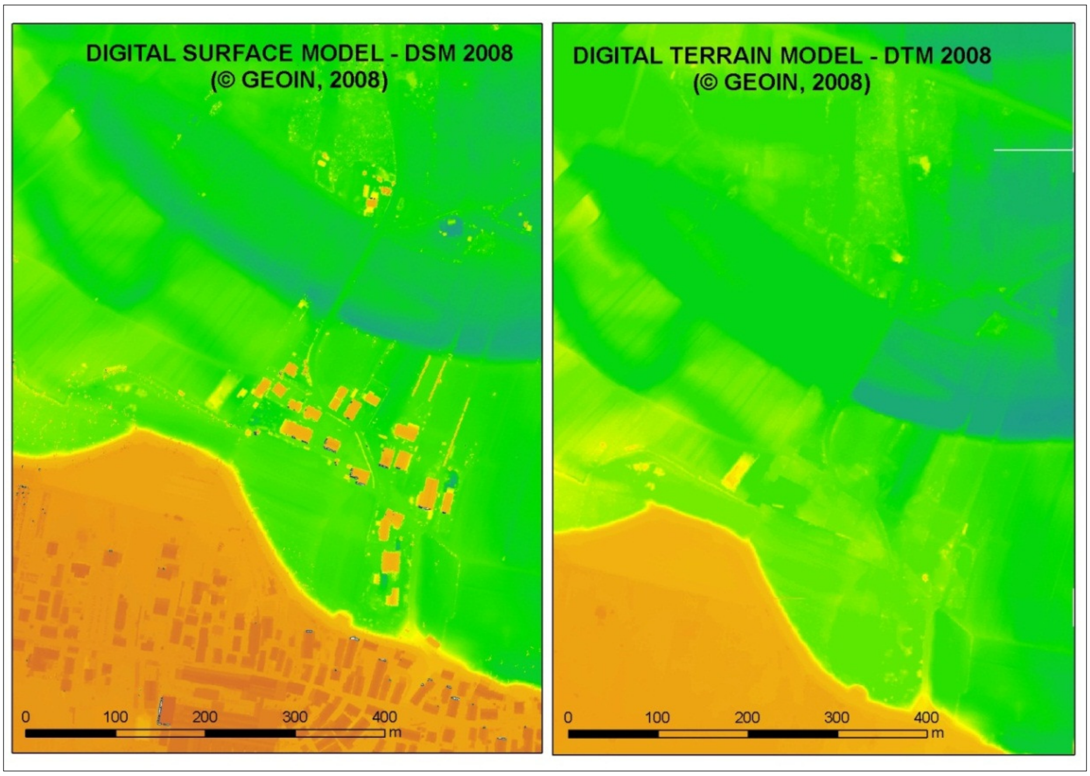


***Figure 23**: Example of DSM (left) and DTM (right), both are based on lidar data (©GEOIN 2008). On the left image the buildings (rectangular shapes) and trees (circular shapes) could be recognized while on the right they have been removed with classification methods.*

Because of the nature of the presented characteristics of the specific 3D surface model the different terms are used in correlation with the methodology of the formation and the type of objects, which are presented on the Earth's surface.
A study of long-term foreign literature on the generation and analysis of 3D models (Ackerman 1978; Doyle 1978; Burrough and McDonnel 1998; Kraus 2004; etc) showed that the DTM and DEM are the two most common terms to be used for 3D (mostly 2.5 D) presentation of landscape while DSM is used for example in forest studies.

However, regarding the method of DTM / DSM production (Figure 24), DSM is the first product of photogrammetric as well as **airborne laser scanning (in continuation ALS)** image processing, as it represents the elevation data of every object, including the trees, the buildings, etc. (Figure 25). The photogrammetric DSM is equivalent to the first reflection in laser scanning, while the DTM is equivalent to the last reflection in laser scanning. The laser is said to be one of the most prominent technological discoveries of the twentieth century. It was quite recently introduced to the photogrammetric community and interest in it has strongly increased. The fact that ALS is still a new technology influences the costs, the maturity of the data processing methods and the imaging system integration, the number of system and service providers, etc. (Baltsavias 1999a). The costs remain high till nowdays.

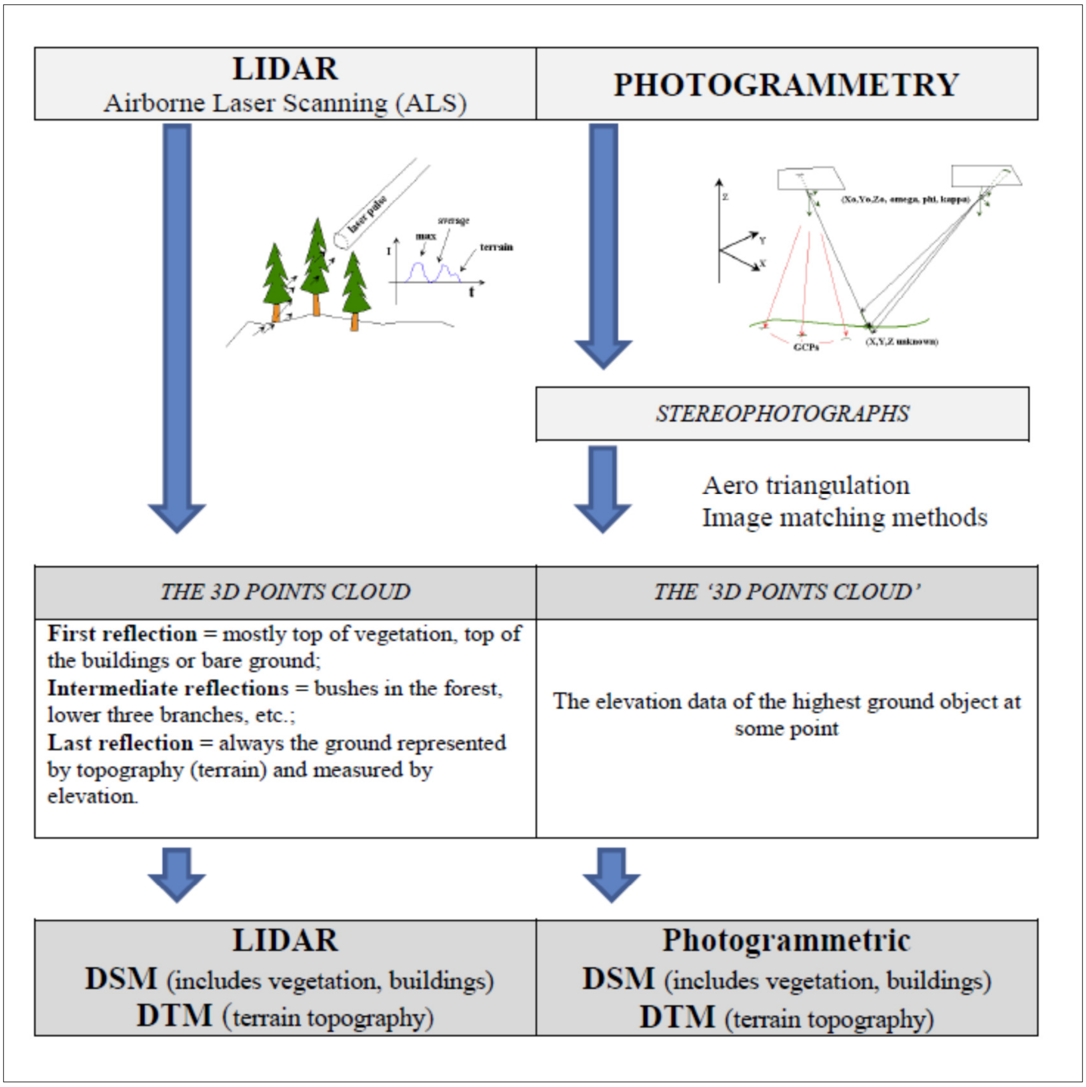


***Figure 24**: The comparison of two methodologies for DSM or DTM production: ALS and photogrammetry.*

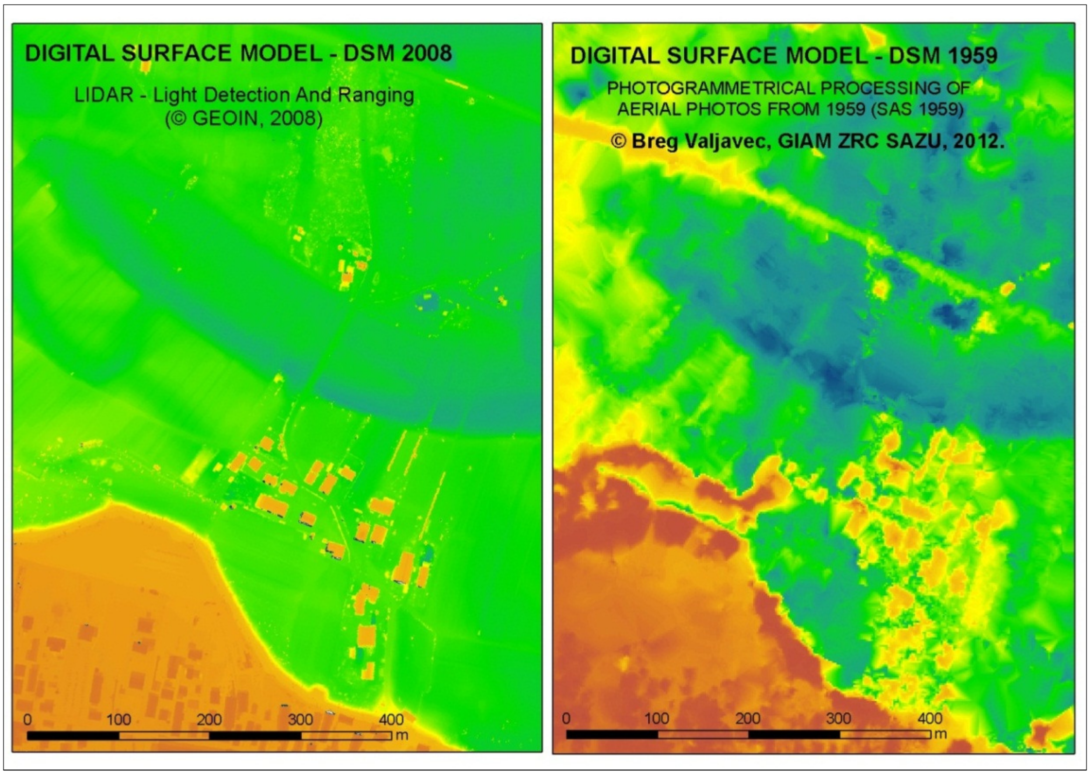


Figure 25*: Examples of two DSMs of the same area, depending on the method of the production. On the left image is an example of DSM made with Lidar technology (left, year 2008) and on the right image the DSM made by photogrammetrical stereo image processing (representing the landscape in 1959).*

6.4.4 Photogrammetric Stereo Processing of Archive Aerial Photographs

In conventional photogrammetry processes, stereo-photographs are usually used for the 3D spatial reconstruction of the photographed objects. The **stereo effect** (Figure 26) is established once the photographs overlap to a satisfactory extent (usually 60% – 80%) and the optical axes are not overly convergent (Triglav et al. 2000, Kraus 2007 etc.). In this chapter, the methodology for the production of DSM / DTM from overlapping aerial photographs will be represented in theory. The application of the methodology will be presented for each case study area in the framework of chapters 6 and 7 with the production of digital surface models (DSM) of past landscapes.

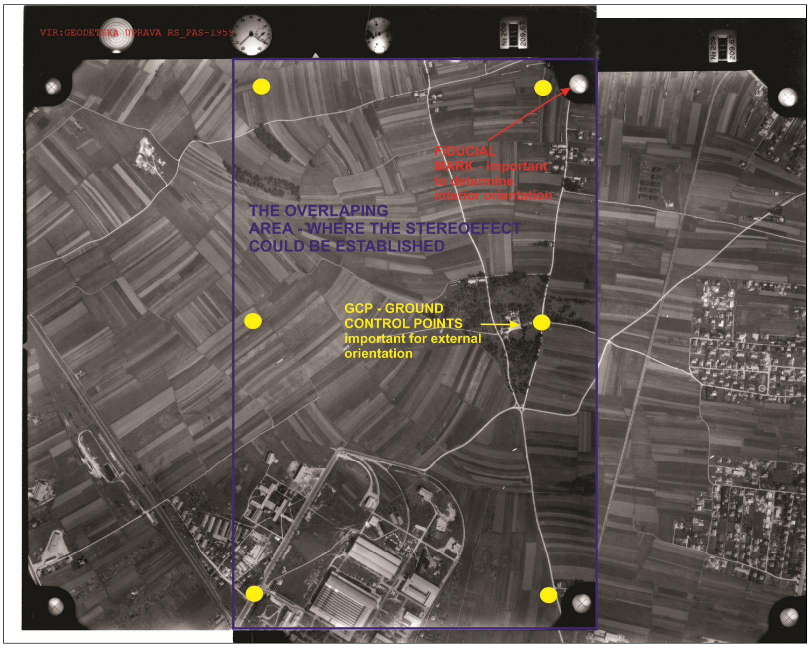


Figure 26*: Two overlapping images are the basis to establish the stereo effect. The DSM / DTM could only be modeled for the area that enables stereo-effect.*

When fashioning a DSM for greater areas, satellite images are used in addition to aerial photographs. Their advantage is covering a large area (a single stereopair), while their greatest disadvantage is the spatial resolution, which no longer represents a limitation with the introduction of high-resolution satellite images (Marsetič and Oštir 2007). Stereo perspective means seeing an area in stereo or 3D. This is important for determining the topographical relief of an area, as well as the height of objects such as trees and buildings. The result is comparable to the Lidar DSM that represents the surface of the first laser reflection.

The procedure of generation of DSM (schematic presentation on Figure 24, Figure 27) includes determining the **interior orientation**, **exterior orientation** and **aerotriangulation** (Triglav et al. 2000; Kraus 2007). The elements of the interior orientation of the aerial photographs include the focal lengths, lens distortion, fiducial marks (Figure 26) and other elements. If any of the internal orientation information is missing, as may happen in the case of archive photographs, aerotriangulation methods can be used to replace the missing information. External sensor (camera) information describes the exact position (airborne GPS and inertial navigation system (INS)) of the camera at the time of the image collection. In the case of an aerial survey, external information is based on the aeroplane position in the moment of snap shooting of an individual image. The position is defined using 3D coordinates (Gauss-Krüger x, y and elevation - z). The orientation of an image at the time of capture is defined in terms of the rotation about three axes: Omega (ω), Phi (φ), and Kappa (κ). If the external sensor model information is not available, most photogrammetric systems can determine the exact position and orientation of each image in a project using the bundle block adjustment approach. Stereophotographs only allow for the reconstruction of the relative dimensions of the depicted objects. In order to attain the absolute coordinates, it is necessary to determine a sufficiently great amount of points with the known spatial coordinates - **ground control points (GCP)**. The results in the spatial coordinate system (local or reference) can be acquired and the control points are then a basis for establishing the correct geometric proportions between the coordinate system of the photograph, the coordinate system of the camera and the coordinate system of the surface (triglav et al. 2000; Kraus 2007 etc.).

In order to execute a precise a**erotriangulation**, so-called **tie points** in the overlapping areas of the stereophotographs must be determined. A tie point is a point with not yet determined coordinates but is visually recognizable on all the overlapping photographs. The points must be homogeneously spread out through the entire area in order to ensure a greater preciseness of the results (Triglav et al. 2000; Kraus 2007). Here, different methods of digital matching of the overlapping photographs are applied (for example a comparison of the greys, patterns).

Once the GCPs and tie points have been collected, the process of establishing an accurate relationship between the images in a project, the camera / sensor, and the ground can be performed. This process is referred to as a **bundle block adjustment**. Since it determines most of the necessary information that is required to create orthophotos, DEMs and 3D features, the bundle block adjustment is an essential part of processing. The components needed to perform a **bundle block adjustment** may include the internal sensor model information, external sensor model information, the 3D coordinates of the tie points, and additional parameters characterizing the sensor model. This output is commonly provided with detailed statistical reports outlining the accuracy and precision of the derived data. For example, if the accuracy of the external sensor model information is known, then the accuracy of 3D GIS data collected from this source data can be determined (©Erdas 2008).

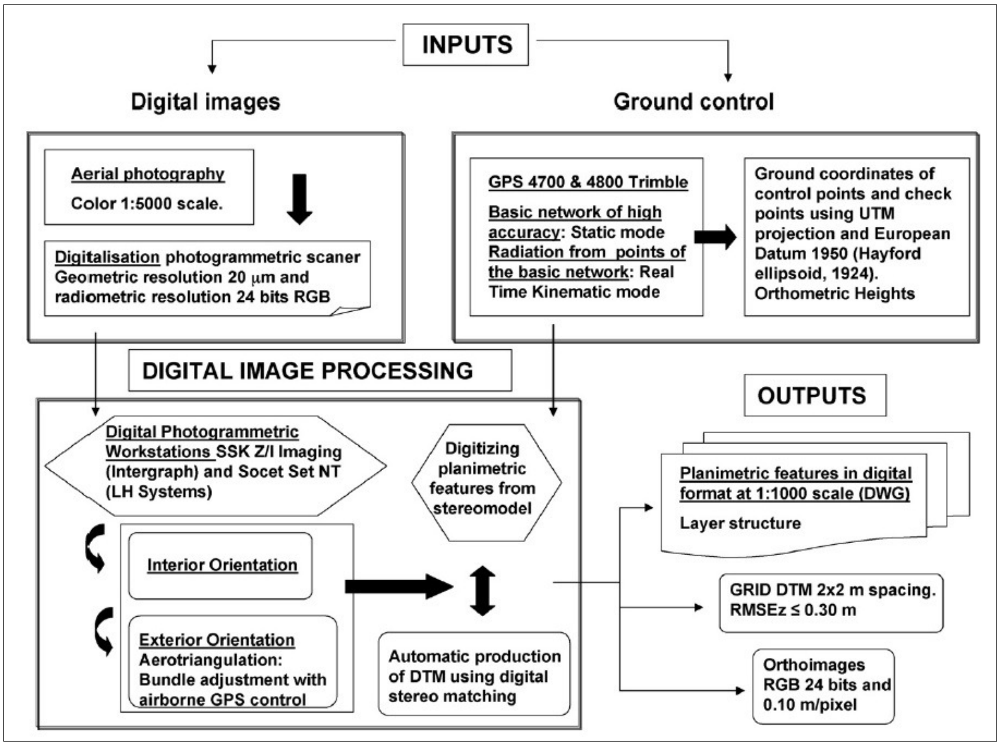


Figure 27*: An example of a scheme flowchart of the methodology to develop the basic digital cartography (Aguilar et al. 2007).*

Based on the generated sensor stereo-model, the characteristics of the surface on the area of the stereo-photographs are determined by using automatic 3D measuring. Stereommetry is used to determine the height of a surface (the relative and absolute altitude) based on the difference in two photographs of the same area, taken from two different view-points. The differences in altitude on the surface are obtained by eliminating the horizontal parallaxes (Triglav Čekada 2004). To achieve this, digital methods of matching up photographs are used, like autocorrelation, which works based on the principle of automatically searching for and measuring the location of common points of the Earth's surface that appear on both overlapping photographs. The end result is a large number of evenly distributed three-dimensional points. Once the automated DEM extraction process has been completed, a series of evenly distributed 3D mass points is located within the geographic area of interest. The 3D mass points can then be interpolated to create a TIN or a raster DEM (©Erdas 2008).

6.4.5 Application of DSMs and DTMs in Environmental and FWDS Research

The DTMs and DSMs represent the basis for environmental analyses, from which we can acquire a variety of information about a specific area. Many methods may be utilized when setting up a DTM and they all give differently precise presentations of the surface that enable the studying the relief and landscape. A DTM can be set up from primary field measurements or the data about the relief from given cartographic sources can be used (for example the digitalization and inter-polarization of contour lines). Primary field measurements can either consist of a classical geodetic measurement of the points in the field or recordings after various methods of remote sensing. From images, acquired with remote sensing, it is possible to form the DTM using various photogrammetric methods (Kvamme et al. 1997). Simple analyses of the DTM can be used for determining quantitative changes of the surface, which are a result of the activities based on various natural or anthropogeneous processes (i.e. waste dumping) within the natural geomorphology of the surface.

By photogrammetric processing of the aerial photographs of the Bílina coal mine (Slovak Republic), the elevation data was obtained. The volumetric analysis was used to calculate the temporal georelief differences completed during the selected years. Within the Bílina mine, almost 1 billion m^3 of material was excavated and transferred (Pacina et al. 2011). A geomorphological method was used to determine the speed of the erosion of the cliff (the erosion level) for the area of Southern Monterey Bay, California, USA, (Conforto Sesto 2004). The author used methods of digital photogrammetry for the formation of the digital terrain model with the intent of reconstructing the relief state as it was in 1984. On the basis of the comparison of the formed digital elevation model (aerial photographs 1984) with more or less recent presentation of the surface, the author managed to determine the level of cliff deviation in the studied time interval. A similar methodological concept was used within some spatial research in the past. In the case of the Triglav glacier, a team of photogrammeters (Triglav et al. 2000) tackled a difficult scientific challenge on how to reconstruct the 3D dimension and the surface of the glacier in different periods from archive photographs taken in regular time intervals on the same spots over several decades with the panoramic Horizont camera. The goal of the project was to form a surface model of the glacier's surface in different periods and to calculate the difference in volume of the glacier regarding these periods (Triglav et al. 2000).

The next research partly touches on the mentioned concept and it was intended for determining the characteristics of the forests units (Kobler 2007). The concept was based on the Lidar data. Using a comparison of differently processed lidar photographs, the author formed the normalized digital surface model (nDSM) of tree-tops based on the following formula nDSM = DSM - DTM, with DTM being the digital terrain model (the altitudes of clear ground, terrain; the last laser scanning reflection) and DSM being the digital surface model (the altitudes of tree-tops; the first laser scanning reflection).

Besides the comparative DTM analyses of past and recent landscape, special geomorphometric analyses could be used to determine the specific characteristics for the concave landforms. The DTM can be divided into classes with the use of geomorphometric parameters, as for example the level of incline curves and topographic openness (measured on different distances). For a more detailed classification of geomorphologic forms, additional parameters may be used, as for example, the accumulation of the water current in order to determine relief forms connected to fluvial processes (Anders et al. 2009). The segmentation of DTM onto landforms, from which concave forms are excluded, can be made by calculating the average curvature of DTM, which is then divided into a set of elements of various relief forms by segmenting the river basin. These relief form elements, which are characteristically formed around curved depressions, can be unified with concave forms (Romstad and Etzelmüller 2009).

6.5 Overview of Spatial Data

6.5.1 Historical (Archive) Aerial Photographs of Slovenia

In Slovenia, remote sensing was introduced after WWII, when the **Military Geographical Institute** (in continuation MGI, slo.'*Vojnogeografski inštitut*') from Belgrade started aerial recordings, mainly to meet the needs of the army. In the early 1970s, the aerial survey of Slovenia fell under the jurisdiction of the **Surveying and Mapping Authority of the Republic of Slovenia** (slo. *Geodetska Uprava Republike Slovenije,* in continuation GURS) with the technical execution by the **Slovenian Geodetic Survey** (Geodetski Zavod Slovenije, in continuation GZS). Systematic photo shoots entitled **Cyclical Aerial Surveys** (in continuation CAS) have been periodically done in Slovenia since 1975, when the entire territory of the country was first photographed in a scale 1:17,500. Recordings from that time still carry the label "strictly confidential" (on serbo-croat '*poverljivo*') and are to be used only in case of army emergency, although the majority of these aerial images are nowadays accessible in the Aerial reconnaissance archive in the property of the GURS institution.

CAS projects have, with interval special recordings, continued from 1975 to this day. The first infra-red aerial photographs in Slovenia were taken in 1980, when the aerial survey covered the entire country on a scale of 1:30,000 from north to south. Recording in the infra-red part of the spectre enabled a better interpretation within areas of agriculture, forestry, hydrology and geology. "*… The most fascinating are those landscape photographs, in which we can clearly distinguish the vegetation from other surfaces…"* (Orožen Adamič 1975a, p. 39).

Before the period of domestic aerial surveys, Slovene territory was recorded by foreign aerial surveys during WWII. Quality black-and-white aerial photographs exist for the period from as early as WWII, when the territory was photographed from airplanes for battle needs by the occupying forces (Germans, Luftwaffe) as well as the allied forces (British, RAF) (Figure 28). The images are archived at the RCHAMS (Scotland, Edinburgh) and can be ordered in digital form.

Figure 28*: Ljubljansko polje alluvial plain with the city of Ljubljana represented on one of the oldest existing archive aerial images from 1945 (© RACHMS, Edinburgh, UK, 2012).*

Figure 29*: The Ljubljansko polje alluvial plain with the city of Ljubljana represented on satellite image from 2010 (© Google Earth, 2012).*

6.5.2 Overview of DTMs in Slovenia

The possibility of DTM production is connected with the development of remote sensing and digital photogrammetry as well as methods and techniques for acquiring, processing, interpreting and measuring digital aerophotos. The first ideas to produce a DTM of Slovenia stem from the late sixties of the and in 1975, the first digital terrain model for the entire Slovenia was produced with a 500 m cell - 'DMR 500'. Until the end of the eighties and in the nineties, there was no significant progress regarding DTM production (Podobnikar 2003).

At the end of the 90s, two DEMs were formed for the entire region of Slovenia with a spatial resolution of 500 and 100 m. Both models were based on the points of the quadrant net within the D48 national coordinate system (Perko 2007). The altitudes were taken manually with the help of a quadratic net, drawn on a foil with corners of quadrants and were determined with a linear interpolation among the elevation lines. Topographic plans were used on a scale of 1:5,000 and 1:10,000. Where plans were unavailable, topographic maps on a scale of 1:25,000 were used (Rihtaršič and Fras 1991 and Perko 2007).

The hundred meter digital elevation model is based on data about altitude points, which are from north to south, or from east to west in a distance of 100 m and represent corners of quadrant cells with the baseline of 100 m, a diagonal of 141 m and the surface of 1 ha (Perko 2001). "… It is the distance between points that lessens the use of this model, as relief forms, which are not bigger than 100 or 141 m, get completely lost or get falsely interpreted. This is especially important when studying a landscape with lots of small relief forms, which are typical of, for example, the karst relief, covering almost half of Slovenia …" (Perko 2007, p. 16).
In 2000, the 25 m high digital elevation model, called the interferometric radar digital elevation model InSAR DEM 25 (by ZRC SZU) was made. It comprises of data about altitudes of points, which are from north to south or from east to west 25m in distance and are corners of quadrant cells with a baseline of 25m, a diagonal of 35m and a surface of 625 m^2. The model was geo-morphologically tested and adequately upgraded, which made it especially suitable for morphometric analyses (Perko 2007).
The Scientific Research Center of the Slovenian Academy of Sciences and Arts (in continuation ZRC SAZU) developed a 12.5-meter digital elevation model in 2005 for the Surveying and Mapping Authority of the Republic of Slovenia (Podobnikar 2002; Podobnikar 2005; Podobnikar 2006). A new improved DEM 12.5 was made with the help of various geodetic data. The method of index addition sources with geomorphologic corrections was used. The advantages of this method are: high resolution levels, vertical precision and geomorphologic quality. The method additionally also covers the close vicinity of Slovenia. The data is suitable for realizing various spatial analyses for use in the visualization or illustration of a specific area, as well as for the formation of topographic and thematic maps, etc.
DEM 5 (made by the GZS) was made with the automatic stereo-assessment of aerial photographs from 2006 with the help of correlation and various geodetic data, where stereo-assessment was not possible. Somewhat older photographs were used in overgrown areas, as well as the existing DEM of Slovenia (Podobnikar 2008).

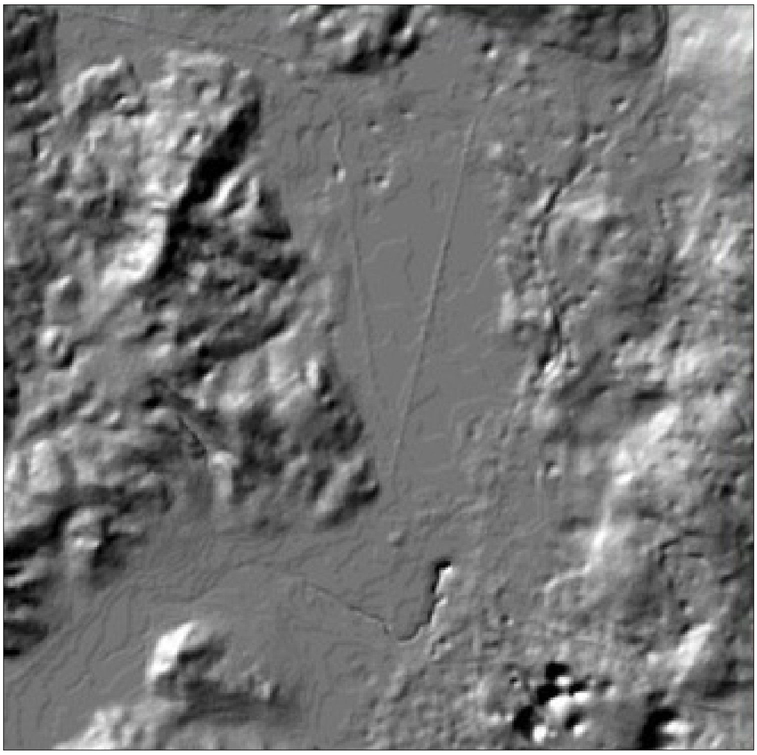


***Figure 30**: DEM 12.5 (©GURS 2005) of Logaško karst polje.*

6.5.3 Overview of the Remote Sensing Data of the Recent Landscape of Slovenia

Compared to other forms of remotely sensed imagery, aerial photo interpretation is generally a straightforward process due to the map-like qualities of imagery and because it includes wavelengths recognizable, or easily understandable, to the human eye. Typical photography includes black and white, panchromatic, or natural color across the visible portion of the electro-magnetic specter. In addition, **CIR** photography (color infra-red; CIR in continuation) that includes the 0700–900 nm near-infrared wavelengths helps to detect the health and stress of the vegetation (Slonecker et al. 2010). Remote sensing images of the recent landscape of Slovenia are basically the result of national aerial surveys and in smaller extent derived from satellites. The latest aerial survey of Slovenia was made in 2010 / 2011 (by GURS), unfortunately only in the visible part of spectrum. In the national CAS project in 2006, the entire area of Slovenia was aero-photographed with a digital camera for the first time. Aero-photographing was made in three bands of **visible colors** - red, green, blue (in continuation RGB), as well as in the **near infrared** (in continuation NIR) part of the spectrum. From 2006 onwards, a prerequisite for acquiring aero-photogrammetric data is the use of a professional big-format aero-digital camera. Only these types of cameras enable the simultaneous acquisition of data in the color technique within the visible part of the light spectrum and within the NIR spectrum enabling a better interpretation of the data in agriculture, forestry, hydrology and geology (Internet 9). Multispectral aerial photographs of a high spatial resolution (up to 1 m) are available for the entire Slovenia in the format of a true RGB color image or as a color infrared image - CIR. In this way, the colors of the landscape as detected by the human eye may be acquired. In order to get information, for example, on the physical characteristics of the objects (temperature, humidity) from the photographs, the information must be in at least one infra-red channel. The red section of the visible color specter is closest to the NIR one and therefore the most appropriate section within the specter to determine the differences in the vegetation. Using an additional infra-red spectral channel, it is possible to create a false infra-red composite image from the NIR, red, and green spectral channel.

Some multispectral satellite images of high spatial resolution (2m and more) are available for some smaller parts of Slovenia, mostly for Ljubljana. The multispectral satellite GeoEye image scene is available for about 100 km² of Ljubljansko polje (©GeoEye 1, 2009-08-17). In view of the fact that satellite images are only available for some areas and the multispectral aerial photographs of CAS 2006 exist for total country area, the latter prevail. The GIS tools (Erdas Imagine 2011; ArcGIS10) were used to provide a four-channel mosaic image by uploading the RGB image (RGB DOP) on channels 1, 2, 3 and the CIR image on channels 4, 5, 6 (CIR DOP). In the next step, channels 5 and 6 were and channels 4, 2, 1 were used to demonstrate CIR and channels 1, 2, 3 to demonstrate RGB. The individual channel was analysed as well by isolating them into separate bands. Using the individual bands, the desired rations between the individual spectral bands made it possible to determine the impacts in the landscape. Aerial photographs of CAS and SAS (Special aerophoto survey, in continuation SAS) of Slovenia are accessible to the public free for non-commercial use, whereas the price of satellite photographs reduces their wider use. As almost all things in life, everything has its advantages as well as disadvantages, which can be evaluated on the basis of wanted results. Aerial photographs have the advantage of enabling the recording of specific smaller areas on the wanted scale at a specific time and adequate weather conditions. On the other hand, satellite photographs are bound to the orbits of their satellites (Triglav 1996).

7 FIELD SURVEY OF FWDS

7.1 Introductory Remarks

The field methods for determining the potential locations of FWDS are based on knowledge and experiences, which were gathered with field registers within the research projects of field mapping illegal waste disposal sites in the Jarški Prod water-protection area (Smrekar et al. 2005) and in the water-protection areas of the City Municipality of Ljubljana (Smrekar et al. 2006) as well as with previous research in karst areas (Breg 2007). Some surface characteristics of landscape factors were established in the area of non-active illegal waste disposal sites, which differ from those outside the waste disposal area.

7.2 Soil Sampling

In order to pinpoint the pedogeographical characteristics of FWDS, pedological sounding with the so-called Dutch soil auger (see Figure 72) is the most appropriate field method. It enables quick determination of soil depth and structure. These two characteristics are key criteria for determining anthropogenously altered soils. The main objective is to generate a soil profile, called the **sounding soil profile** (in Slovene '*sondažni profil'*) after the sounding method. "*…A soil profile is a vertical section through the pedosphere — from its surface — to its original foundation…"* (Lovrenčak 1994, p. 74). Due to the varying pedogenetic factors, different pedogenetic processes occurred, which causes horizontal layers called genetic horizons or horizons to be formed in the soil profile (Lovrenčak 1994). Soils that have been in any way transformed or changed due to anthropogenic impacts are called **anthropogenic soils, anthrosols**. **Technogenic soils** (**technosols)** are soils and soil-like bodies formed or altered by industrial, mining, and urban activities (Stroganova et al. 2004). In Russia, the classification of technogenic soils has been further determined and are distinguished between the categories of **soil** and **zem:** for instance **technogenic soils (technosols**) and **soil-like bodies - technozems, urbanozems.** The zems are newly formed layers on new completely changed bed layers, like waste. A special type of technogenic soil that is formed on waste disposal sites is called **deposol.** According to the Russian classification they could be named also **depozems**. The pedological classification of sampled soils was simplified due to the lack of information on the type of the basic layer (depth of waste) by calling all the soils, under which the existence of waste was proven, **deposols**.

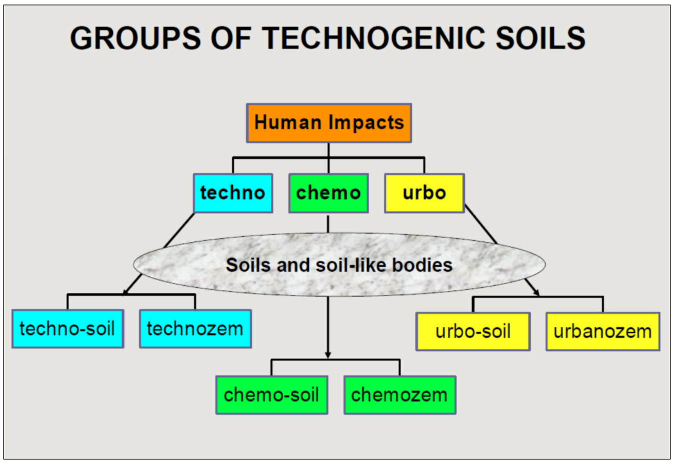


Figure 31*: An example of technosoil topology from Russia (Stroganova et al. 2004).*

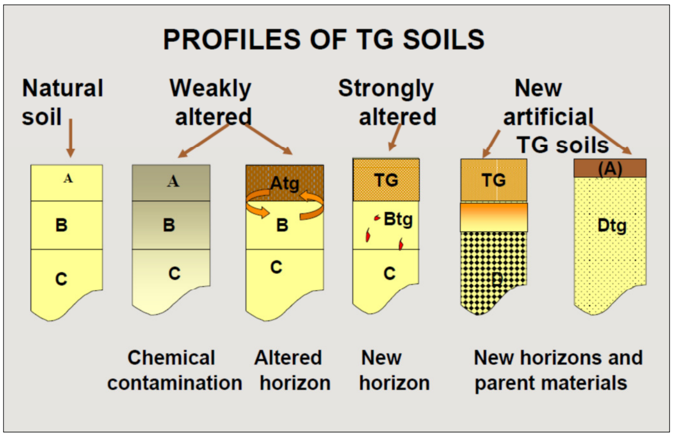


Figure 32*: Profiles of technogenic (TG) soils (Stroganova et al. 2004).*

Figure 33*: Deep industrial technozem on silicate slags (left)*
Figure 34*: Urban technozem on loamy sandy till with brick fragments (right) (Stroganova et al. 2004).*

Pedological sounding is used to determine (Table 5):

- The surface depth to which sounding is possible and with that (if drilling is possible) the soil depth of the original foundation (which can also comprise of waste);
- The basic characteristics of the sounding profile (horizons, color, skeletal particles, etc.);
- Qualitatively determine the elements in the soil profile that are of an anthropogenous origin (brick, concrete, plastic, asphalt, etc.).

In the process, the following criteria were used for determining the deposols and anthrosols.

INGREDIENTS	CHARACTERISTICS
RECENT AND OLD ARTIFACTS	BROWN COLOR
EXCAVATED SOIL	POORLY DECOMPOSED ORGANIC MATERIAL
NATURAL SEDIMENTS (CLAY, GRAVEL)	WEEK STRUCTURE
TECHNOGENIOUS SUBSTANCES	ARTEFACT AFFLUENCE
CONSTRUCTION AND DEMOLITION WASTE, MUNICIPAL WASTE	NEWLY-FORMED MINERALS (COLORFULNESS - MARBLENESS)
	HETEROGENEOUSNESS

Table 5*: Criteria for determining anthropogenic soils depending on the substance origins (Stroganova et al. 2004).*

Parallel to the pedological sounding, it is necessary to perform an inspection of the test area inside the delineated borders and to locate the visibly recognizable differences in the soil surface:

- The presence of greater amounts of anthropogenous objects or waste on the floor (plastic masses, cement block from ruins, parts of asphalt, old furniture and appliances, etc.);
- The mole's activity in comparison to the surroundings, as some occurrences are very useful to determine the pedogeographical anomalies (molehills, tunnel depths, etc.), connected to the soil depth. The mole digs in the root zone (at a depth of 40 – 50 cm), where there are insects they feed with. If the root zone is shallow for any reason, the mole will not dig there and no molehills occur.

The sounding method is appropriate for determining the depth of the soil, the layeredness and also for a potential laboratory analysis; it is the most appropriate for controlling the results of the multispectral aerial photograph analysis. Pedological sampling is a very important field method that acquires ground truth data on sampled surface for multispectral image analyses. The spectral reflectance in the visible and infrared part of spectre is mostly affected by the characteristics of the upper ground layers. The main characteristics of ground are (Matko 1996):

- soil (other top layer) moisture,
- mineral structure of the soil regarding the type and size of the mineral parts,
- humus share,
- soil grain and surface structure,
- surface structures regarding land use.

7.3 Electrical Resistivity Tomography

The measurements of electrical resistivity are one of the most common ones as they enable the researcher to define the nature, structure and stratigraphy of the material. The method is based on the fact that the materials differ according to the electrical resistivity. Its value may change considerably with changes in the water content (drying, moistening) and with fracturedness. The best results are obtained when measurements are made in dry conditions, but the results shall be compared to the known or absolute values. In other cases, the measurements of the known materials should be done before any other measurements. The method is relatively fast and non-destructive; with it, linear data in the length of a few hundred meters and the depth of a few tenths of meters can be obtained. The method can be used for determining the scree depth, investigating of permafrost, the permeability of the material and for determining the differences in carbonate rocks, such as limestone and dolomite. The use of geophysical measurements in geomorphology has recently increased. They are useful for exploring sediments and understanding relief development (Komac 2006).

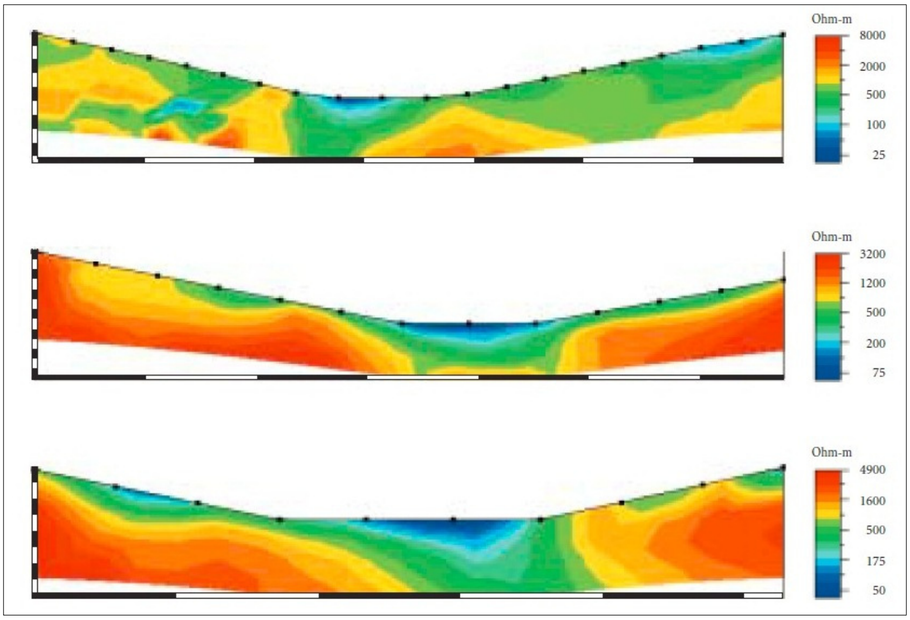


Figure 35*: Transverse section through a dell in the dry state measured 4 June 2005 with the Schlumberger method. The vertically scale is 1 m and horizontally scale 5m (Komac 2006).*

Geoelectric methods are widely used in solving the doline problem. There have been many applications of electrical resistivity methods to detect dolines. Carbonate rock in general has a significantly higher resistivity than clayey deposits because it has a much smaller primary porosity and fewer interconnected pore spaces. The high contrast in resistivity values between carbonate rock and clayey material favors the use of the Electrical resistivity tomography for determining the boundary between the bedrock and the overburden (Zhou et al. 2000). The determination of the structure and depth of the sediment fills on karst with the use of electrical resistivity tomography (also named electrical resistivity imaging) has been conducted by many authors: Cook and Nostrand (1954), Franklin et al. (1981), Komac (2006), Stepišnik (2006, 2007 2008a, 2008b), Stepišnik et al. (2007), Stepišnik and Mihevc (2008a), Sauro (2009), Stepišnik et al. (2008, 2009), Ferk (2009), Ravbar and Kovačič (2010), Zhou et al. (2000).

A variety of arrays has been used for this type of research. Komac (2006) used the Schlumberger array to study genesis of dells, Sauro (2009), Ravbar and Kovačič (2010) used the Wenner array, and Zhou et al. (2000) used the pole-dipole array. The dipole-dipole array was used by Stepišnik (2006, 2007 2008a, 2008b), Stepišnik et al. (2007), Stepišnik and Mihevc (2008a), Stepišnik et al. (2008, 2009), Ferk (2009). Generally, where horizontal structures were emphasized, the Wenner array was used and in cases where vertical depth penetration and high resolution were of high importance, the dipole-dipole array was used.

The electrical resistivity tomography is extremely useful for imaging both the depth and lateral boundaries of landfills. In addition, this method is useful for the detection of leakages in landfills (Internet 11). It is useful for identifying both the lateral boundaries and depth of landfills where there is a measurable electrical resistivity contrast between the landfill materials and the background soils. Most landfills do exhibit a characteristic resistivity that is measurably different from the background (although the actual values vary from site to site) (Young 2010). In some cases, where an intrusive investigation may not be possible due to access constraints (particularly heavy equipment access), a geophysical survey may be the only method available to determine the extents (Young 2010).

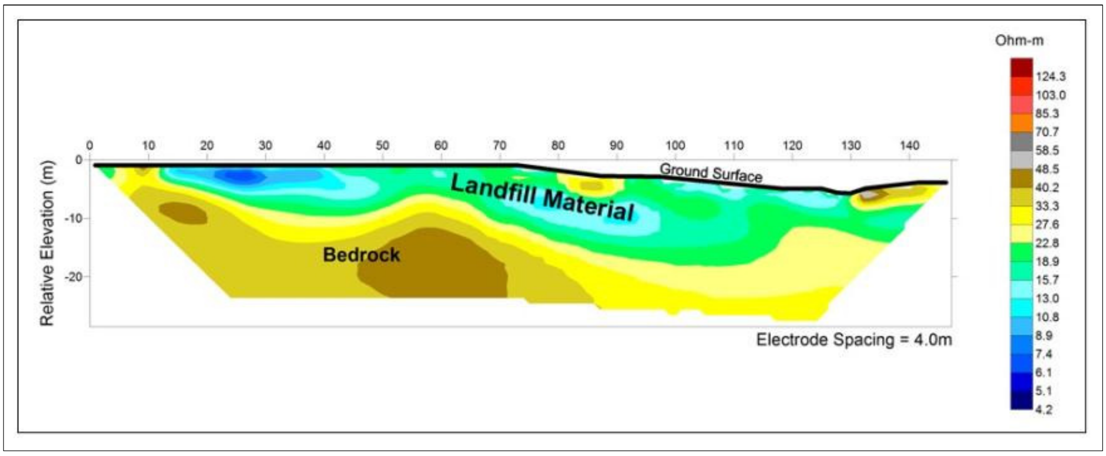


***Figure 36**: An example of determining the depth and boundaries of the landfill (Internet 11).*

Rock / material type	Resistivity range (Ωm)[1]	Resistivity range (Ωm)[2]	Resistivity range (Ωm)[3]
igneous	100–1,000,000	100–250,000,000	
limestone	100–10,000	50–400	50–10,000,000
dolomite			100–10,000
sandstone	100–1,000	8–4.000	1–100,000,000
shale		20–2.000	20–2,000
sand and gravel	600–10,000		1–1,000
clay	10–100	1–100	1–100
unconsolidated wet clay	20		
alluvium		10–800	
soil	1–10		
fresh water	3–100		0.5–300
sea water	0.2–1		0.2

***Table 6**: The electrical resistivity of different materials (Gostinčar 2011).*

[1] Seminar of Resistivity Imaging, 2003.
[2] Loke, 1999.
[3] Geology 228/378, 2011.

A Resistivity Survey is good for "sectional profiles" of deep fills (9 meters) and disposal sites where the disposal fill material's electrical resistance is significantly different than the surrounding geologic formations and deposits. The Resistivity surveys may have a limited value in areas with a high moisture content or in soils with high salinity, e.g. tidal areas, marshlands, bay fills, etc. It can be used to confirm a suspicion of dumped waste in a concave landform, to determine the depth of the deposited waste and the thickness of the top layer, with which the waste is covered (Young 2010).

Determining the profile position and length involves deciding on the distance between the electrodes (spacing) and the placement of the metal electrode carriers, probes (40 cm bars, approximately 1 cm in diameter) that are fixed into the ground. The electrodes are placed on them about 3-4 cm above ground. If needed, the soil surrounding the electrode carriers can be moistened with water, preferably salt water, to improve the contact with the surface. In cases where the surface consists of sand or gravel, it may prove problematic to create a good contact with the surface. The penetration depth is usually 15-20% of the entire profile length (the distance between the first and last electrode). Therefore, if the designated length of the measured profile is 40 meters, then the penetration depth is 40 m / 0.15 = 6 m (Seminar of Resistivity…2003).

The spacing between individual electrodes plays an important part in this respect. The rule applies that it is not possible to perceive objects that are less than half the distance between electrodes in size. For instance, if the distance is 2 m, in theory objects that are larger than 1 m can be perceived. Before making measurements with the Super Sting R1/IP (AGI - Advanced geosciences, lnc, Texas, Austin) device (the type of machine used), it is necessary to choose the type of appropriate electrode field (Dipole-dipole field, Schlumberger, Wenner, Pole-pole). The electrode fields differ according to the way they transmit and receive the electric current to and from the ground. The next step is to designate which two electrodes will be transmitting and which two will be receiving as well as the pattern, the number of repetitions and other variables that may influence the result.

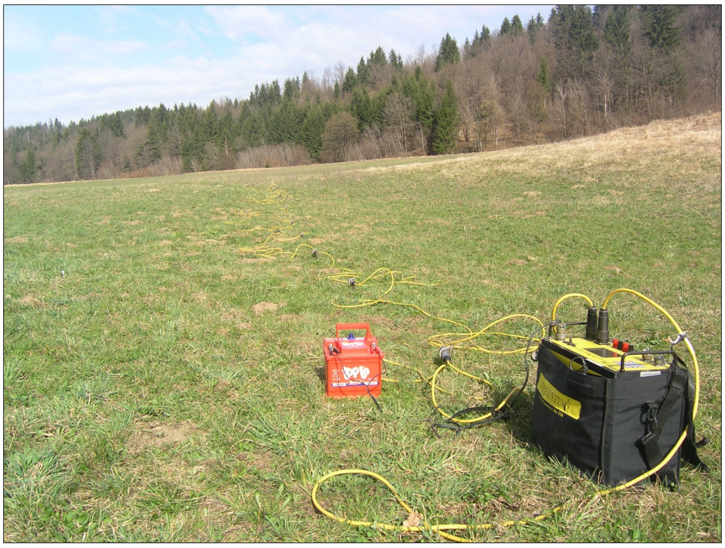


Figure 37*: The device (Super Sting R1/IP) for measuring the electrical resistance of the ground, connected to electrical cables, electrodes and a battery.*

7.4 Field Mapping of Vegetation and Relief

Visibly distinguishable differences in the soils could be recognized indirectly through the type of vegetation: scarce vegetation, a lack trees, smaller and younger trees, areas with non-typical vegetation (cultural vegetation in forests, like tomato), type of vegetation (pioneer types, like moss, which is a result of undeveloped soil types). Visibly distinguishable differences in the micro relief could be recognized in pilled-up land, higher than the surrounding areas; concave and convex anthropogenic landforms; relief anomalies regarding natural surface (relict riverbeds).

Plants are an excellent indicator of changes in soil. The **referential plants** are an indicator of the soil underdevelopment that is typical for filled gravel pits and dolines, where the commonality is the underdevelopment of the horizons, poor soil structure and no humus horizon. These plants include **pioneer** and **ruderal species** like as mosses, dandelion, etc. For example increased nourishments in the soil appear when organic waste lies under it (wood waste, food waste, agricultural waste, etc.). They are called eutrophic (e.g. nitrophic) plants, as they are an indicator of eutrophication (e.g. nitrification) of the soil. They include the common nettle (*Urtica dioica)*, different sorts of broad-leafed dock (*Rumex obtusifolius)*, shepherd's purse (*Capsella bursa-pastoris)* etc. Referential plants could be specified as an indicator of the anthropogenous influences and the grow site degradation. The referential phytocenological list could be used to determine the referential plant species for studied areas.

Vegetation attributes:

- Land cover of the potential gravel pits: active waste disposal site / built-up, partially built-up / fields and gardens / meadow / traditional meadow / sparse trees, overgrowing / overgrowing with bushes / forest / active gravel pit.
- The presence of vegetation / waste: no cover, still visible waste on the surface / completely uncovered / overgrown with natural vegetation / cultural vegetation.
- Mosses: the ground is visibly overgrown with mosses / no present mosses.

Relief attributes :

- The gravel pit / doline can be recognizable in nature by its relief: an expressed concave shape / an expressed convex shape / ridged flat surface / ridged slightly concave surface / ridged slightly convex surface.
- The state of the gravel pit being filled in nature: no signs of filling / partially filled / completely filled.

8 LOGAŠKO KARST POLJE CASE STUDY

8.1 2TL/3E Approach for the Karst Landscape Type

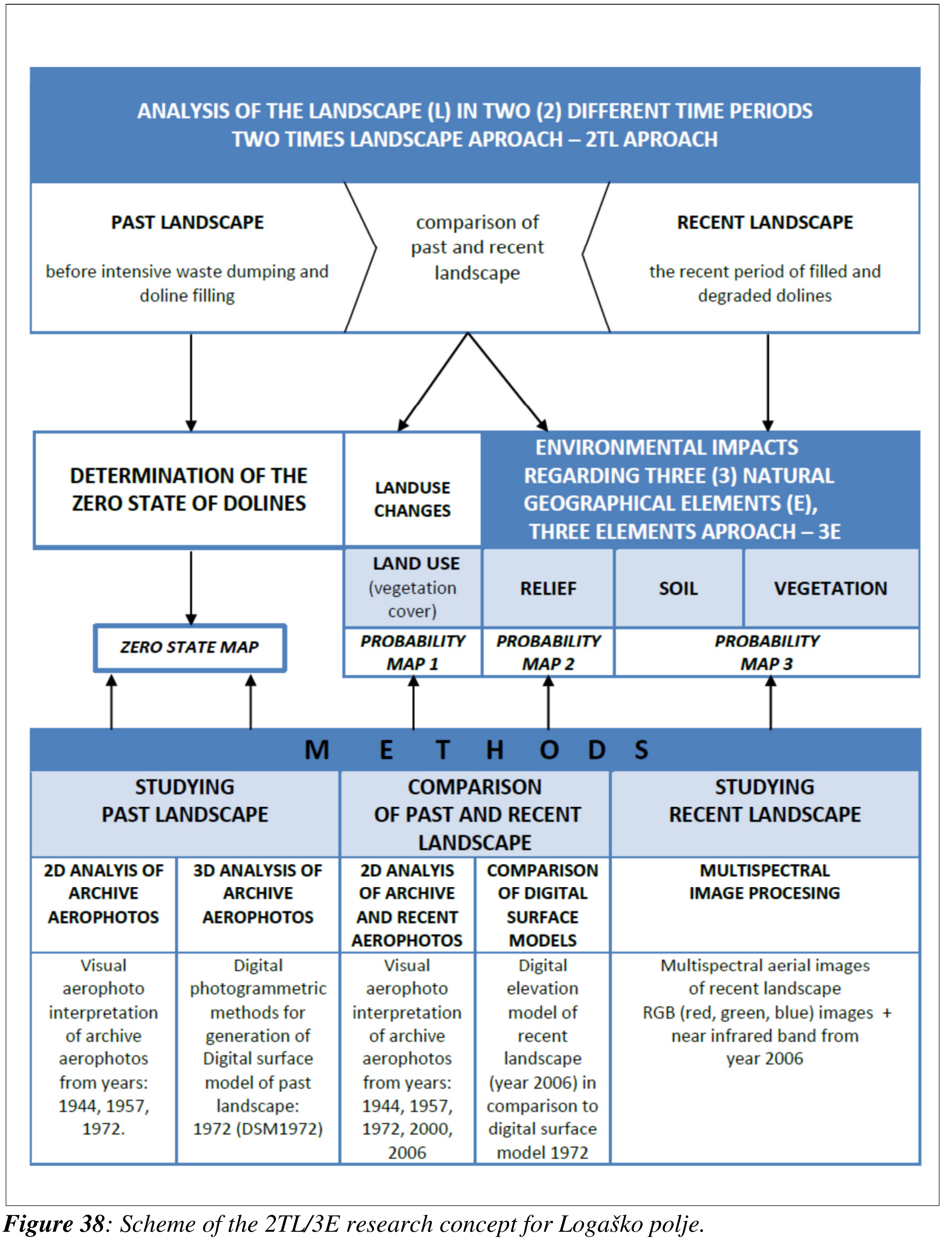


Figure 38: Scheme of the 2TL/3E research concept for Logaško polje.

8.2 Studying the Past Landscape from Archive Aerial Photographs

The main goal of studying archive aerial photographs is to determine the **zero state** of dolines. This includes location, shape and depth of individual doline. The geoinformatic analyses of the past landscape are based on **the 2D and 3D archive aerial photograph analyses**. The 2D object analysis is based on a simple visual image interpretation, while the 3D object analysis is geometric, based on 3D surface modelling. The main goals of the 3D analysis are to determine the doline depth and volume of deposited waste.

Many archive aerial photographs exist for the studied area and had been taken (recorded) from WWII on. Only three consecutive photographs from 1944 (©RACHMS, UK) were available that unfortunately do not cover the entire studied area. This was compensated by analysing the photographs from 1957 and 1972 as being the oldest available. The 1957 and 1972 photographs were taken as part of special aerial photography shoots (SAS) of the GURS institution, executed by the Military Geographical Institute (MGI) from Belgrade and after 1972 by the Slovenian Geodesy Office (GZS).

	RAF1944	**PAS1957**	**PAS1972**	**TTN5**
Shooting period	1944	1957	1972	1974, 1981, 1986, and 1987
Shooting scale	8,400	20,000	15,000	5,000
Resolution (dpi)	1,200	1,200	1,200	96
Dimensions	8552x9972	8615x8531	10736x10848	5316x7088
Basis for scanning	Film	Contact copy	Contact copy	/
Bit depth	8 bit	24 bit	24 bit	1 bit
Information owner	©TARA	©GURS	©GURS	©GURS
Information price (scanning)	50£/unit	30€/unit	30€/unit	free

***Table 7**: The relevant characteristics of the aerial photographs in comparison to TTN5.*

The aerial photographs of the special aerial survey shoot from 1972 (SAS 1972) are also appropriate for further photogrammetric stereo image processing and making a 3D model, DTM or DSM. In addition to using the appropriate scale of the photographs, it is very important for the photogrammetric 3D modeling to have a calibration report of the camera to achieve a better quality of the produced 3D models of the past landscape. In table 7 the main characteristics of the applied archive aerial images and relevant topographic map are represented.

8.2.1 Visual interpretation of Dolines – 2D Analysis

With the help of visual aerophoto-interpretation, based on color (RGB) or black & white photographs, which can be improved or processed with a computer, it is possible to recognize and distinguish real objects on the basis of their visible characteristics. The basic goal of the visual analysis is to determine all, or as many as possible, dolines that existed on the studied area since the initial year for studying onward, based on a sequence of the archive aerial photographs. 1944 was selected as the initial year. In accordance to that, the purpose of the method is adding and improving the data of the zero state, because the photographs from different periods do not always cover the entire studied area.

The identification of dolines on the aerial photographs was based on a photo-interpretation-key that included the following parameters: **shape**, “**visualdepth”** (shadows give an impression of depth), **color** (different shades of grey - the darker ones usually mark the bottom of dolines) and **texture**. The spatial location of a doline on the aerial photograph is usually represented by its drainage focus, which is the lowest point and not necessarily coincident with the geometric centre of the depression (Ford and Williams 2007).

The first step was the analysis of the oldest, black-and-white photographs from 1944. On areas of denser forestation, the data was supplemented with the dolines that were located on the Basic Topographic Plan 1: 5,000 (in continuation TTN5) from the 70s and 80s. The interpretation and location of each individual doline on the TTN5 is based on determining the highest lying connected contour line (the highest altitude) with its center marked by the minus sign (-), pointing to a concaveness of the relief and a decrease in altitude.

In total, 1,633 dolines-like objects were documented from the studied archive aerial photographs and the TTN5. 571 dolines were documented on a 6 km² area, covered with the oldest photographs from 1944. In the first phase, the data was complemented with the 947 objects derived from the TTN5 analysis. The latter data is located outside the area of the photographs from 1944. The object polygons, determined by previously described input data (1944 images, TTN5) were overlapped over the photographs from 1957 and 1972 and supplemented with potential missing dolines. 40 additional doline-like objects were recognized on the 1957 images (34 of the objects lying on the photographed area and 6 outside of it) and 75 objects on the 1972 images.

Dolines that have been recently covered by forest (the western dolomite part of the studied area) were mostly not forested in 1944, neither overgrown but rather opened; for this reason, the results of the photointerpretation were very good in comparison to the TTN5 analysis. The dolines are much less visible on the photographs from 1957 and 1972 due to the deagrarisation and consequential forestation of the landscape after WWII. Finally, some new dolines were recognized on the recent photographs from 2000 and 2006 that had not been located on the earlier photographs due to the poor color quality of the studied archive photographs.

The zero state of dolines (Figure 39) represents 1,365 dolines with a combined surface of 876,617 m^2 and an average surface of 642 m^2 on an approximately 11 km^2 studied area. The combined area of all the dolines in turn covers 7.8% of the entire area.

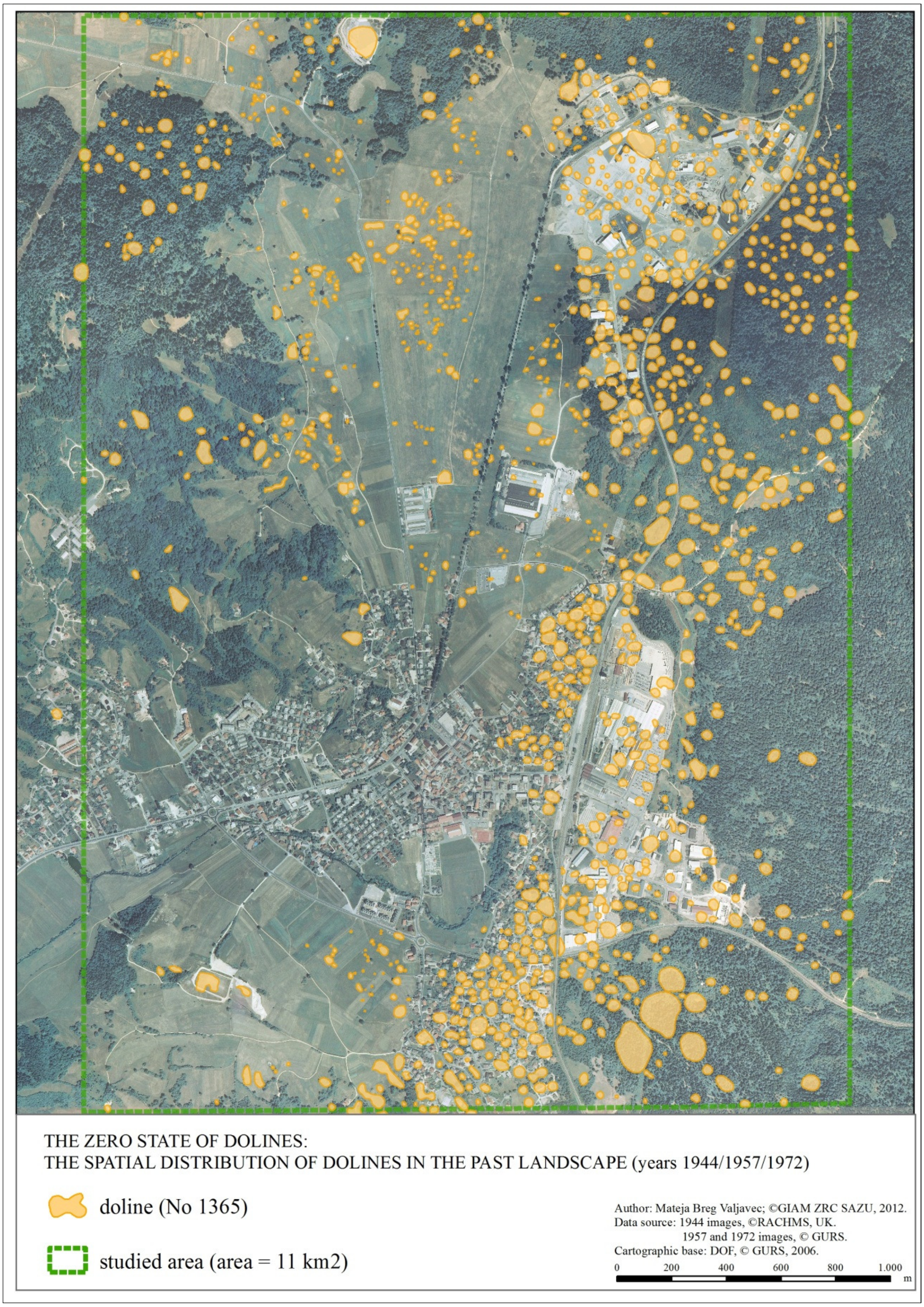


***Figure 39**: Distribution of zero state dolines, identified on images from 1944, 1957 and 1972.*

8.2.2 Photogrammetric DSM 1972

The 3D spatial analysis demands DSM of the past landscape that could also be generated on the basis of archive aerial photographs and using digital photogrammetry methods. In that context, this chapter presents the procedure for the generation of three-dimensional spatial data (in continuation 3D) that was necessary for comparative relief analyses of the past and recent landscape. The methodology and the process are presented on the DSM of Logaško polje for 1972. The DSM for the study area that is bordered by five sequential stereo pairs from 1972 was produced by Erdas Imagine 2011 software, using *LPS – Leica Photogrammetry Suite* and *Automatic Terrain Extraction* module (©Erdas 2011). All the necessary orientation parameters were gathered and calculated and the DSM1972 was produced with photogrammetric methods.

A selection of available, appropriate, as old as possible, archive aerial photographs for the study area was based on previous spatial analyses of metadata (georeferenced vector layers of aerial survey lines for each year). The main work was done in the Aerial archive. The DSM72 generation was carried out for an area of 5 consecutive aerial photographs of the same photographed lane, with at least 60% overlap. Table 8 demonstrates the necessary technical characteristics of the aerial recording of the selected photographs. The calibration report of the WILD RC-8 camera for the SAS 1970 was used and the measurements were included into the sensor model (Figure 41).

Date of shooting	1972-04-03
Platform	Morava L-200, YU-BB12
Fight altitude	2,300 m
Scale of the photographs	1:15,000
Instrument	Camera WILD RC-8
Format	230 x 230 mm
Lens	90
Focal length	152 mm
Overlap	60%

***Table 8**: Technical data of the special aerial photography shoots (PAS), Vrhnika, 1972, taken from shooting list number 9 (©Slovenian Geodesy Office).*

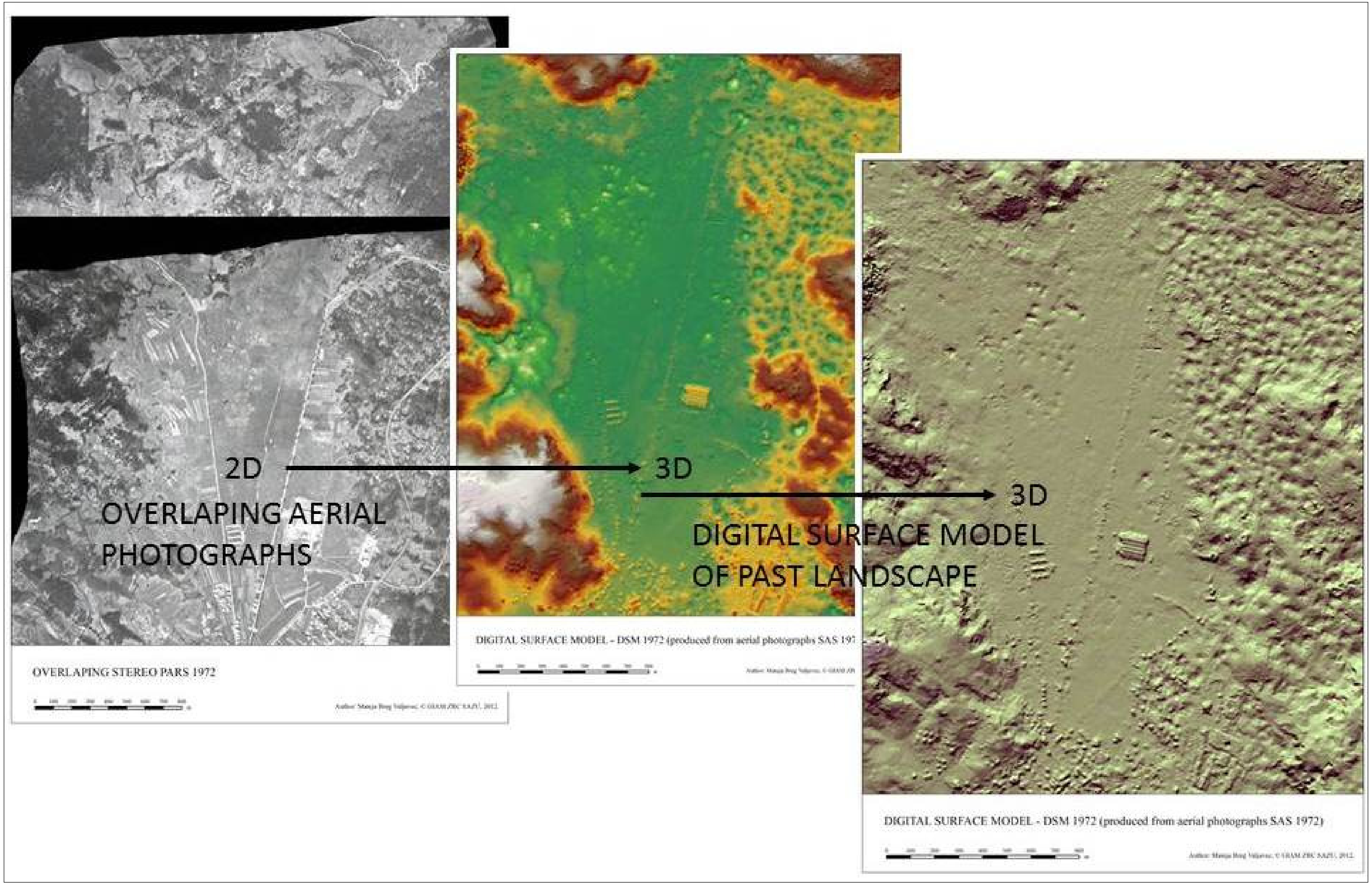


***Figure 40**: The appropriate old aerial photographs from 1972 were selected to generate the final DSM1972. The figure shows an example of 3 overlapping stereo pairs (left) and the results of the 3D modeling – DSM (middle and right).*

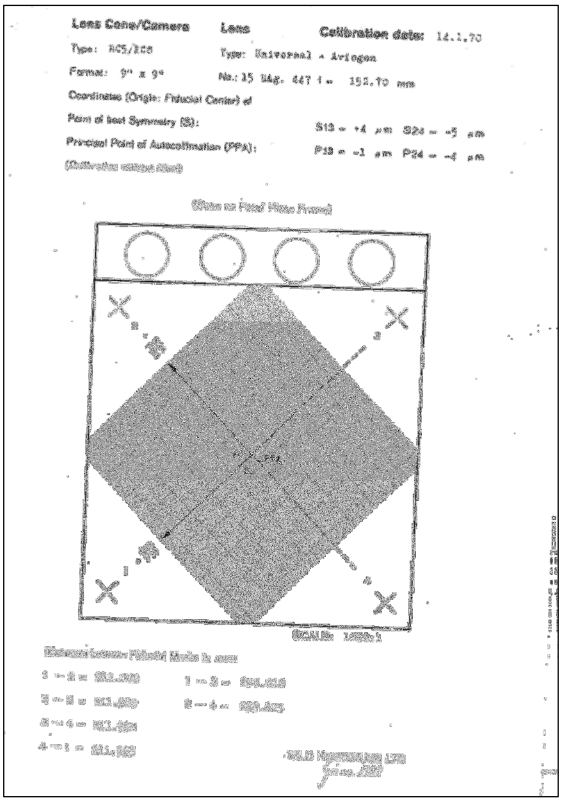


***Figure 41**: Measured interior orientation parameters are evidenced in the camera calibration report. The figure shows a part of scaned calibration report of the Wild RC-8 camera from 1970. This calibration report is also valid for the camera used in 1972.*

The buildings in Logatec that have been preserved from 1972 to this day are appropriate to collect GCP as well as some road intersections. The 3D reference coordinates of the GCP (X and Y coordinates of the Gauss-Krüger coordinate system) were determined from the DOP (© GURS 2006). The third (Z) coordinate of the GCP, the altitude, was determined from the DEM 5 (© GURS 2006). Due to the numerous missing parameters of the exterior orientation (for example, the perspective center coordinates, information on angles etc.), we executed the self-calibrating bundle block adjustment process based on the most precise coordinates of GCPs and tie points. The resulting information was included into the aerotriangulation process. The nearest neighbour interpolation was used for the point cloud to produce a raster DSM 1972 (Figure 44) with a resolution of 5 m.

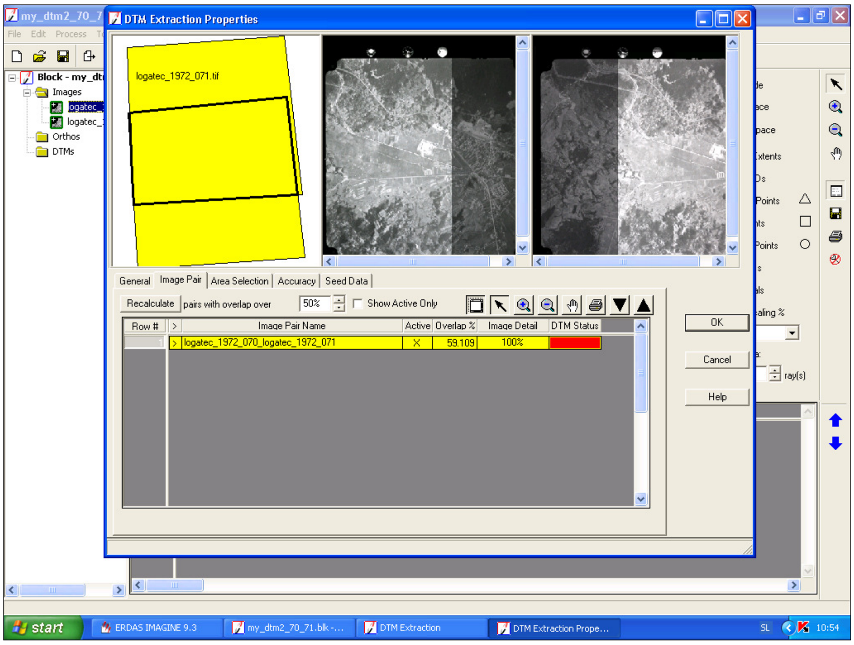


***Figure 42**: The overlapping area of two stereo pairs enables the generation of DSM. The overlapping area is marked as a brighter area on both photographs.*

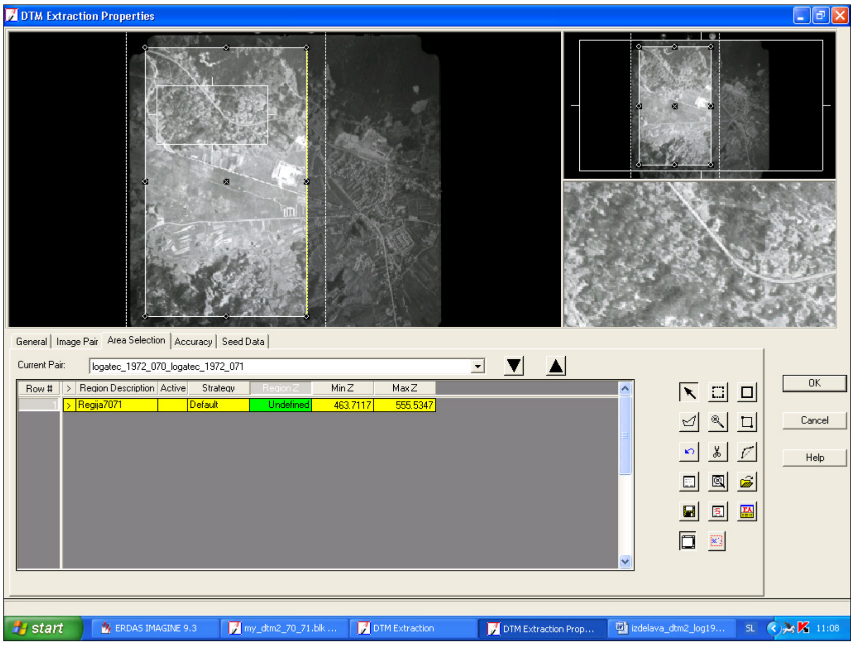


***Figure 43**: The automated procedure requires the exact determination of regional borders of the generated DSM, the lowest and the highest elevation point.*

The result is DSM1972 (Figure 44) of the past landscape. Is a 3D representation of a landscape surface in a certain moment. It represents natural and anthropogenic surface elements: relief, vegetation (trees), buildings, traffic infrastructure (bridges, road and railway embankments), etc.

From the viewpoint of determining the representativeness and usefulness of the DSM72, a referential DEM for the studied area (in continuation DMTTN5, Figure 45) was generated of the past surface based on the TTN5. The contour lines and important relief points (bottom of dolines) were digitalized; then the nearest neighbour interpolation method was used to fashion the DEM with a resolution of 3 m. DMTTN5 is not chronologically and methodologically homogenous due to the input data. The altitude data is summarized from four TTN5 charts that were made in 1974, 1981, 1986, and 1987.

It is evident with ordinary visual comparison of both the generated 3D surfaces (see Figure 44 and Figure 45) that some differences occur as a consequence of different input data and methods. DSM1972 includes all the surface elements; the natural-like relief and vegetation as well as the anthropogenic opposite; the referential DMTTN5 represents only the relief of the past landscape. Those differences have an important role in the quantitative (numerical) comparison analysis and may be noted on Figure 46 where it was subtracted from the DSM1972 surface on the DMTTN5. Regarding the qualitative surface analysis, DSM1972 offers additional surface information about the past landscape that could not be noted on DMTTN5 .

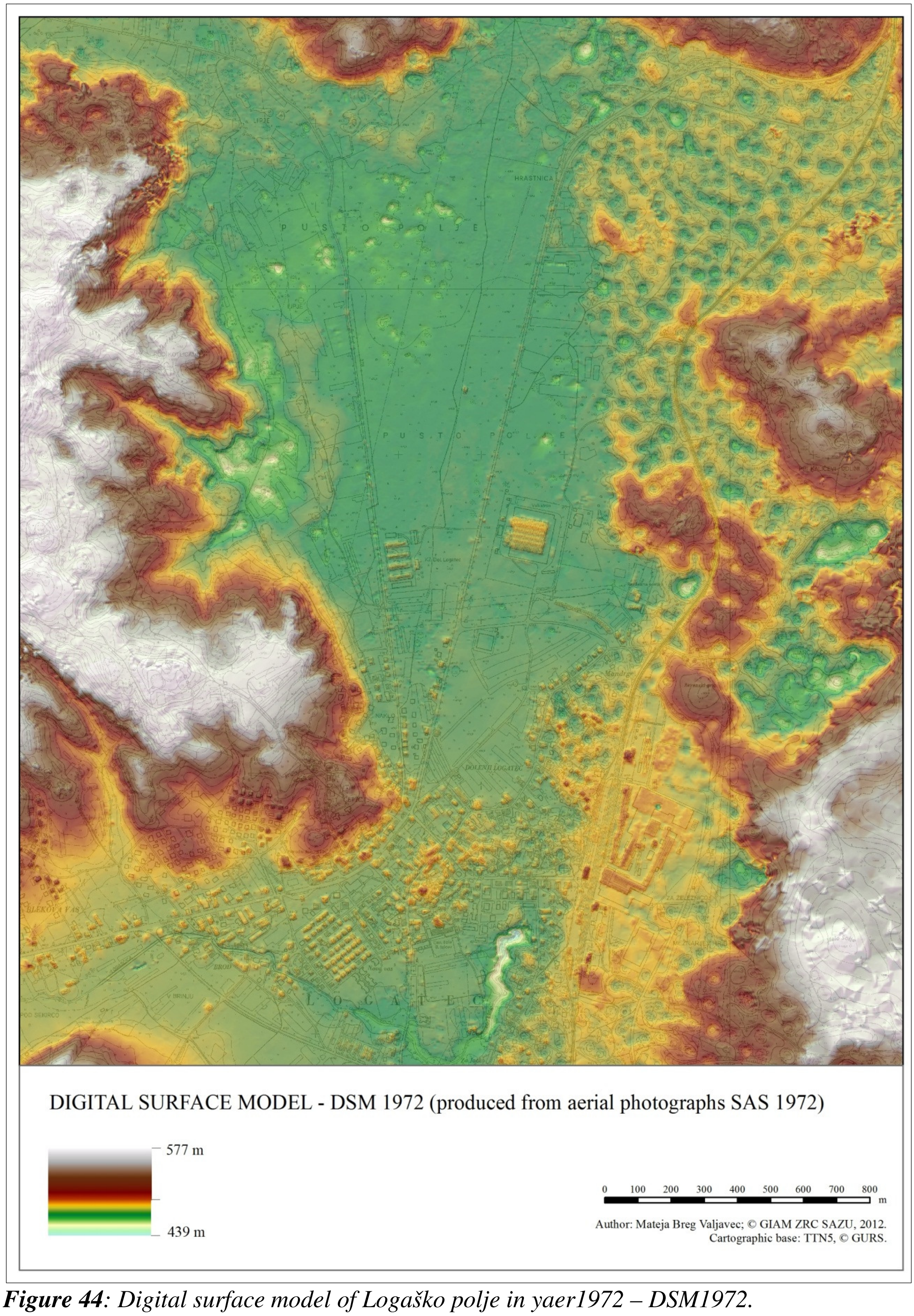


***Figure 44**: Digital surface model of Logaško polje in yaer1972 – DSM1972.*

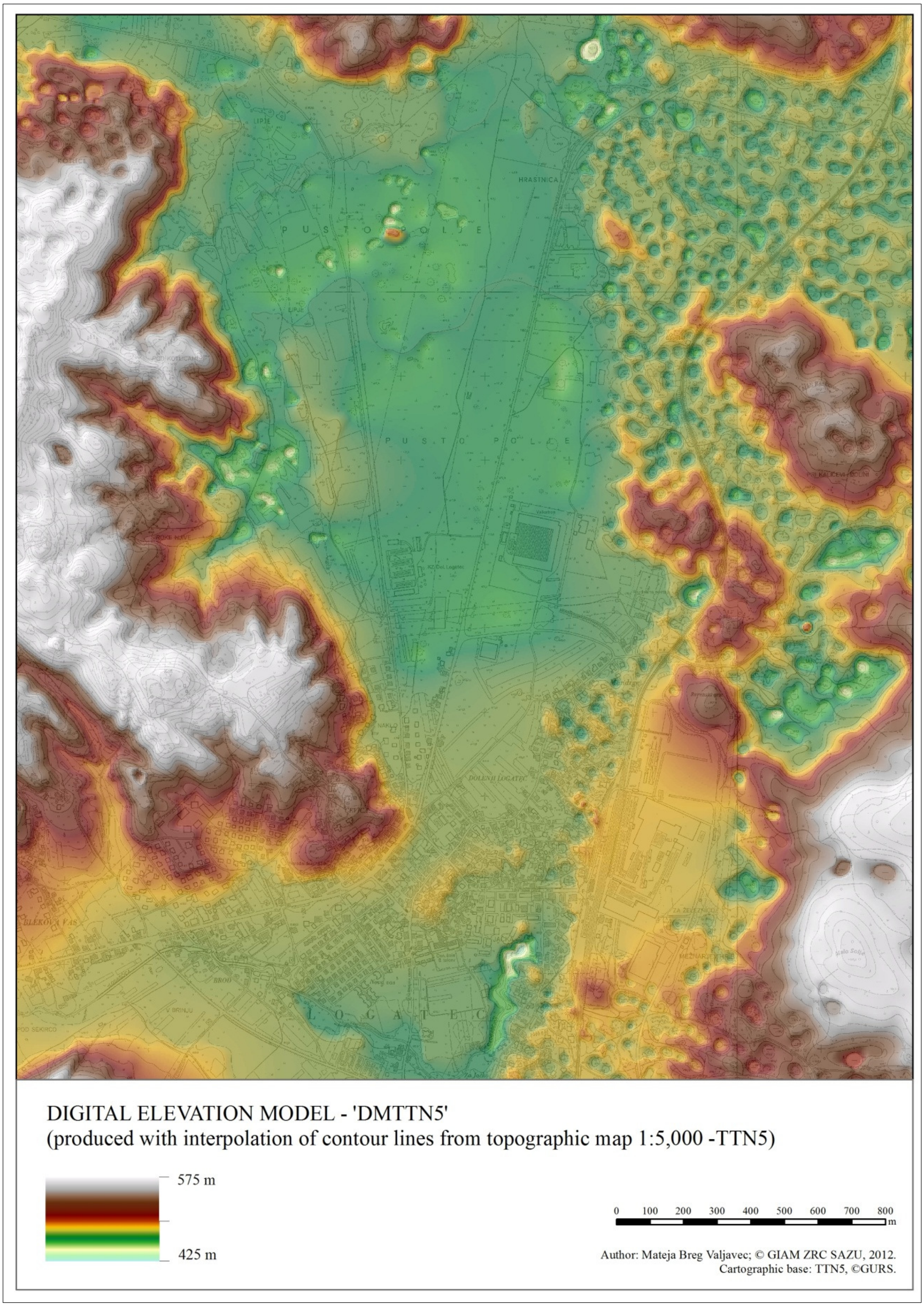


Figure 45: *Reference digital elevation model (DMTTN5) of Logaško polje, based on the topographic map (TTN5) in scale 1:5.000, represents the past landscape of the period 1974–1987.*

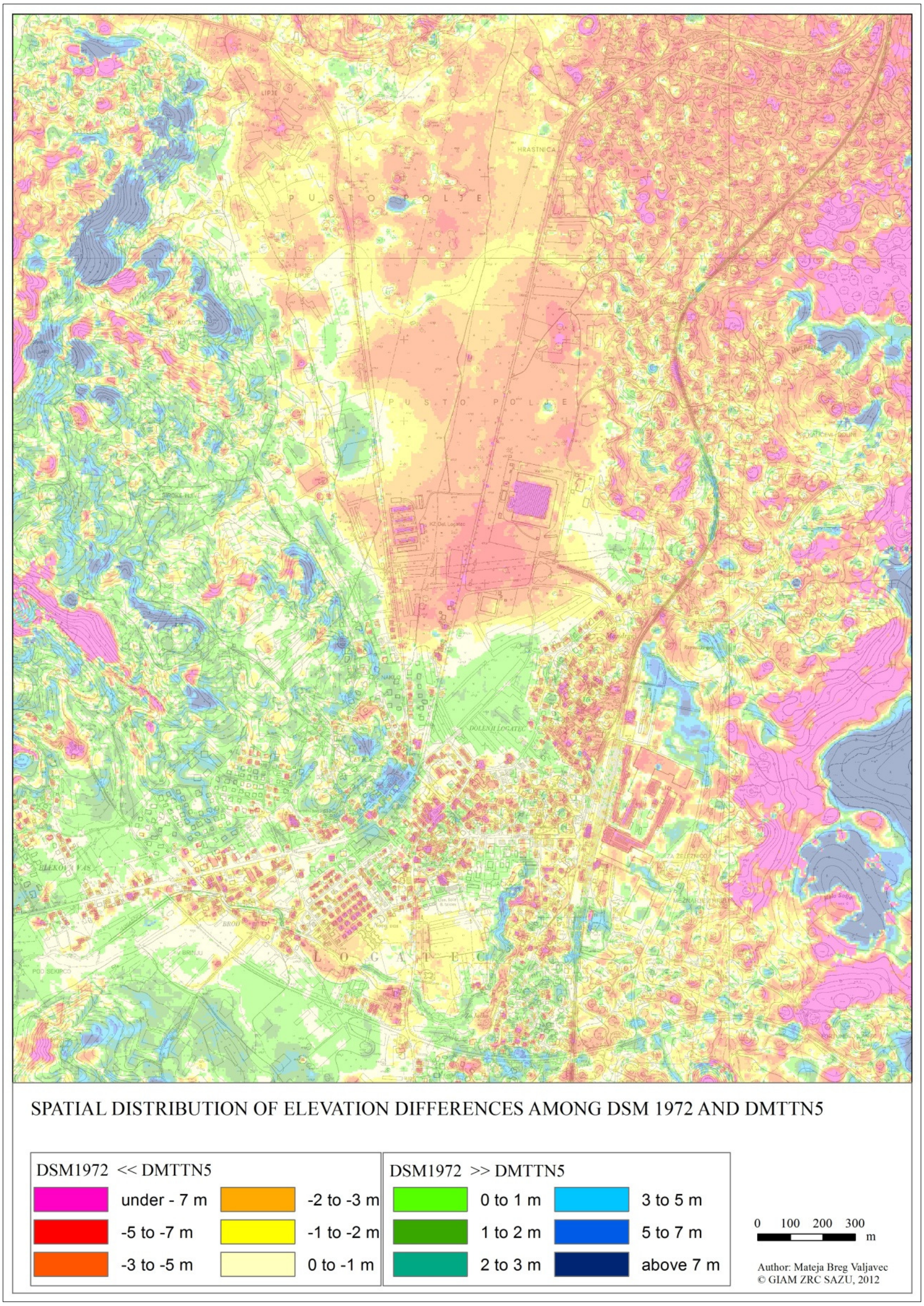


Figure 46: *Height (elevation) differences among DSM1972 and the referential model DMTTN5.*

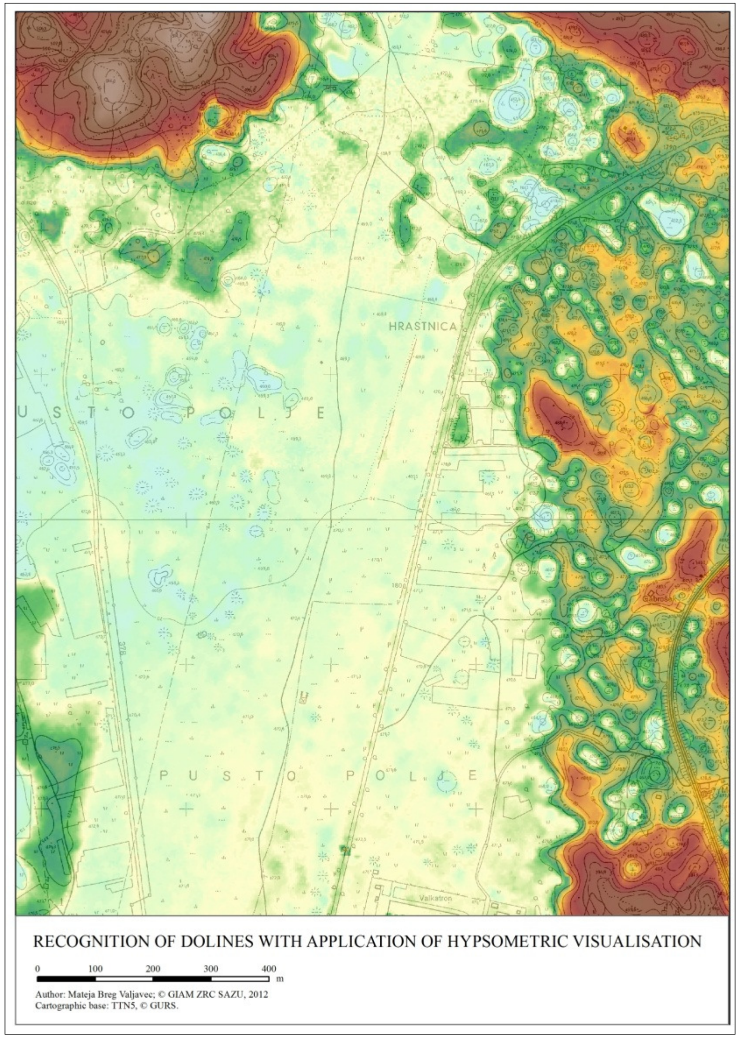
8.2.3 Geomorphometric Analysis of Dolines on DSM 1972

The most accurate data for morphometric analysis are obtained from field survey (Jennings 1975; Šušteršič 1994) but is very time consuming and covers only smaller areas (Ford and Williams 2007). The most practical medium for morphometric analysis of karst is generally found to be large scale (1:15,000) aerial photographs viewed stereoscopically (Ford and Williams 2007) or processed by digital photogrammetric methods.

In this research, two **methods of relief visualisation** were combined with one **automated doline detection**; all based on three-dimensional spatial data. The visual methods (especially analytical shading) provide a first impression of the DTM quality (Podobnikar 2009). *"…Numerical as well as visual analysis of DEM visualisations enable the recognition of landforms, such as ridges, picks, valleys, …"* (Podobnikar and Možina 2008, p. 30).

The visualisation methods, applied to detect dolines in 3D viewing, are robust and founded on relief visualisation using different visualisation techniques. Despite several descriptions of advanced relief demonstration, **analytical shading** remains one of the most common methods (Zakšek et al. 2010). Analytical shading (Figure 48) simply means a computer-assisted assembly of a shaded relief from the DEM. The method, developed by Yoëli (1965), where the value of the grey is in correlation to the cosine of the ray's incidence angle of the direct relief lighting, has become the standard. This is the angle between the direction towards the light source and the perpendicular line to the relief surface. In this way, the areas perpendicular to the ray from the imaginary light source are white, and the areas with an incidence angle of 90˚ or more are in a complete shade or completely black, while the areas between an incidence angle between 0˚ and 90˚ are displayed with the appropriate grey or other color shade (Zakšek et al. 2010).

The **hypsometry** (Figure 47) is a visualisation technic that allows us to adapt the histogram to our needs and expose the smaller shapes and analytical shading. Regardless of the wide specter of its uses, it is important to demonstrate the DSM effectively, as it is the only assurance to guarantee the appropriate result interpretation.



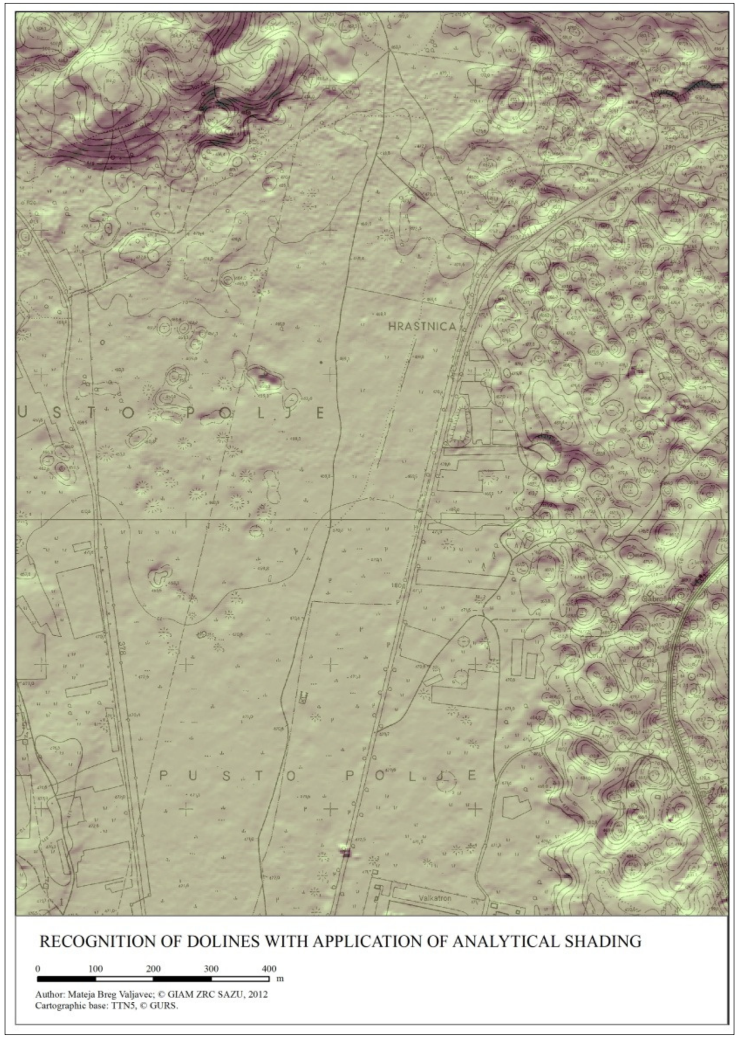


Figure 47: *(left) Hypsometric visualisation technic of DSM1972.* ***Figure 48****(right): Analytical shading / shaded relief visualisation technic of DSM1972.*

More sophisticated and automatized, although not always more effective, are geomorphometric analyses that are based on calculating the geomorphometric parameters (slope, curvature, topographic openness, etc.). For a more precise classification of the geomorphological shapes, additional (e.g. hydrological) parameters may be used, for example, the accumulation of the water current in order to determine the relief forms connected to fluvial processes (Anders et al. 2009).

The selected and tested method is based on **finding & filling relief depressions** in the DSM. In the first phase, the algorithm scans the entire DSM surface and based on calculations of the values of different morphologically-hydrological functions (flow concentration, flow direction, determining concave shapes, river basin, etc.) determines and also fills certain sections of the surface to a pre-determined depth/height (Tarboton et al. 1991). It operates on a system of filling the concave surface area to a quantitatively set limit and repeats the process until all the basins within that height measurement have been filled. In this way, the surface is smoothed out and the initial smoothed area subtracted from it (the basic DSM). The difference can be negative to represent a concave surface or positive to represent a convex surface. In the case of dolines, the difference is depicted with encircled basin areas, as well as individual basins, depending on the density and size of the dolines.
Using half automated modeling (a previously presented method of filling dolines) in combination with visualization technics for the extraction of dolines, 1,276 objects were recognized as a potential doline, while 1,108 objects were recognized using only visualization methods.

Along with the location and the shape, **doline depth** is another important doline characteristic required for generating a cadaster of FWDS in dolines. The depth of an individual doline was determined using the analysis of the past landscape that was achieved with the DSM 1972 and DMTTN5 geomorphometric analyses.
As the DSM 1972 relief of the past surface is elevated on certain areas due to un-removed trees (forest) or buildings, the results of the doline depth on the forested areas are not corect. The chosen method of filling basins means the located dolines on the forested area are too deep. Despite this fact, the issue does not present an insurmountable problem, since most of the dolines on the studied area were

agriculturally cultivated in 1972 and the area surrounding them was uncultivated. The issue lies in the difference with the surroundings that are forested and the empty contents of the dolines. The flaw would be greater, had we determined the doline volume, which was not performed due to the DSM1972 characteristics and the quality. When comparing the locations and circumference of the ranges of certain dolines on the DSM1972 and DMTTN5, considerable differences may be noted. The dolines from the DSM1972 (Figure 49) were located based on a relief analysis, while the ranges taken from the TTN5 were used for determining the doline depth on the DMTTN5 (Figure 50) (also used for the geohistorical locating analysis). In accordance with the differently determined shapes of the doline ranges, the lowest and the highest (border) doline point can differ greatly. The largest absolute differences can be found in the depth of the Logatec collapse sinkholes (collapse dolines), as they appear up to 15 m deeper on the DMTTN5. The depth of sample filled dolines was evaluated using the electrical resistivity tomography.

Figure 49*: Doline location and depth, determined in the past landscape (relief 1972).*

***Figure 50**: Doline location and depth, determined on the basis of the DMTTN5 relief.*

The success of the DSM 1972 analysis was determined by using the same methods to locate dolines on a referential terrain model of the past surface DMTTN5, which was assembled based on the digitalization and interpolation of the contour lines from the TTN5. Due to its obsoleteness (1970s), this source represents a past landscape. 1,067 doline ranges on a surface of 11.2 km² were located with a visual interpretation of the TTN5, which amounts to 95 dolines / km². The basic characteristics of the 1,067 dolines are presented in Table 9.

Doline parameter	**Doline surface (m²)**	**Doline circumference (m)**
Lowest value (individual doline)	35.9	22.3
Highest value (individual doline)	17,633.6	497
Average value	635	84
Total value	600,383	79,331

***Table 9**: Basic characteristics of the dolines on the studied area (Source: TTN5, ©GURS).*

The reference number on the actual number of dolines in 1972 was acquired from the data on the dolines, marked on the TTN5. The interpolation effect is presumed to be minimal, so the theoretical number of dolines on the DMTTN5 corresponds to the number on the TTN5; the main factor of discrepancies is the quality of the chosen method. With the use of the combined automatic modeling (the above described method) and doline elimination, 947 dolines were located on the DMTTN5 analysis (Figure 51) from a total of 1,067 dolines located on the TTN5. Using the same methods, 1,276 dolines were determined on DSM1972.

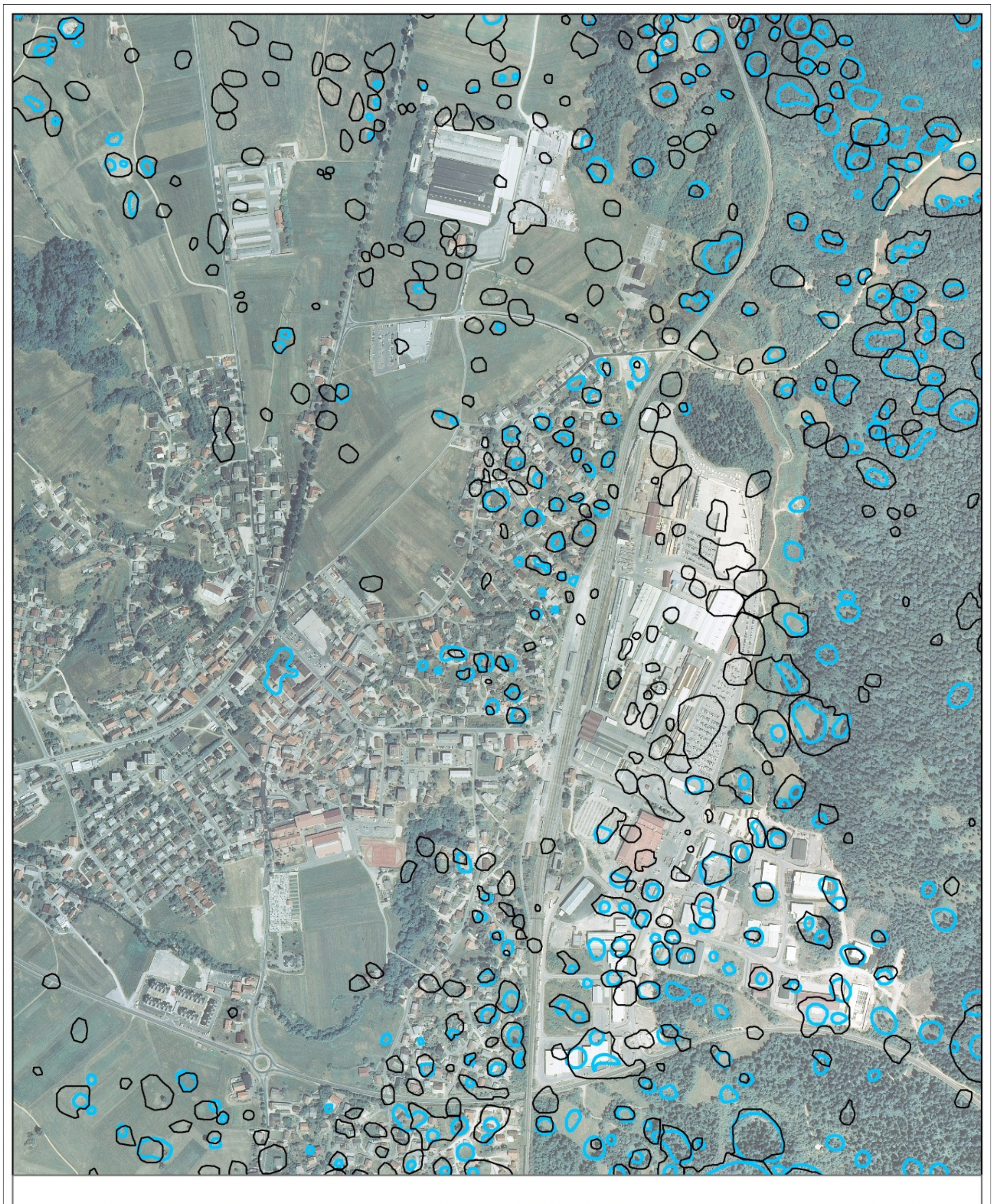


Figure 51*: The result of determining the dolines on the DEM72 in proportion to the referential DMTTN5 (the figure demonstrates a section of the area).*

We have established that the photogrammetric DSM 1972 is appropriate for studying detailed relief characteristics such as dolines. From the viewpoint of generating a photogrammetric relief model, the forest floor undoubtedly represents a weak point, as these are areas where the problem is the difficulty of locating the appropriate points (locatable in the earlier and present landscape) and a sufficient number of ground control points.

8.3 Studying the Recent Landscape

The main goal of studying the recent landscape is to determine FWDS in dolines. The methods are based on determination of soil and vegetation changes by multispectral remote sensing data (aerial photographs from spring 2006).

8.3.1 Introductory Remarks to FWDS Impacts on Soil and Vegetation

In the chapter Hypothesis (1.4) it was assumed that the impacts of waste disposal could be detected in recent soil and vegetation changes, depending on the non-degraded surroundings. The background for the detection of dolines on near-infrared images is generally simple when we consider the moisture loamy doline bottom. Almost all further multispectral analyses express healthy, moisture vegetation in preserved dolines and a in many cases dry vegetation cover of the filled dolines. The type of waste material that was dropped into a doline has a direct influence on the upper soil characteristics as well as on the density and type of vegetation (Figure 52).

CIR DOP (Figure 52) and RGB DOP from the CAS 2006 national project (©GURS 2006) were used for determining the filled dolines depending on the detectable impacts on the soil and vegetation. For the Logatec area, they represent the state of the landscape in June 2006. As these are the most recent available aerial photographs of the studied area, they were selected as the representative ones for the recent landscape study. Soil and vegetation moisture and temperature are closely connected to the soil components, structure and depth. The loamy soils contain more moisture and are cooler than sandy ones, which reflect in the NIR spectrum.

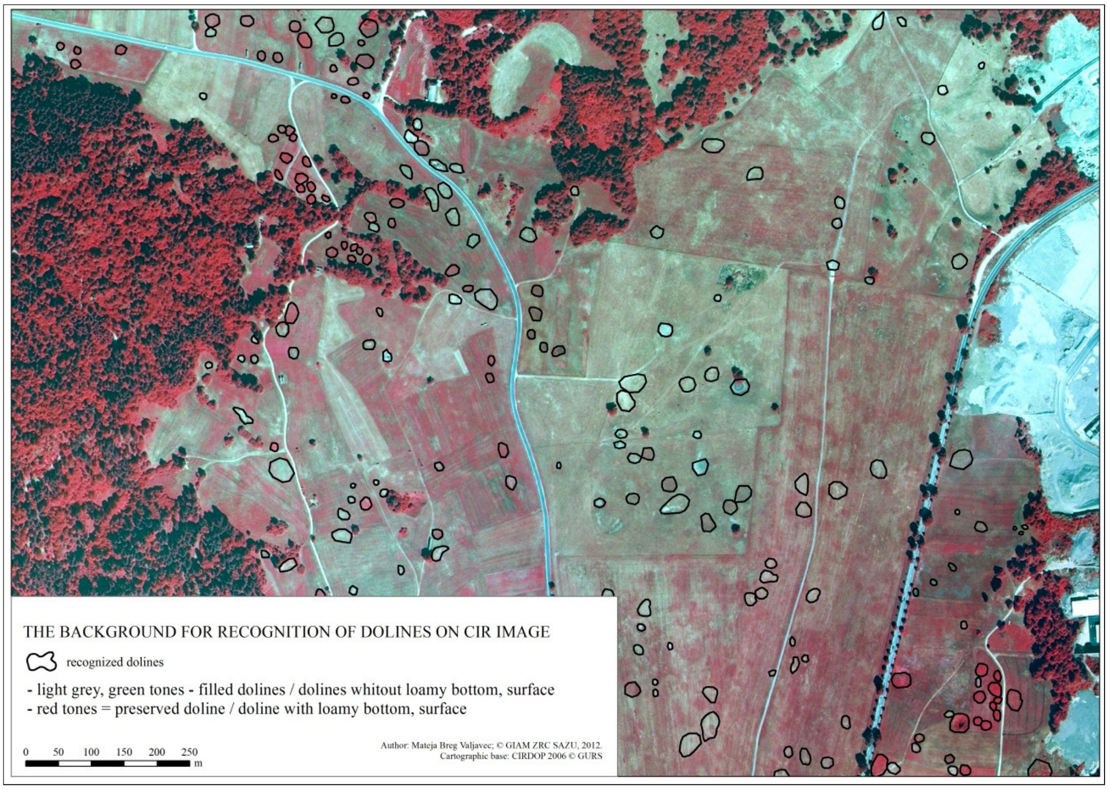


Figure 52*: Visual recognition of dolines on a CIR image (composition image of near infrared, red and green spectral band) (© GURS, 2006).*

8.3.2 Multispectral Image Processing Methods

The difference between the reflection values in the NIR and red band focuses on the dolines according to the type of covering material and divides them into waste filled and not filled (Figure 52, Figure 54).

The automated analysis of multispectral aerophotos is based on unsupervised (ISODATA) clustering. The normalized vegetation index (NDVI in continuation) was calculated based on the original multispectral airborne data.

STEP 1

The first step in the present FWDS analysis was to define a **vegetation mask** (vegetation mask-1) of the area and then to calculate the simple mathematical (arithmetical) relations between the near infra-red and red channel: NDVI, IR/R ratio, IR-R difference, IR+R sum, etc. The NDVI has been in use for many years for measuring and monitoring plant growth, vegetation cover, and biomass production from the multispectral satellite data. The principle behind NDVI is

NDVI = (RED - NIR) / (NIR + RED).

In the RED band of the EMS the chlorophyll causes a considerable absorption of incoming sunlight, whereas in the NIR channel of the EMS the plant's spongy mesophyll leaf structure creates a considerable reflectance (Tucker 1979; Jackson et al.1983; Tucker et al. 1991). As a result, vigorously growing healthy vegetation has low RED reflectance and high NIR reflectance, and hence, high NDVI values. This relatively simple algorithm produces output values in the range of -1.0 to 1.0. NDVI values near zero and decreasing negative values indicate non-vegetated features such as barren surfaces (rock and soil) and water, snow, ice, and clouds.

STEP 2

The next step was to apply the unsupervised classification method (ISODATA) to test the suitability of the selected multispectral aerial photographs represented as four spectral band images (band 1 – blue, band 2 – green, band 3 – red, band 4 - near infrared), which was produced out of existing 3 band RGB images (DOP) and CIRDOP (©GURS 2006). Unsupervised classification was used to exclude the built-up surfaces and the forest surfaces from the remaining surfaces (vegetation mask-2), as it is not possible to determine the consequences on the NIR channel or the 4-channel spectral image due to waste dumping. The areas of meadows, fields, pastures, and opened unforested areas within the forest were the main area of the research focus.

STEP 3

In order to enhance the radiometric contrast inside the vegetated areas, a Principal Component Analysis (in continuation PCA) was applied to the corresponding radiometric classes (NIR, red, green, blue). The PCA was used to produce uncorrelated output bands to segregate the noise component and to reduce the dimensionality of the data set. Two uncorrelated components were extracted and one was applied for the classification of the area.

STEP 4

The analysed area is divided into three classes according to the temperature and moisture characteristics of the soil and vegetation (Figure 53):

1st class: very dry, warm surface (waste-filled dolines);

2nd class: dry and warm surface (mostly traditionally changed and partially preserved dolines, or filled with organic waste and covered by soil);

3 rd class: cold, humid surface (preserved dolines);

476 potential FWDS in dolines were determined with the described multispectral analyses. Figure 53 presents distribution of 1st and 2nd level dolines. FWDS,

determined using the multispectral analysis, were investigated with pedological sounding. In accordance, it was relatively easily to determine the areas of potential dolines that spectrally differ from their surroundings in alluvial part of polje, while the dolines from the first class blend with the surroundings quite efficiently. However, the 3rd class (unfilled and preserved dolines) can express differences with regard to the surroundings, often due to the local differences that are a consequence of a slight concave shape. It is possible to perceive them in the NIR and red band EMS due to the increased humidity (basin, loam, vegetation …) or the dryness.

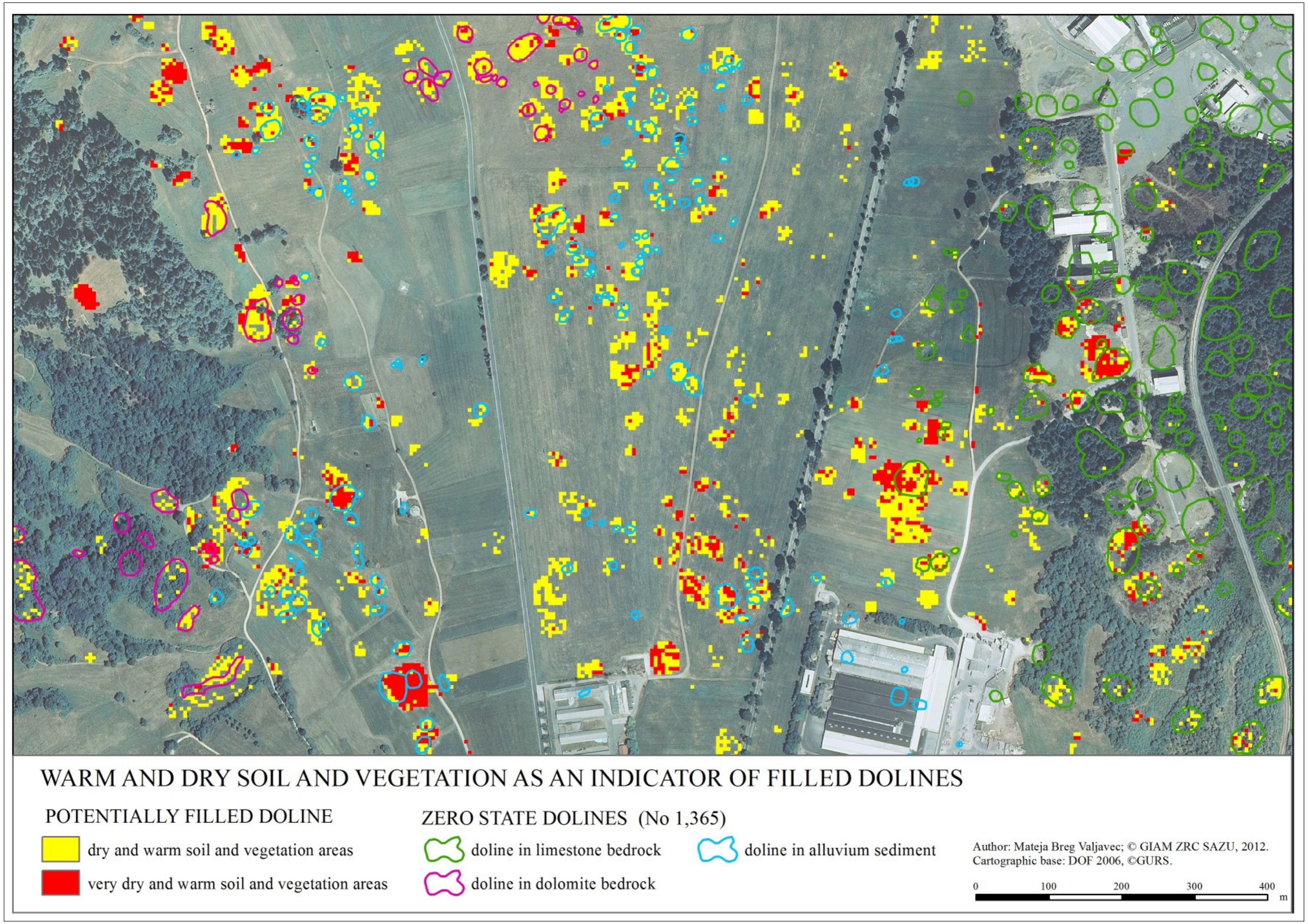


***Figure 53**: The areas of dry soil or vegetation cover (result of unsupervised classification of vegetated surface) are potential FWDS.*

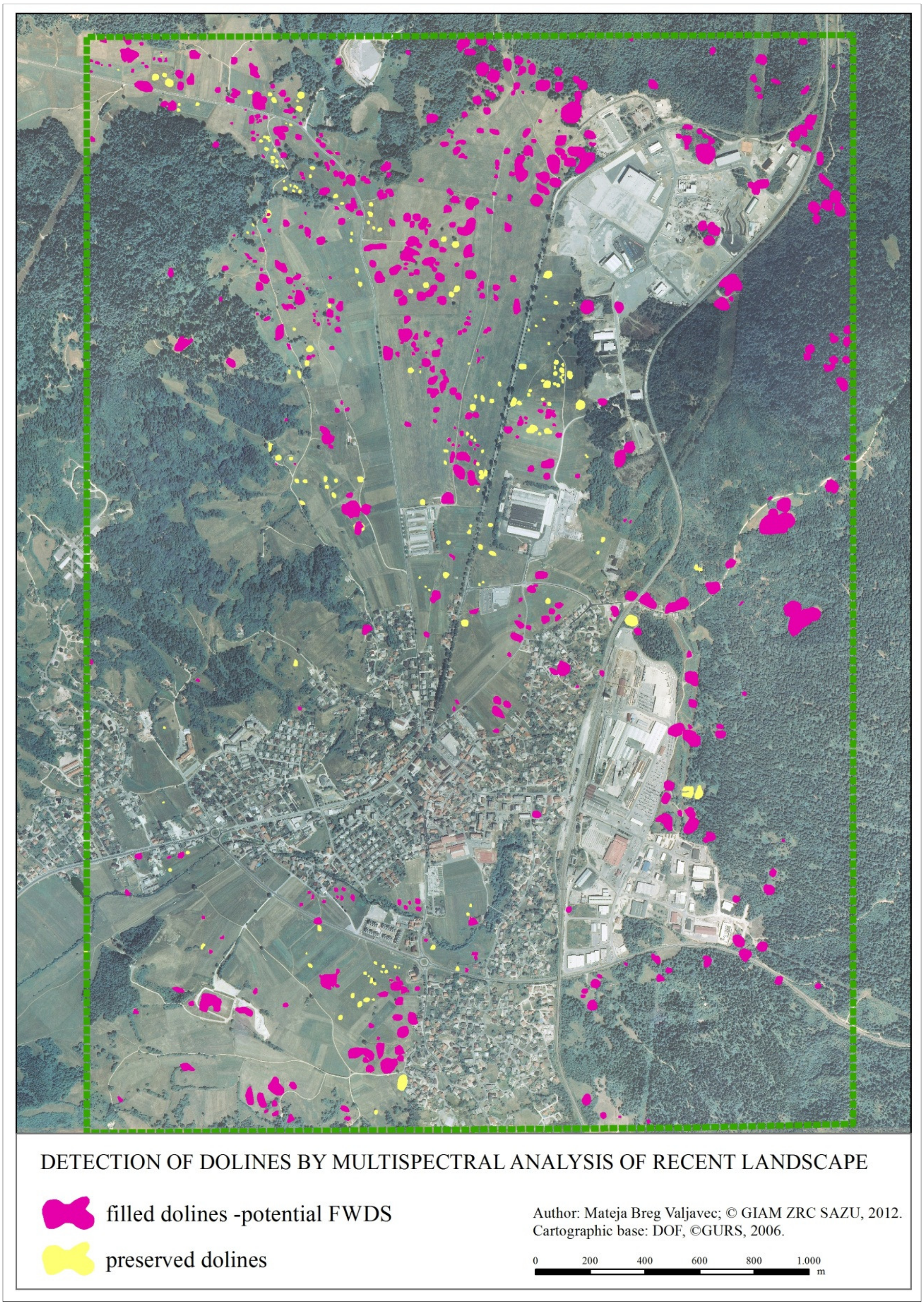


Figure 54: Probability map 1 is the results of the multispectral analysis of vegetated area.

8.4 Comparison of Past and Recent Landscape

Comparative temporal studies of a waste disposal sites combined with archive aerial photography help to determine how an area has changed over time and in turn offers a better understanding of the current site conditions (Erb et al. 1981; Pope et al. 1996). Surveys using archive and current aerial photography as well as 3D elevation data have been employed to produce detailed databases on locations of the present FWDS. The examination of a site over time allows for the analysis of succession or replacement of land cover to determine the status of an abandoned site and to identify any hazardous site that is currently obscured due to new development (Lyon 1987; Nelson et al. 1983). Comparative analysis is more acceptable in karst landscape types since could be made only between two years – the oldest and the newest available spatial data. The oldest represents the zero state of doline.

8.4.1 The Geohistorical Land Use Analysis

The geohistorical analysis was used to determine the land use trend for each of the 1,365 zero state dolines in order to determine the dolines with unusual land use changes in time that could mark potential waste disposal sites. Land use has been studied and determined on the basis of visual aerophoto-interpretation of aerophotos from 1957, 1972, 2000, and 2006. During the image interpretation, six types of land use were exposed and ranked according to the assumed level of land use quality and doline preservation / degradation (Table 10).

Land use type	**The level of degaradation / preservation**	↑	**Rank of land use types** (from negative-1 to positive-6)
forest	Minimal anthropogenic impacts		6
Sparse trees, overgrown	Minimal impact		5
meadow	Partially filled dolines with alogenic soil, to improve agriculture		4
fields and gardens	Partially filled dolines with alogenic soil to improve agriculture		3
built-up or partially built-up	Complete degradation		2
potential waste site	Complete degradation		1

***Table 10**: Ranking of land use type according to temporal land use changes.*

The methodology of geohistorical analysis (Figure 55) is based on determining the trend of the changeability of the land use during the studied four years. If the trend is increasing, this indicates the land use in the doline has been improving with time towards a more natural (positive) land use (forest, sparse trees, meadow); if the trend is decreasing, the land use has been worsening from the aspect of natural doline preservation (waste disposal site, built-up). Each doline has data for the four years or less in cases where it was located outside of the photographed area in 1957 and 1972. The recent photographs (2000 and 2006) cover the entire studied area.

Based on the 6 categories, there are theoretically many possible combinations, which are not always possible in reality. The theoretical combination 1-2-3-4 means a doline that was filled with waste in 1957 was built-up by 1972, than turned into a field or garden by 2000 and into a meadow by 2006. A case of the area of a filled doline that had been built-up turning into a field is quite unlikely in reality. 125 different combinations were calculated for the 1,356 dolines, which were then merged into three categories (Figure 56).

1st CLASS represents PERMANENTLY DEGRADED DOLINES (No 528)

- **Waste sites**: combinations with at least one 1, meaning it was a waste site in at least one of the studied years.
- **Built-up**: the combination ends in a 2 land use type and was not designated as a waste site in any of the years. This includes all the dolines that were built-up or partially built-up in 2006 or earlier.

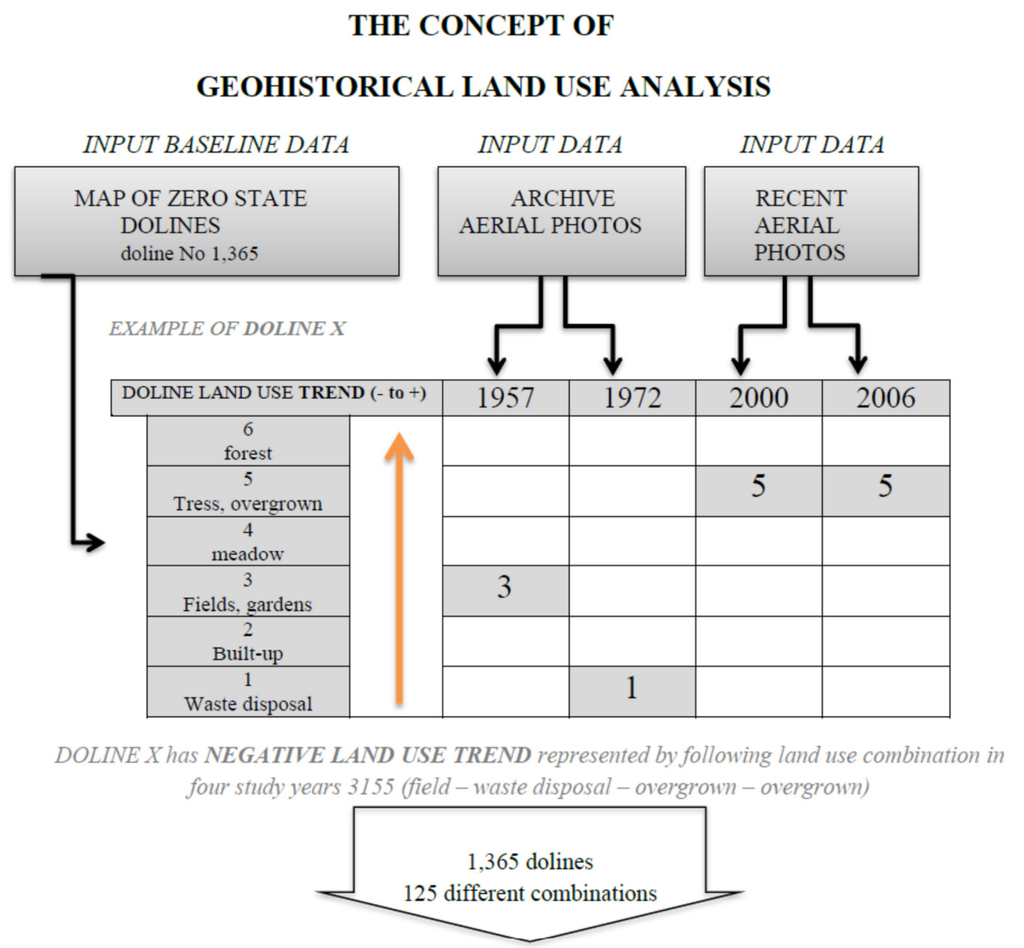
2nd CLASS represents PARTIALLY DEGRADED DOLINES (No 277)

- The land use trend is decreasing or mixed, pointing to greater interventions in the doline. The most common combinations are 5544, 4344, 4544, …

  This category includes abandoned agrarian dolines where the field is abandoned and turned into a meadow or a more negatively oriented use trend, where waste was being dumped, effecting the continued land use.
- Combinations ending with categories 4, 5, or 6 present a linearly increasing or positive trend of a changing land use trend in its basis. This category is an indicator of agrarian dolines being abandoned and the overgrowing of fields with grass, meadows or bushes and forest trees (4455, 5566, 4555, 4466, etc.).

3rd CLASS represents PRESERVED DOLINES (No 560)

- Without any land use changes during the studied time period.



PROBABILITY MAP 2

CLASSIFICATION OF DOLINES	THE MOST OFTEN COMBINATIONS	LAND USE TREND DESCRIPTION	NUMBER OF DOLINES
1th CLASS Potential waste dump	3155, 3166, 4155, 3115, 4145, 4115, …	At least in one studied year it was marked waste disposal (the combination must include No 1)	528
	1222, 6532, 3112, 4112,…	The combination ends in a No 2 (built-up)	
2nd CLASS Suspicious land use	5544, 4344, 4544	Combinations with negative nonlinear land use trend	277
	4455, 5566, 4555, 4666	Combinations with positive trend that ends with land use type 4, 5, 6 represent mostly abandoned agrarian dolines	
3rd CLASS Unchanged land use	3333, 4444, 5555, 6666.	No land use changes exist in studied years	560

*DOLINE No X is classified as a **potential waste dump** regarding geohistorical land use trend analysis.*

***Figure 55**: The scheme of the geohistorical land use analysis.*

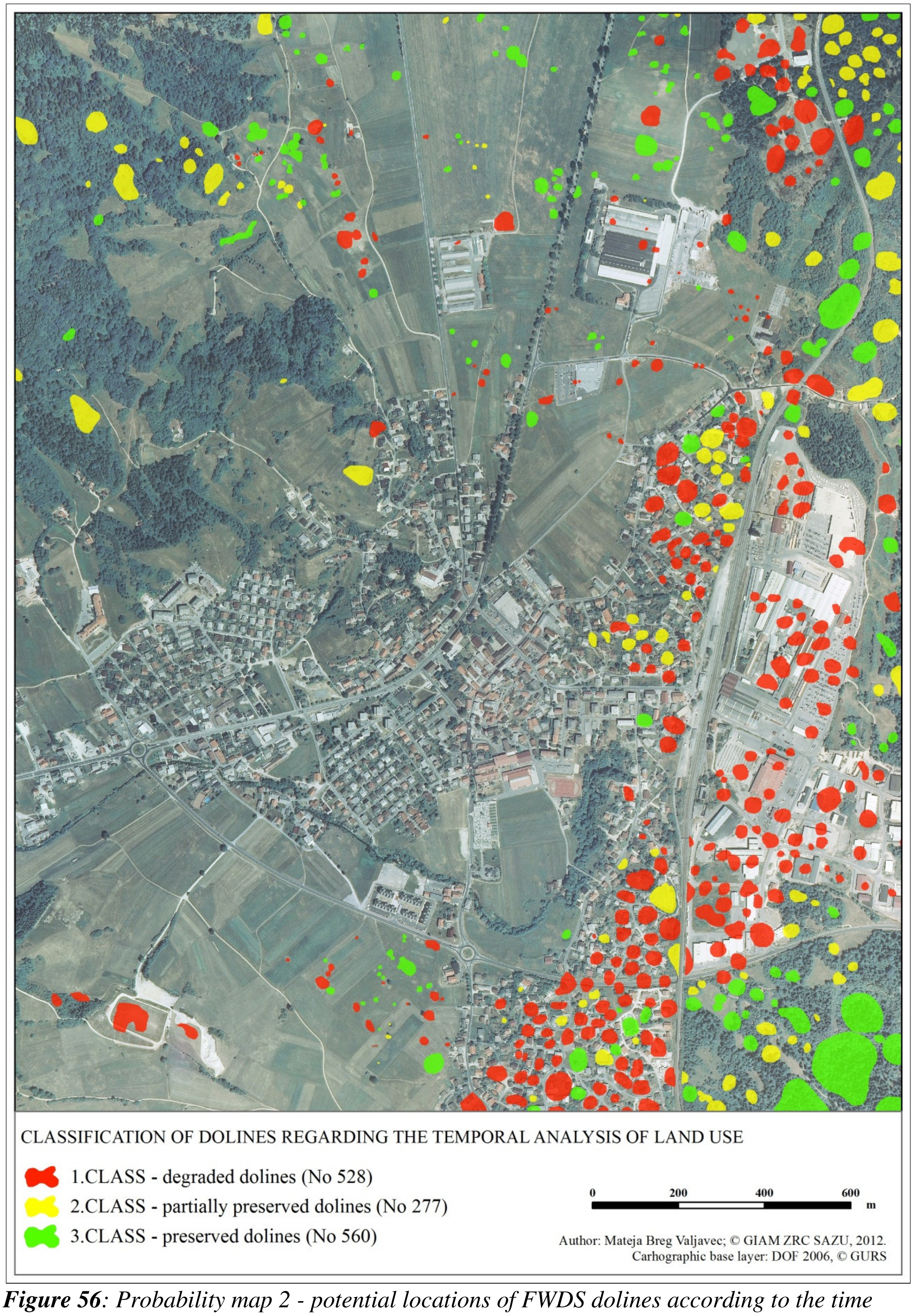


Figure 56*: Probability map 2 - potential locations of FWDS dolines according to the time changes in land use.*

8.4.2 Detection of Relief Changes Between 1970s and 2006

This chapter presents a method for determining FWDS dolines through the comparison of the past relief (DSM) to the recent relief. Starting from the assumption that anthropogenic relief changes are a lot stronger and faster than natural karst-shaping processes, it may be concluded that there are less dolines today than they were 50 years ago.

The studied relief data are based on two 3D models of the past landscape digital surface model DSM1972 and the digital relief model DMTTN5. DSM1972 is a result of photogrammetric image processing methods, while the DMTTN5 was interpolated from map contours (topographic map of scale 1:5,000). The relief of the recent landscape is represented by a digital elevation model called DEM5 (in Slovene DMV5, ©GURS 2006). It is a detailed presentation of today's relief of the Logaško karst polje in 5m spatial resolution (5x5 m cell). Both past 3D models were quantitatively compared with DEM5.

For a better explanation, the procedure of applied methodology is also graphically presented in Figure 57. In the first step, simple mathematical calculations were made to produce two maps of relief differences. Map 1 represents the relief changes between DEM5 and DSM 1972, while Map 2 represents the relief changes between DEM5 and DMTTN5.

In the second step, the values of both maps (rasters) were classified into two classes:

1st class represents a higher surface in 2006 (pixel value 1)

2 nd class represents a lower surface in 2006 (pixel value 0).

In the third step, the classified (raster) maps were overlapped and summarized. The result is a **probability map 3** that represents the doline classification according to the relief changes between 1970s and 2006:

- Dolines that are determined as reaching a **higher surface** in both the past surface analyses' models, pointing to them being filled (pixel value 2).
- Dolines that are determined to reach a **higher surface** on only one model, (pixel value 1).
- Dolines that do not reach above a higher surface on any of the levels (pixel value 0)

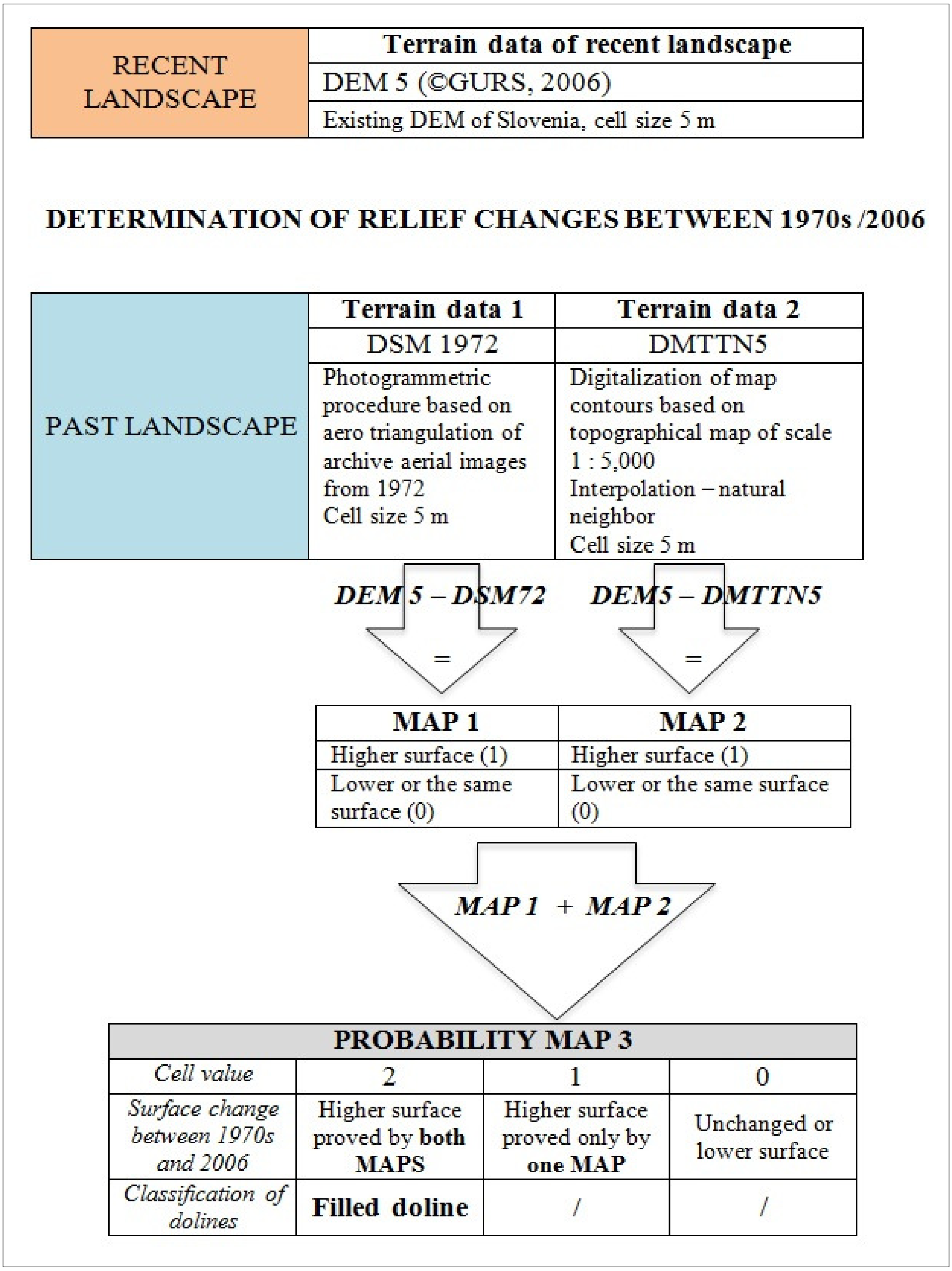


Figure 57*: Scheme of the comparative relief analysis.*

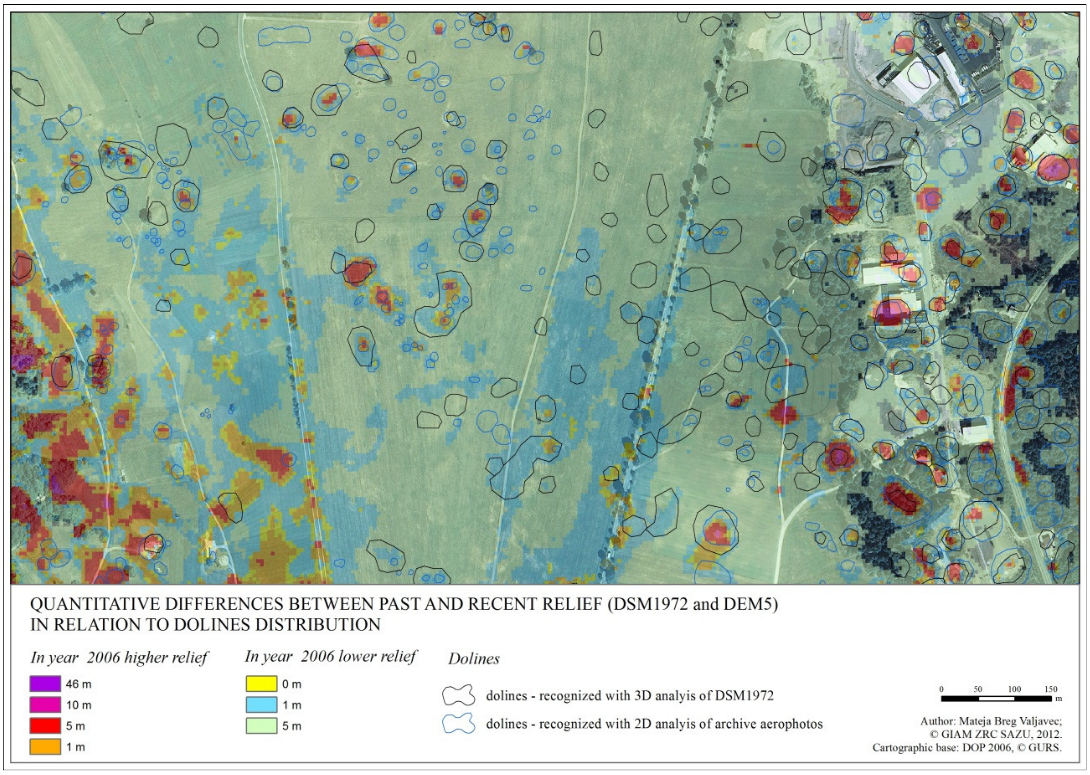


Figure 58*: Quantitative comparison of past relief (DSM1972) and the recent relief (DEM5).*

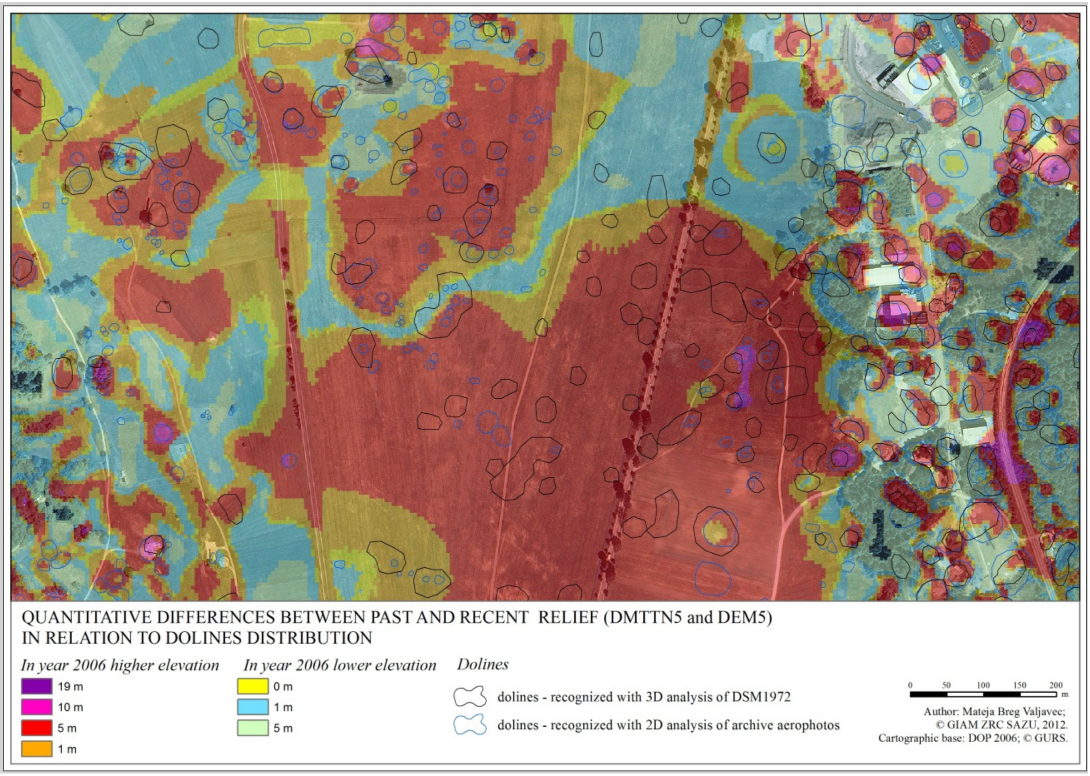


Figure 59*: Quantitative comparison of past relief (DMTTN5) and the recent relief (DEM5).*

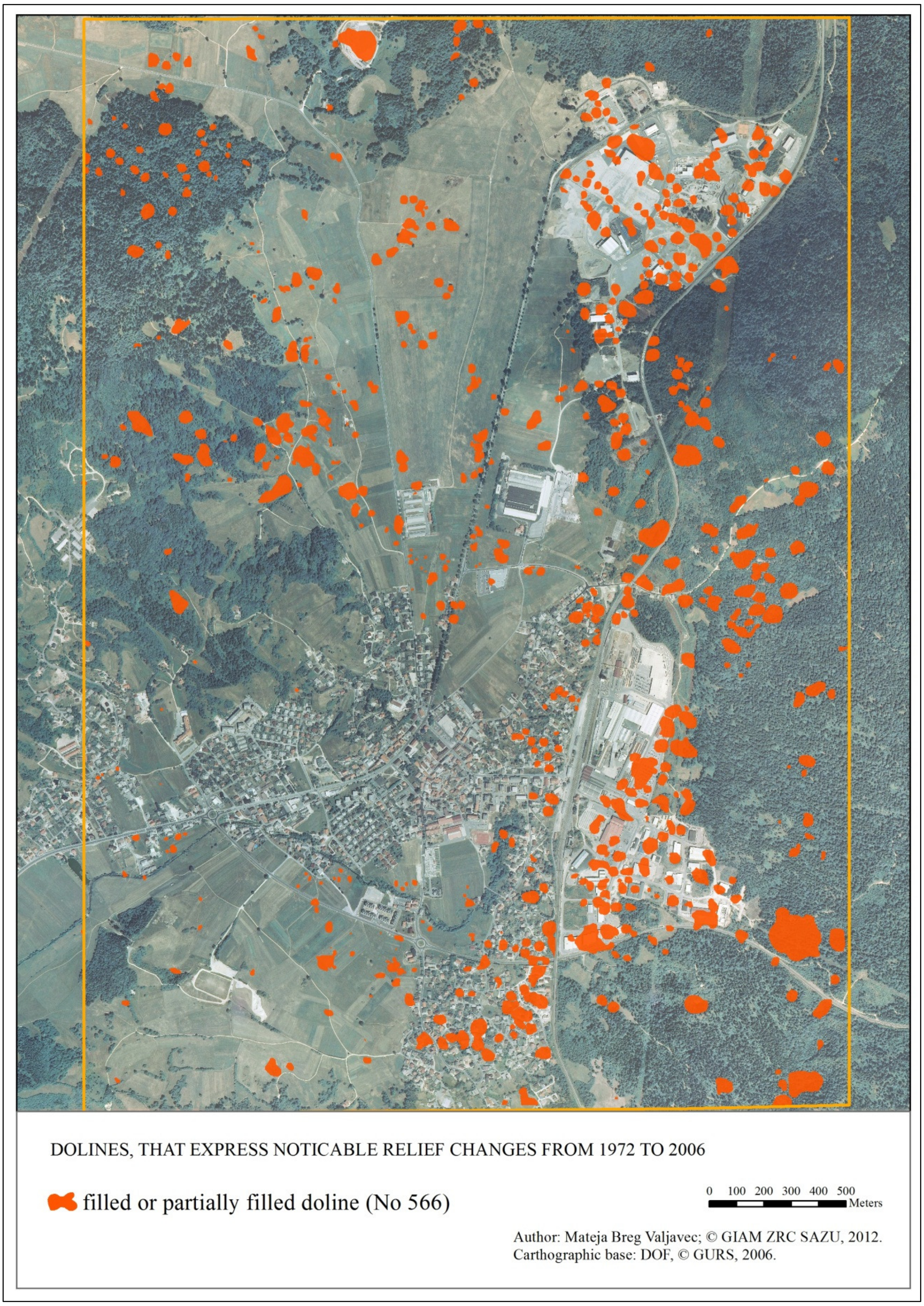


Figure 60*: Probability map 3 - potentially filled dolines, determined by relief changes between the recent and past landscapes.*

By determining the relief changes, 566 dolines were categorized as filled or partially filled dolines (Figure 60) in order to be potential waste disposal sites. Some among them had to be removed due to a flaw in the data on the recent landscape. In some cases, the doline is undetectable on the DEM5 of the recent landscape, the recent surface is expressed higher (flat) and the comparison detected as a filled doline. Verifying the dolines in the field at the very beginning of research namely showed that many of the dolines are simply excluded and do not appear on DEM5. This involves a large number of smaller dolines as well as numerous dolines up to 6 m in depth. An example of this is the only preserved non-filled doline on Pusto polje, 350 m to the north of Valkarton (presented on Figure 2), which of course, shows up as filled by comparing both past reliefs with the recent relief.

There are consequently many such cases and it is therefore impossible to attain more quality data on filled dolines. Precise Lidar data would be required for more detailed comparison; unfortunately, there is no such data available at this time or it would demand an individual photogrammetric DEM to be made from the CAS 2006 photographs.

A DTM from the laser scanning data would provide infinitely more reliable results as to the level to which the dolines are filled. In that case, the level could be determined based on a single relief model, while the other doline categories would remain the same or the first and second categories could be combined together, as they both represent a higher surface. Unfortunately, we were unable to acquire lidar data for Logatec (liquidation of the company that carried out the scanning of Slovenia), so we illustrate the data with an example from the area around Divača (Lidar 2010).

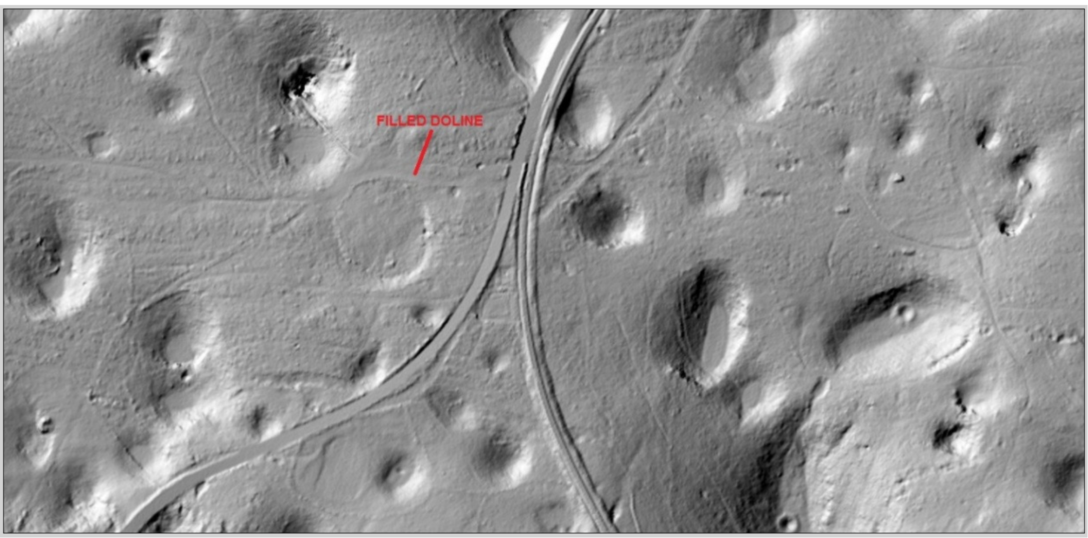


***Figure 61**: Visualization of the lidar relief of Divača (analytical shading) enables the determination of the filled dolines.*

8.5 The FWDS Cadaster in Dolines

A digital cadaster of potential FWDS on the sample area of Logaško polje was generated based on the synthesis map. The results of the geoinformatic methods were combined to determine those dolines that are most likely filled with waste. Since the doline density is very high and because the anthropogeneous interventions were of varying intensity, it was a great challenge to exclude dolines that were FWDS and separate them from those that were partially filled but were not FWDS.

By overlapping the three basic probability maps in the raster form (5m cell), a final synthesis map was made as a result of overlapping the following layers regarding the type of analysis:

Probability map 1 – the soil degradation map (geoinformatic analysis of the recent landscape);

Probability map 2 – the land use change map (geoinformatic analysis of the past and recent landscape);

Probability map 3 – the filled dolines map (geoinformatic analysis based on comparison of the past and recent relief).

By summing up the raster layers, where each one has pixels with values of 0, 1, and 2, a matrix of possible values (sums) of the image was generated, which was useful for estimating the areas from the aspect of FWDS.

Evaluating the cadaster is based on the following presupposition – the more methods that determine a doline as a FWDS, the greater the possibility that it is in fact a FWDS. The synthesis map (Figure 62) was covered by a layer of doline polygons (being a result of the geohistorical and 3D surface analyses) only on the locations of the previously located dolines. In this way, the risk areas were located only for the doline ranges.

In accordance with table 11, the level of environmental risk (Figure 62) a certain doline area has due to the deposited waste was determined:

1. dolines that pose no environmental risk (cell value from 0 to 3);
2. dolines that pose a low level of environmental risk (cell value 4),
3. dolines that pose a middle level of environmental risk (cell value 5),
4. dolines that pose a high level of environmental risk (cell value 6).

Atribute value (pixel value)			Sum	Doline type	The level of environmental risk
Method 1	Method 2	Method 3			
1	1	1	≤ 3	preserved doline	no environmental risk
1	1	2	4	partially preserved doline	low environmental risk
1	2	2	5	probably a FWDS	medium environmental risk
2	**2**	**2**	**6**	**FWDS**	**high environmental risk**

Table 11*: The matrix of possible values of the synthesis map and the appropriate doline classification.*

The FWDS cadaster on the studied area includes 92 FWDS objects with the highest environmental risk (Figure 62). Every object is a potential environment polluter until it is proven that it is not a FWDS. Regarding this the FWDS cadaster was compared with existing data of old waste disposal sites. Applied registers, methodology and results are explained in next chapter (Chapter 8.6).

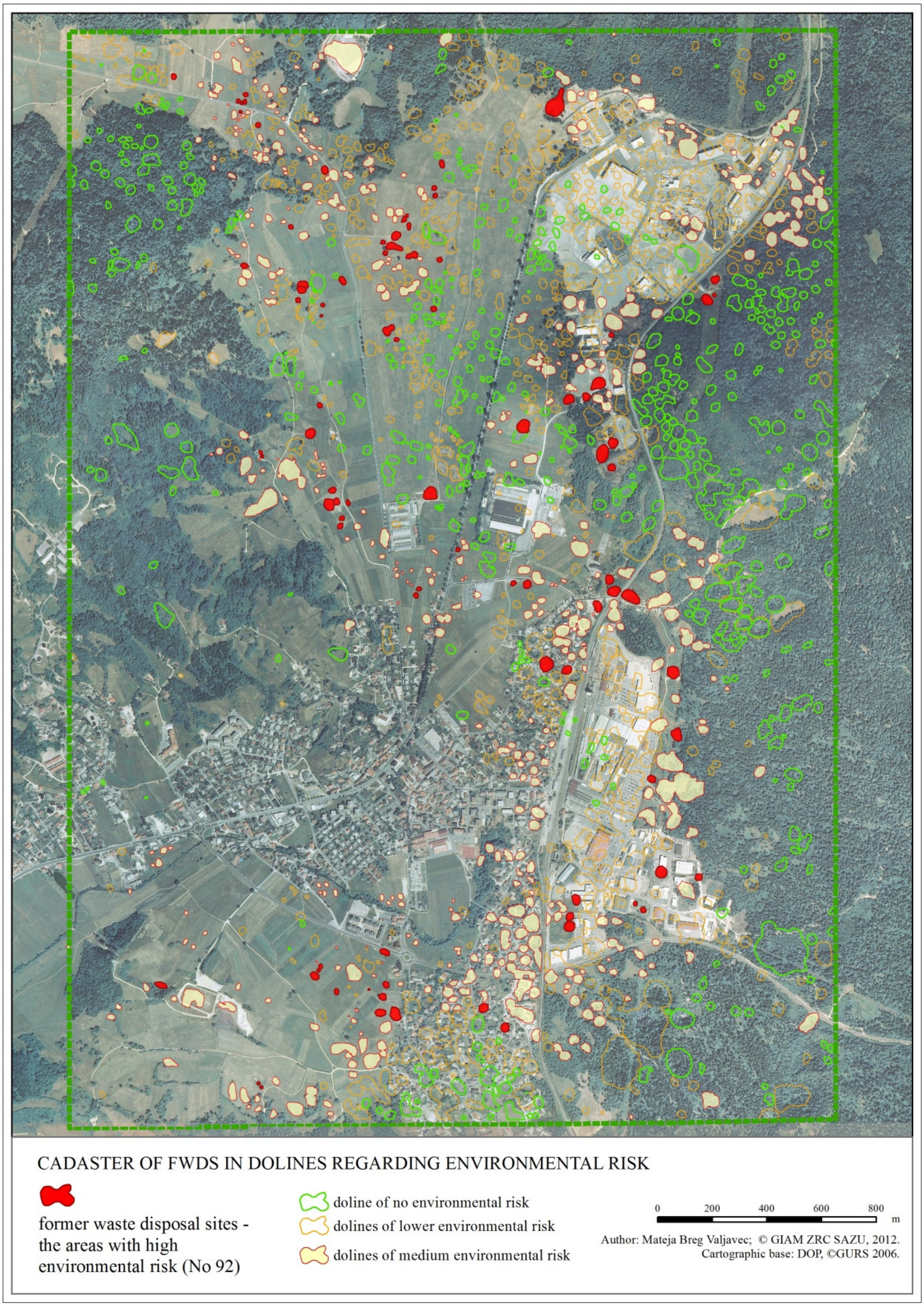


Figure 62*: Classification of dolines, regarding the environmental risk.*

8.6 Comparison with Existing Registers

The FWDS cadaster must represent a reliable state of FWDS in dolines, which is mirrored in the landscape changes. The locations were first determined with geoinformatic analyses, presented in the previous three sub-chapters, and evaluated with the existing data from different oral and written existing registers on illegal waste sites. Only the data that could be geolocated was used.

Three sources of data was used, which was sub-digitalized and georeferenced accordingly to (see figure 63):

1. the locations of FWDS (14 locations), acquired through interviews with the locals in 2006 (Breg 2006);
2. the locations of former waste disposal sites (33 locations), marked in questionnaires by people in 2007 on provided aerial photographs (DOF 2006) (Breg and Smrekar 2007);
3. the locations of former waste disposal sites (33 locations) from the 1988 census (Bricelj 1988) that were marked on the topographic map 1:50,000.

Due to the varying spatial accuracy of the individual sources, the point data was changed into buffer areas, within which lies the greatest possibility of the waste site being located (Figure 63). The most accurate source were the testimonials of the locals, during which the FWDS were marked at the site itself on a 1:5,000 scale map and the coordinates added using a GPS device. The accuracy is very high, so the buffer zone is only 50 m. The locations marked in the questionnaire overlapped in many places and in some cases the same waste site was marked with a lapse. Considering the flaw from the questionnaire caused by the poorer spatial orientation on the photograph, a buffer zone of 100 m was delineated around the potential locations. The locations from the 1988 census (Bricelj 1988), would undoubtedly have been even more precise if the map scale were greater or the information chart also included the x and y coordinates. The waste sites are marked as active waste disposal sites or as waste-filled karst depressions on the 1:50,000 map. Since 1 cm on the map translates to 500 m in nature, the point was placed in the middle of the cell with 1 cm edges, meaning a 5 mm radius, which is analogous to a 250 m buffer zone.

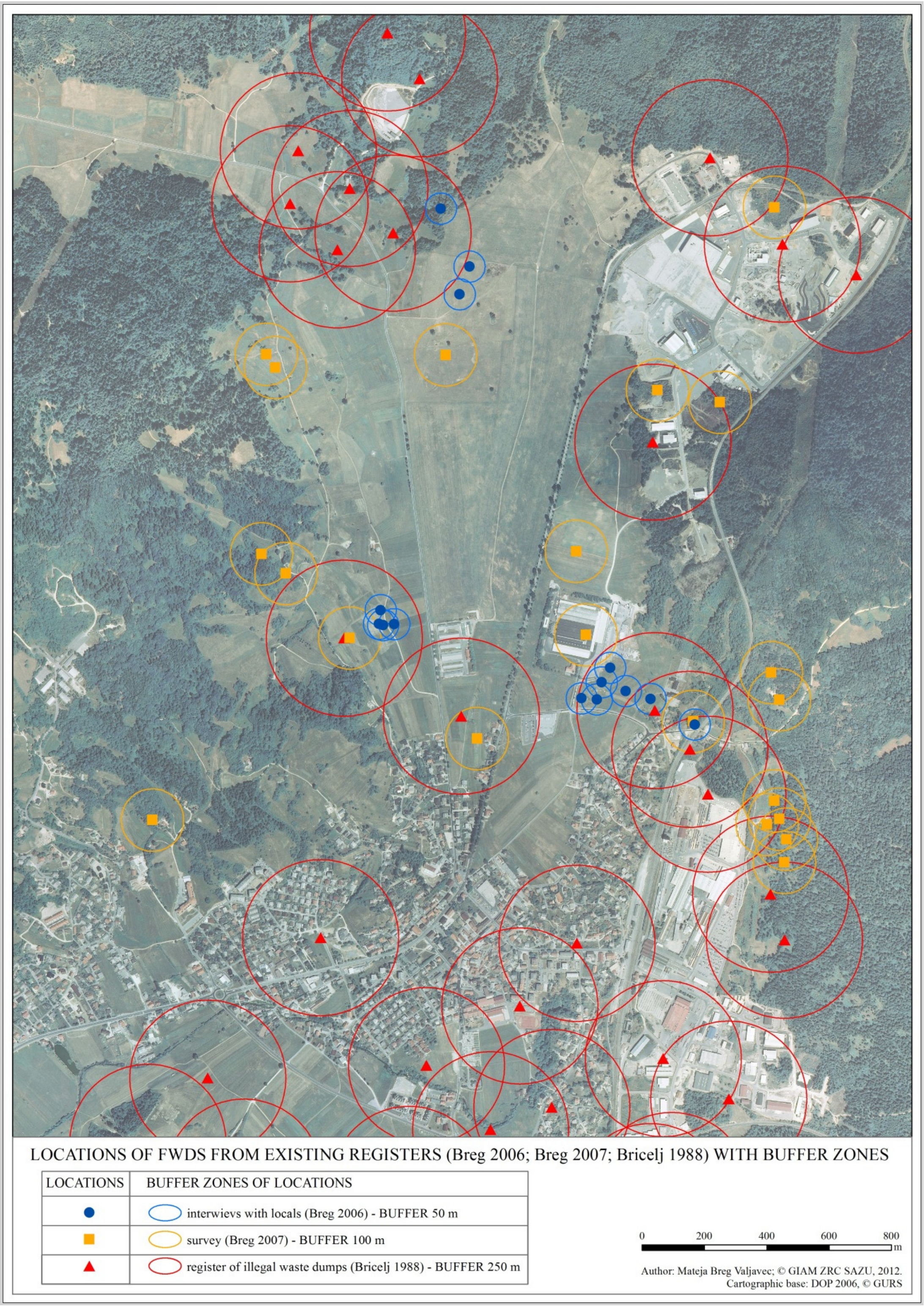


***Figure 63**: Locations of FWDS, based on existing registers (1988, 2006 and 2007).*

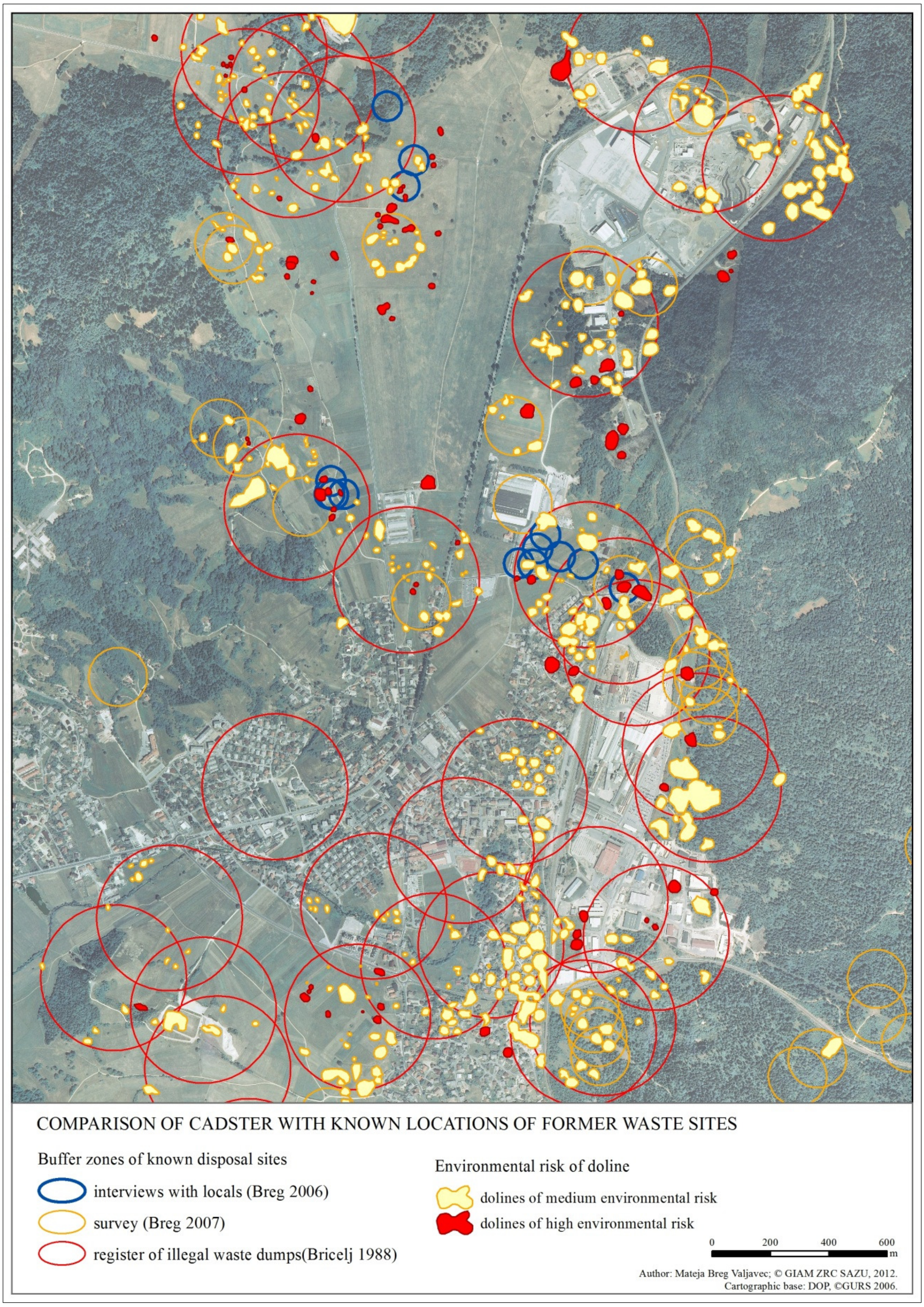


***Figure 64**: The FWDS map overlapped by buffer zones, based on known locations of FWDS.*

The FWDS cadaster on the studied area includes 92 FWDS objects of high environmental risk. 64 FWDS dolines fall inside buffer zones and 28 outside buffer zones. 423 dolines with a medium environmental risk and 366 dolines of a lower environmental risk fall inside the buffer zones. All 530 dolines without environmental risk lies outside of buffer zones.

The final validation of results of all three methods was performed.

In the first phase of the **multispectral analysis** (probability map 1), - the results were spatially generalized and 476 locations of potential FWDS were determined. To evaluate the results, they were placed over the buffer areas layer and only those dolines that were lying within the buffer zones (No **359**) were assigned to be FWDS.

By the **land use trend** (probability map 2), the most probable FWDS can be determined by picking the doline from the group (potential waste site) that overlaps with the buffer zones (their centroid lies within the buffer zone). There are 277 such dolines, including all the presently built up dolines. Excluding all the built up dolines, the final sum of the FWDS that could be rehabilitated amounts to **161**.

By determining the **relief changes** (probability map 3), 566 dolines were placed under the category of FWDS. **286** of them lie within the buffer zones and have a higher probability of being a FWDS. The remaining 355 dolines that were determined as being filled on both models fall outside the buffer zones.

8.7 Validation with Field Methods

8.7.1 Introductory Remarks

The main purpose of the field research was to **verify some the potential locations of FWDS in dolines and confirm or discard the suspicion about the disposed and filled waste**. During the field research, all the precisely detected locations were determined and **the differences in relief, soil, and vegetation in relation to the non-degraded surroundings were determined**. We chose three methods of field research (control methods) on Logaško polje, differing according to their invasiveness into space and some other options regarding the execution:

1. Soil sounding (with a soil auger):

- The object is physically intervened by making a drill in the diameter of 10 cm into the surface to the original foundation, maximum 1.5 meter;
- The method was executed on 20 doline locations;

The soils on dolines where it was not possible to prove waste but had been anthropogenously changed due to farming were named **antrosols,** for soils on FWDS the term **deposol** was used. The naturally occurring soils with no present proof of human reformulating were named according to the soil classification in the digital pedological map (CPVO, 2001).

The soil auger tip is 7 cm in diameter, depending on the chosen shape, and is approximately 25 cm long. Accordingly, the profile pieces (partial drills) are stacked together 25 cm at a time into a sounding profile, which is then placed on the ground and the characteristics are analysed. Each profile was photographed next to a measuring tape so that the depth is clearly visible and together with the drill where the tip points to the profile depth. In addition, photographs of details to certain photographs that were pedologic interesting or stood out in some way were added. As the drilling is done by hand, it is limited by “non-porous” hard mineral layers (dolomite particles, construction and demolition waste, glass). It is also very difficult to drill deep profiles at the bottom of agriculturally cultivated dolines and dolines, filled with organic waste that have a thick covering layer of soil (1m) due to subsequent agromeliorations. We carried out sounding mostly on meadows, fields and pastures. In addition, the filled dolines in the forest that are merely grown over with grass or are only grown over by bushes are appropriate for sounding. Built-up surfaces were excluded from the field analyses, as numerous dolines are filled, permanently built-up (parking lots, playgrounds, buildings …) and physically inaccessible.

2. Phytocenologic mapping:

Due to the magnitude of the occurrence, the plant species on the area of only one representative filled doline (V75) were documented first. The results were compared to the list of the surrounding vegetation. This allowed the acquirement of data on the typical plants and their use in other cases.

- The method does not include any physical interventions into the object and is based on a visual detection of anomalies;
- The method is executable and has been executed for only a few objects.

3. Measuring the electrical resistivity:

- The method cannot be executed on the areas of electrical power lines, in the vicinity of railway tracks, next to major traffic routes;
- In the first phase, a referential filled gravel pit was chosen that was confirmed using all the geoinformatic methods, field charting and sounding; after that, the most appropriate measuring method was determined (placing of the electrode field).

Six sample areas were chosen on Logaško polje (Figure 65), which differ according to their relief characteristics, original foundation, pedological characteristics and use of space. Some of the areas were named after their field names from the TTN5 (areas 2, 3, 4, 5) and one after an important industrial plant (area 1):

1 INDUSTRIAL AREA TRANSITIONING TO AN AGRARIAN AREA (VALKARTON company – AREA 1A, KLI company – AREA 1B)

2 BROJSKO POLJE – AGRARIAN AREA TRANSITIONING TO AN URBAN AREA

3 PUSTO POLJE – AGRARIAN AREA

4 LIPJE - AGRARIAN AREA

5 POD KOTLICAMI / ŠIROKE NJIVE – AGRARIAN AREA

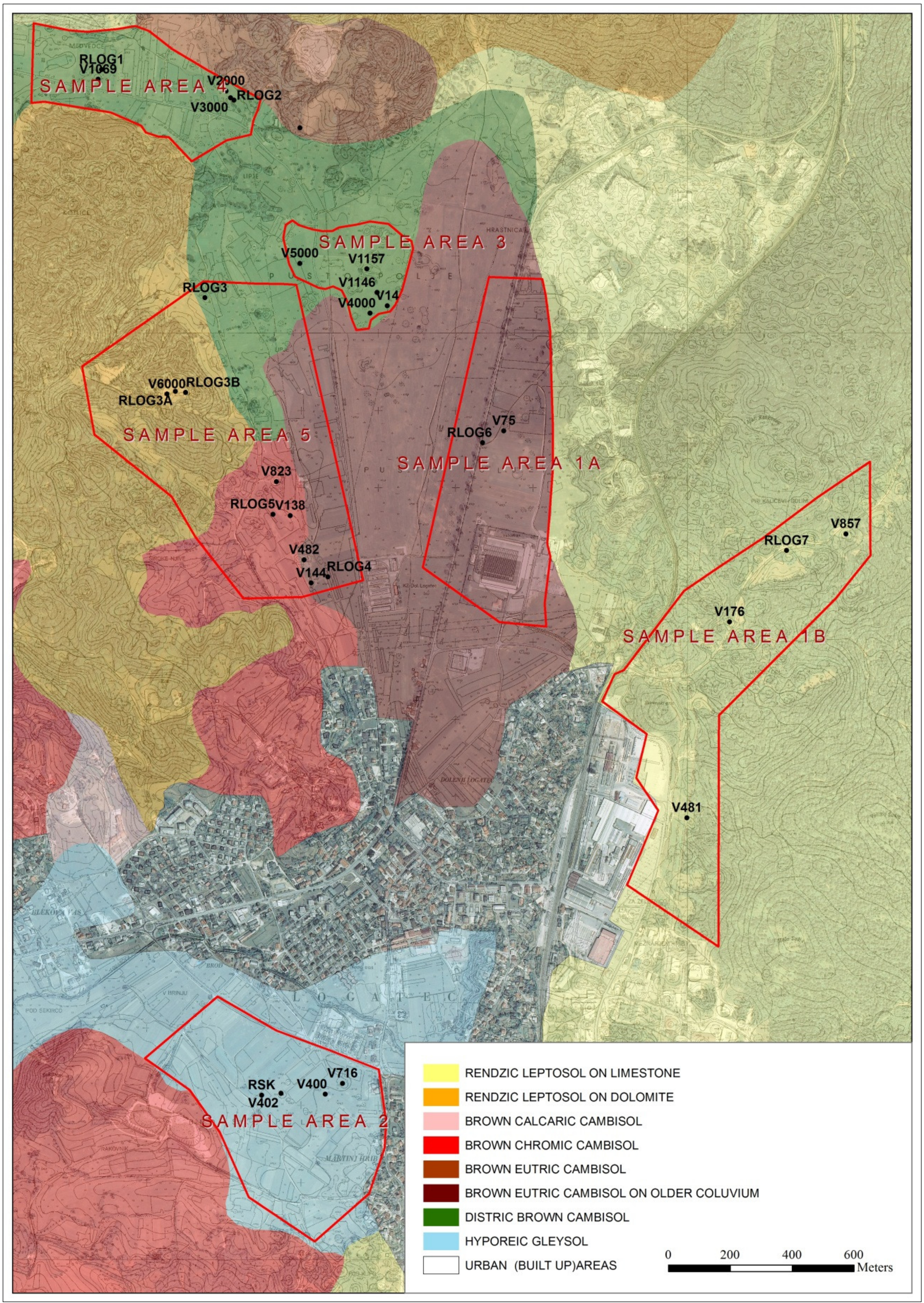


***Figure 65**: Areas of the field research and the precise profile locations according to their peodgeographical units (© CPVO 2001).*

The final objective of sounding is to determine the type of soil according to the anthropogenics influences and to divide the dolines into individual groups based on some common characteristics.

8.7.2 Results of Field Research

8.7.2.1 Pusto polje around Valkarton Company

Sample area 1A (Figure 66) is a completely flat area on Pusto polje, with prevailing eutric cambisol on colluvial loam. Dolomite is prevalent in the foundation of Pusto polje with intermittent oolitic limestone and noncarbonate Triassic slate and a varying alluvium thickness.

Another characteristic of Pusto polje are cover dolines. The predominant agrarian character of the area is intertwined with a paper and cardboard producing plant of the Valkatron Company. A great majority of the dolines in the alluvium is at least partly filled and the organic waste is prevailing.

Name	Land use	Depth (cm)	Horizon	Anthropo. parts	Soil base	Vegetation	Soil type
RLOG6	grassland	150	3	none	loam	grasses	eutric cambisol
V75	meadow	200	none	organic	waste	eutrophic	deposol

Table 12*: Results of the pedological sampling of referential profiles and profiles of the filled dolines on the 1A area.*

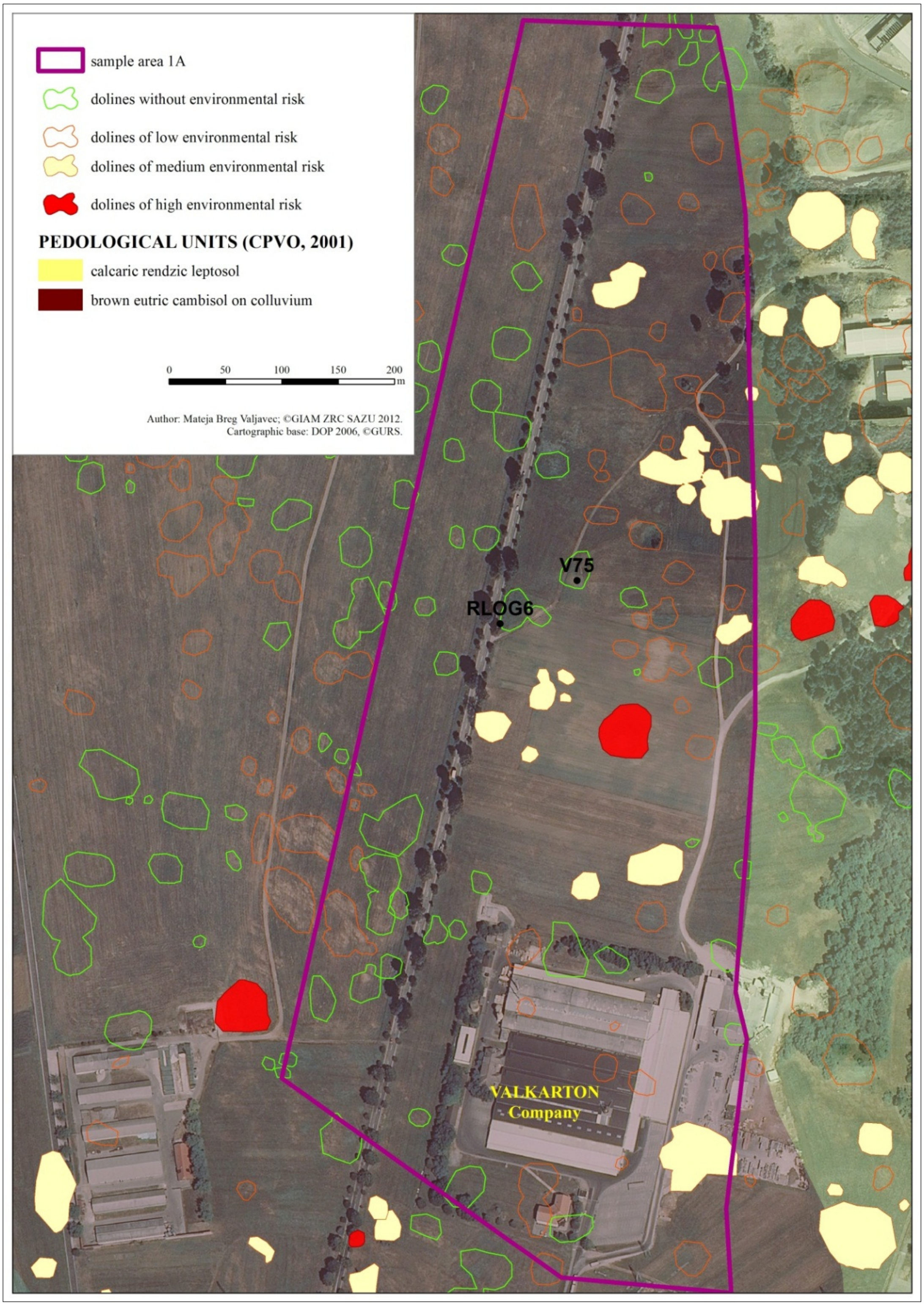


***Figure 66**: Delineating the 1A sampling area and the locations of the sounding profiles (pedological map and a color aerial photograph over the relief foundation).*

The RLOG6 referential profile for the 1A area was executed on a meadow (Figure 67). The profile (Figure 68) depth is 150 cm and represents an eutric cambisol on a loam colluvium. It is topped by 20 cm of humus horizon, transitioning into a transitional horizon and then a loam original foundation.

***Figure 67**: RLOG6 (referential profile of area 1A) sampling location.*

***Figure 68**: The entire RLOG6 profile composes of an eutric cambisol on a loam colluvium.*

Doline 75 is one of the numerous filled dolines in the vicinity of Valkaton, whose doline filling is a legacy of the agrarian and industrial development on Logaško polje. With the visual aerophoto-interpretation and 3D visualization, doline 75 was determined as a grassland cowered doline. The recent landform is slightly concave, 1 m in depth. We sounded in two places and reached organic waste mixed with other communal waste at a depth of approximately 1 m. Above it lies a brown poorly structured layer without horizons.

Figure 69: *Doline V75 is lightly concave, deep about 1 m and mostly filled with waste.*

Figure 70: *Sounding profile V75 (filled doline north of Valkarton). The waste appears at a depth of 110 cm. The soil is a eutrophic deposol.*

Figure 71: *Details (waste) in the V75 profile at a depth bellow 110 cm.*

Figure 72*: Demonstration of the V75 profile depth in relation to the depth of the soil auger and the height of a human. On the left the length of the auger in relation to the height of a human and on the right the remainder of the auger that sticks out of the surface while drilling.*

The vegetation cover in the area of the filled doline (approximately 100 m^2) visibly differs (Figure 73) from the surrounding grass vegetation that represents a cultivated meadow. Inside the filled doline grow eutrophic plants that do not appear in the surroundings. Based on the phytocenological list of V75 and the surrounding cultivated meadow, it is possible to conclude that the waste that fills the doline is of an organic origin (wood waste from Valkarton, organic waste from farms and households), topped with a 1 m thick layer of soil. Nutrients (nitrogen) are excreted from the decaying waste, which cause the soil to eutrophication and eutrophic plants to flourish (the dolines are grown over by nettles and broad-leafed dock, which are an indicator of over-fertilization).

Figure 73*: Vegetation in the filled doline with prevalent eutrophic species (nettles in the center).*

A phytocenological list was completed inside doline V75 on a 100 m² square and compared to a phytocenological list on a square of the same size outside the doline, on a non-degraded area. The phytocenological and floristic lists represented a good insight into the diversity, the layout and plant ecology on a certain area. The Braun-Blanquet scale was used, a Middle-European method of the French-Swiss or the Zürich-Montpelier school. It consists of a six-stage scale, where 5 denotes a high dominance and + a low dominance. The scale is combined, as it combines the abundance and dominance estimates.

The values to quantify the plant abundance		
Qualitative assesmet	share	mark
Only a few plants	< 1 %	+
The plant is very rare	1-10 %	1
The plant is rare	10-25 %	2
The plant is medium dense	25-50 %	3
The plant is dense	50-75 %	4
the plant is very dense	75-100 %	5

Table 13*: Braun-Blanquet scale for the dominance and the abundance of the plant species.*

Phytocenological list (Braun-Blanquet scale, date: 2012-05-24) of doline V75 (eutrophic, ruderal) was fulfilled in cooperation with biologist Andraž Čarni PhD and environmental engineer Daniela Alexandra Teixeira da Costa Ribeiro, MSc:

-*Dactylis glomerata* (orchard grass) (3)
- *Urtica dioica* (common nettle) (2)
-*Rumex obtusifolius* (broad-leafed dock) (2)
-*Silene alba* (white champion) (1)
- *Veronica polita* (grey-field speedwell) (+)
-*Capsella bursa-pastoris* (shepherd's purse) (1)
-*Taraxacum officinale* (common dandelion) (1)
- *Arrhenatherum elatius* (false oat-grass) (1)
-*Poa trivialis* (rough bluegrass) (1)
-*Vicia sepium* (bush vetch) (+)
-*Convolvulus arvensis* (field bindweed) (+)
-*Stellaria media* (common chickweed) (+)
-*Ranunculus bulbosus* (bulbous buttercup) (+)
-*Cirsium arvense* (creeping thistle) (1)
-*Bromus hordeaceus* (bull grass) (1)
-*Achillea millefolium* (common yarrow)(+)
-*Allium sp.* (wild onion) (+)
-*Plantago lanceolata* (ribwort plantain) (+)
-*Ranunculus repens* (creeping buttercup) (1)
-*Galium mollugo* (wild madder) (+)
-*Daucus carota* (wild carrot) (+)

Phytocenological list (Braun-Blanquet scale, date: 2012-05-24) of souerounding meadow was fulfilled in cooperation with biologist Andraž Čarni PhD and environmental engineer Daniela Alexandra Teixeira da Costa Ribeiro, MSc:

-*Arrhenatherum elatius* (false oat-grass) (4)
-*Salvia pratensis* (meadow clary) (1)
-*Cynosurus cristatus* (crested dog's-tail) (+)
-*Trifolium pratense* (red clover) (2)
-*Leucanthemum vulgare* (oxeye daisy) (1)
-*Rumex acetosa* (common sorrel) (1)
-*Ranunculus acris* (meadow buttercup) (1)
-*Myosotis arvensis* (field forget-me-not) (1)
-*Veronica arvensis* (common speedwell) (+)
-*Knautia arvensis* (field scabious) (+)
-*Galium mollugo* (wild madder) (+)
-*Trisetum flavescens* (golden oat grass) (+)
-*Silene alba* (white champion) (+)
-*Taraxacum officinale* (common dandelion) (1)
-*Ranunculus bulbosus* (bulbous buttercup) (+)
-*Campanula longistyla* (lavender bellflower) (+)
- *Dactylis glomerata* (orchard grass) (2)
-*Bromus erectus* (upright brome) (+)
-*Plantago lanceolata* (ribwort plantain) (1)
-*Veronica chamaedris* (germander speedwell) (+)
-*Allium sp.* (wild onion) (+)
-*Achillea millefolium* (common yarrow) (1)
-*Anthriscus sylvestris* (cow parsley) (+)
-*Vicia sepium* (bush vetch) (+)

-*Crepis biennis* (rough hawksbeard) (+)
-*Ajuga reptans* (blue bugle) (+)
-*Trifolium* (yellow flower) (+)
-*Holcus lanatus* (velvet grass) (1)
- *Cerastium holosteoides* (common mouse-ear) (+)
-*Lychnis flos-cuculi* (ragged robin) (+)
-*Centaurea eacea* ?(+) (Centaurea montana 'black sprite')
Bromus hordeaceus (soft brome) (+)
-*Poa trivialis* (rough bluegrass) (1)
-*Silena* (without hair) (+)

The phytocenological list was completed only in doline V75 and represents the basis for further phytogeological research of filled dolines, which, unfortunately, superceeds the goals of this thesis. In the presentations of the rest of the sample locations, the vegetation diffferences with the surroundings was therefore only visually evaluated.

The electrical resistivity of doline 75 (Figure 74) was measured to test the method on the aluvial part of karst polje and to prove dumped waste with different methods. The characteristics of profile are: date: 2012-04-27 (after a rainy April); length: 57 m; number of electrodes: 20; distance between electrodes: 3m.

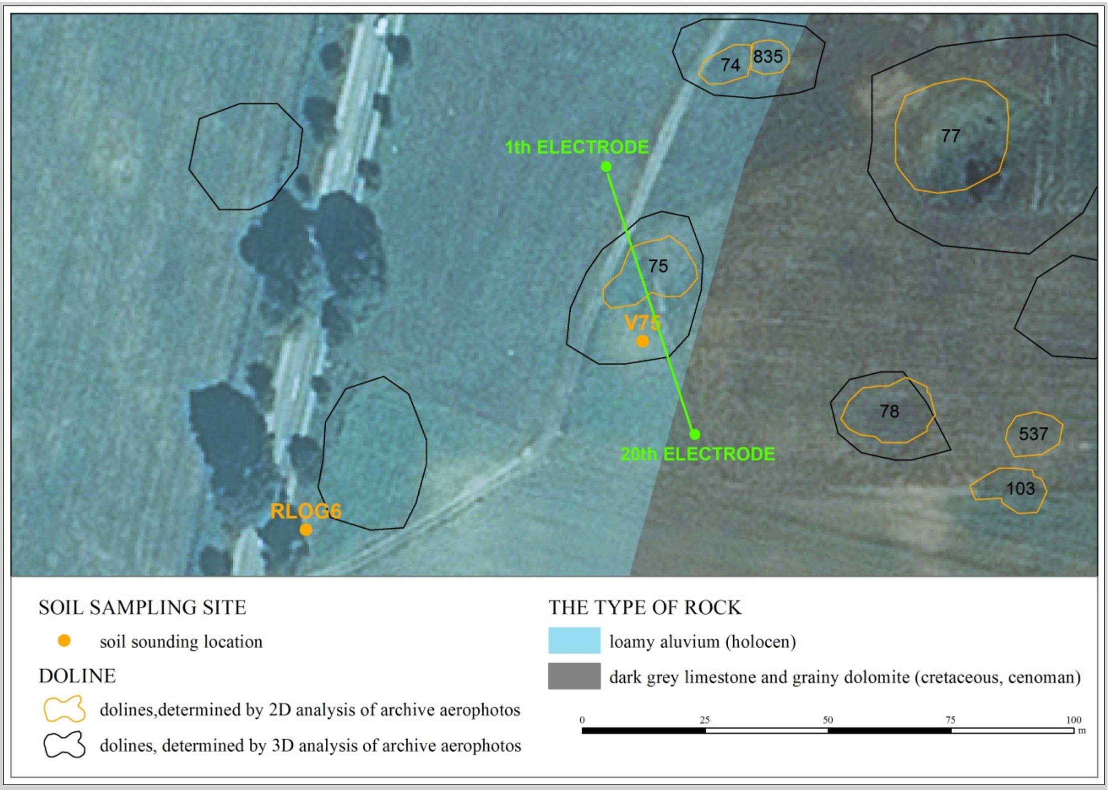


***Figure 74**: Position of the electrical resistivity section in relation to the doline V75 and the locations of pedological sampling profiles RLOG6 and V75.*

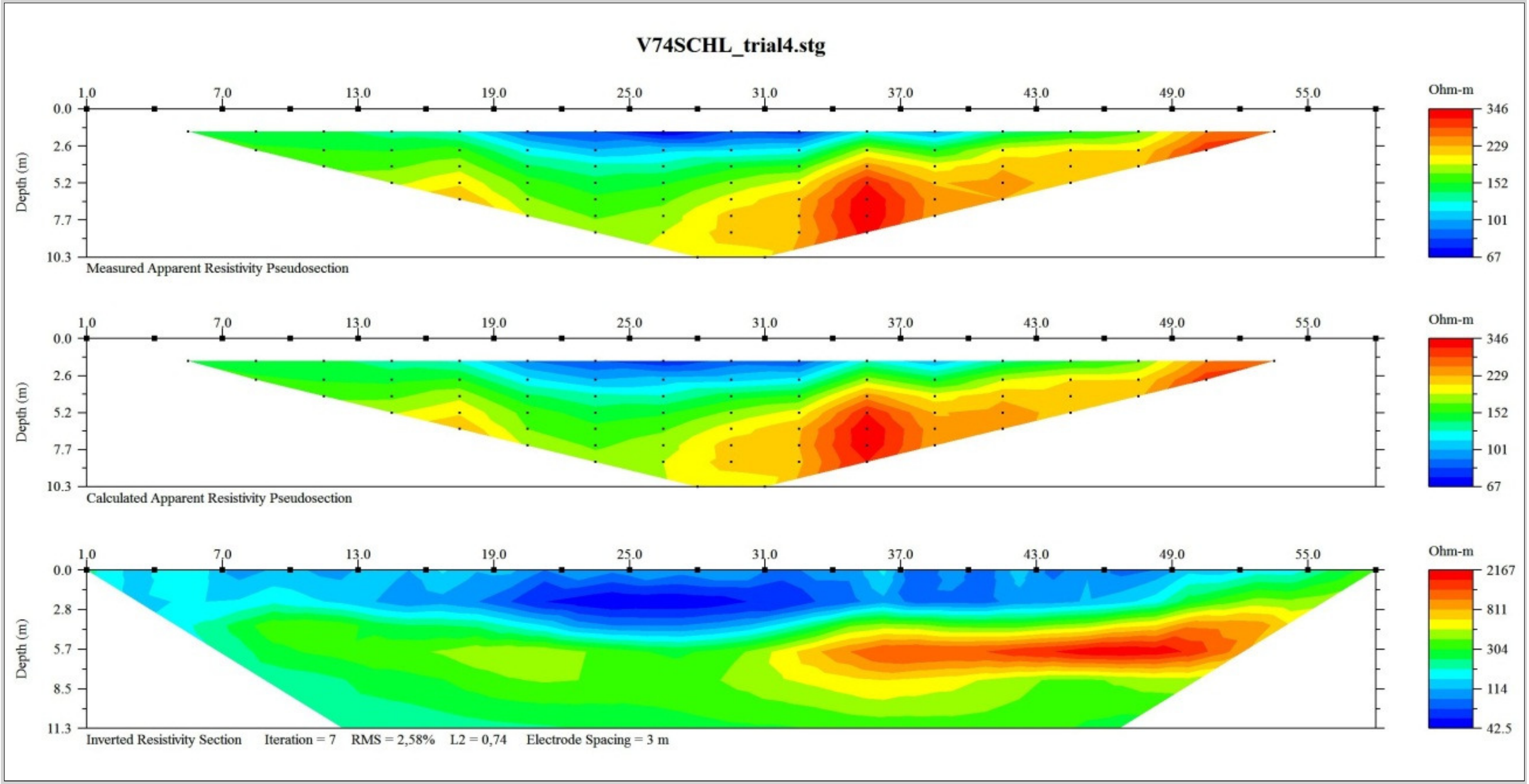


Figure 75*: The electrical resistivity section through doline V75, using the Schlumberger method. The waste is marked in blue.*

The 3 m distance between the electrodes allows us to make measurements with a 1.5 m accuracy (half the distance between electrodes), so the measurement of 1.5 m in depth is just the result of the interpolation within the inversion method and not an actual measurement, or a lesser one. According to the geological map (1:100,000), V75 is located on the border between the limestone and the alluvium, which is partially confirmed by the interpretation of Figure 74, Figure 75 and Figure 76. The blue represents the waste, the green an alluvium while the red may be a fractured limestone filled with loam, showing a lower resistance due to the greater moisture of the loam. However, the depth of the alluvium is too deep. This is a smaller cover doline filled with waste to a depth of 5 m.

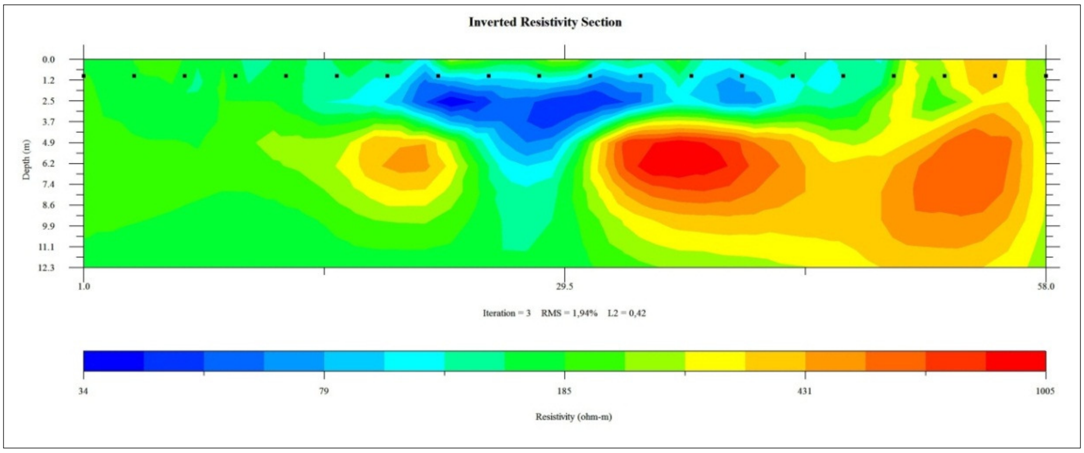


Figure 76*: An image presentation of the electrical resistivity section of doline V75, using dipol/ dipol method.*

The dipole dipole method reveals that there are actually several different limestones under the alluvium that have varying resistance. The stacked limestones have a greater resistance than the cracked, fractured limestones with clay-filled loams, because all this has an effect on the rock moisture and the electrical conductivity or the resistance of the layer.

The ground resistivity profile that was measured using the dipole dipole method (Figure 76) has a greater accuracy of measuring depth and shows an interesting funnel-shaped doline, which points to leaking material seeping in the lower lying layers and into the karst underground. The data inversion was repeated several times using different input parameters in order to confirm this was a case of leakage. Based on the results, this thesis cannot be entirely confirmed, as the plume did not show the same intensity in every case. In order to unequivocally prove this thesis, it would be necessary to repeat the measurements in different time periods after heavy rainfall. Doline 75 was not determined as a potential FWDS with the geoinformatic methods; this was only recognizable in the recent landscape using the NIR layer analysis and also as an area of unusually dry / droughty soils within the loamy alluvium. It was not determined as filled nor was it detected as a potential waste site in the past landscape. Based on the described methodology of the synthesis map, it was categorized among the dolines that pose no environmental risk. Due to the fact that the doline was located on the recent landscape, it was also sampled in the field and it was determined that upon field evaluation of the recent landscape, it expresses a completely different vegetation than the surroundings. It was verified using pedological sampling and a profile of the electrical resistance of the ground was also generated and both methods confirmed this was a FWDS. Waste of an organic origin was proven in the doline. As they decay, the area is saturated with different gasses that cause an eutrophication of the area and also a higher temperature that can be detected in the NIR part of the electromagnetic specter.

8.7.2.2 Karstic plateau around Kli Company

Test area 1B (Figure 77) is located on Logaško polje on heavily karstified limestone bedrock, which is illustrated in a very high number of dolines. Inside the dolines on the bottom, agrarian soils occur on loam, while limestone residue is prevalent in the surroundings. The agrarian cultivated dolines are intermittent with heavily degraded dolines due to industrial waste (closer to roads and the industrial zone).

Name	**Land use**	**Depth (cm)**	**Horizon**	**Antrop. parts**	**Soil base**	**Vegetation**	**Soil type**
RLOG7	meadow	70	yes	none	loam	grass	brownn eutric cambisol
V857	meadow	30 – 50	yes	none	loam	grass	antrosol
V176	meadow	35	none	none	loam	grass	antrosol
V481	overgrown	30	none	glas, brick, concrete, plastic,…	waste	ruderal, eutrophic	deposol

Table 14*: Results of the pedological sampling of the referential profiles and profiles of the filled dolines on the 1B area.*

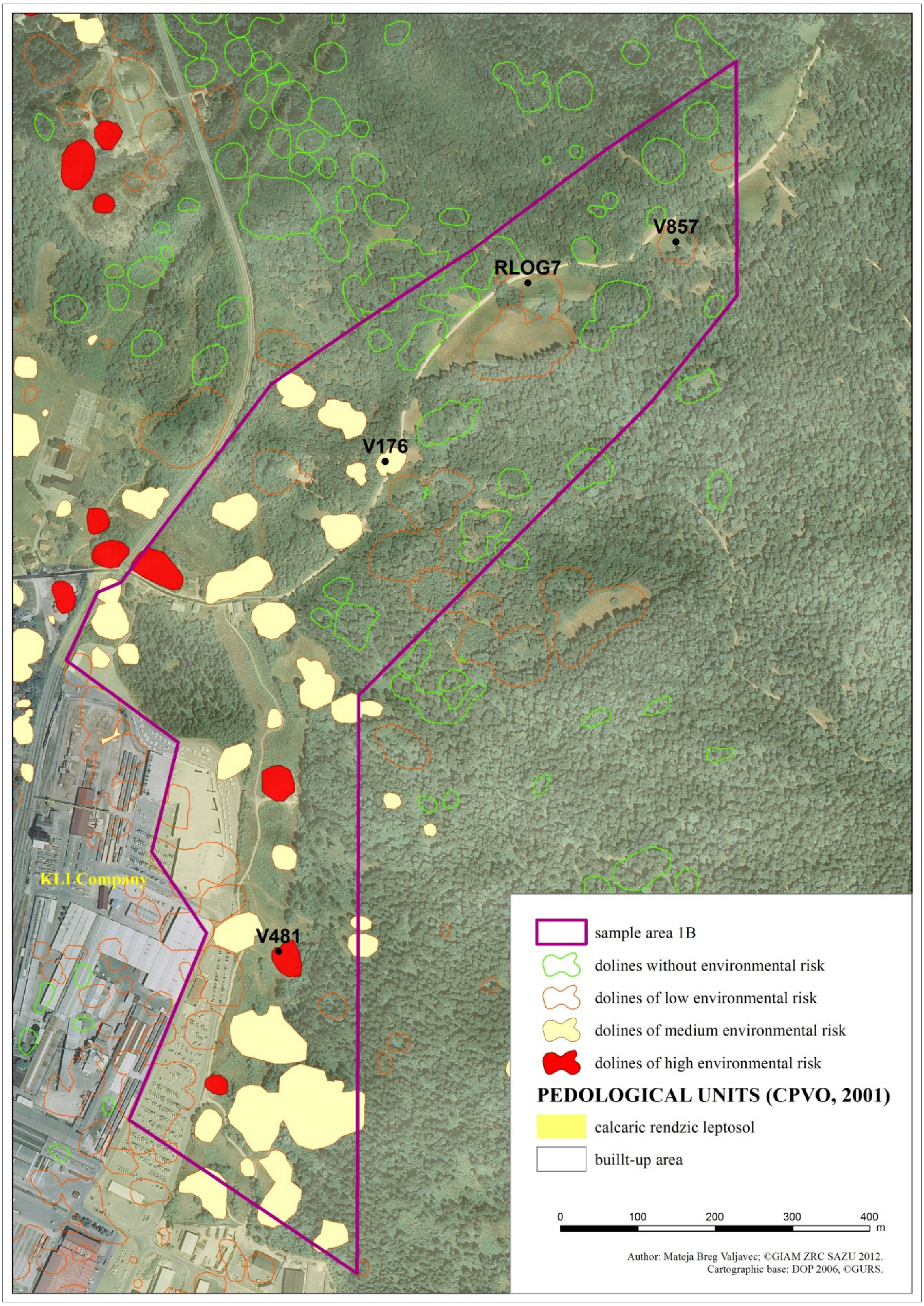


Figure 77*: Delineating the 1B area and the locations of the sounding profiles (pedological map and a color aerial photograph overlapping the shaded relief).*

Figure 78*: The area's referential profile RLOG7 is represented by the soil on the doline slope.*

Doline 857 is a cultivated meadow, which was once a field appropriate for motorized cultivation due to its wide bottom and wide exit.

Figure 79*: The V857 sounding was executed in a concave relief shape.*

Figure 80*: The sounding pedological profile of a traditionally agrarian altered doline V857, an example of agrarian antrosol.*

The top of the profile consists of a humus layer, underneath it lays a mineral layer, slowly transitioning into a deeper, damper loam horizon above the loam. This is an agrarian antrosol.

The V176 location lies at the bottom of a partially filled meadow doline.

Figure 81*: The V176 sounding was executed in a concave relief shape.*

Figure 82*: Sounding pedological profile V176 shows agrarian antrosol.*

The sounding profile is similar to the previous doline and the soil falls within the category of agrarian antrosol.

The area of the V481 doline represents an industrially degraded area, where, due to the vicinity of Kli, industrial waste was also dumped. The waste was poorly covered or was not covered at all and ruderal vegetation is developing on it (Figure 84).

Figure 83*: The V481 sounding profile (Kli filled doline), deposol on mixed waste.*

During sounding, an impenetrable layer of waste was quickly encountered, covered with a thin layer of earth or the waste was completely uncovered. Eutrophic plant species grow on them (nettles, broad-leafed dock, mint, absinthe, etc.) as well as invasive species (*Solidago canadensis)*.

***Figure 84**: V481 location (filled doline by the Kli Company) and industrial zone objects in the background.*

Doline V481 is filled with different waste, and judging by the vicinity of Kli, probably also with industrial waste. The pedological sounding confirmed the suspicions about deposited waste. The waste was not covered, only overgrown with meadow vegetation.

A section of the electrical resistance of the ground was generated (Figure 85). The profile characteristics are as follows: date: 2012-04-26; length: 76 m; number of electrodes: 20; distance between electrodes: 4 m.

The measurements on the same section were repeated using three methods: Schlumberger, Wenner and dipole / dipole; there were several commonalities proving that there is waste in the doline. It was possible to determine waste in all the sections (blue), filling the basin in limestones.

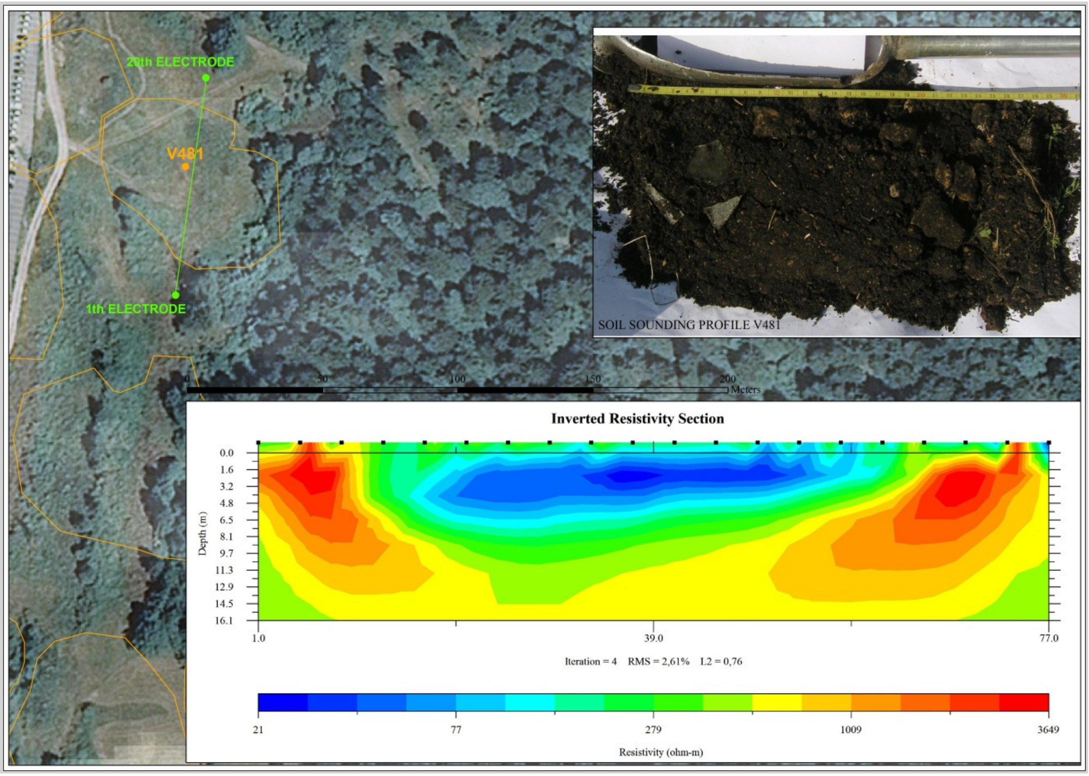


Figure 85*: The location of the electrical resistivity profile (green line) delineating doline V481 and a graphical presentation of the results of two field test methods.*

The image of the section clearly indicates the shape of the former doline in hard stacked limestones with a high resistance (red). The basin is filled with waste (blue) with no soil on top, as it would be visible on top of the section in a thicker layer with a higher resistance.

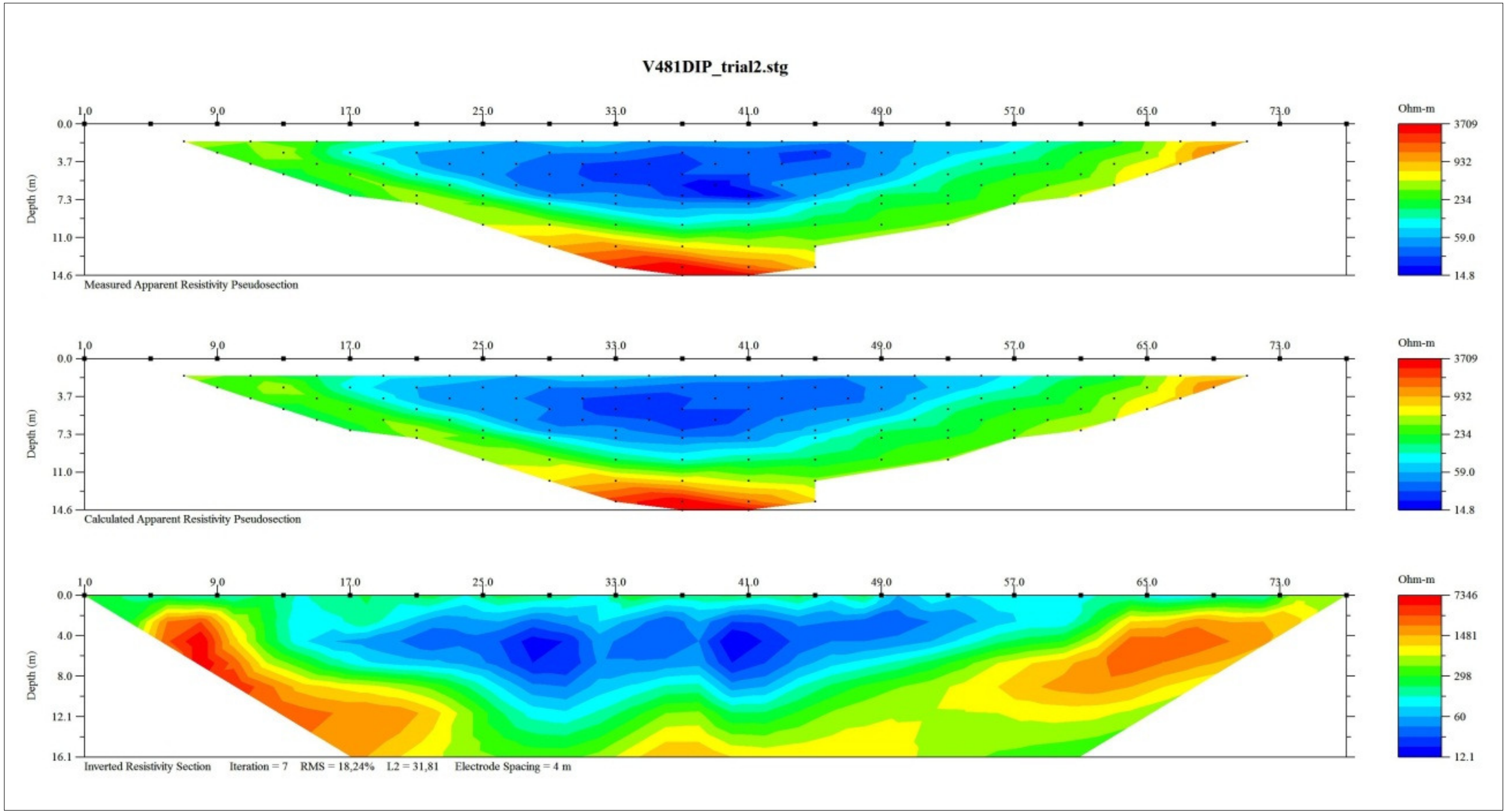


Figure 86: *A measured electrical resistivity section of doline V481, applying Schlumberger method.*

8.7.2.3 Brojsko polje

Sample area 2 - Brojsko polje (Figure 87) is a completely flat area, deposited by the Logaščica stream, flowing from the dolomite catchment area in the west. Since the Logaščica stream sinks into the karst underground in the direct vicinity, Brojsko polje is also a flooding surface. Eutric middle mineral hipogleys have developed on the clay alluvium. Cover dolines and subsidences are rare in Brojsko polje, their density is greater in the vicinity of the rock cut terrace in the south-west. On the eastern side of Brojsko and Pusto polje lies an up-to 10 m high rock cut terrace spreading on Cretaceous limestone, interlaced with dolines.

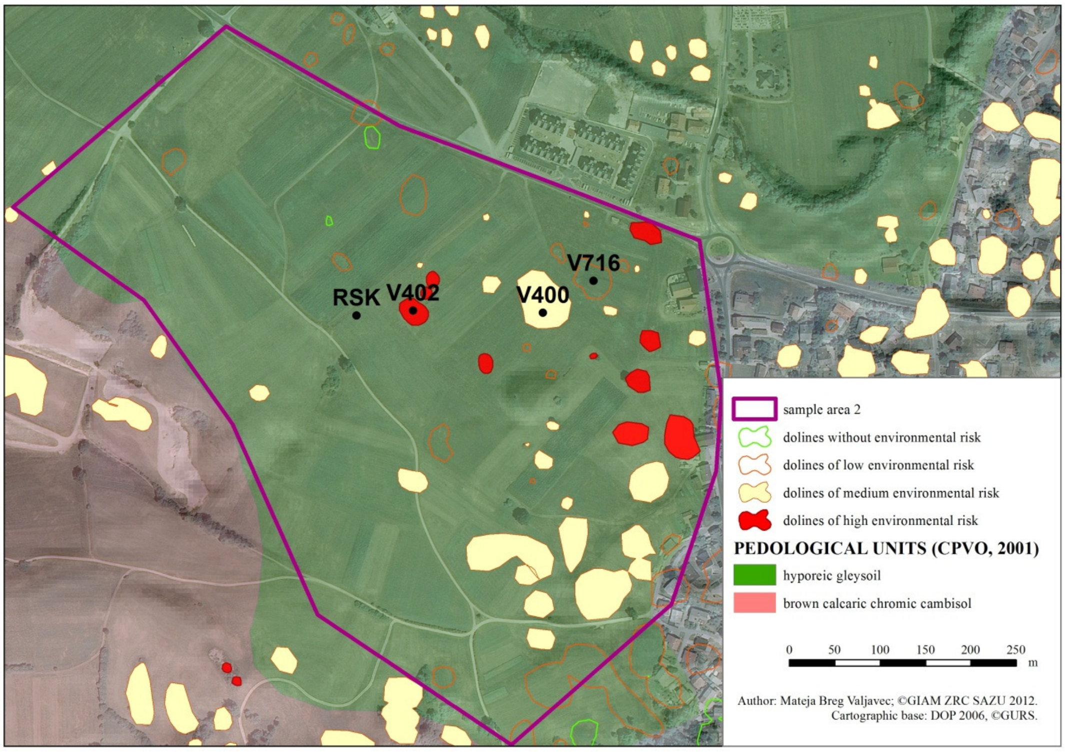


Figure 87*: Delineating area 2 and the locations of the sounding profiles (pedological map and a color aerial photograph overlapping the shaded relief foundation).*

Name	Land use	Depth (cm)	Horizons	Anthrop. part	Soil base	Vegetation	Soil type
RSK	meadow	100	2 horizons	none	loamy sediment	grass	brown eutric cambisol
V402	meadow	30 – 50	none	construct. waste	dolomite debris	pioneer, ruderal	deposol
V400	meadow	35	none	none	dolomite debris	eutrophic, ruderal	deposol
V716	meadow	45	2 horizons	none	dolomite debris	eutrophic, ruderal	deposol

Table 15*: Results of the pedological sampling of the referential profiles and profiles of the potentially filled dolines on area 2.*

The referential pedological profile RSK of area 2 was done on a meadow surface (Figure 88) where, based on the data of the aerial photograph analysis, there has not been a doline for at least the last sixty years and where the area is composed of a natural loam sediment. The profile (Figure 89) is 100 cm deep with 2 soil horizons and ends at a depth of approximately 70 cm in a loam layer.

Figure 88*: Area of the referential profile sampling for area 2.*

Figure 89*: RSK referential profile, eutric cambisol.*

Doline 402 was detected with all the geoinformatic methods and has been inspected using all three methods for studying filled dolines. The pedological sounding (Figure 90) confirmed that the area falls in the 1st class of degraded soils.

Figure 90*: Profile 402 a, deposol on construction and demolition waste.*

Figure 91*: Profile 402 b, deposol on construction and demolition waste.*

Figure 92*: The blossoming dandelion is concentrated on the area of the filled doline, reflecting the differences in soils on the area of the filled doline (26 April 2012).*

The vegetation on the area of filled doline 402 visibly differs from the surrounding one and points to a recent "rehabilitation" doline area, where pioneer and ruderal plants are flourishing, predominantly dandelion. The uncovered area offers excellent conditions for the spreading of dandelion, which has rosette-shaped leaves and therefore demands a greater growing surface (A. Čarni, oral source). Smaller empty patches between the grass are covered by mosses, which point to the underdevelopment of the soil.

The electrical resistivity of the ground was measured on the area of the potentially filled doline V402, with the following profile characteristics: date: 2012-03-29; length: 78m; number of electrodes: 20; distance between electrodes: 4m.

Waste was proven to be lying just beneath the surface without a developed soil layer on top by testing two methods, Schlumberger and dipole / dipole. The profile demonstrates that this is actually one larger doline that was clearly noticeable with the 3D past surface relief analysis (1972), while the marked doline is notably smaller when observed with the visual 2D archive photograph analysis. The depth of the basin is approximately 6m, according to the level of gradient from a lower into a higher ground resistance. Next to the larger doline, there is a smaller doline detectable to its right, also marked on Figure 93 (small doline, marked as 401).

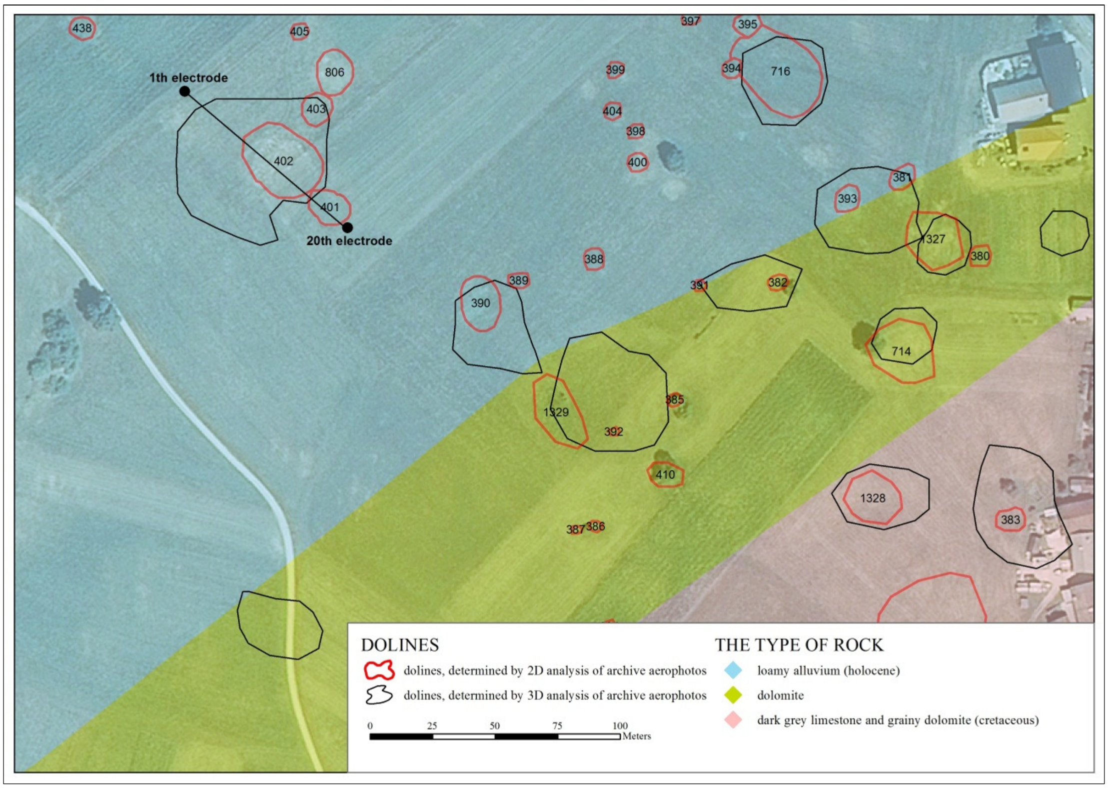


Figure 93*: The location of the electrical resistivity section with respect to doline V402 and V401.*

The profile section features the basin in rocks with a higher ground resistance. These may be fractured and loam-filled limestones or dolomites or loam sediment. There are three larger clusters of waste inside the doline (blue) with slight breaks with a minutely higher resistance, which can mean different waste or even natural loamy deposit.

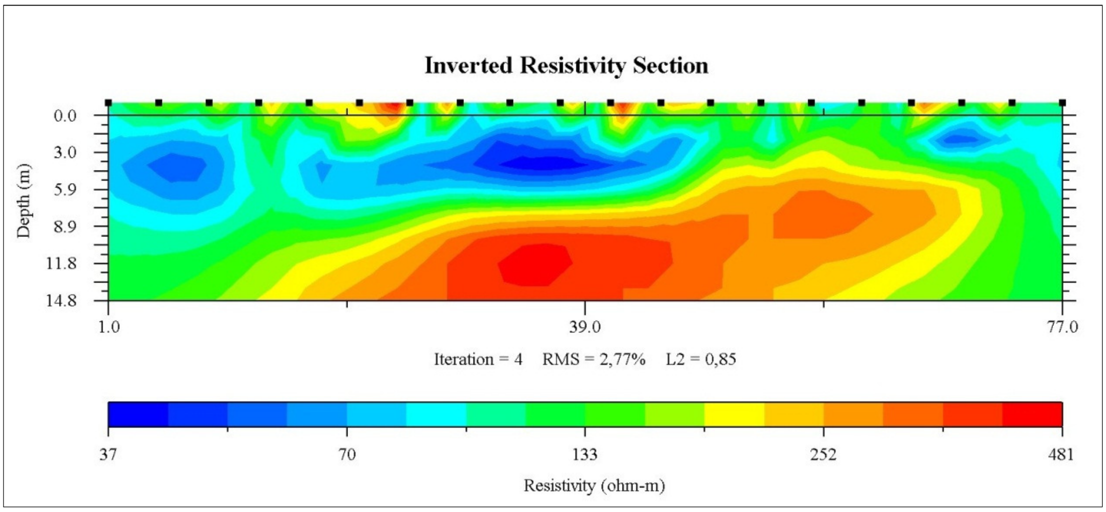


Figure 94*: Electrical resistivity section for doline V402, using the dipol / dipol method.*

The dipole / dipole method demonstrates the three waste clusters even more prominently. Doline 402 was also identified in the recent landscape using multispectral analysis.

D**oline V 400** was located using aerial photograph analysis and the multispectral analysis of recent photographs. The latter method enabled the location of the potential filled doline to fall in the 1st class of soil degradation, which was also confirmed with the sounding. The approximately 10 cm thick layer represents an underdeveloped humus layer or a root zone that quickly ends in a hard surface. The doline has undoubtedly been filled.

Figure 95*: A shallow pedological V400profile, deposol with an allogenic dolomite foundation.*

Unlike dolines 402 and 400, most of **doline V716** was classified in the 3rd class of soil degradation level. The pedological profile was possible to the depth of 50 cm and has a 20 cm layer of humus horizon on the top, which shifts to a skeletal horizon with fragments of dolomite. The auger was unable to drill deeper than 50 cm, because the quantity of dolomite dramatically increases at that depth. This is a rather large doline, which had been filled a long time ago. Since 1944, the land use has retained its meadow function, which is understandable, as this is a flooding surface, unsuitable for fields.

Figure 96*: A shallow V716 profile with a developed humus horizon on top, deposol with an allogenic dolomite foundation.*

Eutrophic plants flourish in doline V716 that do not appear elsewhere in the surroundings. Figure 97 shows white flowered parsley plants (*Apiaceae*) in a slight depression (next to the man), however there are no meadow buttercups, otherwise typical for a cultivated meadow in the area.

Figure 97*: Sample profile location V716 (18 May 2012) with noticeable differences in vegetation (white flowers).*

8.7.2.4 Pusto polje

Sample area 3 - Pusto polje's name (Barren Field) (Figure 98) already reveals that there is no surface water flow there. Since underground draining of rainwater is prevalent, suffusion dolines are formed in a loamy alluvium, covering limestone. The sample area lies on the shift from a dystric to an eutric cambisol and is intended for farming use. After WWII, the farming lands on Pusto polje were taken from the local farmers in Logatec and were nationalized; they remain nationalized to this day. Most of the area belongs to the Faculty of Biotechnic of the University of Ljubljana, where the Department for Zootechnic studies cattle.

The extensive agromeliorations that ended in the 1980s on Pusto polje have had an even more intense role in reshaping the traditionally cultivated dolines. Their main goal was to improve the agrarian surfaces, which means they would fill the bottoms of the dolines with anything that would fill up the volume, while leaving the top layer of earth, which enabled a motorized cultivation (meadow, pasture).

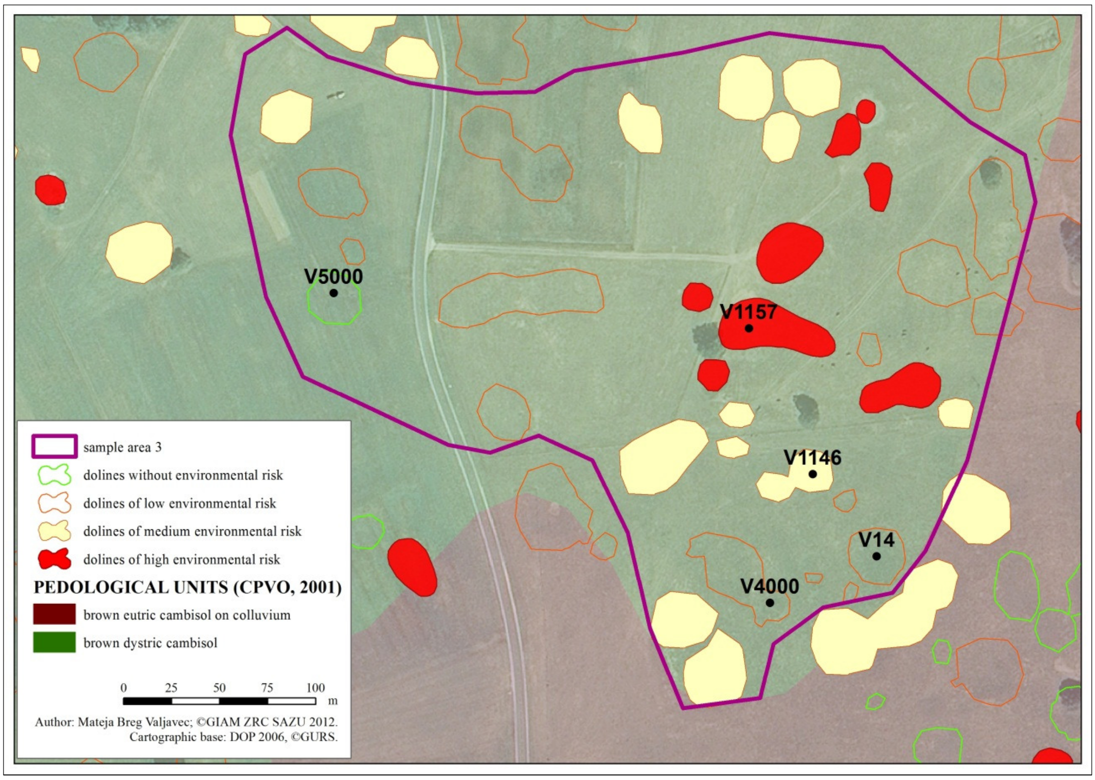


***Figure 98**: Delineating area 3 and the locations of the sounding profiles (pedological map and a color aerial photograph over the shaded relief).*

Name	Land use	Depth (cm)	Horizons	Anthr. parts	Soil base	Vegetation	Soil type
RLOG8	meadow	120	3 horizons	none	loamy sediment	traditional meadow	brown dystric cambisol
V1157	pasture	25	none	yes	constr. waste	eutrophic	deposol
V1146	meadow	150	none	none	unknown	eutrophic	antrosol
V14	meadow	140	2 horizons	organic	organic waste	eutrophic	deposol
V4000	meadow	180	2 horizons	organic	organic waste	eutrophic	antrosol
V5000	meadow	130	2 horizons	organic	eutrophic	eutrophic	antrosol

Table 16*: Results of the pedological sampling of the referential profiles and profiles of the filled dolines on area 3.*

The RLOG8 (Figure 99) referential profile was sounded in the vicinity of doline V1146 in an area that was also subject to agromeliorations. Despite that fact, it was maintained as a representative profile outside the dolines, as a loam original foundation was stumbled upon at a depth of 1 m and it was not possible get a better result. The depth of the entire profile is 120 cm. The dark brown color of the top-most unstructured horizon changes into a dark brown loam horizon at a depth of 50 cm. The lates connects to the loam layer at a depth of 90 cm.

Figure 99*: RLOG8 referential profile.*

D**oline V1157** (Figure 100) was partially filled and has a slight concave shape; it is overgrown by meadow vegetation in the present. It was located using all of the geoinformatic methods, placing it into the 1st class of environmental risk. A very shallow soil profile (Figure 101) was drilled with the help of pedological sounding to the depth of 25 cm. Further drilling is obstructed by the hard particles of the construction and demolition waste.

Figure 100*: Doline V1157 is overgrown with meadow vegetation despite its undeveloped soil; bottom right stems of dandelion can be seen. The soil is a deposol.*

Figure 101*: The very shallow profile of V1157 proves the doline was recently filled and / or covered with construction and demolition waste.*

V 1146 is an agromeliorated doline (Figure 102). Organic matter at the bottom of sounding profaile (Figure 103) may point to organic waste.

Figure 102*: Doline V1146 is completely leveled with its surroundings.*

Figure 103: *The extremely deep antrosol profile of V1146 stops at a depth of 150 cm in a dark organic matter.*

Figure 104: *Doline V14 is filled, but still retains some of its concave shape.*

Figure 105: *A very deep V14 profile (180 cm), which darkens at 130 cm of depth, presumably due to a compost organic matter.*

Figure 106: *Detail of the organic matter in profile V14 (left).*
Figure 107: *Detail of the organic matter in auger tip (from V14 sounding profile) (right).*

Doline **V4000** (Figure 108) has similar characteristics as dolines V1146 and V14.

Figure 108*: A deep profile of V4000 (180 cm) with a dark brown humus horizon, shifting into a loam mineral horizon, visibly darkens at 110 cm of depth due to a composted organic matter.*

Doline **V5000** was located using only the 3D analysis of past landscape, based on DSM1972 relief data. In the field, the doline area was completely unrecognizable; however, there were noticeable differences in the vegetation (Figure 109), with eutrophic plants prevalent within the doline area that were not detectable in larger numbers in the surroundings.

Figures 109*: Meadow vegetation of V5000 is differing from the sourounding meadow vegetation.*

Figure 110*: The deep sounding profile ends in a loamy layer at a depth of 130 cm.*

There was no organic matter present at the end of the profile in doline 5000 (Figure 110), but it appeared in fragments, scattered throughout the entire profile. It was not possible to explain the increased soil eutrophication reflected in the vegetation with the pedological sounding. Based on the V14 and V1146 profiles, where the organic matter appears at a depth of 130 or even 150 cm, it would be pertinent to somewhat deepen the profile and drill in more locations inside the doline to reach any organic matter.

8.7.2.5 Lipje

Sample area 4 - Lipje (Figure 111) represents a widened valley in limestone, covered with silicate gravel (4 m), originating from the river basins of Rovtarica, Petkovščica and streams from the lake south of Prezid. On the western side, the dry valley of Rovtarica flows into Lipje and to the east it is separated from Pusto polje on the eastern side by a few meters high terrace in limestone. The soils are distric cambisols, as this is a noncarbonated original surface.

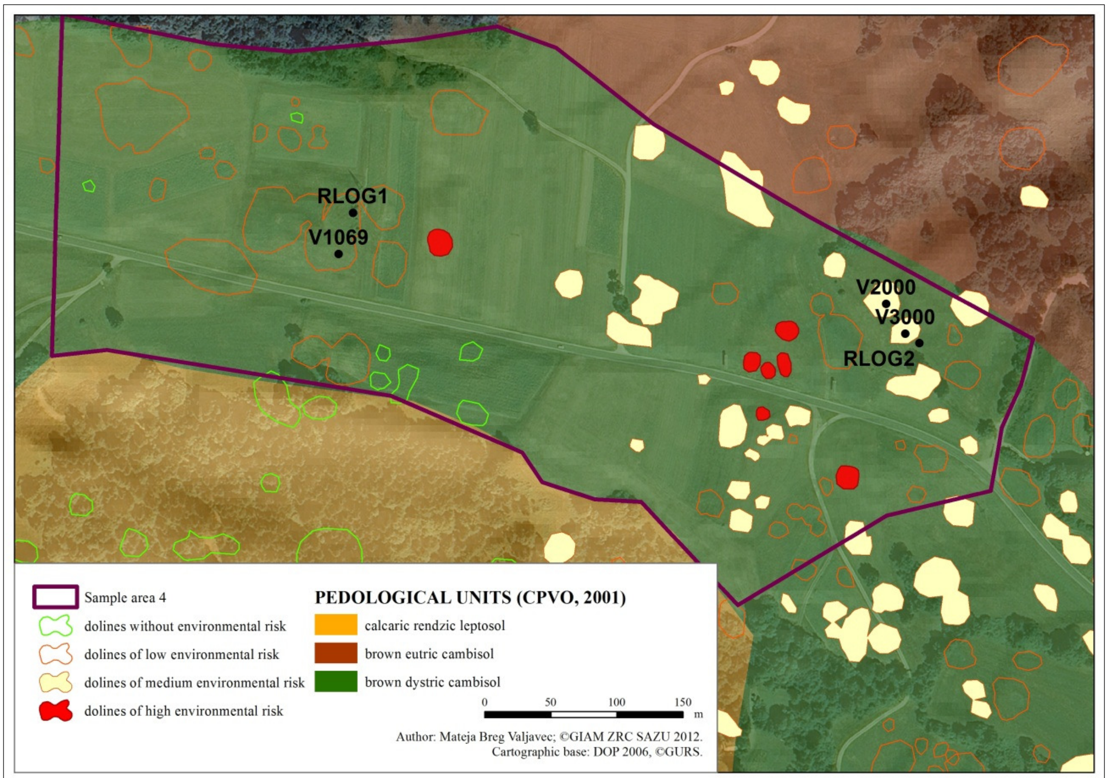


***Figure 111**: Delineating area 4 and the sounding profile location (pedological map and a color aerial photograph over a 3D relief surface).*

Due to the karst carbonate foundation, the karst process of suffusion occurs; this is a removal of fine sediment, dissolved in water (clay, loam), through the rock cracks in the underlying karst carbonate rock into the karst underground. Therefore the highest number of suffusion subsidences and dolines can be found in Lipje, with their density increasing toward the east. The area has been entirely agromeliorated, so numerous dolines have been filled with a deposited allogenic loam material, which was proven by soil sounding inside the dolines and comparing the results to the profiles from the doline surroundings. It is presumed that the soil outside the dolines had not been as expressly transformed as the soil in the dolines.

Limestone can be found at the bottom of the newly-formed suffusion subsidences (Figure 113) or cover dolines. The need for farming surfaces means that every newly-formed alluvial subsidence is promptly filled.

***Figure 112**: A photography of a slightly wavy Lipje landscape due the agromeliorations, filling of the cover dolines (left of the Rovtarska cesta towards Žiri).*

***Figure 113**: Newly-formed alluvial subsidence in Lipje on Logaško polje.*

The sampling of referential profile RLOG1 (Figure 114) was done on a smaller slightly convex relief shape, where the phenomenon is not a filled doline. While the neighbouring plots are cultivated or at least grown over with grass, this one is in the phase of being grown over with bushes and trees with an electric transformer standing in the middle of the plot.

Name	Land use	Depth (cm)	Horizons	Anthrop. parts	Soil base	Soil type
RLOG1	meadow	55	mixed	none	loam mixed with non-carbonate gravel	brown dystric cambisol
RLOG2	meadow	60	mixed	none	loam mixed with non-carbonate gravel	brown dystric cambisol
V2000	meadow	120	none	organic parts (at 1 m depth)	excavated soil	antrosol
V3000	meadow	150	none	none	excavated soil	antrosol
V1069	meadow	10	none	black organic parts	excavated soil	deposol

Table 17*: Results of the pedological sampling of the referential profiles and the profiles of the filled dolines in area 4.*

Minute gravel stones of different colors (non-carbonate) appear in the loam foundation in the profile (Figure 114). The sounding of referential profile RLOG2 (Figure 115) was done in a meadow next to dolines V2000 and V3000. Here, the surface starts to slope slowly into the limestone catchment area.

Figure 114*: Referential profile RLog1 (next to doline V1069) up to a depth of 55 cm is composed of a deposol on a loam deposit with small non-carbonate gravel stones (5 mm in diameter).*

Figure 115: Referential profile Log2 next to the V2000 doline was drilled to a depth of 60 cm, where thick loam appears preventing further profile deepening.

Doline V2000 is a completely filled doline, almost leveled with the surounding surface (Figure 116). The filling material has somewhat subsided, which has caused a slight relief depression, within which the vegetation visibly differs from the surroudings. Along with doline V3000, it was located using only the multipsectral photograph analysis, where it demontrated a very good, healthy vegetation reflectance, which is a reflection of a greater humidity and with that, soil coolness. The dolines were also clearly recognizable in the field.

***Figure 116**: The filled dolines 2000 and 3000 were recognizable in the nature by their vegetation, which differed from the surrounding area even in the winter. The area in the middle shows an image with taller, drier, more grey-colored grass (February 2012) and sampling locations.*

***Figure 117**: Sounding profile depth of doline V2000.*

The pedological profile of V2000 (Figure 117) is proof that this is a filled doline, because charred organic matter was encountered at a depth of 110 cm, which can point to two conclusions. This may be a relict humus horizon, covered in the time of agromeliorations with 1 m of material or it is organic waste, lying at a deeper depth than we sounded.

Since the aim was to explain the differences in vegetation on the area of doline V2000, which was not possible to do with pedological sounding, the Schlumberger method was used to measure the ground resistance. The section characteristics are as follows: date: 2012-04-25; the length: 28.5 m; number of electrodes: 20; distance between electrodes: 1.5 m.

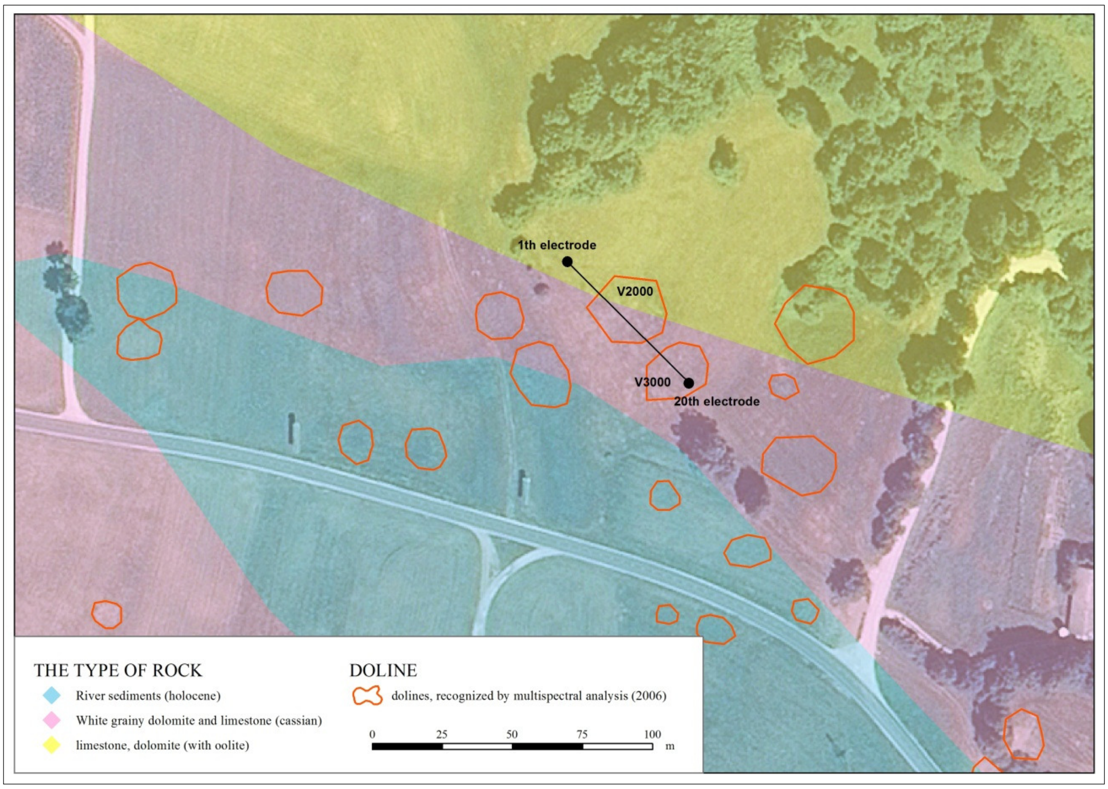


***Figure 118**: Location of the electrical resistivity profile in reference to doline V2000.*

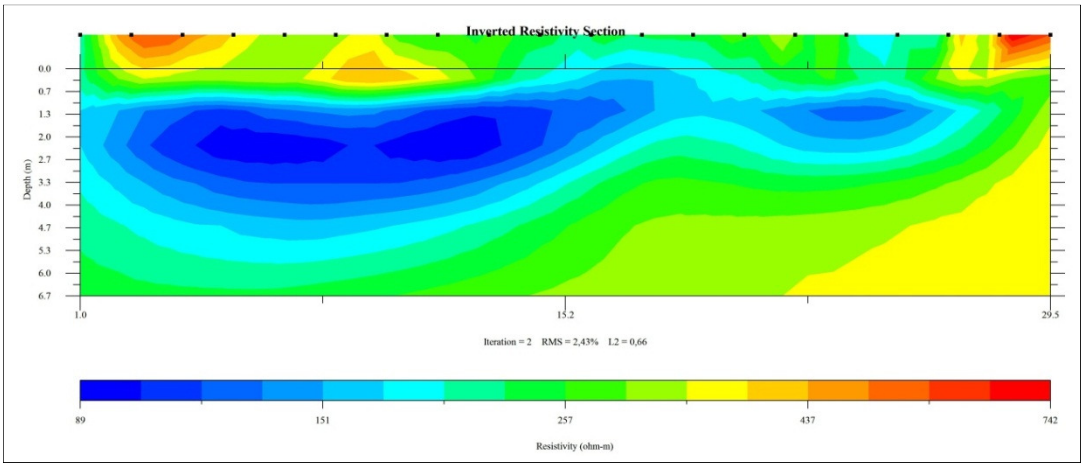


Figure 119: *Electrical resistivity section of filled doline V2000 and nearby V3000.*

Based on the measured electrical resistance of the ground (Figure 119), it was confirmed that V2000 is a filled doline. Doline V2000 is nearly 7 m deep. A layer with a higher ground resistance lies above the waste that appears to be a non-layered soil according to the pedological profile.

Doline V3000 is located in the immediate vicinity of doline V2000 and has similar soil characteristics, as is demonstrated in Figure 120.

Figure 120*: Depth and structure of V3000.*

The depth of the V3000 sounding profile is much greater than the referential surrounding profile RLOG2; there was also no thick light brown loam at the depth of 50 cm in it. This proves that it is a case of a filled doline. There are particles of degraded brick at a depth of 80 cm. It should also be pointed out that there was a darkened profile the deeper the profile was drilled, which indicates an organic matter.

The electrical conductivity was also measured on the doline surface and a profile was created. The section of doline V2000 reached outside it towards V3000, which appears on the section (right of the V2000 in the Figures 118 and 119). Doline V3000 was also determined to contain waste. Based on the latter, it is possible to prove that the doline had been filled with waste at the bottom but at the top it was covered with an almost 1.5 m thick covering layer of loamy soil due to agromeliorations.

D**oline V1069** was not filled to its top, but is still somewhat concave in its shape and up to 1.5 m deep. It was partially filled during agromeliorations and adjusting it to farming use, motorized cultivation and serves as a meadow in the present. The pedological sounding stops at a depth of up to 10 cm on black particles, which prevent deepening. The sounding was repeated on several different places inside the doline and ran upon similar black particles at the same depth. The soil is completely unstructured, as is shown in Figure 121.

Figure 121*: A sampled deposol of the V1069 inside the area of the potentially filled doline.*

Figure 122*: A detail of the black waste at the tip of the auger.*

Based on the sample profiles in the filled dolines and the non-natural characteristics of the referential profiles, it may be concluded that the entire area has been thoroughly altered due to anthropogenous factors. In addition to the agromeliorations, intervening construction for the road and electrical infrastructure construction (power line, transformers, etc.) were important factors in reshaping the relief, as several excavations and fillings occurred at the time.

8.7.2.6 Pod kotlicami

Sample area 5 (Figure 123) is a geologically and geomorphologically very diverse area, which is expressed in the present soils as well in a land use. With regard to the fluvio-karstic relief, rendzic leptosol and post-carbonate cambisol on dolomite appear, while the dystrict cambisols on the alluvial plain in the north shift into eutric cambisol on loamy sediment bedrock in the south. The dolomite area is partially forested, partially grown over with grass and cultivated by fields, while the plain is almost completely agrarian and practically used entirely for meadows with rare fields.

Name	**Land use**	**Depth (cm)**	**Horizons**	**Anthr. parts**	**Soil base**	**Vegetation**	**Soil type**
RLOG3	meadow	150	2 horizons	none	dolomite	grass	chromic cambisol
RLOG3A	meadow	80	2 horizons	none	dolomite	grass	Loamy sediment on dolomite
RLOG3B	meadow	20	1 horizon		dolomite	grass	rendzic leptosol
RLOG4	meadow	190	2 horizons	none	Loamy sediment	grass	Brown eutric cambisol
RLOG5	field	40	2 horizons	none	dolomite	grass	chromic cambisol
V6000	meadow	20	none	none	dolomite	grass	rendzic leptosol
V823	meadow	20	none	excavat. material	loam	grass	deposol
V144	meadow	30	none	construct. waste	waste	grass	deposol
V482	field	60	none	construct. waste	waste	cultivated plants	deposol
V138	meadow	215	2 horizons	organic parts, depth 60-70 cm	loam	grass	antrosol

***Table 18**: Results of the pedological sampling of the referential profiles and profiles of the filled dolines on area 5.*

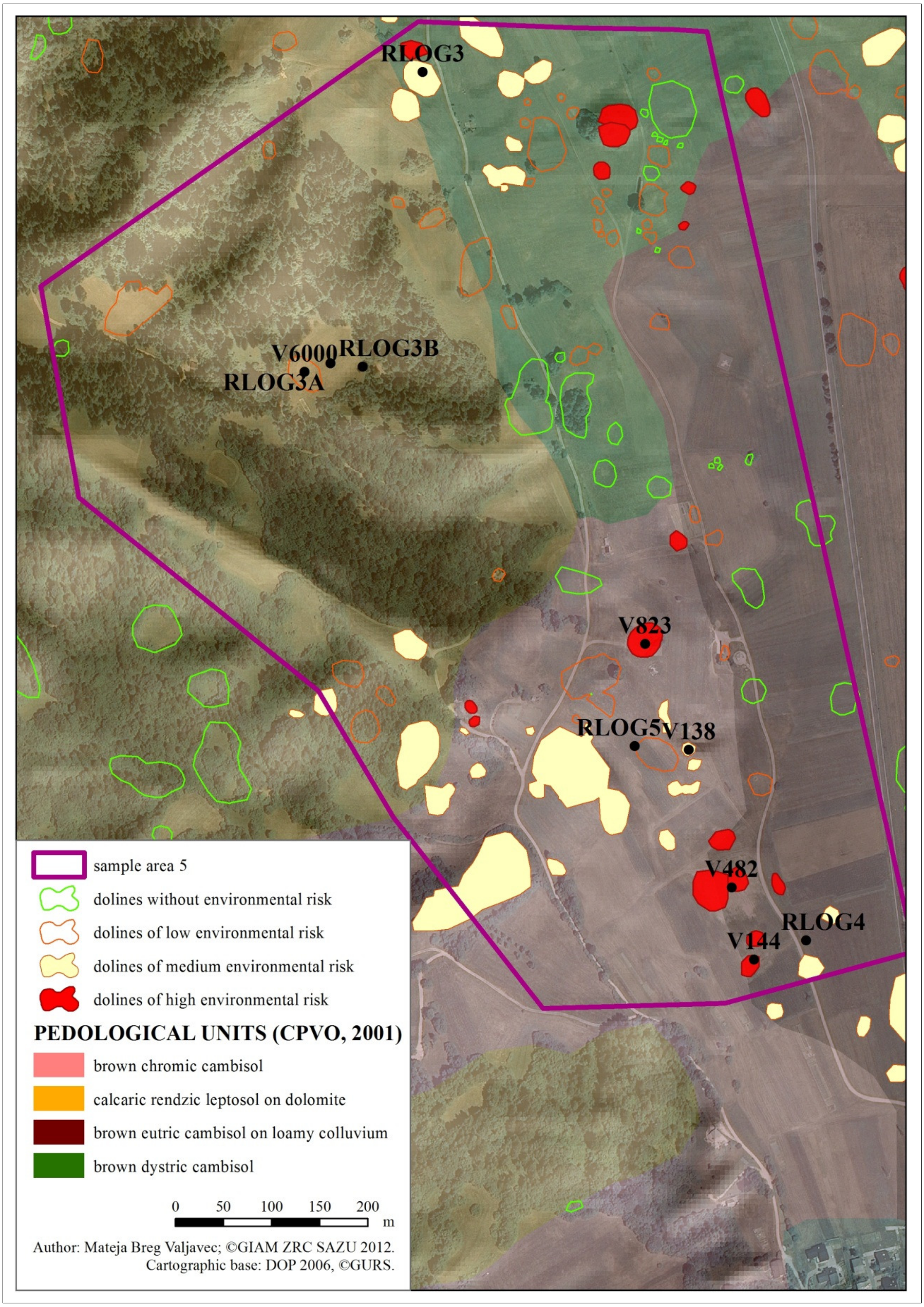


Figure 123: *Delineating area 5 and the sounding profile locations.*

Figure 123 depicts the sampling area of the RLOG 3 referential profile of chromic cambisol on the dolomite bedrock (green color – white grainy crushable dolomite) with district cambisols on a noncarbonate Ice Age gravel and sand surface.

The results of the pedological sampling (Figure 124) indicated a fairly deep, well-structured skeletal soil. The auger drilled to a depth of 150 cm, where a greater concentration of larger crushed dolomite particles appeared, which prevented further deepening. Along the length of the entire profile from 20 cm on, smaller dolomite particles are present that increase in quantity with depth, also expressed in the profile color.

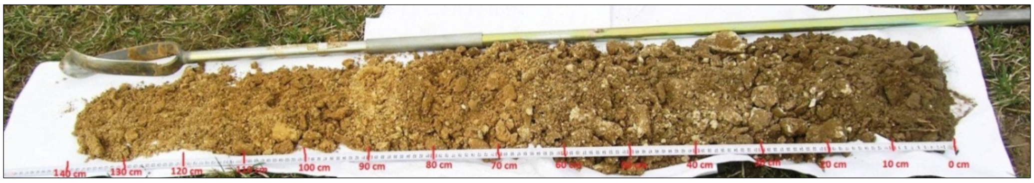


***Figure 124**: Referential sounding profile RLOG3 for the chromic cambisol on dolomite.*

Profiles RLOG3A (Figure 125) and RLOG3B (Figure 126) are a typical case of soil forming on a natural dolomite bedrock in relation to the geomorphological structure. RLOG3B is referential on a convex or sloping relief shape (Figure 131), from which the decaying matter is washed away into the concave shape (forming indentation, valley), where the RLOG3A reference profile was taken. The first profile is extremely shallow, as a dolomite original foundation was encountered at only 20 cm (crushable dolomite) and is a rendzic leptosol on dolomite, while the RLOG3A is at least 80 cm deep (deeper sounding was not possible due to the dense loam) and is an eutric colluvial cambisol on a loam foundation.

***Figure 125**: Referential profile RLOG3A consisting of an eutric cambisol on the colluvial loam.*

The **RLOG4** referential profile was taken in an area of a cultivated meadow (Figure 127) on the flat (plain) part of area 5. The eutric cambisoils on colluvial loam bedrock are depicted in Figure 128, where the profile is heavily deepened into the alluvial loam foundation.

Figure 126*: Pedological profile RLOG3B demonstrating a shallow rendzic leptosol (left). Detail in the auger – a crushable dolomite, white bedrock in the tip (right).*

Figure 127*: Locations of the referential profile RLOG4 and V144 profile in the landscape.*

Figure 128*: The sounding pedological profile RLOG4 represents the referential profile of eutric cambisol on an older loamy colluvium.*

The **RLOG5** referential profile was taken on a dolomite area that is used as a field (Figure 130). The representative soil of this area is shallow brown chromic cambisol (Figure 129).

Figure 129*: The sounding soil profile RLOG5 represents the referential profile of a shallow chromic cambisol on dolomite (40 cm depth).*

Figure 130: *Sampling of RLOG5 on cultivated field.*

Based on the multispectral analysis, doline area **V6000** was designated as a potentially filled doline. It was tested by pedological sounding and the results showed (Figure 132, 133) that this is a case of an entirely natural convex landform.

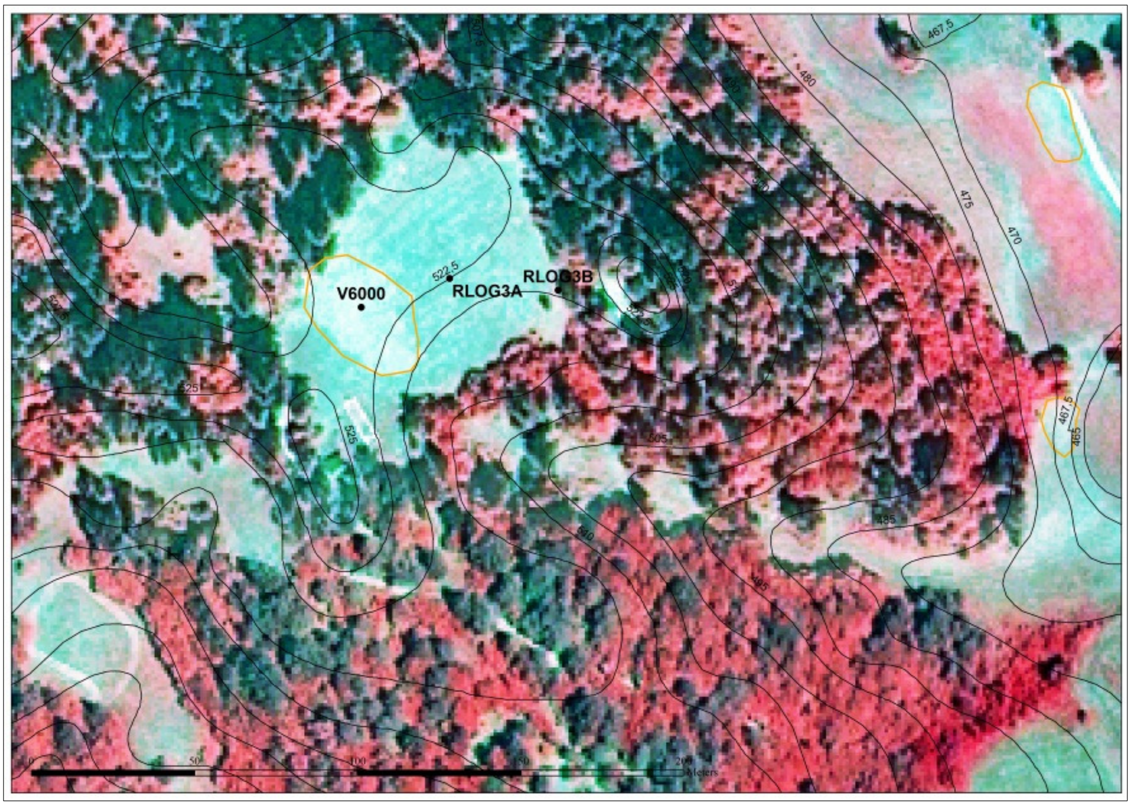


Figure 131*: Locations of sounding profiles V6000, RLOG3A, RLOG3B with regard to the relief diversity and the radiometric characteristics of the surface reflection (surface in color infra-red image; includes 3 layers: infra-red, red, green).*

***Figure 132**: Sounding pedological profile V6000. This is a shallow rendzic laptosol on dolomite, depth up to 20 cm. The sounding was executed on a slightly convex relief shape.*

***Figure 133**: Detail in the auger – a white crushable dolomite bedrock in the tip (right).*

V482 is a larger doline, detected on the archive aerial photographs with the DSM 1972 analysis, multispectral analysis and confirmed in the field with soil sounding (Figure 134). Until 1979, the doline was a communal Logatec waste disposal site, in which the public waste management company dumped waste, gathered with a regular organized communal garbage pickup. After the opening of the still current Ostri vrh landfill, the waste disposal site was rehabilitated by covering it with a mineral covering layer. According to the locals, there is a large amount of hazardous material from the period in the doline (car bodyworks, car batteries, etc.).

***Figure 134**: Under the thin layer of covering material (20 cm), particles of construction and demolition material appear in the V482 filled doline.*

Doline V144 was located using the same methods as doline V482 and was filled with communal waste and "rehabilitated" with a layer of construction and demolition waste and allogenic soil (a construction excavation from Gorenji Logatec).

***Figure 135**: The sounding profile of filled doline V144 with particles of construction and demolition waste at a depth of 20 cm. The soil is completely unstructured deposol.*

***Figure 136**: An detail in auger tip – soil sampling in V144.*

Doline V823 was located using the same methods as dolines V482 and V144. It is filled with an allogenic material, which is covered with debris of Permo-Carbon slate claystone. The deposol is very shallow (Figure 137).

***Figure 137**: A violet anthropogenous horizon (excavation material - slate claystone) appears at a depth of 20 cm.*

Pioneer and ruderal species can be found inside a filled doline V823 (red polygon in Figure 138), typical for undeveloped layers without a humus horizon (e.g. dandelion). The figure clearly depicts the doline as a slight depression, surrounded by typical cultivated meadow vegetation, blooming nicely in mid-May (buttercup, bellflower), while the blooming vegetation inside the filled dolines is limited to sparse white parsley flowers and dandelion seed heads.

Figure 138*: The location of doline V823 in the present landscape; slightly concave landform covered by ruderal vegetation.*

Doline area V138 is a very old traditionally cultivated agrarian doline on dolomite with prevailing post-carbonate soils. It was located using archive aerial photograph analysis, where the land use in 1944, 1957, and 1972 was determined as a meadow, while the use was not designated on the TTN5. A part of the doline is still a meadow and the other part a planted field (Figure 139).

Figure 139*: The location of doline 138 in the recent landscape.*

The aerial photographs from year 2000 designate the area of doline as a potential filled doline. This could be expressed in the soil profile (Figures 140, 141), which allowed us to establish that this is a doline, filled with 120 cm of material in the final stage, under which a "relict humus horizon" appears. This is a traditionally cultivated doline (most of the doline is a meadow today and part of it still a planted field).

***Figure 140**: An interesting feature in the profile is an approximately 20 cm thick black layer (organic origin) = relict humus horizon, which appears at a depth of 120 cm above a loamy layer.*

***Figure 141**: An enlarged view of the relic humus horizon.*

8.8 Conclusive Remarks for Further Geoinformatic Studies

Some new conclusions were made about the direct and indirect impacts of waste disposal on landforms, soil and vegetation, mostly through detailed laboratory and field research. It is almost impossible to find a completely natural doline in the studied area, starting with the traditionally cultivated dolines that are ranked as partially preserved. The filled dolines on Logaško polje differ from one another according to the type of filled waste material, which is often different as the covering layer that was used for the covering of the waste and "remediation" of place. The vegetation that developed on the covering layer is a reflection of both. The amount of soil moisture available to the plants depends on characteristics of top layer, while the underlying waste can be a source of nutrients (decaying organic waste – nitrogen) or of toxic substances (industrial waste from the KLI company's galvans – chromium).

Numerous waste filled dolines have been "remediated" in the project of agromelioration in the 80s. The waste material was covered with more or less inert material like allogenic soils, excavation material or crushable dolomite tailings from the quarry, with the intent to facilitate easier mechanical cultivation of the farming surface in the dolines. This top layer is often very thick (up to 1 m) and makes it possible to reach the underlying waste with pedological sounding. However, when the top layer consists of dolomite or construction and demolition waste, deeper sounding is prevented due to the hard rock particles; in such cases it was not possible to acquire direct data on the type of lower lying waste. Electrical resistivity tomography was selected and tested as an appropriate none-intrusive method.

In general, the three main factors for classifying the filled dolines on Logaško polje were stressed, mainly supported by the conclusions of the field research in comparison to the geoinformatic analysis results.

The type of covering material, detectable in the covering layer with pedological sounding in the field, has a major role in the multispectral aerial photograph analysis. This layer represents the physical basis on which the vegetation is growing:

- mixed waste (communal, industrial),
- natural loamy soil or allogenic loamy sediment (unable to distinguish by multispectral analysis),
- dolomite tailings (from the Smolevc or the Skirica dolomite quarry),
- mineral construction and demolition waste,
- Perma-Carbon slate claystone.

2. The presence of referential plant species, which are an indicator for the deviation from the surrounding vegetation:

- pioneer and ruderal species are an indicator of soil underdevelopment, expressed in the absence of a humus horizon on top: various mosses, dandelion;
- eutrophic species are an indicator of an increased content of nutrients in the soil, which are an indicator or decaying organic waste: nettles, broad-leaf dock; bellflowers,
- invasive species.

3. Type of filling material:

- waste of an organic origin according to their amount:
- industrial organic waste, mostly wood waste from the Valkarton and Kli companies,
- communal/household organic waste,
- farming organic waste,
- traffic organic waste in the shape of cinders from steam locomotives

- Toxic waste:
  - industrial hazardous waste from companies (galvanic sludge and former galvans from the Kli company),
  - household hazardous waste (batteries, car batteries, …),
  - farming hazardous waste (packaging and remnant of phytopharmaceutical substances for plant protection).
- Inert waste:
  - construction and demolition waste, waste of mineral origin (concrete, brick, asphalt, etc.).

With respect to the described criteria, it is possible to divide the filled dolines on Logaško polje in the following four groups:

Agrarian dolines are filled dolines, where no suspicion exists on the above described waste. The pedological profiles of the typical dolines (V857) point to agrarian use so the soils are called **agrarian antrosols**. As is typical for the other areas on a karst surface, the bottoms of the dolines were filled with surrounding soils in this area as well, in order to increase the soil depth and the cultivation surface at the bottom of the doline. These dolines were never filled with waste. This was the reason why it was possible reach the brown-orange colored loam at the end of the profile depths. Depending on the elapsed time since the field fell into disuse, the vegetation in this transitional period is characteristic of a cultivated meadow. However, there is no presence of plants that would indicate an increased amount of nutrients in the soil. Such dolines were studied in the eastern part of the studied area 1B, which consists of heavily karstified limestone (V176, V857), on sample area 3 (V5000, V1146), sample area 4 (V2000, V3000) and the dolomite part of sample area 5 (V138 – doline with a relic humus horizon). This doline type allows us to perceive only the relief changes using geoinformatic analyses, with no visible soil and vegetation anomalies. The relief changes may be quite old, so it is not always possible to determine them with the analysis of post-war digital surface models. In some cases, the dolines were also marked on infrared images as very cold, humid areas.

Filled dolines with a hard mineral covering surface, where the covering surface consists of dolomite tailings, Permo-Carbon slate claystone, limestone material or construction and demolition waste. This type of FWDS is the most frequent on Logaško polje. There are no soils or they are very shallow, skeletal, undeveloped soil-like layers, **deposols** that represent lesser pedogeographical conditions. Due to the hardness of the covering layer, it is not possible to protrude deeper into the doline's filling material to prove the type of the below lying waste. Such dolines can be found on the alluvial part of the Logatec study area, which have been rehabilitated in order to alleviate the motorized cultivation of the farming surfaces. The typical covering surface, which visibly differs from the neighbouring surface (loam alluvium), makes these filled dolines the best from the aspect of multispectral photograph analysis. The areas of shallow rendzic laptosols (V6000, up to 20 cm) on convex dolomite and limestone areas or with heavily skeletal brown chromic cambisols (RLOG3) present a methodological problem. This requires the multispectral analysis to be combined with the data on the recent relief and geological data to exclude areas with no potential to be a filled doline.

Bricelj (1988) noted that industrial and communal waste had been dumped in dolines on a limestone and dolomite area and it was later covered with construction and demolition waste or dolomite tailings. Such dolines are not distinguishable from their surroundings by multispectral photograph analysis and require a field, soil and vegetation, research or geomorphometrical modelling of very accurate relief data.

The vegetation reflection is expressed in the field in the greater presence of a large amount of pioneer plant species on meadow areas (V402 – prominent density of dandelion on the fill site, V400, V 823), in the larger chunks of construction and demolition material noticeable on the planted fields (V482 – a Dolenji Logatec communal waste site up to 1979, today rehabilitated and a field, V144, V 107). Dandelion (*Taraxacum officinale)* habitats include lawns, gardens, degraded meadows, vacant lots, and sunny areas along roads and railroads. Dandelion has little capacity to invade high quality natural habitats, always preferring open areas that are disturbed and degraded by human-related activities.

This doline type allows the use of geoinformatic methods to perceive the relief changes (probability map–3) and the differences in the spectral reflection (probability map–1), which are a consequence of the presence of anthropogenous soils, mostly deposols. These dolines were filled after WWII and were often rehabilitated by being covered. Using geoinformatic methods, most of these dolines were determined to be FWDS.

Filled dolines with a soft mineral cover, where the waste is covered by a natural allogenic loamy alluvium or soil. The presence of organic, inert, or toxic waste separates them from agrarian dolines, with the presence of such waste reflected in the eutrophic plants on the doline surface. These dolines don't show up in CIR image (false infra-red color, infra-red, red, green), as they express similar pedogeographical conditions as the surroundings (V75, V14, V4000, V716). They are an indicator that the covering layer of the filled doline is the main factor influencing the reflection values in the NIR channel of the aerial photographs on grassland (meadow, pasture, planted field, planted garden). Only field research reveals the influence of the below lying waste (especially organic). Dolines of this type can be located using geoinformatic analyses of the relief change, but there are no visible anomalies of the soil and vegetation that could be sensed remotely (only thermal IR images). The field methods of soil sampling and vegetation charting allow us to prove they are FWDS in cases where they are filled with organic waste, as it causes soil eutrophication. We were unable to determine these dolines as FWDS using geoinformatic methods.

Filled dolines without a mineral cover. These are dolines, filled with different communal and industrial waste that have not been covered with a mineral layer, which has caused the vegetation to develop directly on the waste (V 481). This is another example of eutrophic, ruderal and invasive plants that grow on larger surfaces of filled dolines that are not found in the surroundings being an indicator in addition to the pedological analyses. Dolines of this type can be perceived with geoinformatic analyses of relief change and with multispectral surface analysis as well due to the absence of soil. The reflection is quite similar to dolines with a hard mineral cover, as the surface seems dry and warmer in both cases on the NIR band of the specter. Similarly to dolines of the second type, it was possible to classify these dolines among FWDS with great success using geoinformatic methods especially in the alluvial part of study area.

9 LJUBLJANSKO POLJE CASE STUDY

9.1 2TL/3E Approach for the Alluvial Plain

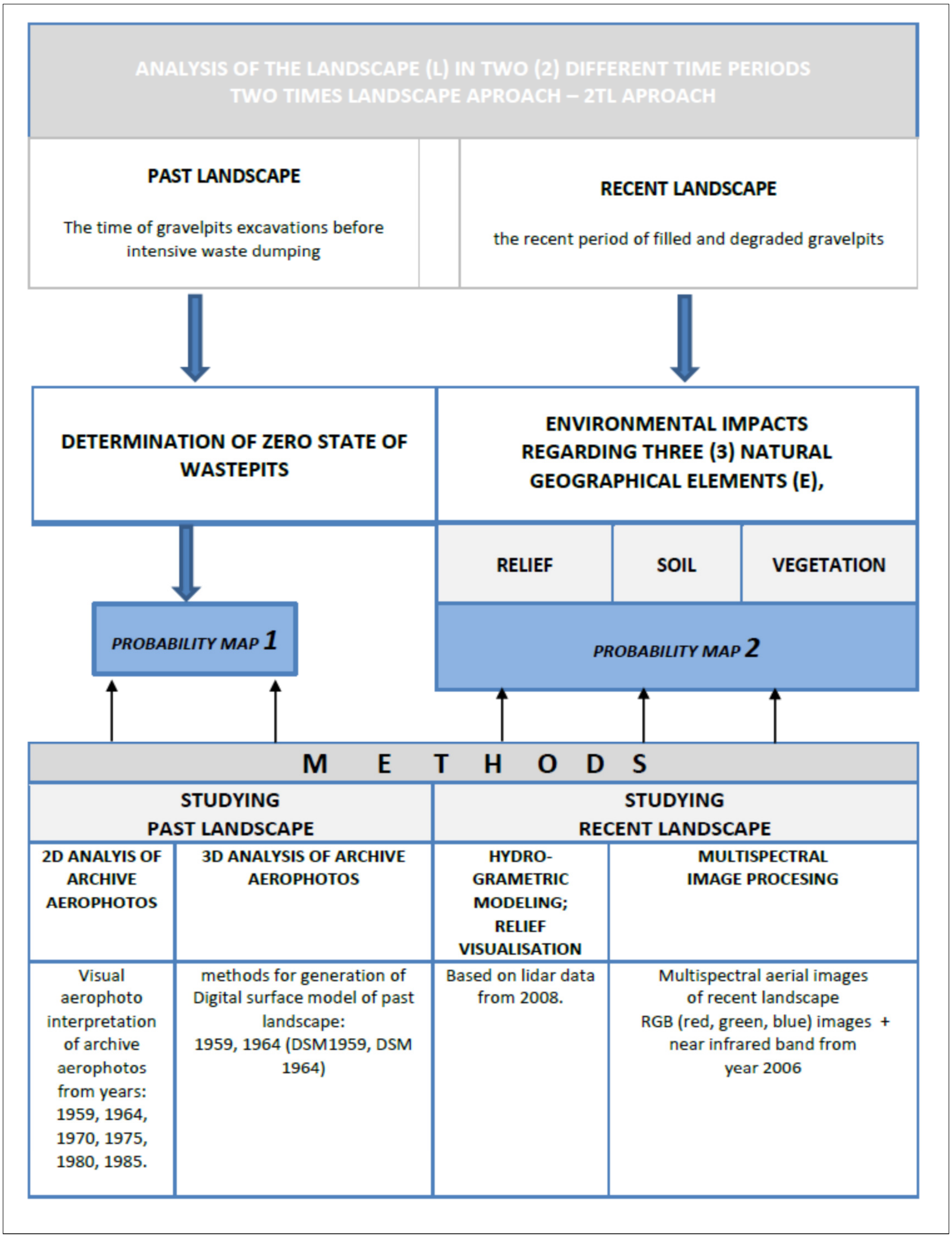


***Figure 142**: The people in the survey are willing to actively participate in solving the issue.*

9.2 Studying Past Landscape from Archive Aerial Photographs

The main goal of studying archive aerial photographs is to determine the zero state of gravel pits. That includes location, shape and depth of individual gravel pit.

9.2.1 Visual Aerophoto Interpretation of Gravel pits – 2D Analysis

The analyses were carried out on the data of the past landscape. The first is visual on screen interpretation of archive photographs and the second analogue stereo-interpretation (with stereo-glasses). The first analysis is completely two-dimensional (Figure 143), since data about object depth cannot be acquired. With this analysis it was possible to determine the gravel pit shape (with vector polygon was marked), while the objects were pinpointed during the second analysis. Stereoscopic image interpretation is a three-dimensional analysis. The determination of the depth is only visual but not quantitative.

The year of the gravel pit's first appearance in the database was determined and its state on later images, representing more recent landscapes. Both the visual and the stereoscopic gravel pit analysis are based on a photointerpretation key with the following variables:

- the object shape (gravel pits are of an irregular shape) is important for separating the concave shapes – gravel pits from construction excavations;
- the object color (gravel pits are white on the black-and-white photographs as well as on the color images; if they are overgrown, they appear in different shades of grey or green);
- the depth (stereo-interpretation allows for the detection of the relief concaveness, while the analyser determined shadows during the screen interpretation). This is a very important variable for separating gravel pits from filled parking lots and non-concave surfaces.
- the texture or the pattern (important with overgrown gravel pits).

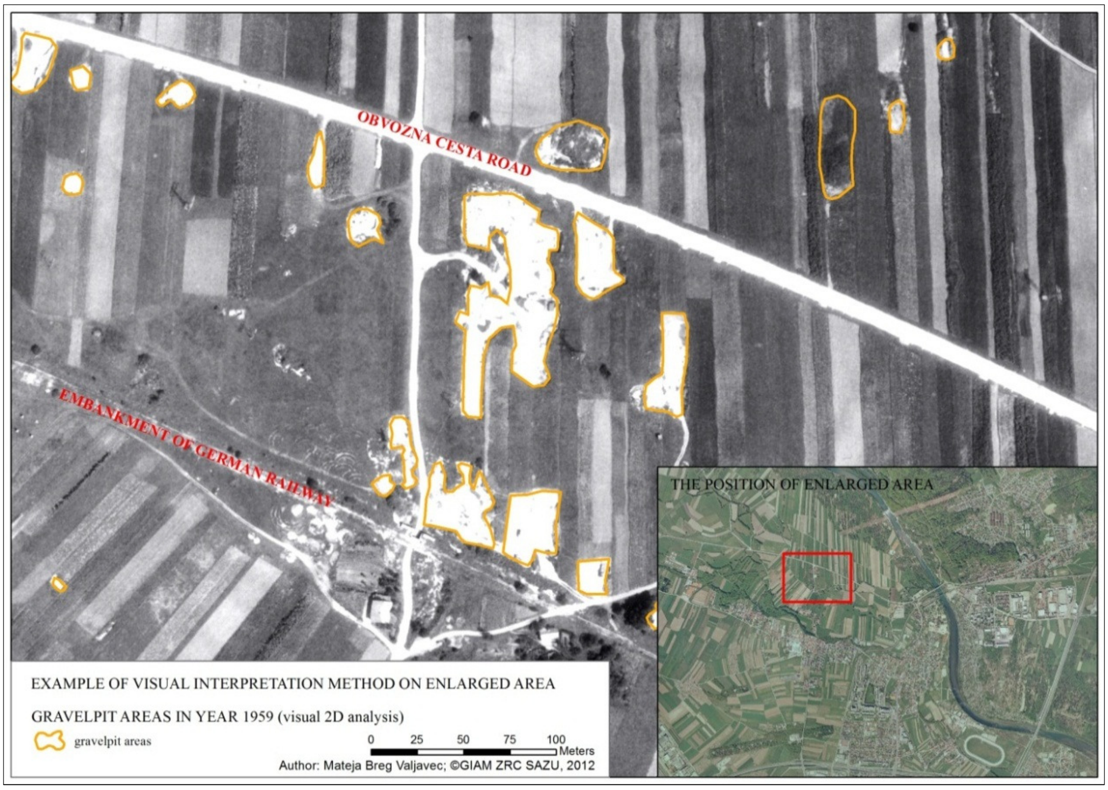


Figure 143*: Gravel pit ranges (polygons), located using on-screen vectorization, based on the DOP 1959 visual interpretation.*

The on screen visual interpretation resulted (Figure 144) in 315 areas of potential gravel pits on the photographs from the following years: 1959, 1964, 1970, 1975, 1979, 1985, 1989, 1995, and 1994. The photographs from individual years did not cover the studied area in its entirety.

The stereoscopic photograph analysis from the years 1959, 1964, 1975, 1985, and 1994 resulted (Figure 145) in 186 new occurrences of gravel pits on the area of Ljubljansko polje. Their state, especially the transformations of the gravel pits, was observed to the present day using both methods.

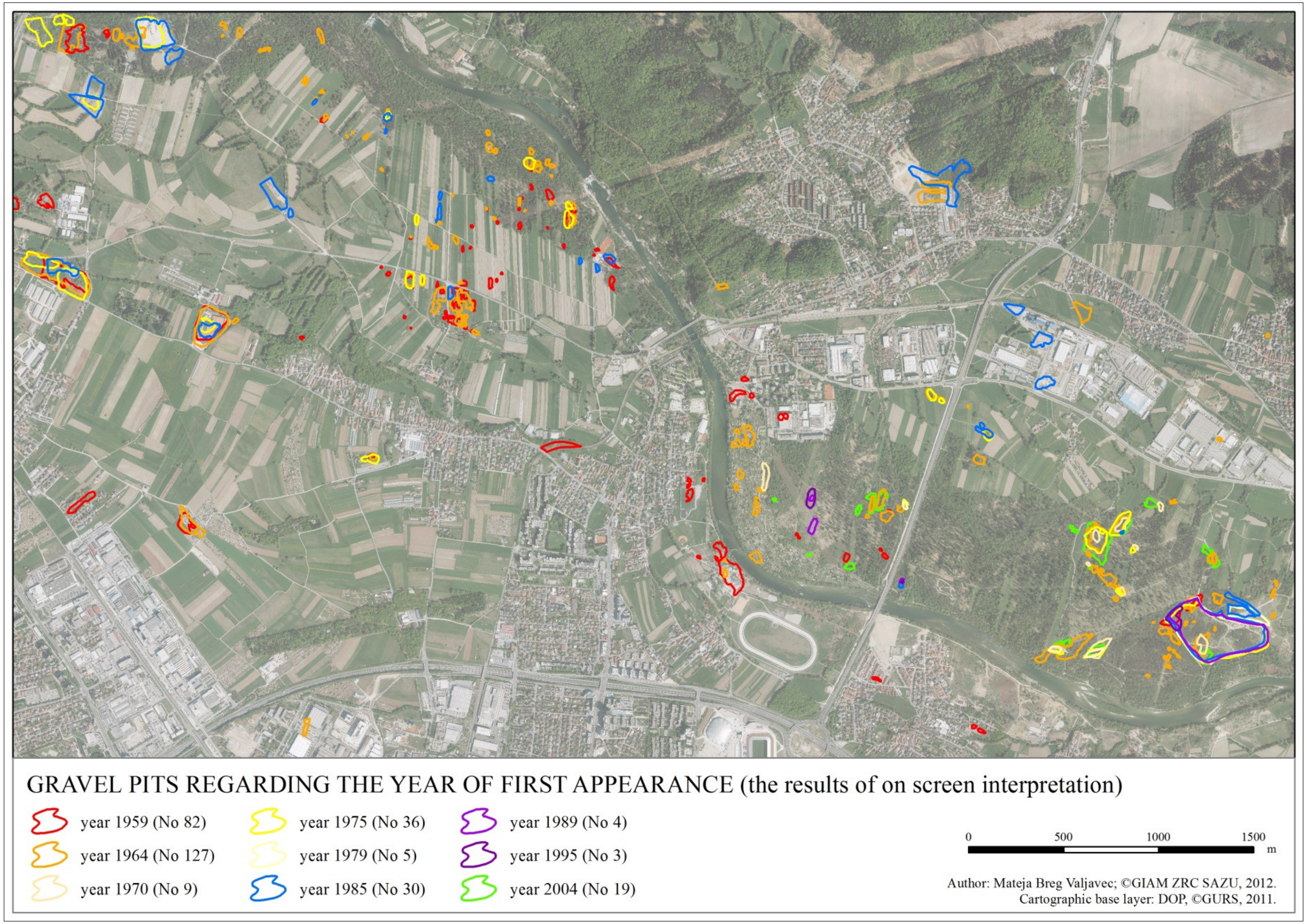


Figure 144: *Gravel pit location, shape and size, determined by using on- screen interpretation of the archive aerial photographs.*

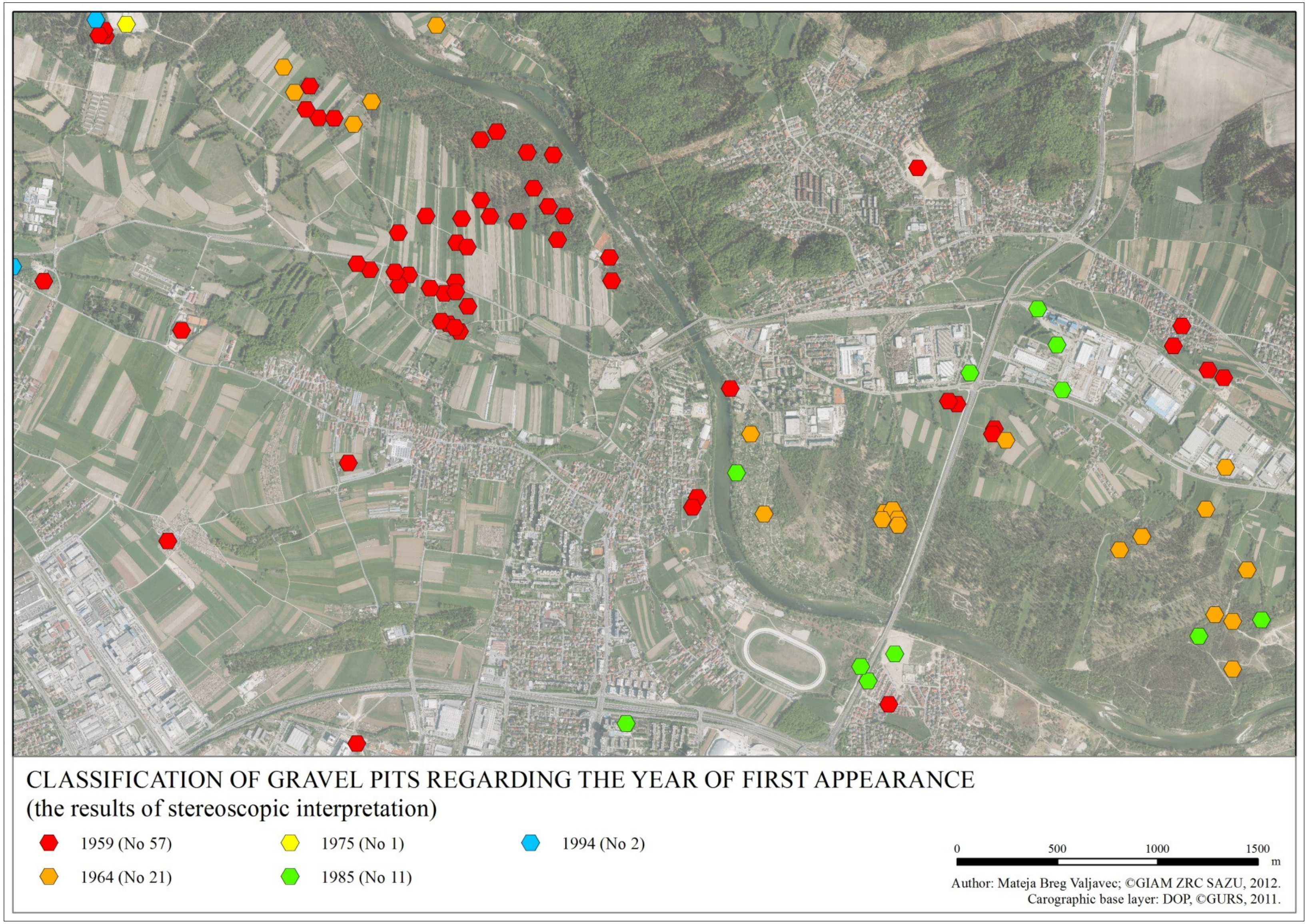


Figure 145*: Gravel pit locations, determined using stereoscopic analysis of archive aerial photographs.*

9.2.2 Digital Surface Models of Past Landscape

An example of a generated digital surface model for Ljubljansko polje is presented on Figure 148, we made from archive aerial images from 1964 (Figure 146).

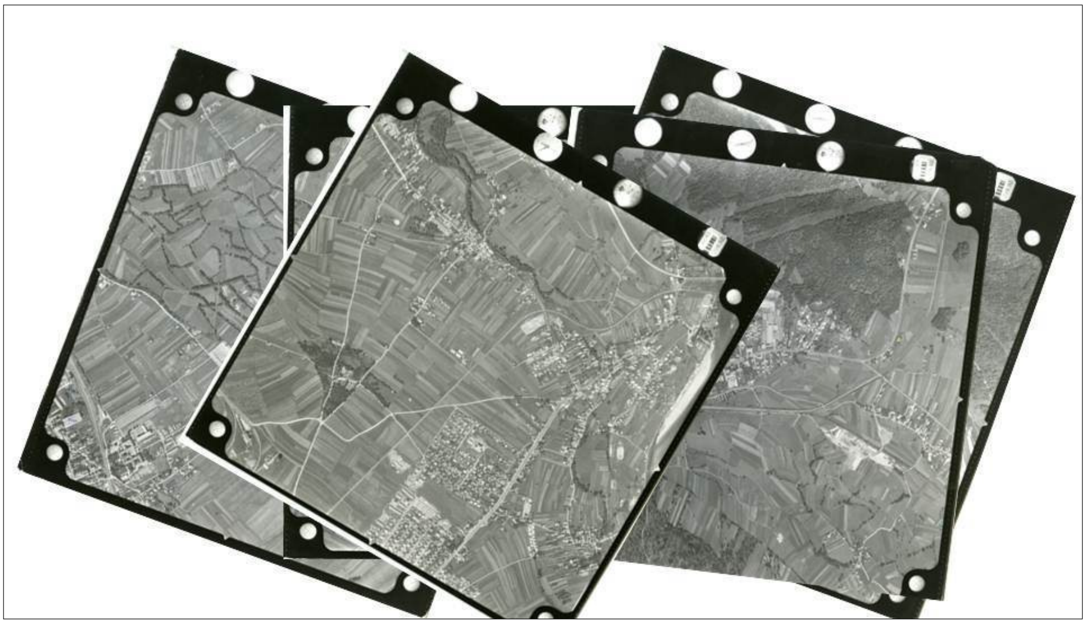


Figure 146: *Archive aerophotos of Ljubljana from 1964 (© GURS)..*

The stereo-pairs were oriented (Figure 147) in the same way as those for Logaško polje. The main difference is that it was not possible to include the calibration report data, since they do not exist anymore. Pin-pointing the locations on the DSM is possible by using different methods, which are all based on determining the depth or the local concentric concaveness of the relief that is typical for a gravel pits.

Figure 147: *The 1964 digital ortophoto was made on the basis of the archive aerial images from 1964 (Figure 146) and DSM1964 (Figure 147).*

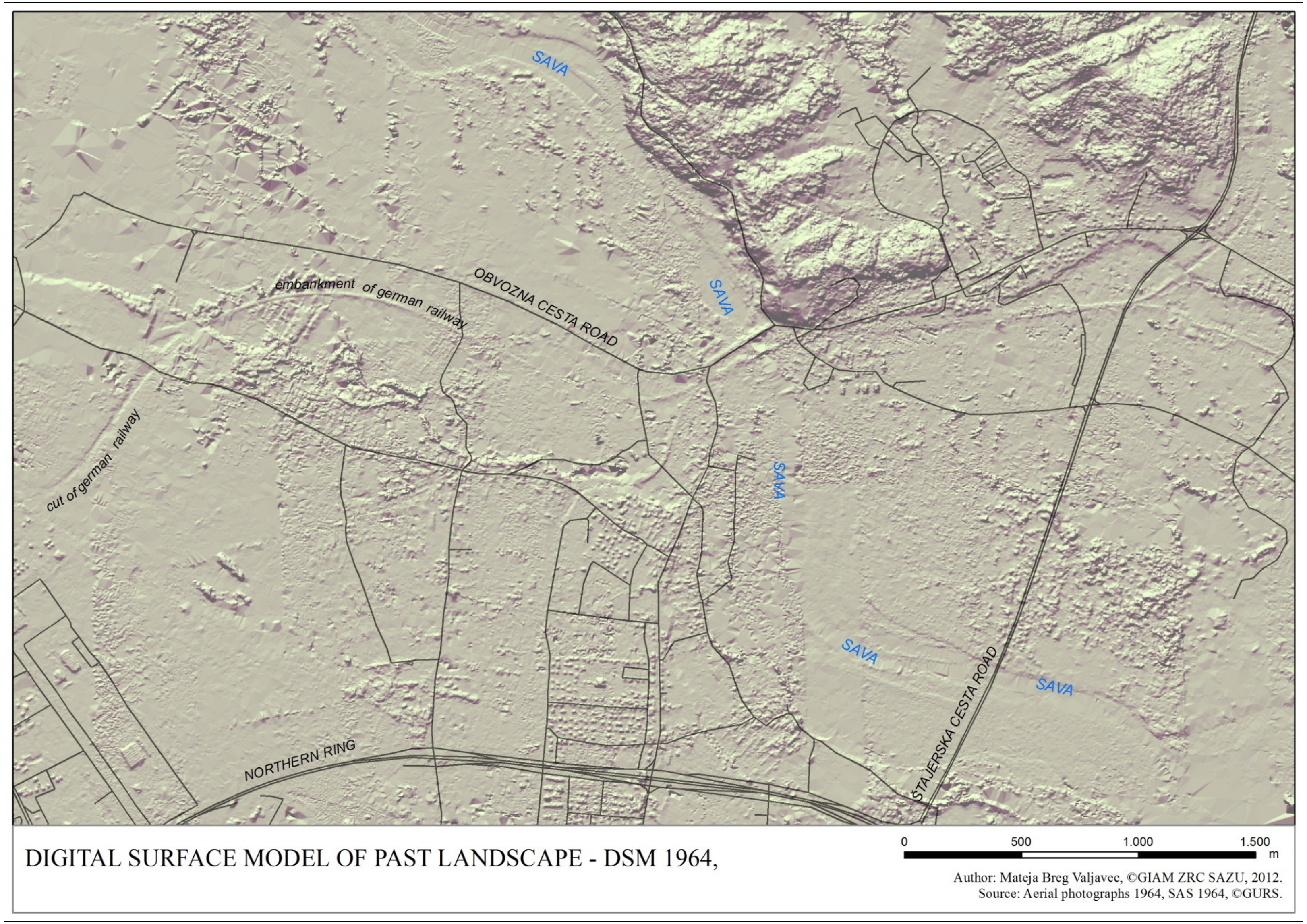


Figure 148: *DSM1964 of Ljubljansko polje was generated by a triangulation of archive aerophotographs (Figure 146).*

9.2.3 Determination of Zero State Gravel pits with the 3D Method

The analysis is based on a DSM of the past landscape, where the third dimension takes precedence (height, depth) and separates the gravel pits from the surface. For this reason, the analysis is called 3D object analysis. In contrast, the object image in the two dimension analysis is that the visual and stereo-interpretations are in the foreground, so the difference in the methods is why it is called 2D analysis. The 3D method is based on visually determining those concave landforms that are a consequence of gravel excavation and other interferences into the relief (road section construction). As the 3D models are a representation of the past surface, the appropriate referential data was not available for the vegetation and built-up surfaces, so it was removed.

This method is demonstrated on the DSM 1959 sample model, on the right bank of the Sava River above the Kleče village, where smaller gravel pits have already been located using the 2D analysis of the DOP 1959, enabling a better comparison of the results.

The gravel pits were located on the raster and vector DSM format. The vector layer overlapped over the raster layer of the DSM (Figure 149). The DSM can be visualized with a hypsometrical scale (combined with analytical shading) and the histogram equalizing used to increase the color contrast (Figure 150). The vector DSM is a reflection of the automatic height acquiring model from two overlapping stereo pairs (image matching). Therefore, the point distribution is related to the object edges, which can also be determined with the visual analysis. This means the difference in color of the aerial photograph within the gravel pit and outside it is visible and the points are located on the edges of the objects, along with their coordinates. The gravel pit is located based on the shape and the altitude of the gravel pit edge. The next step is to manually digitalize all the concave objects. The method is very successful on an open area, fields, meadows, open surfaces within the forest, where smaller differences, variations in the surface heights appear (no buildings, no trees).

The described process was used to describe the DSM 1959 and DSM 1964 in order to determine the gravel pits that were located in the past landscape as concave relief shapes. Figure 150 depicts the gravel pit areas (2D results of the DOP 1959 interpretation) that were placed on the raster DSM 1959 and made from the same aerial photographs (SAS 1959). The areas and concave shapes overlap. The raster and vector surface models overlap on Figure 149. The marked points in orange of the vector surface model reflect a gravel pit shape (circumference) and their match with the concave parts on the raster model. The point mass, determined as a gravel pit, was used to determine the gravel pit depth as well.

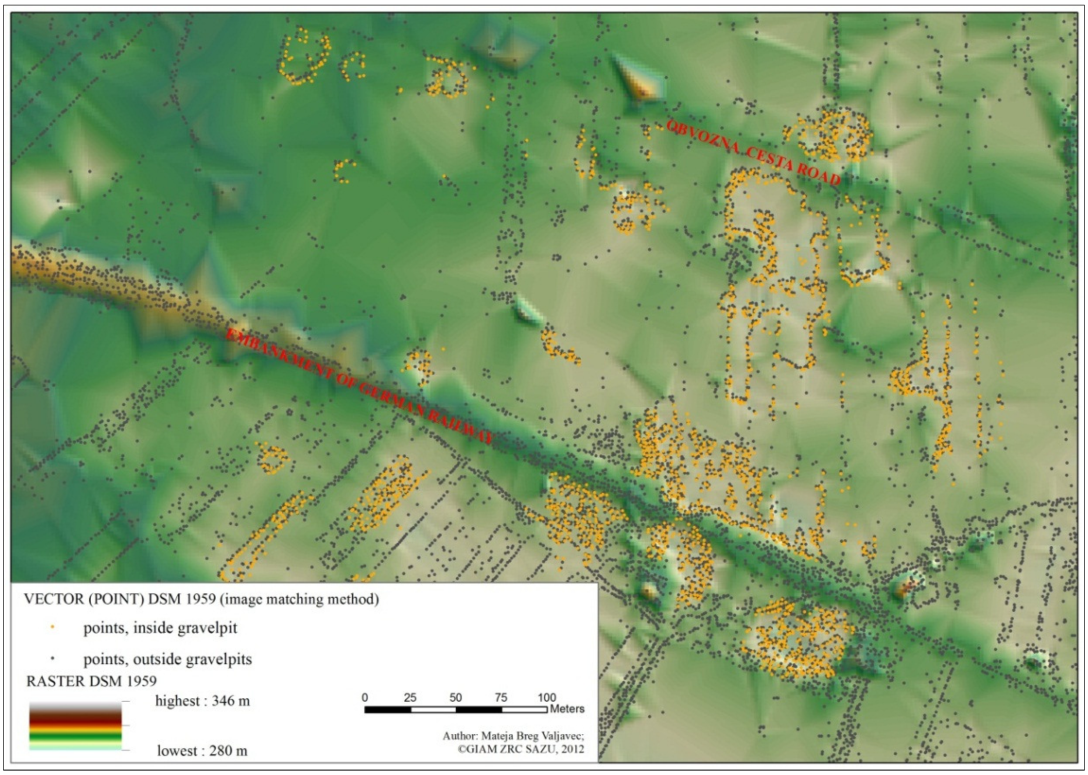


Figure 149*: Determining gravel pits with a combination of the point/vector (determining shape) and raster (determining concaveness) on the DEM 1959 using visualization methods. The same area is shown on figure 126 in a black-white image.*

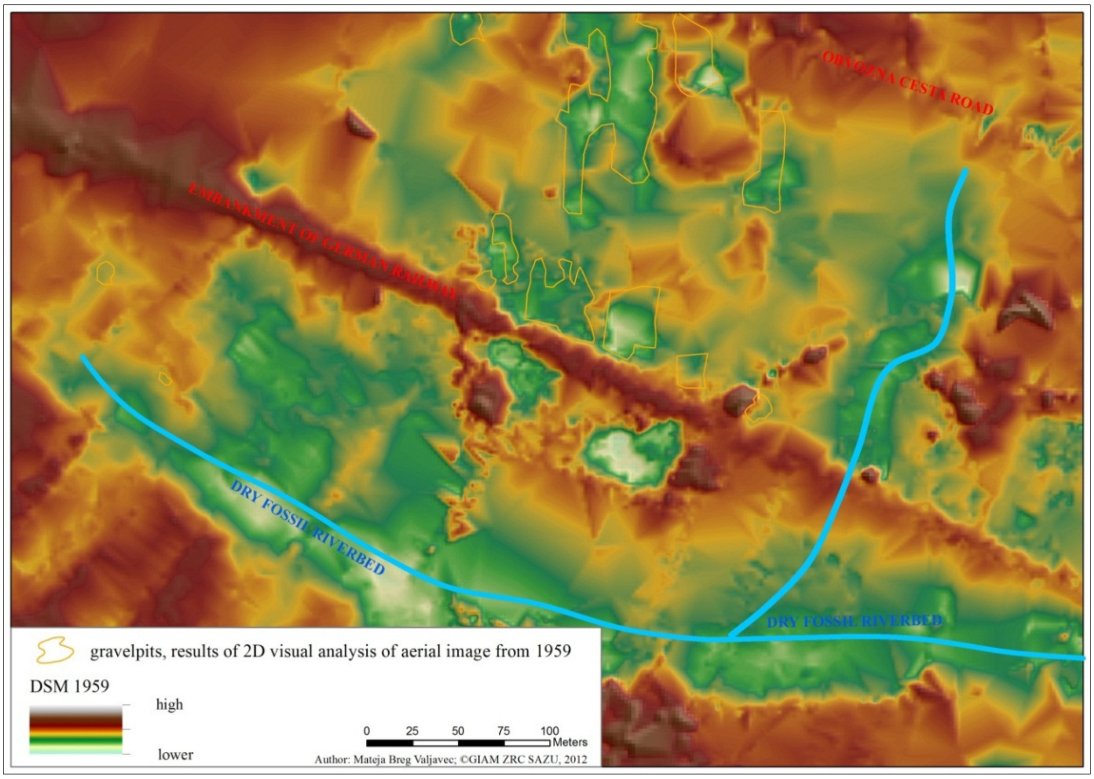


***Figure 150**: The use of visualization methods in order to improve the contrast (e.g. equalizer histogram) is very useful for determining the concave/convex shapes on areas with minute differences in elevation. The same area is shown on figure 126 in a black-white image.*

As the depth of the filled gravel pits is unknown and undetermined today, it was not possible to determine the amount of waste with which it is filled. The digital surface models of 1959 and 1964 are not appropriate for a quantitative comparison to the digital model of the recent relief (e.g. DEM 5), as was attempted on the case of Logaško polje. The problem is in the way they are generated and consequently their poorer absolute elevation accuracy. They were made without a camera calibration report (it was not preserved in the archive). Since there are immeasurably less gravel pits than dolines, the depth for each one was determined non-automatically. The depth was determined for the basin area (ranges determined on the DSM 1959 or the DSM 1964), based on the vector (point) DSM as being the difference between the lowest and the highest range point, which is represented by a multitude of points on the vector relief model. The depths (Figure 151) of gravel pits were examined in the field by making sections of the electrical resistance tomography of the ground. They are presented in the chapter on field methods (see e.g. G42 – area 3, G249 – area 5). The described 3D method enables a precise three-dimensional locating of the position and shape (spatial dimension) and depth of the concave objects. Combined with the 2D method, the period when the object was formed is determined. The execution and the results of the 3D method are extremely dependent on the quality of the generated digital models of the past surface. For this, many archive aerial photographs of a high quality are necessary. The acquired photographs were of a very different quality at first and were difficult to compare to each other between years, or were unavailable for the key years. Based on these, it was necessary to prepare data specifically for this research (generate DEM, DSM). In accordance, the volume sum of the deposited material is inaccurate. It is not possible to determine the type of filling material using this method. The quality of the results depends on the land use, where the smaller objects are harder to identify, especially in the forest. The method is extremely time-consuming in comparison to the recent surface analysis.

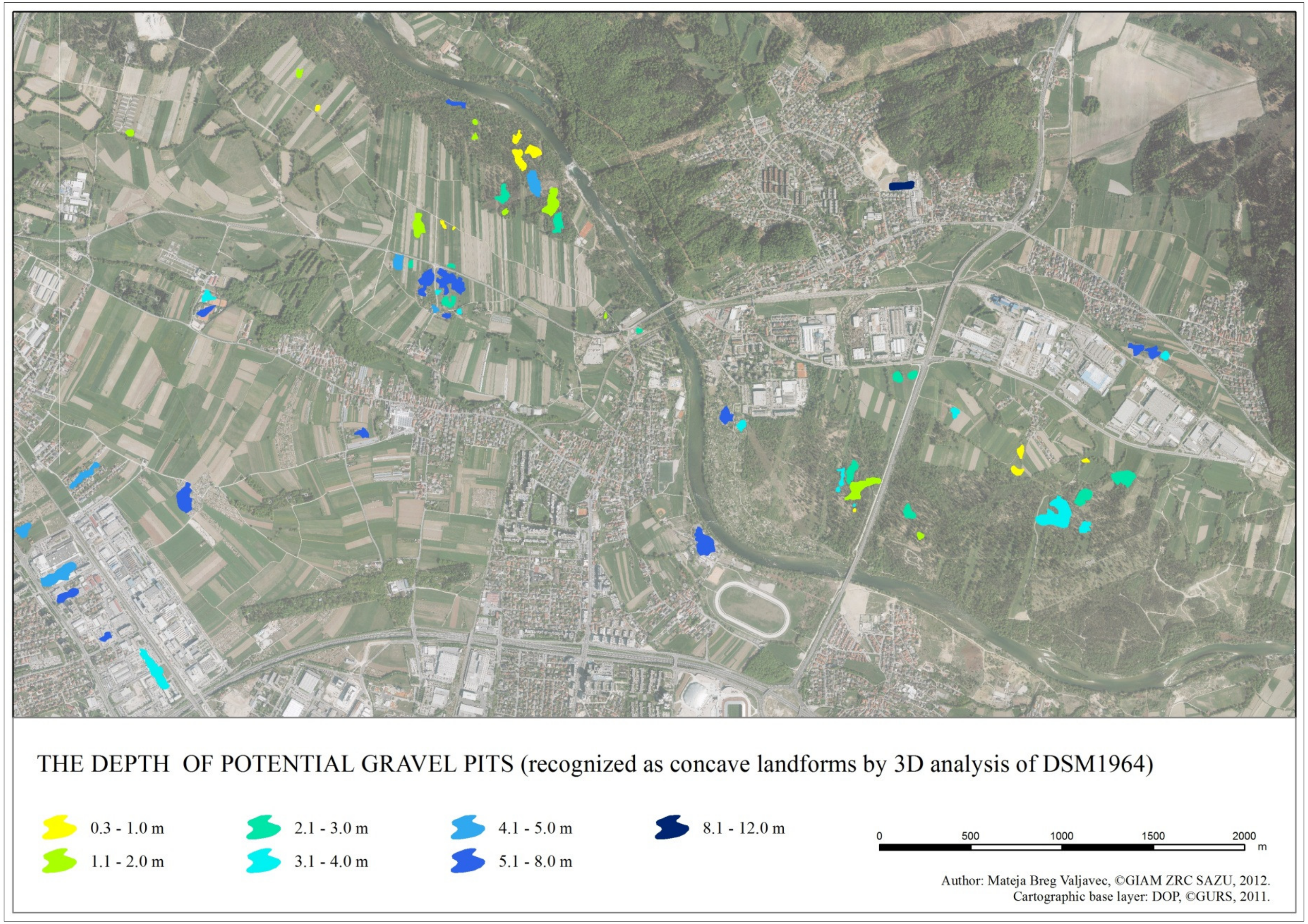


***Figure 151**: The measured basin depth is an important variable, which, in addition to others, proves that the object is a gravel pit.*

9.2.4 Conclusive Remarks about Results of Zero State

The past landscape analysis started in year 1959. Already in that time several smaller gravel pits were excavated, which were almost entirely filled by 1975. The largest gravel pit in 1959 encompassed 22,000 m² of surface. The gravel pit was dug into a terrace edge of a Pleistocene terrace of the Sava River, so it would be possible to speak of a slope gravel pit, which was not appropriate for filling due to the morphology of the relief. The gravel pit is not detectable in the landscape anymore. In the recent relief, the remainder of this anthropogenic formation can be detectable as eating into the terrace edge. The excavation area is partly overgrown, partly built-up.

The so-called Gradis gravel pit was somewhat smaller and also dug up into the terrace edge of the Sava River and has been preserved to this day. It encompasses 20,000 m². It is located in the immediate vicinity of the former route of the German railway, built during 1942/43, which was removed soon after the war. For a while, part of that railway served for transporting gravel from this gravel pit from the location of Vižmarje. The gravel pit reaches the eastern part of the water protection area of the Šentvid water plant and is on the drainage side in relation to the groundwater flow. It has been rehabilitated into a sport recreational facility (tennis courts) in the present day. A gravel pit of 4,000 m² was among the larger gravel pits in the inflowing direction of the Kleče water plant (800 m to the north-east), which is filled today and cultivated with gardens.

A mere visual interpretation without considering the stereo-effect does not suffice in the case of locating gravel pits, as flaws occur due to the similar reflection values for gravel pits and open surfaces, like, for example, gravel parking lots, construction sites, etc. The flaw can occur during relief basin interpretation when a construction excavation is mistaken for a gravel pit. Even though the differential criterion is the shape, this is not completely true. There are several smaller earth excavations visible on the 1959 photographs of the Roje area, tied to land plot distribution within a single plot and consequently often very regular in shape (rectangle). The land use analysis on recent photographs showed whether these are construction excavations (built-up surfaces) or gravel pits (unbuilt-up surfaces). Acquiring the other content information like surface, depth, volume is undoubtedly more precise and more sensible when using digital quantitive methods (DEM generation, their analysis and comparison to the recent landscape state).

The gravel pits that saw an active state of carbonate gravel excavation highly reflect light, so the gravel pit can be completely white on the black-and-white image and it was not possible to determine its texture. This indicates a very homogenous area, within which it is difficult to find points that the image matching method could detect. Because of this, the detection of the elevation points that are on two or more overlapping stereo-images was carried out. If the gravel pit texture is more heterogeneous, as is typical of dolines, there are theoretically more matching points on both images and a more precise gravel pit detection is possible. Non-concave surfaces that are covered with sand or gravel (like disarrayed open surfaces, parking lots – the shape is the defining factor) have a similar reflection as active gravel pits and visual interpretation must be used in order to determine them as a gravel pit.

Gravel pits that are no longer seeing gravel excavation and are in the phase of automatic overgrowing (secondary succession) have a much poorer reflection and blend into the surroundings easier. Such cases of gravel pits are often overlooked using only visual analysis, because the focus is on finding white areas. Such objects may also be overlooked during the visual stereo-interpretation, so generating a DEM is very important as a supplement. Using the DEM analysis, this object can be more precisely delineated and its depth and other characteristics can be determined as well.

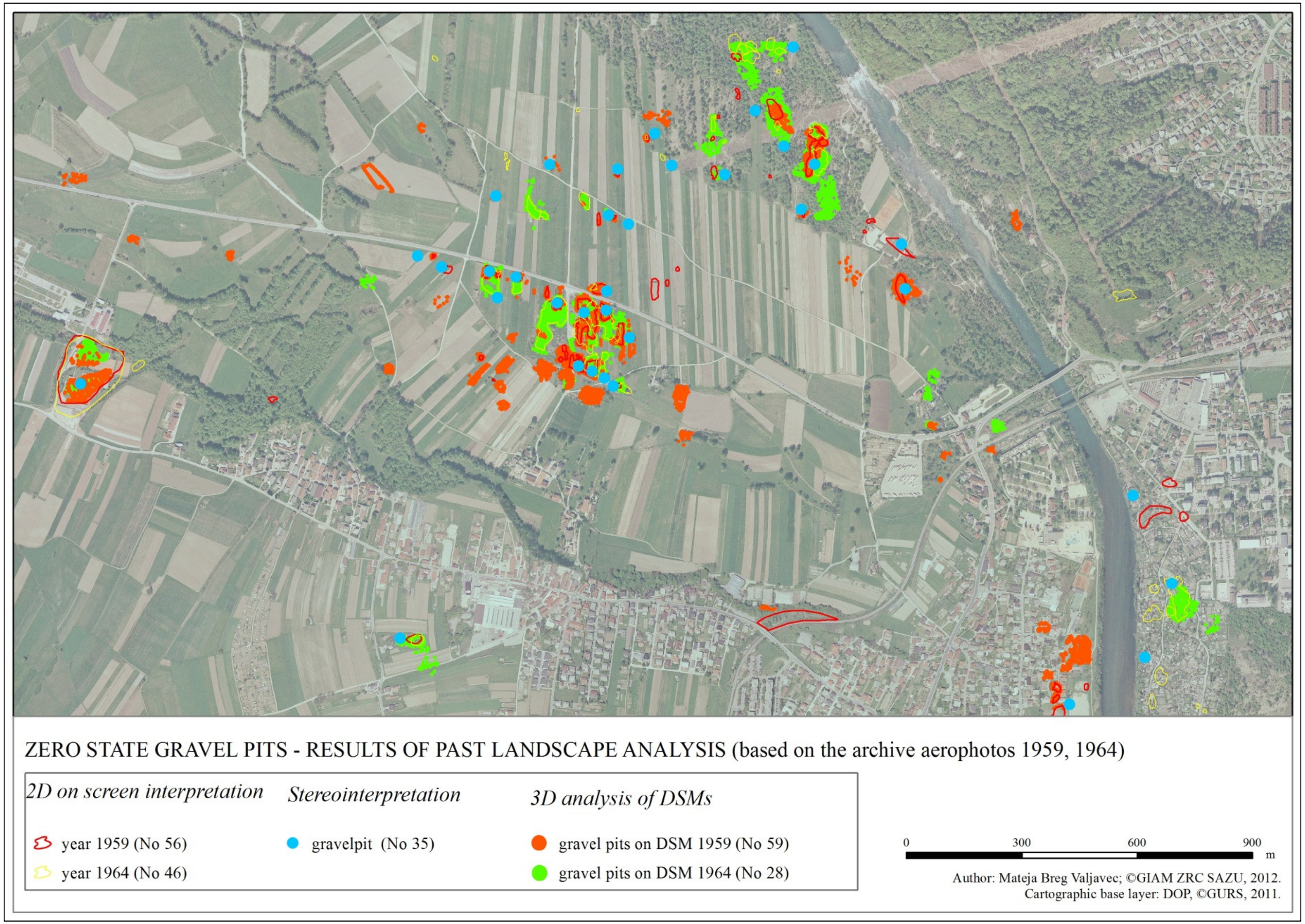


***Figure 152**: Gravel pits – recognized by 2D and 3D analyses of archive aerial photographs from years 1959 and 1964*

9.3 Studying the Recent Landscape

The main goal of studying the recent landscape is to determine FWDS in gravel pits. The methods are based on determination of relif, soil and vegetation changes by multispectral remote sensing data.

9.3.1 Background for Recent Relief Analyses

The relief analyses of the recent landscape were planned on very precise data regarding height and location – the DTM was generated using the laser surface. The methodology and the DTM based on it is called Lidar or Lidar DTM. This data enables a precise modeling of the relief processes and shapes, so it is possible to distinguish between natural landforms and anthropogenic ones. The method must be founded on a good knowledge of the natural geomorphology and processes, so that the anthropogenic landforms may be excluded. The relief features and ways of distinguishing between the natural and anthropogenous relief are presented below.

Ljubljansko polje falls is the fluvial relief type, which is formed with laminar and concentrated surface water flows. The Sava River and the denudation processes are the most important factors in this. The denudation acts plenary and linearly and slowly, but efficiently lowers the relief. During its long geological history, the Sava River on Ljubljansko polje shifted its current, depositing gravel, sand, loam, and other transport materials as well as deepened the riverbed into its own alluviums, forming the polje surface. As the river floods, it does not return to its old riverbed anymore because of the amount of material it transports and deposits on the flooding plain, but shapes a new riverbed. In such cases, the process is very quick, while the river meanders slowly on the flooding plain and shifts its current while it is in the normal state (the water flow is within the limits of the riverbed). During this, it erodes (the process is called river erosions) material (alluvium) on the outer sides of the meanders and deposits (the process of depositing – sedimentation) material on the inner side of the meanders. The denudation processes are less intense, but are constantly present.

The main natural landforms that have formed with the described processes are dry or old, relict riverbeds through which the Sava River does not flow through anymore in the present. These are longitudinal concave relief shapes that can be identified in the relief as lowerings in altitude, which is clearly visible on very precise Lidar relief models.

The anthropogenic relief changes on the studied area of Ljubljansko polje were expressed through history with gravel excavation. Smaller excavations occurred (often in the shape of a land lot). Some have been preserved to this day as concave relief shapes that have been overgrown with vegetation of overflown by groundwater. The filled gravel pits do not particularly stand out in the relief, as they were leveled with the surrounding relief when they were filled. Gravel pit is an anthropogenic landform that is very dynamic in its spatial development. In the excavation period, their shape is concave, changing and growing in size during the time of excavations. The anthropogenic relief re-shaping is most expressed in distinct concave (basins of unfilled gravel pits) and convex (embankments) relief shapes. Such shapes can be quickly determined even on less precise digital terrain models (e.g. DEM5, ©GURS 2006). After the excavations cease, the relief shape remains concave and is swiftly overgrown by pioneer vegetation. The gravel pits that had been filled with waste may be partly or completely filled. The partly filled gravel pits retain a concave shape, while most of the filled gravel pits have only a slightly convex or concave surface. Since the waste is very heterogeneous, it decays with different speeds. In accordance, a ridged surface is formed, which is a foreign body in the fluvial relief of the alluvial plain. The fluvial relief (Lat. *Fluvio* means river), as the Latin name designates, is shaped by the river or the surface water. The laminar flow runs into a linear one due to its tendency to concentrate; for this reason, fluvial relief forms are typical of the linear relief type. The flow is irregular, chaotic, dispersed, unconcentrated on the areas of filled gravel pits.

The relief data was analyzed using two approaches, since it is possible to determine the landforms types with greater certainty with several different methods compared to each other (Ciglič and Gostinčar 2011). The first is the visualization and interpretation of the Lidar relief data. Based on an extensive knowledge of the geomorphological processes and shapes of the studied area, different anthropogenic landforms were determined that are not typical of the natural landscape. The second approach is hydro-geomorphometric modeling. A DTM was used, generated using the data from the laser surface shooting (Lidar 2008, ©GEOIN). The DTM was processed with automatic geomorphometric analyses (using SAGA software), based primarily on locating special hydro-morphometric surface characteristics, which include locating different morphometric surface indexes.

The starting point is the same for both approaches and is based on the water network analysis. The network is constructed of relict riverbeds in connection to a modeled micro-hydrographic network of denudation currents, whose construction is intensely connected to the existing land use. A precise laser DTM is spatially so precise (10 points per 1m) that it enables the generation of an extremely precise model of the hydrographic network. The areas of filled gravel pits are showed as a break or a distinct interruption in the water flows. The breaks are therefore detectable on the level of larger channels, like relict riverbeds, as well as smaller currents outside the area of relict riverbeds. These methodological platforms allow areas of filled gravel pits to be located in the relict riverbeds (fillings of riverbed deepenings), next to riverbeds and on intermittent areas outside the relict riverbeds (fossil bar points).

9.3.1.1 Relief Visualization

The Lidar digital relief model was visualized using different methods and method combinations and the relief anomalies that are mostly of an anthropogenic origin were located in the recent landscape. This research was mostly based on knowledge of natural geomorphological area characteristics, mainly on the analysis of relict riverbeds.

The relief anomalies were identified in the riverbeds that are a consequence of human activity and are shown as a convex landform (embankment), which interrupts the riverbed flow on a certain section of the river and can then continue on once more (Figure 153). Concave landforms that may be only party filled gravel pits or completely preserved excavations were also located in the recent landscape.

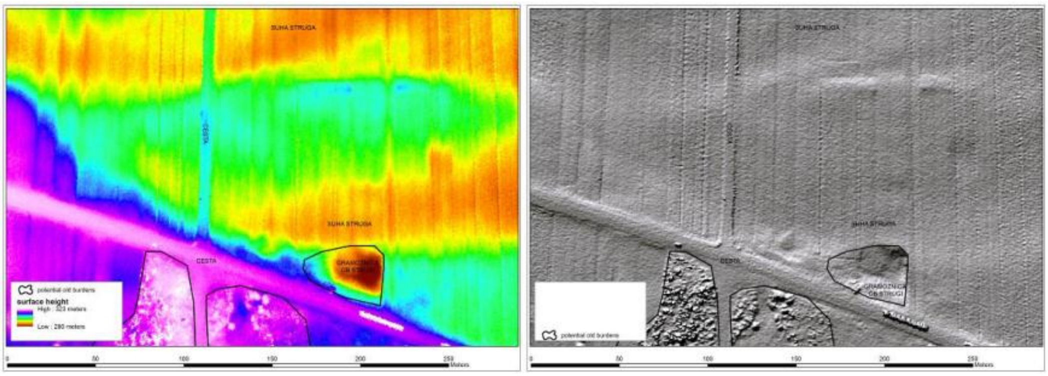


***Figure 153**: An example of locating concave anthropogenous relief shapes; left a hypsometric display with the use of the histogram equalizer method and right analytical shading.*

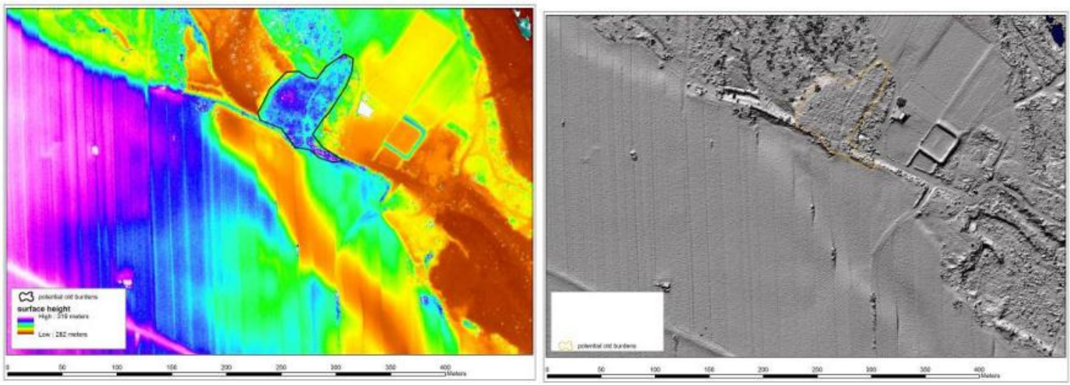


***Figure 154**: An example of locating convex anthropogenous relief shapes; left a hypsometric display with the use of the histogram equalizer method and right analytical shading.*

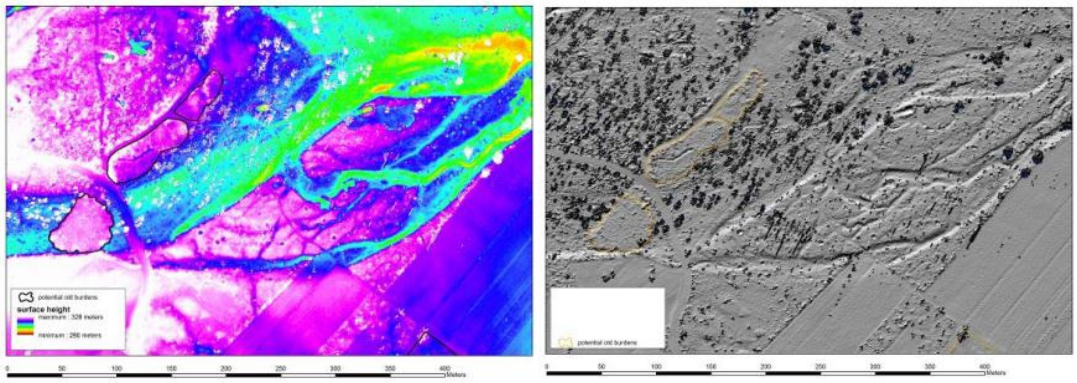


***Figure 155**: A combination of two standard methods of visualization, hypsometric scale and analytical shading, provides very good results when determining the breaks in the relict riverbeds due to the filling with waste.*

The visual analysis results amount to 140 objects on a 8.2km² of surface, for which Lidar data from 2008 was available (© GEOIN, 2008). Their joint surface is 282,196.79m². The average shape amounts to 2,015.69m², the smallest of those 14.22m² and the largest 37,415.49m².

The landforms were divided into five groups according to their relief formation (Figure 156):

1. ridged surface (alleged filled gravel pit)
    - ridged (slightly) convex surface,
    - ridged level surface,
    - ridged (slightly) concave;
2. (intensively) convex surface (allegedly filled gravel pit or just a larger pile of dumped waste, expressly elevated above the surroundings);
3. (intensively) concave area (allegedly unfilled gravel pit of relict riverbed, the deciding indicator is the depth).

Using the visual interpretation of the digital relief model, it was confirmed that the gravel pits, filled with waste or unfilled, co-shape the surface of the hydrological network. The filled gravel pits (FWDS) depict a ridged level, a ridged slightly concave surface (depending on the waste decay), which causes the modeled hydrological network in these areas to be temporarily interrupted.

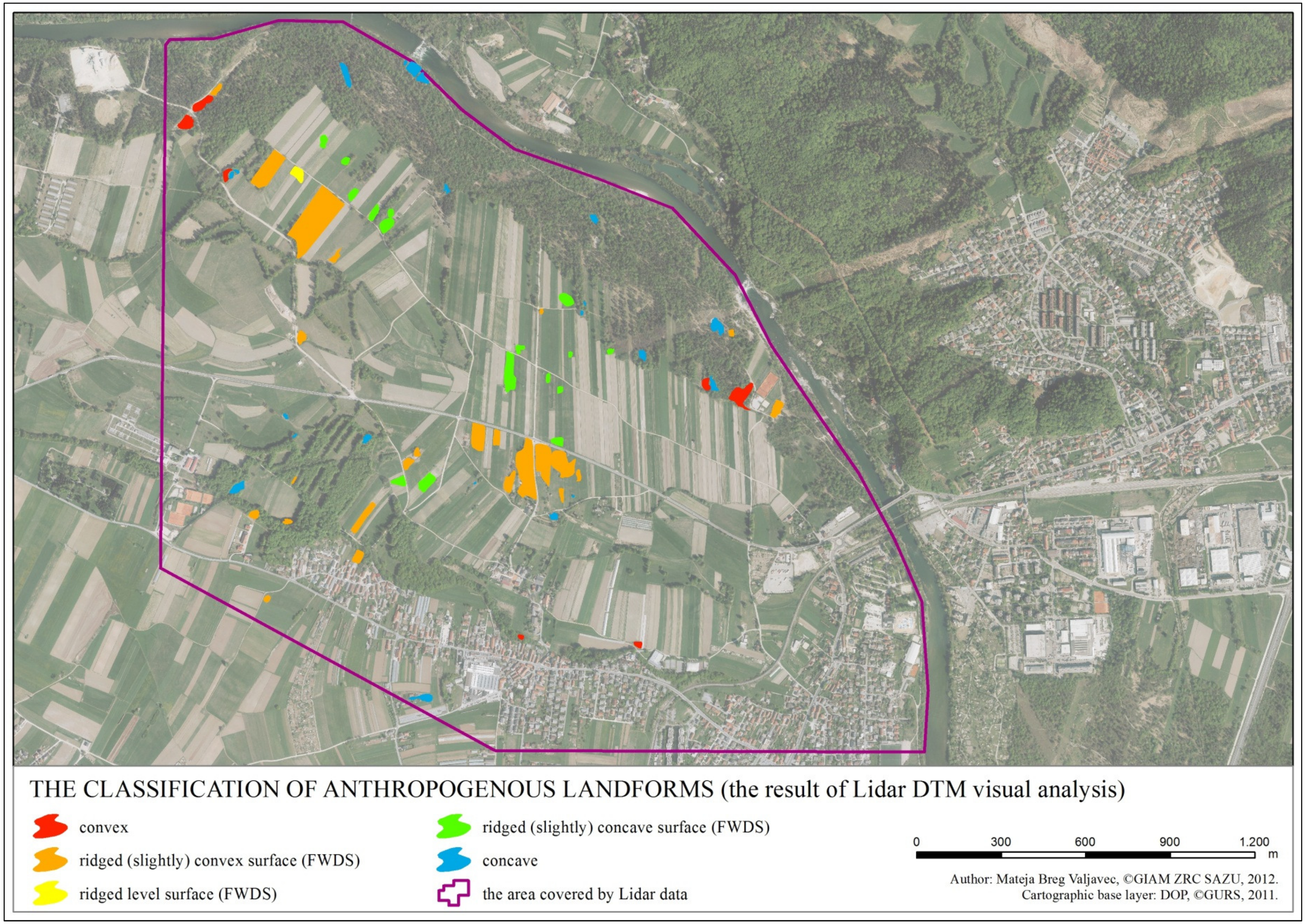


***Figure 156**: The areas of relief anomalies are the indicator of the anthropogenous relief reshaping, excavation as well as filled gravel pits.*

9.3.1.2 Hydro-geomorphometric Modeling of FWDS Areas

The second method is relief modeling and excluding the areas that have the relief and hydrographic characteristics of a filled gravel pits. The natural relief shapes were first identified and the hydromorphological processes that help shape them were defined.

The hydrological processes on Ljubljansko polje occur on extremely large and flat surfaces, with very small relative differences in altitude, so the consequences of their processes are locally more difficult to perceive. The very precise DTM (Lidar) regarding location and altitude enables a hydrological and geomorphometric analysis of the natural occurrences and processes. In this case it requires a precise water current modeling and determining the anthropogenous relief elements, which point to a non-linear shape. The formation of the hydrologic network on the studied area is a result of the actions of natural and anthropogenous factors. The amount of rainfall is the same on the entire area and there are no essential differences in the geological structure. Gravels, sands, clays and loam interchange, enabling a vertical drain of the surface water into the underground aquifer. Therefore the relief has an important effect on the formation of the surface network on such a small area. The natural landforms are represented mostly by relict riverbeds while the anthropogenic landforms are artificial channels, embankments (former German railroad), filled and unfilled gravel pits etc.

Due to a large size of the Lidar data, which is a consequence of the immense spatial and elevation relief preciseness, the modeling was narrowed down to one sample area - Roje. In accordance, the final synthesis will be made for the Roje sample area. The DTM made from the laser surface scanning data was appropriately processed for more precise geomorphometric analyses. The model was leveled by filling up the smaller “sinks”, which are a consequence of the point data interpolation method and other technical errors. basic geomorphometric analyses (determining the surface slope, relief curvature …) were executed and, based on the results, the areas of relict riverbeds were partially reconstructed. The essential geomorphologic characteristic of relict riverbeds are very low slopes at the bottom of the riverbed (under 0.5˚) that quickly increase on the fold to the slope and increase for a few degrees. The next step was to generate a vector model of the hydrologic network of the studied area, which is presented with water current lines, concentrated in the relict riverbeds. Despite the low slopes and the small relative differences in altitude, the surface of the polje is very diverse with the interlacing of relict riverbeds, so the hydrologic networks is consequently diverse and dynamic. The old riverbed system is connected to the recent "surface" network of water currents that are mostly of a denudation origin. The denudation processes occur in the form of floor water flowing and so the relict riverbeds still represent an important draining vein of the surface water, even though there is no surface water in them and could therefore be called relict riverbeds (Figure 157).

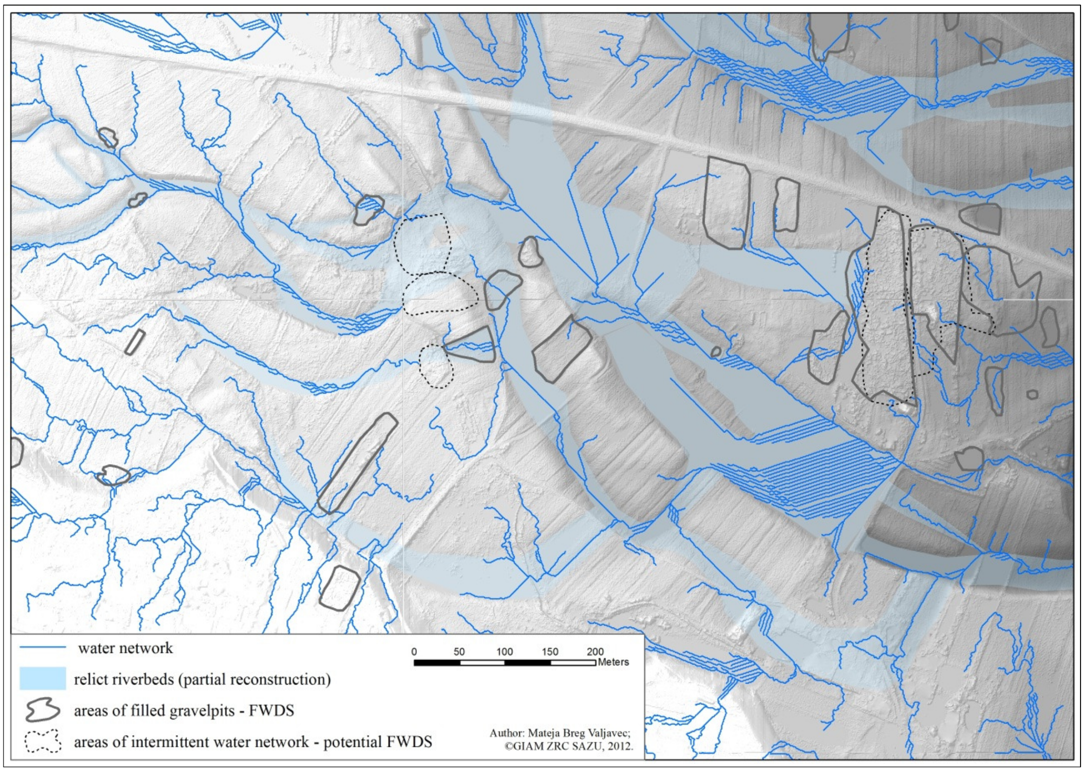


Figure 157*: The area of potential locations of filled gravel pits in relation to the hydrographic surface network.*

Based on the described starting points, multi-criteria (GIS) relief modeling was used to determine the areas that have relief characteristics similar to filled gravel pits. They were named **areas with a high relief potential for filled gravel pits**. Using the Convergence index geomorphometric model in the SAGA program, the areas of the converging surface waters were identified.

The module calculates an index of convergence/divergence (Figure 158) regarding to the overland flow. By its meaning, it is similar to a plan or horizontal curvature, but gives much smoother results. The calculation uses the aspects of surrounding cells, i.e. it looks to which degree the surrounding cells point to the center cell. The result is given as percentages; negative values correspond to convergent, positive to divergent flow conditions. Minus 100 would be like a peak of a cone (a), plus 100 a pit (c), and 0 an even slope (b) (Internet 12).

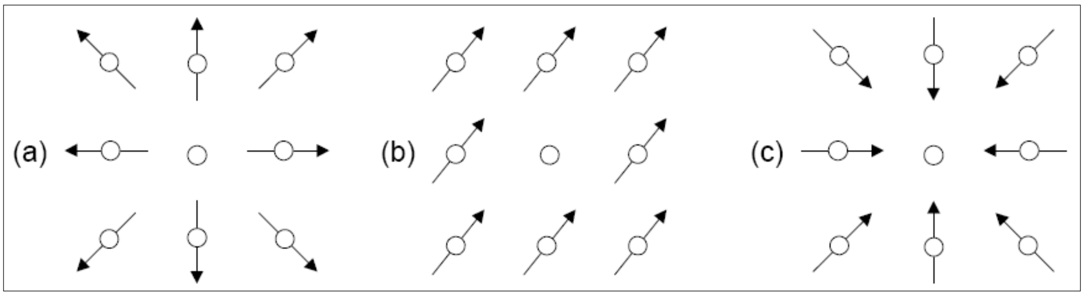


***Figure 158**: The convergence index results in relation to the water flow direction.*

The index may be used to exclude the converging areas, as they are not typical for the area of filled gravel pits and represent natural concave relief shapes (relict riverbeds) and unfilled gravel pits.

The areas of the leveled relief were separated from the not leveled one (wavy, ridged) with a multiresolution index of valley bottom flatness (MrVBF), which is an independent module in the SAGA program, intended for charting the sedimentation areas (in this case relict riverbeds).

The MrVBF algorithm (Gallant and Dowling, 2003) works on raster DTMs. The Valley Flatness (VF) at a single scale is calculated as a function of (1) the local topographic position of a cell within a moving window and (2) the slope of a 3x3 cell window. A cell is part of a flat valley when it is locally low and has a low slope. Fuzzy VF values for multiple resolutions are calculated by resampling the DEM to increasingly coarse solutions and then repeating the procedure. The MrVBF index is then a weighted combination of the individual VF values, with those VFs less than 0.5 being considered as ridges and consequently being excluded. The main potential issue with the MrVBF algorithm is that it achieves a multi-scale result by using multiple resolutions, rather than multiple operational scales. The coarser resolutions obtained by resampling the original DEM will reduce the relief information of the original DEM, although such smoothing can be desirable in some cases.

The model is composed of data layers from the described geomorphometric indexes. These are connected to the areas of land use that is possible in the area of the filled gravel pits. The land use was categorized based on the data for the agrarian land use (© MKGP 2005, 2009), which precisely delineates mostly the categories of agrarian use. The raster layers have values of 0 and 1, with 1denoting the characteristic of a filled gravel pit:

- **Layer 1 – convergence/divergence index of the surface**: 1- areas of divergence (a), 0 – different areas of converging, draining (b, c). (MRVBF_1_0)
- **Layer 2 - multiresolution index of valley bottom flatness**: 1 = unleveled areas, wavy (ridged, wavy relief) and 0 = level areas (CONVERG_1_0)
- **Layer 3 – land use: 1 = negative lande use** (permanent meadows, overgrowing surfaces,) and 0 = positive land use, with a very small possibility for deposited waste (fields, built-up surfaces) (MKGP_1_0)

The raster data levels were overlapped and merged into a single layer with the following equation:

(MRVBF_1_0 + CONVERG_1_0)*MKGP_1_0.

The result is a raster layer with values 0, 1, and 2. Value 0 designates the areas where the consequences of waste dumping in gravel pits are not reflected in the relief characteristics. Value 2 marks the areas with a high relief potential and reflects relief characteristics that are a consequence of dumping waste into filled gravel pits. The areas valued with 1 are somewhere in between. The potential gravel pits that had been located with the relief visualization (in the previous chapter) and that completely matched the areas of a high relief potential (Figure 159) may be categorized among the gravel pits whose relief consequences are detectable with geoinformatic analyses due to waste dumping. The areas were then compared with the results of the other methods and with the synthesis map; then the environmental risk for potential gravel pits was unequivocally evaluated.

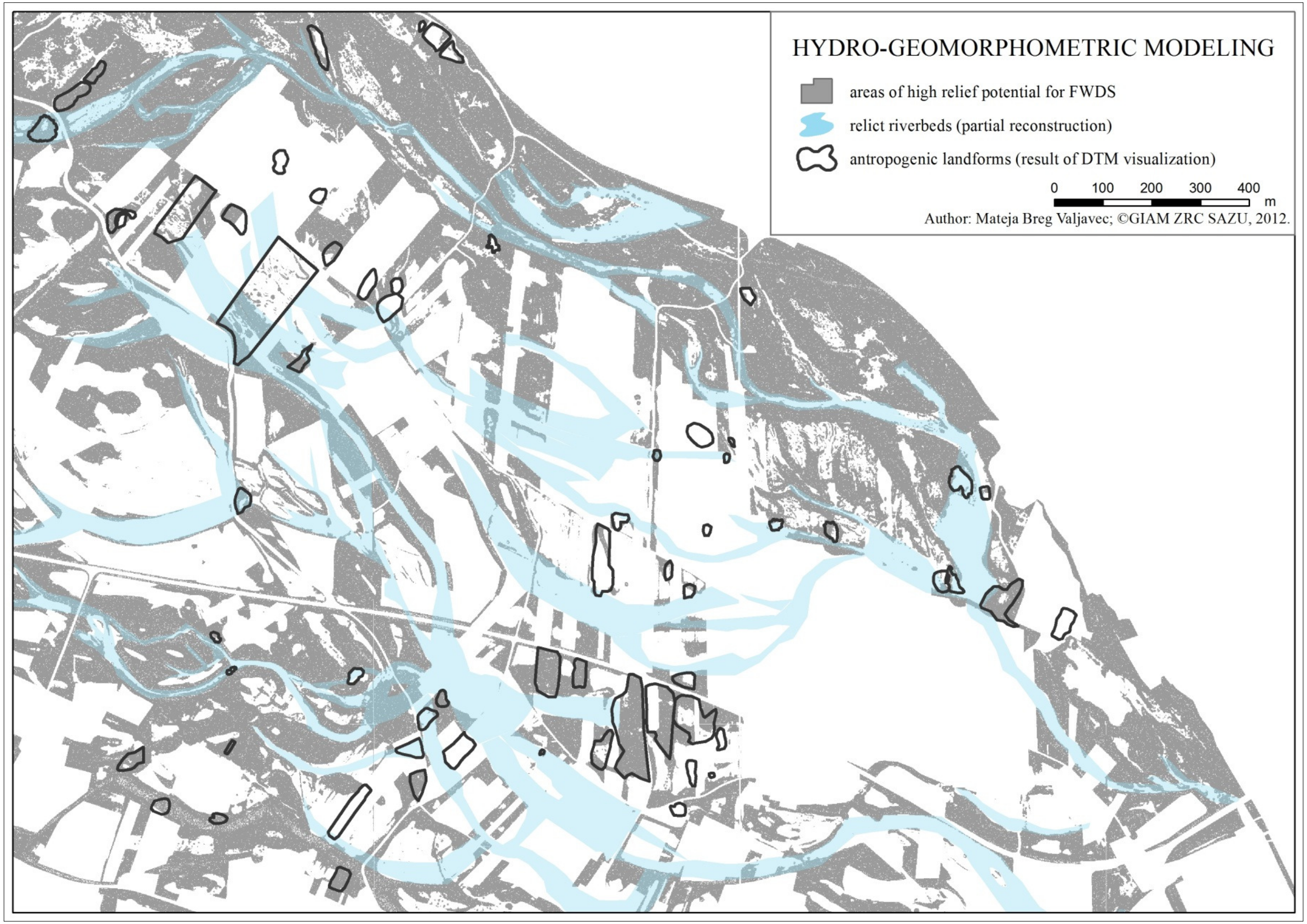


Figure 159*: Aareas of anhropogenic landforms that match / overlap the areas of a high relief potential, are most likely filled gravel pits.*

9.3.2 Multispectral Image Processing Methods

When attempting to locate filled gravel pits on multispectral aerial photographs, it is necessary to first have a very good knowledge of the natural physical-geographical characteristics of the studied area. It is also necessary to determine the physical characteristics and how they reflect on the multispectral photographs and on which channel they appear most notably. The second prerequisite is to be familiar with the physical-geographical and physical characteristics of filled gravel pits and determine how they are reflected on those photographs.

In our research, the focus lay on the relief, the pedogeographical and the phytogeographic characteristics. In addition to the geological structure and the climate, the fluvial relief is an essential hydro and pedogeographical factor, so there are detectable connections between the relief shapes, the water flow directions (presented in the previous chapter on surface modeling) and the soil characteristics. One of the important characteristics is soil depth. Because the weathering material is carried away, the soils on the slopes are thinner than at the bottom of valleys, where the material is accumulated. The relict riverbeds are of a slightly concave relief shape, where the weathering material is collected during the denudation process and deeper loamy soils develop that have a greater water retaining ability than the soils outside relict riverbeds. This hypothesis was also proven using pedological sounding on sample area 6. The sounding pedological profile depth (RR1) inside the relict riverbed is 90 cm (with gravelstones beneath), while outside the relict riverbed, it is just 25 cm above the gravelstones (RR2). The areas between the relict (fossil) riverbeds can also be called fossil point bars.

The infra-red parts of the light specter are appropriate for visual determining of the differences in the vegetation reflection values, which is a consequence of the temperature differences or the differences in the ground moisture. The areas of the relict riverbeds (Figure 160) are clearly visible as red colored streaks on meadow surfaces and designate cooler, moister surface, deeper loamy soils. An additional proof that the riverbeds are not dry is the overlapping of areas of relict riverbeds with lines of the modeled surface water flows (Figure 160). The moisture is a consequence of surface water flow concentration and a greater ability to retain moisture in the deeper loamy soils. Relict riverbeds where forest vegetation flourishes also have a rich hydrofilneous undergrowth. The hydrofilenous perennials (common snowbell Lat. *Galanthus nivalis*, cyclamen Lat. *Cyclamen*) in slightly concave relief shapes are a good separating element between the natural and anthropogenous slightly concave shapes (may be a filled gravel pit), while no differences in the meadow vegetation were noticed.

Figure 160: *The connection between the modeled water flows and areas of relict riverbeds (on the CIR image – red streaks), which delineate cooler or more moist areas (similar reflection to forests, healthy vegetation).*

Identifying relict riverbeds and filled gravel pits on multispectral photographs highly depends on the **land use or the land cover** (Figure 161, Figure 162). The differences between the two terms can be best explained on the case of the land use of a field that may have a varying vegetation cover of the planted vegetation or does not have a vegetation cover during the time of the recording. The areas of the relict riverbeds stand out the most on areas with low vegetation like meadows and planted ("greened") fields.

Most of the gravel pits have been rehabilitated by covering them with construction and demolition waste, and tilling is consequently not possible. In accordance, a filled gravel pit is almost certainly not a **planted field** but most often a permanent meadow. Waste-filled gravel pits are also not **built-up**, as the foundation (waste) does not allow the construction of statically demanding objects (buildings), but only statically undemanding objects like parking lots, roads. A filled gravel pit within planted agrarian lands can also be a smaller unplanted part of the land, often irregular in shape or round and overgrown with bushes. In the forest, a filled gravel pit is an area without tall trees. Based on these characteristics, the first **vegetation area mask** was generated.

The soils on the studied area are shallow, skeletal and highly porous. The rainfall runs through it into the groundwater very quickly. The areas of relict riverbeds are areas of deeper loamy, more water-retaining soils. The cover layers of the FWDS gravel pits are composed of thick layers of heterogeneous waste (with prevailing construction and demolition waste), mixed with a loamy excavation material that retains moisture and causes the reflection to be spatially more diverse. They can be visually separated from relict riverbeds that have a heterogeneous color texture (red), while a diverse pattern forms in filled gravel pits, which is a reflection of varying moisture and the selective decay of waste. Based on the described pedogeographical characteristics, the areas of relict riverbeds with a homogenous spectral reflection were excluded and the second **mask of areas outside relict riverbeds** was generated**.** The mask is complemented with the relief modeling of relict riverbeds. The selected spectral layers can be used to study only the areas with sparse and low **vegetation** in the forest area, where the ground influence on the reflection value is much higher than in the dense forest. The areas of filled and unfilled deserted gravel pits within the forest are never overgrown with tall trees. Due to the infertile soil and the poor foundation static (loose waste), tall trees do not flourish on areas of filled gravel pits. The aerial photographs enable us to identify areas of poorer reflection, which is a combination of the reflections of dry, shallow ground and sparse, predominantly bushy vegetation.

The spectral vegetation pattern is influenced by the vegetation type (forest, grass, corn, bushes, …), the phenological and physiological state of the plant (age, exposure to harmful substances), reflective characteristics of the assimilation organs (leaves, needles), placement and distribution of the assimilation organs, the vegetation vertical structure (height) and the proportion between the parts of the lightened and shadowed leaves or needles, the structure according to the vegetation type. The reflection rules of the Sun’s radiation from the bare ground are relatively simple in relation to the vegetation.

Figure 161: *The recognizability of relict riverbeds on the CIR image regarding land use.*

Figure 162*: The recognizability of relict riverbeds on the RGB image regarding land use.*

Underground dumped and covered non-hazardous waste is the hardest or almost impossible to detect, as it does not cause any phenomena connected to soil contamination, like, for example, damage to the vegetation or abnormally high soil temperatures. This kind of waste is mostly generated in construction and demolition and is inert. It can be detected using the high-resolution multispectral image analysis (GeoEye1, IKONOS), accounting for the vegetation characteristics that do not flourish well on such areas and the reflection characteristic of the soil or the ground that is unaltered due to the waste on the surface. Multispectral aerial photographs or NIR-DOP (cell 1 m) were used that include the NIR layer in addition to the visible part of the electromagnetic specter (red, green, blue). They were taken as part of a project of cyclical aerial photo shoots in the spring of 2006 (DOP 2006, ©GURS). The GEOEYE-1 four-channel satellite image (cell 2 m) from 2009 was also analyzed as it has spectral channels, comparable to the DOP 2006: layer 1 – blue, layer 2 – green, layer 3 –red, layer 4 – NIR.

The most common methods for categorizing the objects on the Earth's surface using remote perception are different forms of controlled and uncontrolled classification. In this case, the uncontrolled ISODATA classification ("Iterative Self-Organizing Data Analysis Technique") was used along with different vegetation indexes of the surface (NDVI, IR/R) that are based on the analysis of the near infra-red (NIR) and red (R) spectral channels. In the case of the aerial photographs, the data layers for the NIR and the R part of the specter were isolated, which best show the differences in agrarian, unforested and unbuilt-up areas.

ISODATA is iterative in that it repeatedly performs an entire classification (outputting a thematic raster layer) and recalculates statistics. "Self-Organizing" refers to the way in which it locates the clusters that are inherent in the data. The ISODATA clustering method uses the minimum spectral distance formula to form clusters. It begins with either arbitrary cluster means or means of an existing signature set, and each time the clustering repeats, the means of these clusters are shifted. The new cluster means are used for the next iteration.
The ISODATA utility repeats the clustering of the image until either:

- a maximum number of iterations has been performed, or
- a maximum percentage of unchanged pixels has been reached between two iterations.

During the ISODATA process, the focus was on analyzing the vegetation surfaces (mask for excluding all the other non-vegetation surfaces according to the ground cover, also unplanted fields). This process allowed the amount of data to be diminished and the effectiveness of identifying the poorer vegetation to be increased, meaning sparser, low, and dry vegetation. The method is as follows:

1. The first step of the process includes differentiating the vegetation areas by using the ISODATA classification of 9 classes.
2. Based on the results of this classification the **first vegetation mask** was generated, which eliminated all the non-vegetation cells (also unplanted fields), covered by shades.
3. In addition, the vegetation index (NDVI) was calculated from the original data – a layer demonstrating the vegetation distribution. The exclusion of all the potential data on vegetation was decreased by the generation of the **second vegetation mask**.
4. The NDVI, IR/R vegetation indexes were calculated on the isolated area of the vegetation surfaces as well as other relations between the NIR and R layer.

There is no unified process for the mask generation; several analyses are necessary to determine the process for generating the masks for excluding and eliminating the data:

- Uncontrolled classification (ISODATA):
- Processing the photographs with the main components methods (PCA):
- Calculating the vegetation indexes (NDVI, IR/R).

Multispectral analysis, based on the described analysis of the 4-channed satellite or aerial photographs (blue, green, red, NIR) and determining the vegetation stress over the vegetation indexes (NDVI, IR/R), does not suffice as an independent method for professional FWDS detection. This method can be used to determine the areas of dry vegetation, sparser vegetation that develops over the vegetation, to separate the areas of moist and dry soils and their reaction on the grass and bush vegetation. This method was not used to exclude the areas with damaged vegetation that would point to toxic waste. Quite the opposite, the calculated NDVI surface indexes on filled gravel pits, overgrown with grassland is very changeable, but high in average, which is a consequence of increased moisture, reflected in the NIR spectral channel. The vegetation stress is not present on these areas but quite the opposite. The field vegetation charting did not result in any substantial vegetation differences with the surroundings ether.

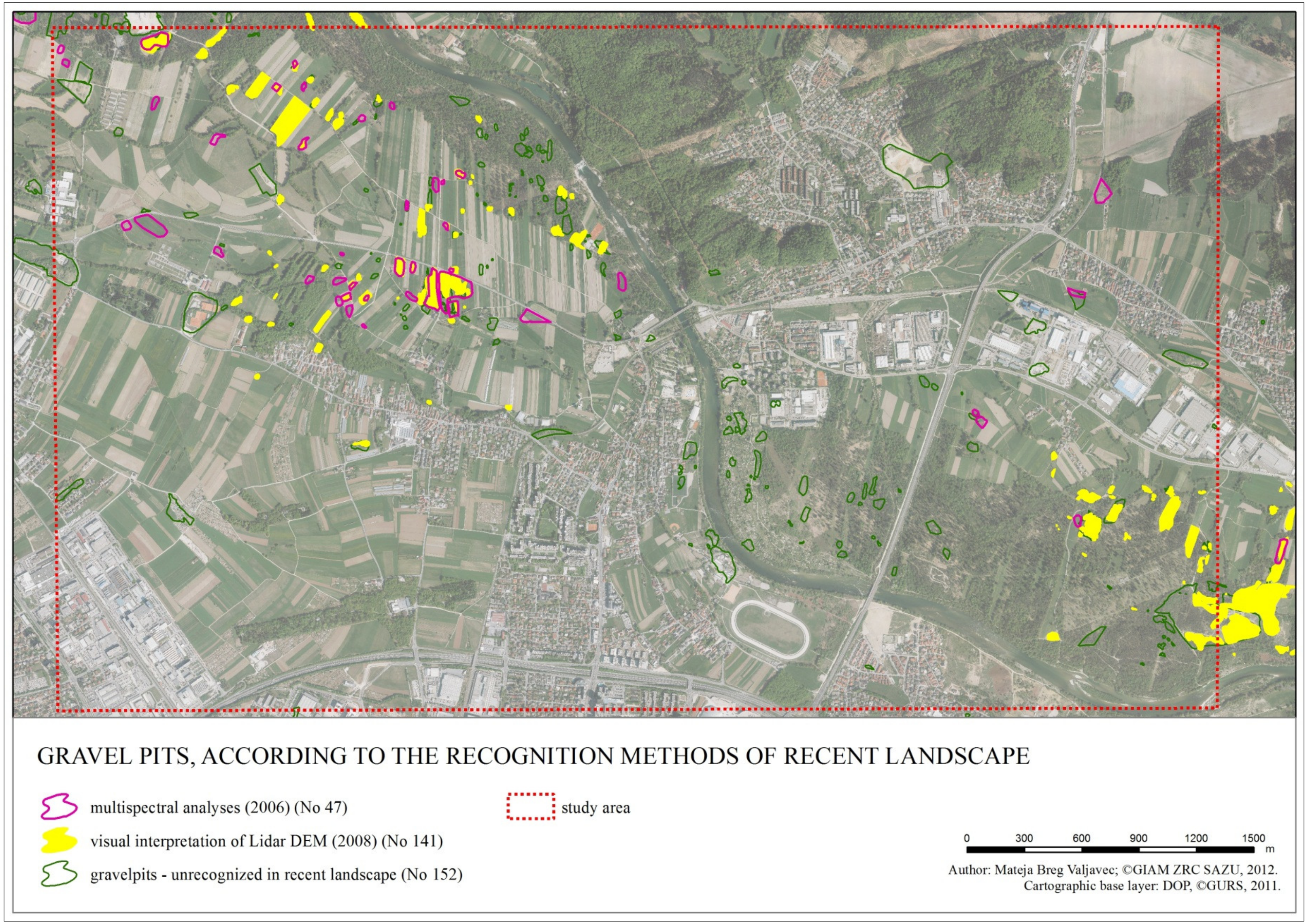


Figure 163*: Gravel pits, recognized by geoinformatic analyses of the recent landscape.*

9.4 The FWDS Cadaster in Gravel Pits

The FWDS cadaster on the studied area includes 324 objects; geoinformatic methods were used to determine certain characteristics that gravel pits have. In this way, as many as possible potential sources of pollution from gravel pits were documented. Every object is a potential environment polluter until it is proven that it is not a filled gravel pit.

The presented geoinformatic analyses of the past and recent landscape were used to determine the occurrence of gravel pits with the goal of determining the waste-filled and covered gravel pits – FWDS. The gravel pits were included in different periods in different states or excavation phases, filling of overgrowing with vegetation. Every method was used to determine the position of the gravel pits and also the shape of some (screen interpretation, 3D DSM analysis). The results are presented in a vector form (points or polygons).

The more geoinformatic methods that were used to determine a gravel pit, the greater the possibility that the object is a FWDS. 9 gravel pits were determined using all five methods (Figure 164). All 9 were proved to be filled gravel pits with the field methods. 14 gravel pits were located using 4 methods, 41 with three and the other with two or one.

The complete success of the geoinformatic methods can be estimated only on sample areas, for which all the spatial data is available on which to test the selected methods.

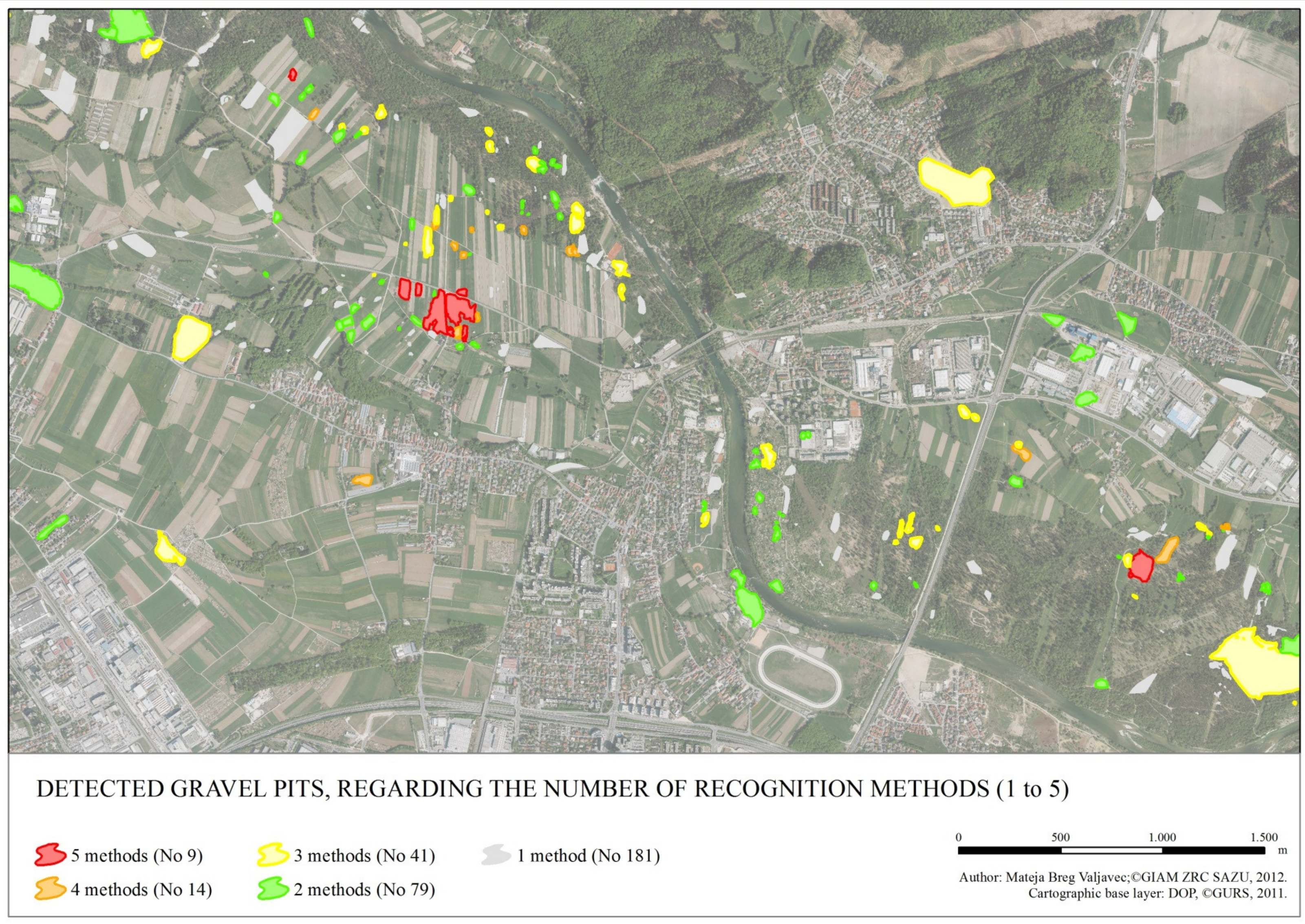


Figure 164*: Potential FWDS, according to the number of the geoinformatic methods that detected the gravel pit.*

9.5 Comparison with Existing Registers

The results synthesis is based on all the collected data. The first step was to merge all the objects that were included in the past landscape analysis and to determine the level or probability that the object is really a gravel pit. The objects that were located using both the 2D analyses and have a certain depth based on the 3D analysis are the most probable gravel pits. It was not possible to reliably evaluate the other areas as part of the past landscape analysis, so they were placed in the context of the results of the recent landscape research. The individual gravel pit locations were located in the recent landscape using the visualization and interpretation of the lidar relief data, the multispectral satellite and aerial photographs. A special approach to the recent landscape study is the two-step GIS modeling that is based on relief modeling and the uncontrolled classification of the multispectral aerial photographs.

The level of reliability was determined with a comparison of the results of the past landscape analysis results. This could be executed in its entirety only for the area where all the data overlaps, while the rest of the object were tested using the control methods (lab and / or field). This means that if the gravel pit was located with the 2D and 3D past landscape analysis and these consequences can be detected with at least one recent landscape analysis, on the relief or the vegetation / ground, then the object may be confirmed to be a filled gravel pit with the highest level of certainty

The results of the geoinformatic methods were evaluated (Figure 165) using the visible waste disposal sites data (Smrekar et al. 2006), which encompasses the entire water protection area of Ljubljansko polje. There were 761 documented illegal waste disposal sites on the studied area; 208 raise a suspicion that the waste was deposited and buried under the surface. 39 waste disposal sites are located in gravel pits, mostly in the sparse forest near the Sava River (Jarški prod, Roje). The waste disposal sites are smaller in Roje, the largest cases reach 500 m². The visible waste disposal sites on Jarški prod encompass 5000 m². 35 waste disposal sites are estimated as completely inactive and overgrown and only a few (5) are located on areas of gravel pits (Smrekar et al. 2006).

The waste disposal centroids were layered on ranges of all the located gravel pits. 74 out of 318 gravel pits coincide with the locations of active waste disposal sites. The results are presented on figure 165 and the evaluation is also explained in table 19. While evaluating the gravel pit cadaster, the same type of method that was used to determine a gravel pit and it was taken into account whether the gravel pit was located in the past and recent landscape or on only one type of landscape, like, for example, only in the recent one. The other control criteria were data about the gravel pits overlapping with illegal waste disposal sites.

The gravel pits were classified into 4 classes (Figure 165) and it was determined which gravel pits are classed among FWDS based on the control classifying criteria (Table 19). Based on the described evaluating method, 118 gravel pits were classified among FWDS with a high level of environmental risk. 200 gravel pits were not confirmed using the described method, so they were attempted to be determined using field methods.

			CLASSIFYING CRITERIA			
			THE TYPE OF GEOINFORMATICS		**EXISTING REGISTER OF WASTE DUMPS** (Smrekar et al. 2006)	
GRAVEL PIT	No	No	**RECENT**	**PAST**	**WASTE DUMP**	**NO WASTE DUMP**
1st level **FWDS**	23	118	x	x	x	
2nd level **FWDS**	44		x	x		x
3rd level **FWDS**	51		x		x	
				x	x	
4th level	200	200	x			x
				x		x

***Table 19**: Classifying gravel pits into FWDS based on two classifying criteria.*

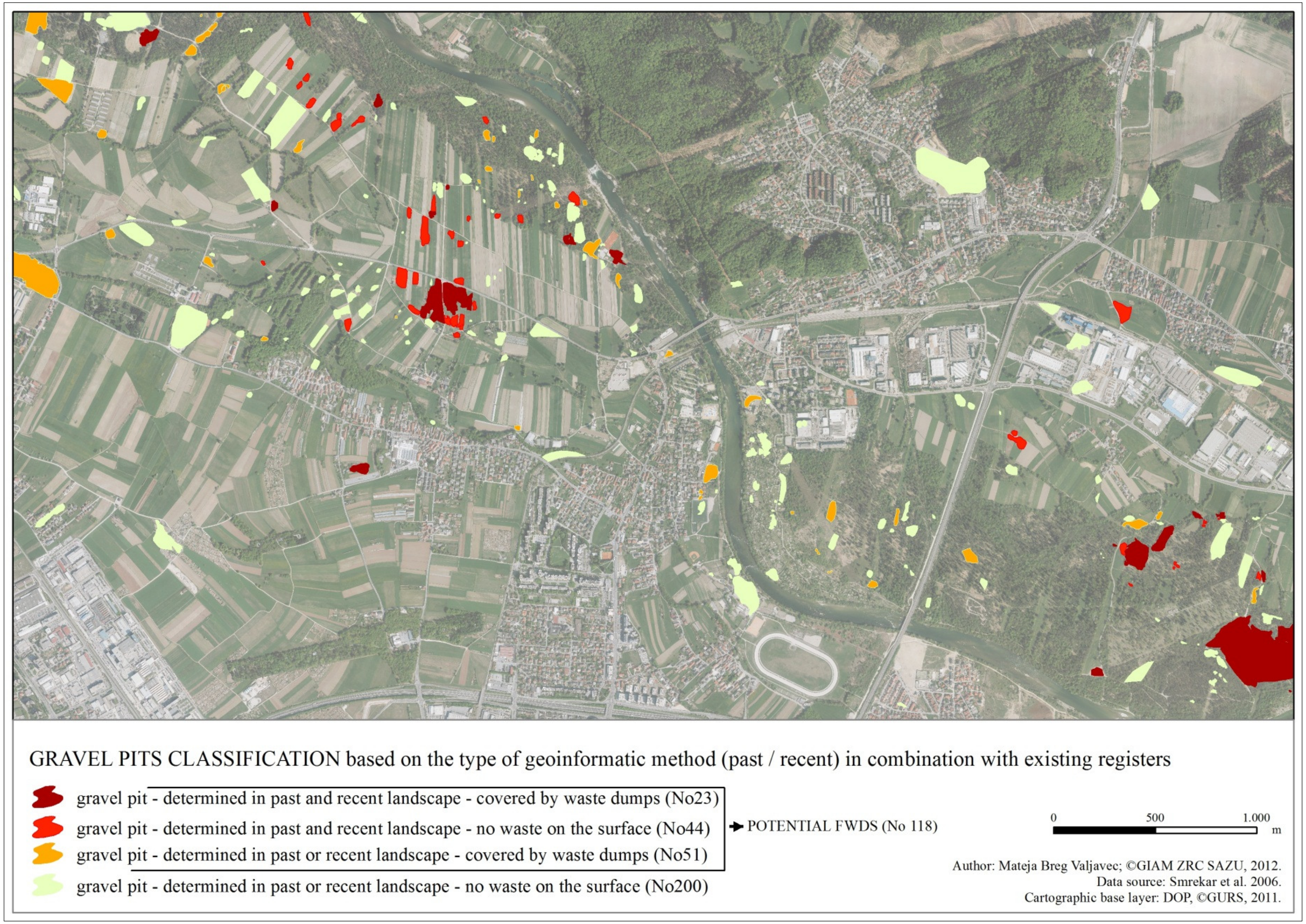


Figure 165*: The cadaster of gravel pits in relation with the register of active illegal waste dumps (Smrekar et al. 2006).*

9.6 Validation with Field Methods

9.6.1 Introductory Remarks

The main purpose of the field research was to verify all the potential locations of FWDS in gravel pits and confirm the suspicion about the disposed and filled waste.

Filled gravel pits are meadows, fields, forest and are mostly privately owned today, where and it is not possible to get the pedological profiles of 1x1m or use a geological drill on all 273 locations. The main goal is to partially verify the results of the geoinformatic methods with field research and confirm the suspicion of filled waste in a gravel pit. During the field research, all the precisely detected locations were determined and **the differences in relief, soil, and vegetation in relation to the surroundings that are not degraded were determined**. The methodology is based on experience from the field charting of illegal waste sites on Ljubljansko polje (Smrekar et al. 2005, 2006), where similar objects were met. Construction and demolition waste is prevalent on active as well as non-active waste sites. The decay of these has developed a top layer, on which pioneer vegetation species flourish.

Three methods of field research (control methods) on Ljubljansko polje were chosen, which differ according to their invasion into space and some other options regarding the execution:

1. **Soil sounding:**

The method was thoroughly executed in the field on sample objects that were determined with the geoinformatic analysis and classified regarding environmental risk. The sample represents 25 gravel pits locations.

The invasive field method of pedological sounding was used to determine the occurrence of a specific kind of anthropogenous soils named **deposols**, which developed on the surface of the FWDS gravel pit. No further laboratory analyses were made, with which to determine the origin of the waste with more precision. For this reason, the soils that formed above the filled waste were named deposols. A referential soil profile was also made for every measurement location, with which the characteristics of the surrounding prevailing natural soil were determined or at least the agrarian soils (agrarian soils are also antrosols) if natural were not present. The following characteristics were determined: the profile depth to the original surface, the quantitive estimate of the soil structure, the presence of horizons that are characteristic of natural soils in the studied area.

Each sample location / pedological profile is graphically presented on the photographs. The tip of the auger shows the direction of drilling and is also used as a measure.

***Figure 166**: An elevated layer of soil in the shape of corridors was noticed in a mole-hill on the surface of the filled gravel pits that lead to a mole-hill with a lot of small waste that the mole "pushes out" to the surface.*

2. **Measuring the electrical resistivity of the ground** (the approach is the same as on Logaško polje)**:**
3. **Field mapping of relief changes:**
   - The method is executable and has been executed for almost all the objects (273 gravel pits) except within fenced areas (water protection area 0, fenced military areas, private yards);
   - The subjective estimate of the register is present, so field experience and geomorphological knowledge is very important for recognizing degraded areas and anthropogenous changes in the landscape (anthropogenous landforms, vegetation changes on a micro level).

9.6.2 Results of the Field Research

Poorly developed shallow fluvisols appear on Pleistocene and Holocene carbonate gravel along the Sava River with tree and bush vegetation and meadows. These soils are very young according to their origin, as they were formed about 100 years on still active gravel sites. Carbonate soils with a **sandy gravel texture** appear on gravel sites and sand dunes closer to the river. This soil is inappropriate for any kind of use and is classified in the 5th to 6th category of appropriateness for agriculture. In some places, a humus horizon in the shape of weathering organic matter, gathering along the roots of modest vegetation, is forming. The sand dunes and gravel sites serve for acquiring sand and gravel.

With distance from the river into the interior, the soils on the gravel terraces are still shallow, but have nevertheless developed riparian soils: **rendzine and cambisols**. The humus horizon is mull-like and very light and almost fine. The producing capability of these soils is highly dependent on the amount of gravel; a higher share of gravel points to a poor fertility. They are appropriate for cultivation soon after rainfall, because the water is quickly drained and sinks.

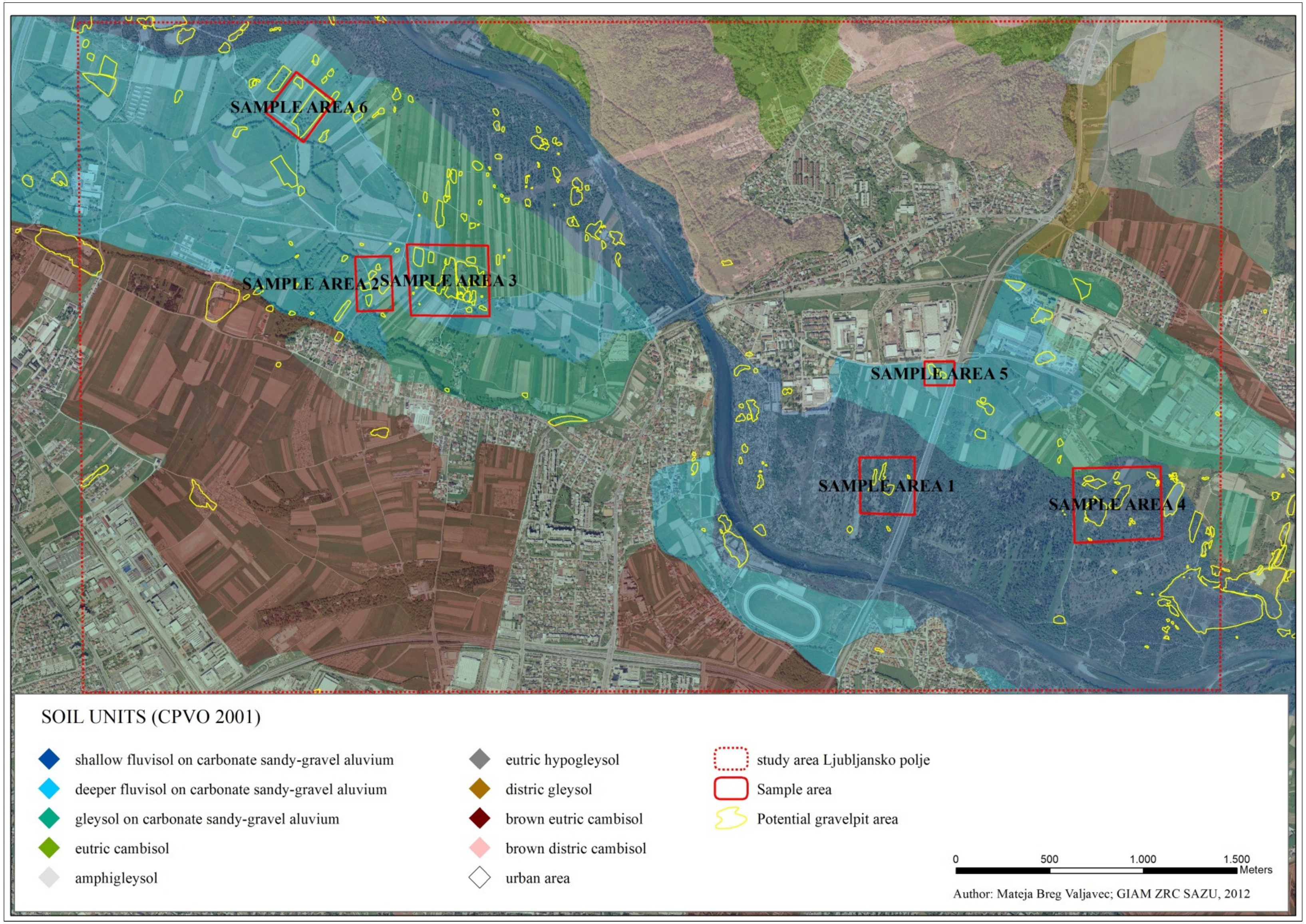


Figure 167*: The map of sample areas, regarding pedogeographical units – soil types (© CPVO 2001).*

Figure 168*: An extremely large amount of gravelstones on a cultivated field along the Obvozna cesta road.*

Figure 169*: River Sava at Jarški prod on Ljubljansko polje.*

The experience (Smrekar et al. 2005) showed that anthropogenous soils can also be developed on inactive waste disposal sites. Like the original rock foundation, waste also decays, creating the foundation for pioneer or ruderal species to flourish. The waste itself is overgrown by mosses. The types of soils that develop depend on the structure of the waste. In certain cases, where gravel excavation was more extensive, the gravel pits were filled with different excavated material and with trees planted on top of that layer (the area between Jarški prod and the Sava River water plants) or the area was left to natural overgrowing (Smrekar et al. 2005).

Tree and bush vegetation grows on the shallow soils. A sparse forest is spread along a 500 m stretch of the Sava River. Coniferous trees are common among the trees, especially pioneer species of Scots pine (*Pinus sylvestris*). Deeper soils, where meadows and fields were in farming use once are being overgrown with thorny bush vegetation in the present. The farming plots on Jarški prod had been in use 20 years ago. These were mostly meadows and sparse fields owned by Agroemona Domžale and later came under the possession of the Farmland and Forest Fund of the Republic of Slovenia or are privately owned.

9.6.2.1 Jarški prod 1

Sample area 1 is located on an alluvial flooding plain (area of catastrophic floods, © ARSO) of the Sava River, 400 m north of the river on an extensive point bar, overgrown by a sparse mixed forest that is partly of a natural and partially an anthropogenous origin. The groundwater depth is small, resulting in the soils being flooded with groundwater at high tide. Those soils were developed on a carbonate gravel-sand original surface. There are **undeveloped fluvisols** closer to the river and **fluvial carbonate soils on a gravel-sand alluvium** a small distance away. The FAO classification places them among calcaric fluvisols (©CPVO 2001).

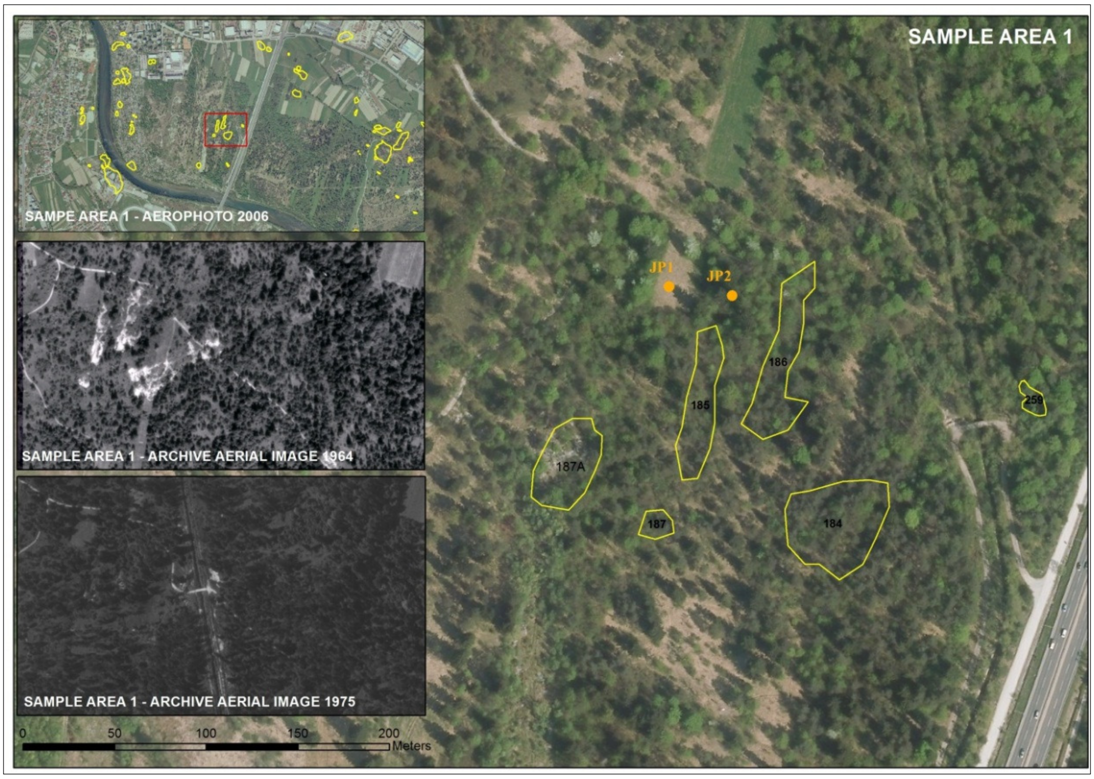


Figure 170*: Map of sampling area 1.*

Area 1 includes 4 larger gravel pits (G184, G185, G186, G187). The excavation happened over sixty years (SAS 1964, ©GURS), while no gravel pits are visible on the photographs from 1959 (SAS 1959, ©GURS) and are also not recognizable on the photographs from 1975 (CAS 1975, ©GURS), as they are already overgrowing. As is visible form the 1964 photograph (Figure 170), the excavations were spatially not connected, so the gravel pits do not have regular shapes, but a sort of "tree-like" structure. That is a consequence of disorganized gravel excavation of individuals from near-by settlements in that period.

The field charting ascertained that all four gravel pits are recognizable on the relief, since they retained a shallow concave shape up to 3m in depth. The gravel pits are not filled, with some waste appearing in some locations that were brought with trucks (due to the amount of construction and demolition waste) and had been deposited a while ago, because the gravel pits are now accessible only by foot through thick bushes and other undergrowth.

Name	Land use	Depth (cm)	Horizons	Anthropo. parts	Soil base	Vegetation	Soil type
JP1	Unculti. field	25	non	none	gravel	grass	calcaric fluvisol
JP2	forest	40	2	none	gravel, sand	forest snowbells	calcaric fluvisol
G 185	bushes	10	none	none	gravel	bushes, small trees, smow bells	calcaric fluvisol

***Table 20**: The results of pedological sounding in the area 1.*

We made referential sounding profiles on two areas, “marked on figure 171” on two areas: one of an abandoned field (JP1) and one in a forest (JP2). Sounding with the soil auger in the abandoned field (JP1) (Figure 171) was only possible to a depth of 25 cm; further drilling was prevented by gravelstones, which increased in frequency. This is a shallow alluvial soil that is anthropogeneously altered due to tilling and other farming activities, so it was only possible to determine the tilling horizon on an original surface. The carbonate gravelstones are very close to the surface because of the shallowness of the soil and the tiling (at 15cm).

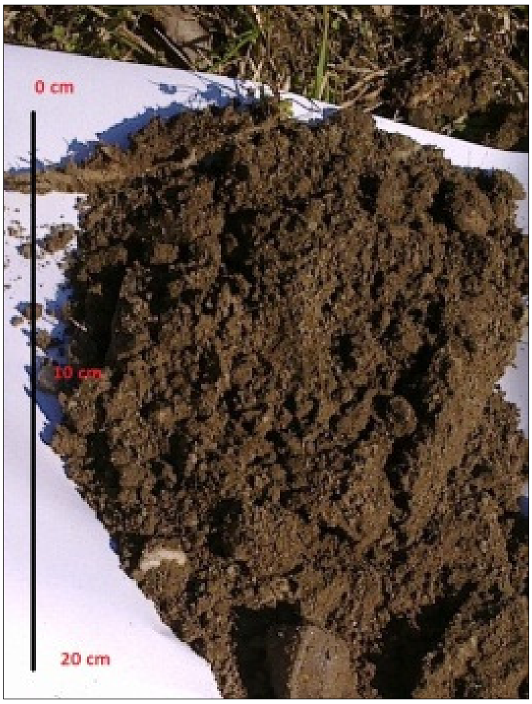


***Figure 171**: Structure of the JP1 reference profile, 25 cm depth.*

Referential profile JP2 (172) Figure in the forest was drilled to a depth of 40 cm, a gravel-sand original surface was encountered. The top humus layer was 10 cm thick and a dark cambisol to a depth of 20 cm underneath, which lightens on the next 20 cm, gets moister and has a greater content of clay and sand particles.

Figure 172*: The structure of the JP2 referential profile to a depth of 40 cm.*

The soil characteristics are reflected in the vegetation. High spruce trees (about 15 m), different deciduous trees (Montpelier maple) grow there and snowdrops flourish in the undergrowth in early March. The root zone reaches down to the original surface at 40 cm. The soil is not anthropogeneously altered and, according to the developedness and depth, can be categorized as a **fluvisol on a sand-gravel carbonate bedrock**.

The next sounding profile **G185** (Figure 173) was taken on the north part of the gravel pit 185. The gravel pit is a concave shape up to 3 m deep. The tree vegetation is much sparser than in the surroundings, notably lower (up to 10 m) with prevailing bushy deciduous trees (the common hazel, Lat. *Corylus avellana*). Tall spruce trees grow outside the gravel pits. There are smaller waste piles present in the gravel pit, overgrown by moss.

Figure 173*: Unstructured profile of G185.*

Sounding was possible only to a depth of 10cm, with a thin humus layer on top (5cm) and a sandy moist brown gravel layer. The root layer reaches through both layers. Despite the shallow undeveloped soil, snowbells (*Galanthus nivalis)* were growing in the gravel pit, because the shallow groundwater makes the area at the bottom of the gravel pit quite moist. The soil is young, shallow, undeveloped, formed on a natural original foundation, not anthropogenously altered; its age can be estimated at about 40 years and falls under shallow **fluvisols**. Sounding partially proved that the soil was not formed on an anthropogenous allogenic surface and falls among natural soils. Sounding was also repeated on the surrounding gravel pits (G184, G186, G187) and resulted in the same findings. The results of the pedological sounding on area 1 prove that the potential gravel pits are of an anthropogenous origin and allow us to exclude the suspicion of natural relief basins, like, for example, relict riverbeds. The depth of the gravel excavation is low (maximum 3m) due to the shallowness of the groundwater and the danger of overflowing the bottom.

We determined that there were gravel pits on sample area 1 that stayed more or less unfilled. Smaller piles of very old waste occur in individual gravel pits, overgrowing with mosses (depending on the type of waste, the decaying rate). They represent a good example of natural secondary succession, because a very thin layer of soil has developed in 50 years, mostly from organic decayed particles, which is noticeably shallower than the surrounding forest soils, which was proven with the JP2 and G185 profiles (see figures 172 and 173).

Gravel pits are not determinable using the analysis of multispectral aerial photographs. We do not have lidar data available for the studied area, but as these are expressly concave basins that could be easily determined using relief geoinformatic analyses.

9.6.2.2 Pod ježo

The **sample area 2** (Figure 174) is located north of the Kleče village, under the Ice Age Sava terrace. It is about 1,200 meters away from the Sava River. The ground use is traditionally agrarian with meadows and fields and intermittent protective forest, as buffer zones (*mejica*). The soils are **fluvisols on a gravel-sand alluvium** and are mixed with **gleysoils on a gravel-sand alluvium** depending on the depth of the groundwater.

Figure 174: *Map of sampling area 2.*

The area includes 6 gravel pits (37, 38, 39, 40, 127, 130). There is no information available on the excavation of those gravel pits. They were located using the geoinformatic methods for studying the recent landscape or the relief laser data analysis (lidar, © Geoin 2008) or the multispectral photograph analysis (CAS 2006, © GURS). The gravel pits are located next to or just south of the former German railway track, which was constructed during WWII and was deconstructed soon after (see Figure 174 photographs from 1959 and 1964, the embankment on the upper part). The first referential profile was made on a meadow (KL1) and the other in a forest (KL2).

Name	**Land use**	**Depth (cm)**	**Horizons**	**Antropogenic parts**	**Vegetation**	**Soil base**	**Soil type**
KL1	meadow	85	none	none	grass	gravel	fluvisol
KL2	forest	50	2	none	trees	gravel	fluvisol
G 38/1	field	50	none	none	none	gravel	undefined
G 38/2	field	80	none	none	none	loam	fluvisol
G 39	intensive meadow	17	none	construction waste	grass	waste	deposol
G 40	field	20	none	construction waste	none	waste	deposol
G 127	meadow	22	none	construction waste	grass	waste	deposol
G 130	meadow	80	2	loam	grass	loam	fluvisol

Table 21: *Characteristics of the soil profiles for sample area 2.*

The referential KL1 profile was drilled to a depth of 80cm, where larger gravelstones start to appear (>2cm), preventing further sounding. The profile (Figure 175) is homogenous, without detectable horizons; this prompts the conclusion that the natural horizons are anthropogeneously mixed (long-term tilling) and that the meadow is an abandoned field (this is also confirmed by the vicinity of the Kleče village).

Figure 175: *Referential profile KL1 was sampled on meadow (depth 85cm).*

The **KL2 profile** (Figure 176) was sounded in a forest (*mejica*) next to the 127 gravel pit. The vegetation is English oak (*Quercus robur*) (tree height to 20 meters) and the common snowbell (*Galanthus nivalis)* grows in March. The soils are poorly developed riparian soils with a high concentration of skeletal soil on the entire profile, reaching to a depth of 50cm.

Figure 176: *KL2 referential profile in the forest and the prevailing undergrowth in March - snowbells.*

The **gravel pit G38** range was determined with the recent relief analysis, since it stands out as a slightly concave area that is not ridged. On the aerial photographs from 2006, where three layers are available (near infra-red, red, and green) pictured in the false infra-red color, there is a concentric anomaly in the middle of the range, se samples were taken on that area (G38/1) and outside of it (G38/2) (Figure 177, 178, 179).

Figure 177*: Gravel pit G38 – sounding locations G38/1 and G38/2.*

Figure 178*: Sounding profile G38/1 (50cm deep) in detail (right) unstructured gravelstone at 30cm depth.*

Figure 179*: Pedological profile G38/2 (depth 70cm, loamy layer at 30-40cm depth).*

Area G38 is not entirely a filled gravel pit, because area G38/2 lying on a loamy original foundation is an agrarian antrosol with no horizons and with no anthropogenous particles. The soil is much shallower at the G38/1 location, on an original foundation that includes construction and demolition waste. The original rock affects the moisture and the different reflection values in the infra-red part of the electromagnetic specter.

The area of potential **gravel pit G39** overlaps with the track of the former German railway (Figure 174), so there are deposit remnants present in the original foundation, which was removed soon after WWII. The sounded soil is classified as deposol (Figure 180).

***Figure 180**: Pedological profile G39 is very shallow and unstructured – bigger gravelstone in the upper layer and smaller bellow (20cm depth, small parts of construction material mixed with gravelstone at 10cm depth).*

Like gravel pit G39, the area of potential gravel pit **G40** also partially overlaps with the railway embankment, which affects the presence of the alogenic particles (Figure 181). The gravel pit was not located using the recent landscape analysis, so it was not possible to determine whether this is a filled gravel pit or just a surface deposit, which overlaps with the construction of the German railway.

Figure 181*: Gravel pit G40 profile is 20cm deep, foundation of construction and demolition waste at a depth of 20cm, a visible crushed material of an alogenic origin.*

The **gravel pit G127** analysis of the old aerial photographs and the chronological comparison of the ground cover express greater changes in the cover types, since the area was overgrown by forest from 1959 to 1964 and became a meadow in 1985 and is still one today. On the photographs from 1975, anthropogenous intervention into the space in the form of gravel excavation (Figure 177) is visible. Sounding on the area of potential gravel pit 127 (G127) (Figure 182) was carried out in several places, but drilling was only possible to a depth of 20 cm (the lower widened part of the auger measures 25 cm) anywhere. There are drills of "soil" at that depth consisting of pieces of brick and other construction and demolition waste.

Figure 182*: Pedological profile of gravel pit G127 is only 27 cm deep, it ends in construction waste. Smaller parts of orange brick can be seen in auger tip (right).*

In accordance with the pedological profile (Figure 182), it may be assumed that the area was undoubtedly filled, but the suspicion of it being a gravel pit (filled) cannot be confirmed so the method of measuring the electrical resistance of the ground was used on the area, which confirmed (Figure 184) the suspicion about the gravel pit:

date: 2012-03-27; length: 36m; number of electrodes: 16; distance between electrodes: 3m.

Figure 183: *Location of profile regarding the sampled gravel pit G127 and on the left side gravel pit recognition on different input data for previous geoinformatic methods.*

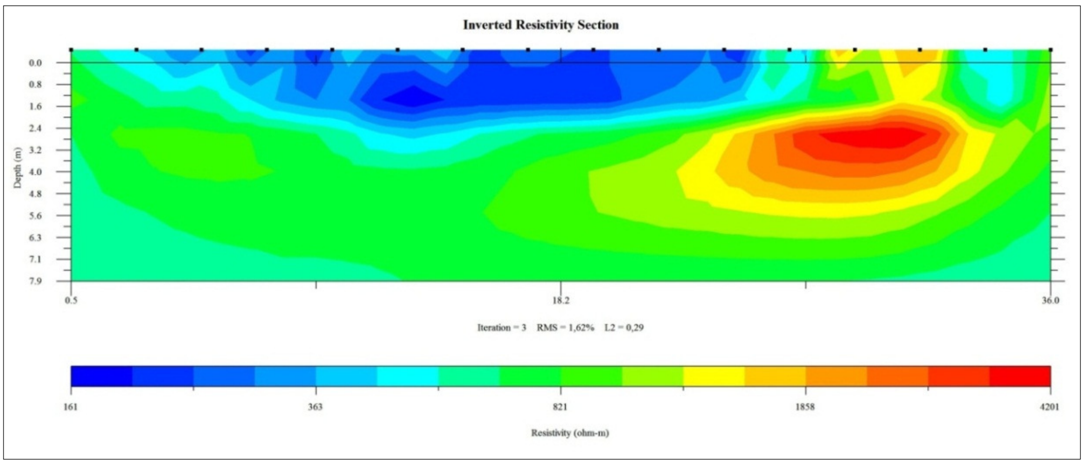


Figure 184: *The profile of the measured electrical resistivity through gravel pit G127, using the Schlumberger method. The blue colored parts of the profile indicate waste in a concave landform in a surrounding rock with higher resistivity (gravel).*

Area **G130** is located inside a relict riverbed, because the sounding profile is composed of loamy deposits, which appear at a depth of 80cm and prevent further profile sounding (Figure 185).

Figure 185*: The pedological profile of G130 is an example of soils with a deep loamy layer, typical for natural soils in relict riverbeds.*

9.6.2.3 Savlje

Sample area 3 (Figure 186) is located north of the Savlje village, along the Obvozna cesta road. It is about 1,000 m southern from the Sava River. The land use is traditionally agrarian with meadows and fields. The soils are **middle gleysoils on a gravel-sand alluvium** (CPVO 2001).

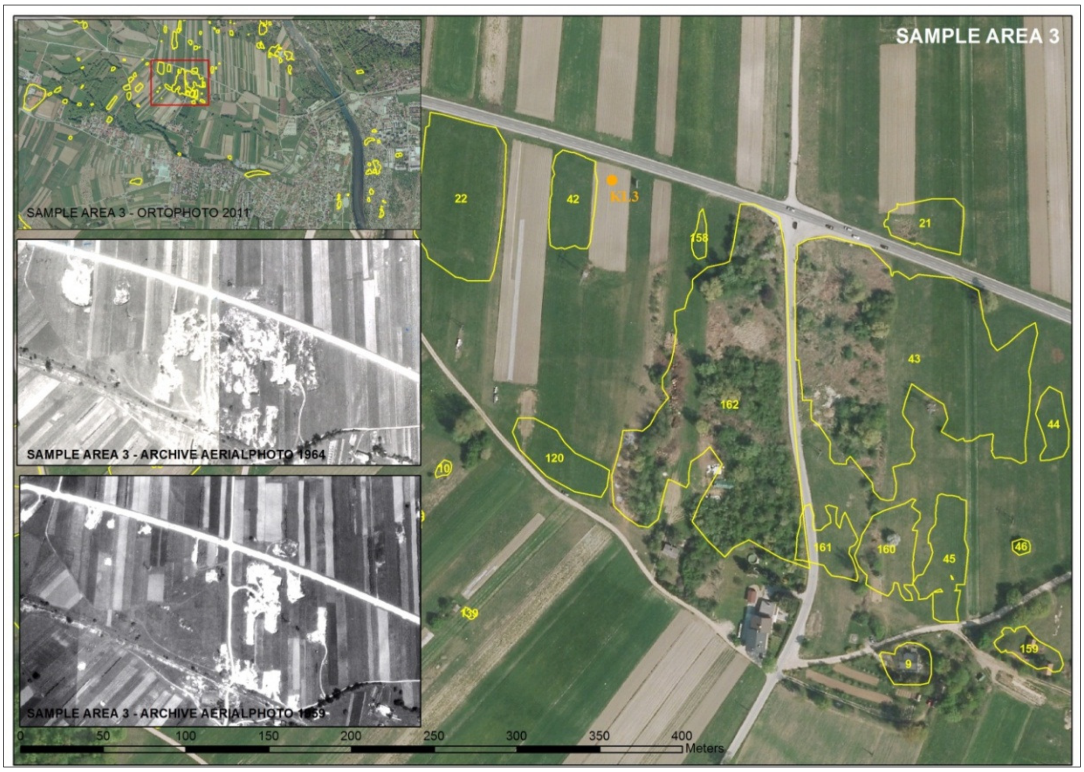


Figure 186*: Cartographic presentation of sample area 3, near Obvozna cesta road.*

The area includes a larger surface of potentially filled gravel pits (G21, G22, G42, G43, G120, G162 etc., see Figure 186), which are visible on the relief laser scanning data as well as in the field in the shape of ridged slightly convex shapes and are hard to delineate or separate from each other. In 1959, the excavation depth on larger gravel pits amounted to as much as 5m (e.g. in G43). In 1964, most of the gravel pits were in the filling state, except for gravel pit G22.

Name	**Land use**	**Depth (cm)**	**Horizon**	**Anthr. parts**	**Soil base**	**Vegetation**	**Soil type**
Kl3	field	70	2	none	gravel, sand	cultivated plants	antrosol
G 21	meadow	25, 27, 25	none	construction waste	construction waste	grass	deposol
G 22	meadow	35	none	construction waste	construction waste	grass	deposol
G 42	meadow		none	construction waste	construction waste	grass	deposol
G 43	meadow	29	none	construction waste (brick)	construction waste	grass	deposol
G 120	meadow	25	none	construction waste	construction waste	grass	deposol
G 162	bushes	24	none	construction waste	construction waste	bushes, small trees	deposol

***Table 22**: The characteristics of pedological profiles in sample area 3.*

Referential profile KL3 (Figure 187) was sounded to a depth of 70 cm, where an increased gravelstone density appeared, which prevented further profile deepening. The soil is a dark cambisol to a depth of 30 cm and contains a great share of organic matters. This is the tilling horizon with a layer underneath that is noticeably sandier and uncultivated.

***Figure 187**: Referential profile – KL3 is a 70 cm deep antrosol.*

According to the referential profile depth (KL3 - 70cm), the sounding profiles of the "soils" on potential gravel pits are noticeably shallower, on average to a maximum depth of 30 cm. In all the cases, the results are in line with the projected ones, because there is much evidence that the areas are filled gravel pits (archive photographs, DSM of the former surface, lidar, etc.).

Figure 188: *Profiles of shallow deposol G21 (left) and G22 (right). The material is very unstructured, no horizons and many small parts of an antropogenic origin.*

Figure 189: *Profiles of shallow deposols on construction waste in G43 (left) and G42 (right).*

Gravel pit G120 (Figure 190) is an exception, because it had not been defined with past landscape analysis (archive photographs) but only on the infra-red photographs of recent landscape.

Figure 190: *Gravel pit 120 – profile G120 (25 cm depth, foundation with construction and demolition waste under 10 cm) (left), detail of the construction and demolition waste in the auger tip at the depth of 20 cm (right).*

Figure 191*: Profile of a shallow deposol on construction waste in G62 is overgrown by moss that indicates bad undeveloped soils.*

Area 3 represents a highly degraded landscape with large areas filled with waste. Construction and demolition waste can be seen on the surface, which was most likely used in the "rehabilitation" phase in order to cover other types of waste (household, industrial, etc.).

The results were also tested with a electrical resistivity tomography on two filled gravel pits G42 (Figure 192) and G21 (Figure 196).

Figure 192*: Location of the profile (black line) regarding the observed gravel pit 42 and a recognition of the gravel pit in the recent and past landscape.*

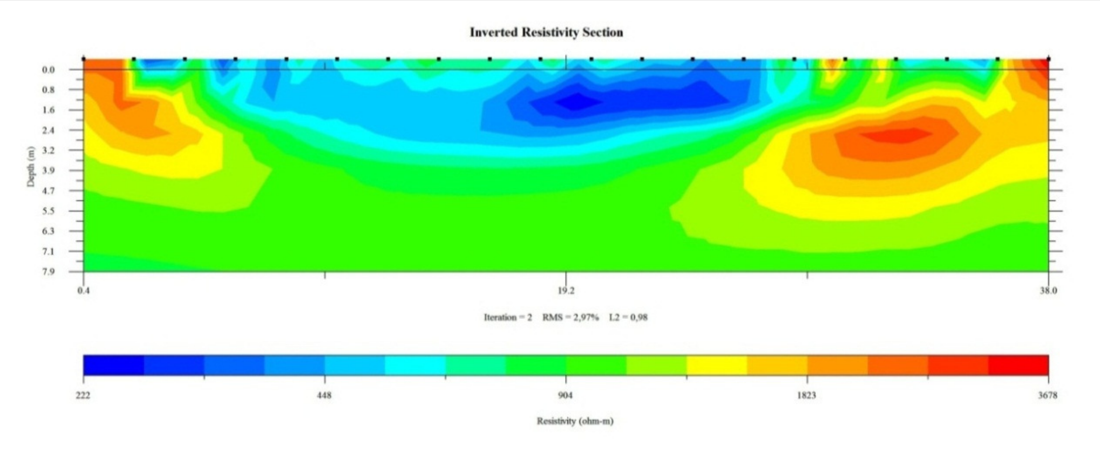


***Figure 193**: Electrical resistivity section of G42, Schlumberger-method.*

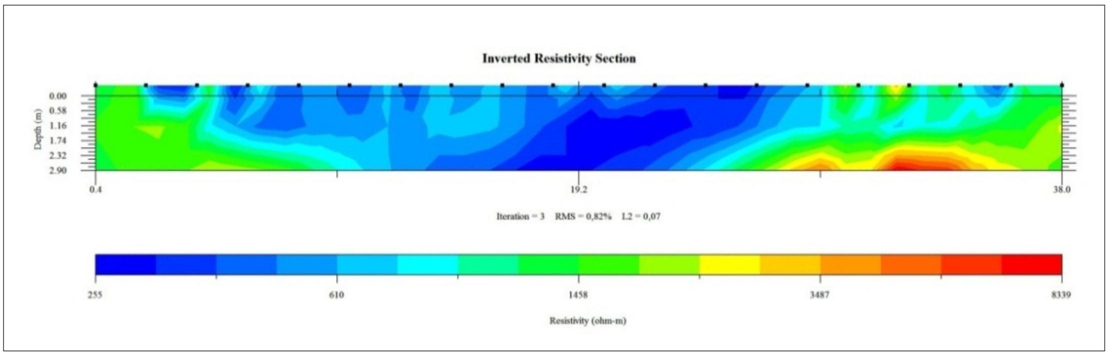


***Figure 194**: Electrical resistivity section of G42, Wenner-method.*

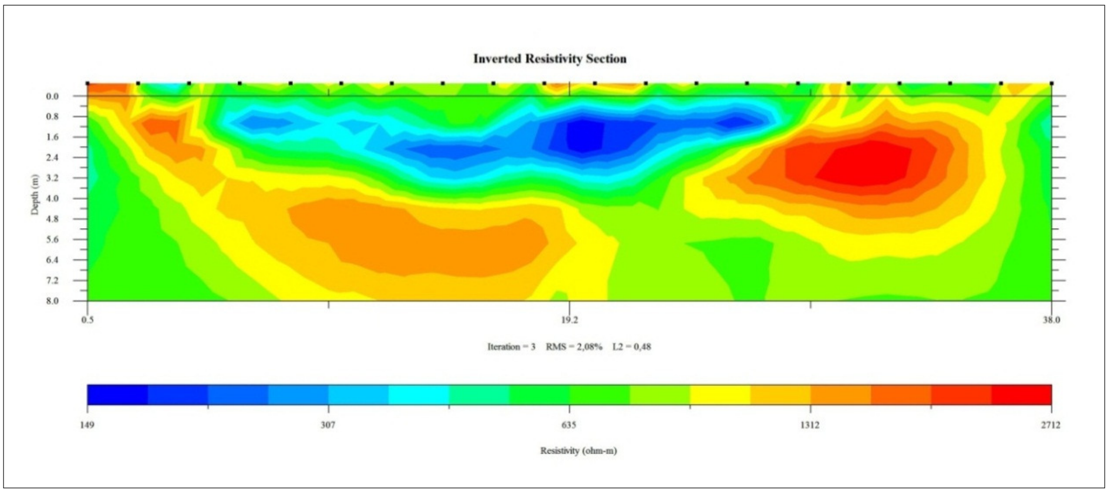


***Figure 195**: Electrical resistivity section of G42, dipole /dipole method.*

All the sections of the measured electrical resistivity (Figures 193, 194, 195) show that the area is a filled gravel pit. The waste has a relatively high resistance (about 200 Ωm) in comparison to the results gotten on Logaško polje for the waste in the dolines (up to 100 Ωm). The difference can be a consequence of the actual difference in the type of waste or a consequence of the soil moistness. The electrical resistivity tomography on Ljubljansko polje was measured in mid-March, after a longer period of heavy rainfall, which had lasted since the autumn of 2011. We measured the resistance on Logaško polje in late-April, when the ground was very moist after a month-long rainy period.

Gravel pit G21 (Figure 196) is a smaller gravel pit that is partially filled, so the resistance was measured on the slope above the waste, parallel to Obvozna cesta road, 11 m away from the road. The gravel pit was recognized by lidar interpretation, as well as with past landscape studies: the 2D visual photointerpretation and the 3D analysis of aerial photos from 1959, 1964.

The ground resistance was much higher than the one on Logaško polje in this case as well. Figure 197 demonstrates a visible layer of groundwater at a depth of 8 m and deeper (light blue), which was 5 m under the gravel pit bottom, where the waste starts, 23 March 2012. Due to the long-lasting drought, the groundwater is in the low groundwater state.

Characteristics of the resistivity profile: date: 2012-03-23; length: 76m; number of electrodes: 20; distance between electrodes: 4m.

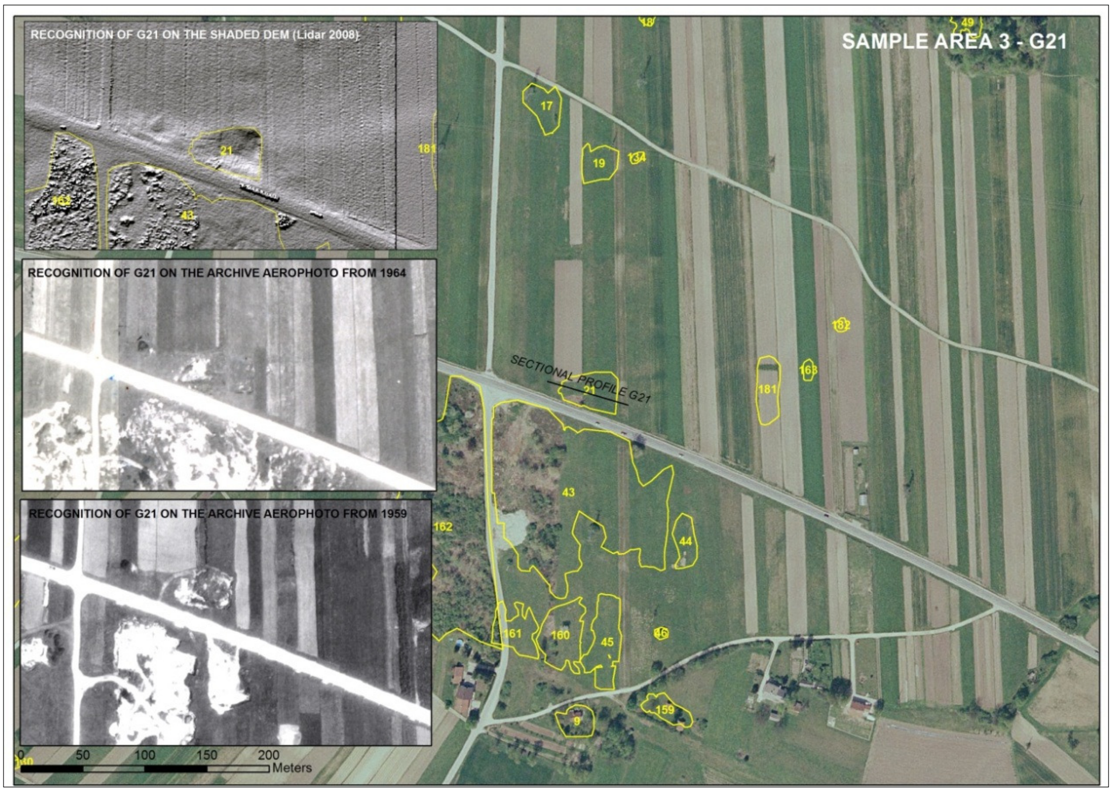


***Figure 196**: Location of the profile (black line) regarding the observed gravel pit 21 and a recognition of the gravel pit in the recent and past landscape.*

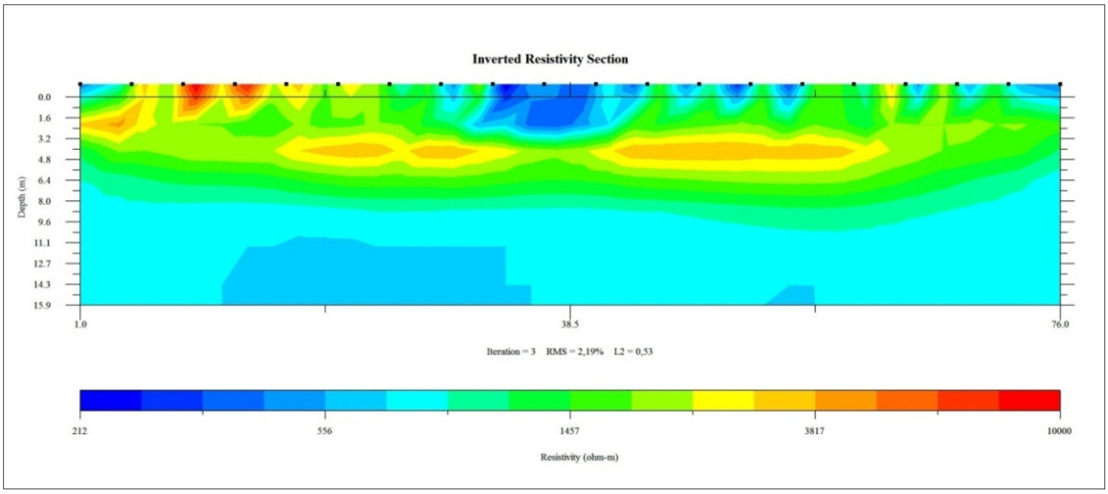


Figure 197: *Electrical resistivity section of G21, Schlumberger-method. Blue color in the deeper layer below 8 meters indicates groundwater.*

9.6.2.4 Jarški prod 2

The sample area 4 (Figure 198) lies south of the Brod village and is about 700 m away from the Sava River and 250 m from the Jarški prod water plant. The area is overgrown by a sparse forest of poor quality that is intermittent with areas or meadows overgrowing and an area of overgrowing former filled and unfilled gravel pits.

The vegetation grows on **fluvisols on a gravel-sand alluvium,** with undeveloped riparian soils closer to Sava. The area is classified into the flooding zone of catastrophic floods. The area includes gravel pits (23, 24, 30, 31, 192, 115, 71, 72, 26, 7374) that are shown in the shape of ridged slightly concave relief shapes or slightly convex relief shapes on the relief laser scanning data. Some gravel pits were also determined on the archive photographs, like the DEM of the former surface (PAS 1964). In 1964, the excavation depth in larger dolines (e.g. G 31) amounted to as much as 5 m. By 1975, most of the gravel pits were filled and in the overgrowing phase.

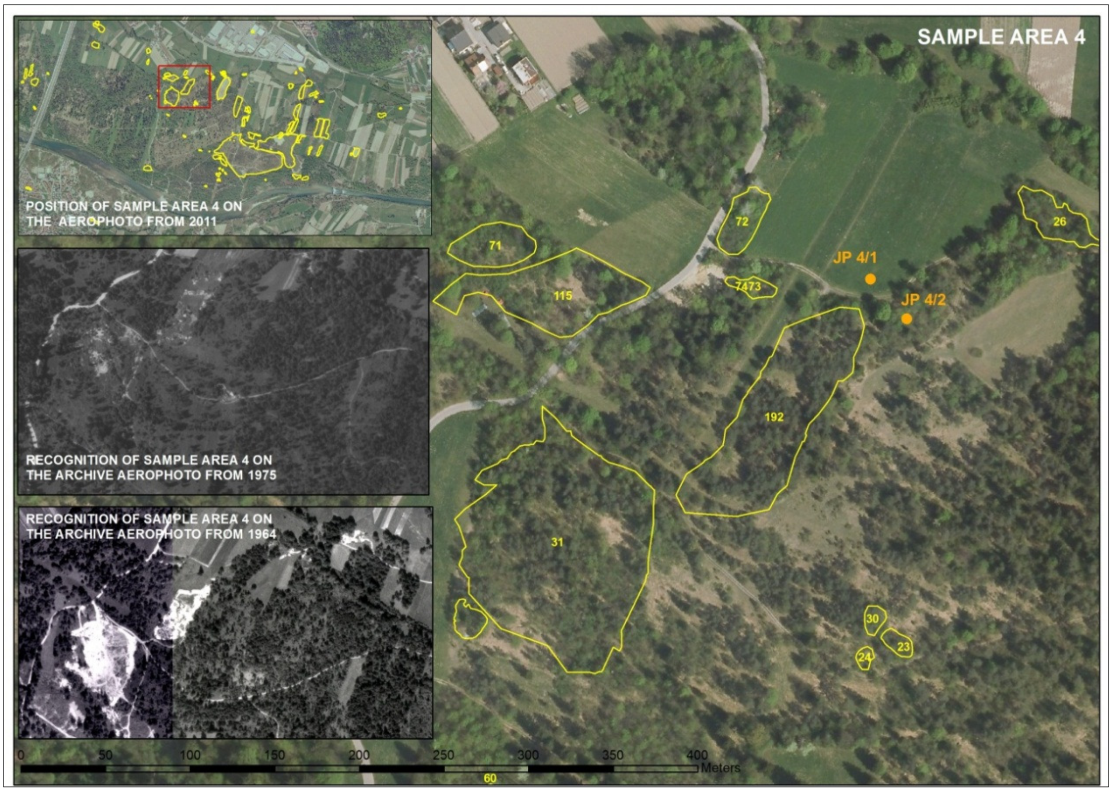


__Figure 198__: Location of sample area 4 in relation to the observed gravel pits and a recognition of the gravel pits in the past landscape.

Name	Land use	Depth (cm)	Horizons	Anthropo. parts	Soil base	Soil type
JP4/1	meadow	55	2 (loamy layer above sandy layer)	none	gravel	calcaric fluvisol
JP4/2	forest	40	2 (loamy layer above sandy layer)	none	gravel	calcaric fluvisol
G 26	forest	24	none	construction waste	gravel, waste	deposol
G 31	bushes	20	none	construction waste	gravel, waste	deposol
G 72	forest	60	none	none	gravel	calcaric fluvisol
G 77	meadow	40	none	none	gravel	calcaric fluvisol
G 115	bushes	75	2 (loamy layer above sandy layer)	none	gravel	natural loamy fluvisol
G 192	bushes	10	none	Construct. waste	unstructured gravel	deposol

__Table 23__: Results of the pedological sounding in sample area 4.

Figure 199*: The referential profile JP4/1, sampled in the meadow is 50cm deep fluvisol.*

Figure 200*: Referential profile JP4/2 40 cm deep fluvisol in the forest. Detail of the roots in the auger tip (right).*

Both referential profiles (Figure 199, Figure 200) are examples of a shallow fluviosol with gravelstones in the bedrock. The soil on the meadow is deeper, loamier, with no humus top layer, which indicates anthropogenous alterations of an agrarian nature (tilling), where the natural horizons got mixed together. The deeper loamy soil is also expressed in the more moist surface reflection in the NIR part of the EMS and coincides with a smaller relict riverbed that is of a more recent origin due to its proximity to the Sava River. The Sava River flowed on this area in a branched out manner about 100 years ago, before it was moved south with hydromeliorations (Breg 2007). Based on this, it may be assumed that the alluvial soils on area 4 are approximately 100 years old and that the speed of soil generation is accordingly 40cm / 100 years.

Figure 201*: The soil profile of shallow deposol with unstructured gravel bedrock in G26.*

Figure 202: *Figure demonstrates profile G31 (20cm deep, gravel bedrock 10cm). It shows unusually big gravel stones at 10 cm depth. The profile is an example of deposol.*

Figure 203: *Profile G72 is 50cm deep soil on sandy gravel bedrock at 50cm depth (left), detail in auger (right) presents upper humus horizon.*

Figure 204: *Profile G 77 represents a natural calcaric fluvisol.*

Figure 205: *Profile G115 (upper) and detail in the auger tip of upper an humus horizon with roots (25 cm).*

The sampled soil on the area of gravel pit 192 (Figure 2006) is too shallow to be categorized among natural soils according to the JP4/1 and JP4/2 referential profiles. The gravelstones vary greatly in size at a depth of 10 cm, which indicates unstructured material of an allogenic origin. The sounding of natural riparian soil on a gravel surface proves how the density and size of the gravelstones increase with the profile depth, which points to a natural adequate sorting of skeletal particles in the soil.

Figure 206*: Very shallow unstructured deposol on G192.*

9.6.2.5 Jarški prod 3

Sample area 5 lays 1km north of the Sava River, to the left of the Štajerska cesta regional road and south of the Črnuče industrial zone. Due to a greater distance from the river, the soils are deeper and more developed.

Two potential gravel pits (Figure 207) in the area were studied, which were located using methods of the past landscape analysis, but not with a high degree of certainty. The photographs from 1964, 1975, 2006, and 2010 were compared. They reflected great changes in the use of the surface. The basins were noticed to be in the overgrowing phase on the photograph from 1964 and the area was completely overgrown in 1975, while the area was a meadow once again in 2006 and a forest (*mejica*) in 2010 on the G250 area. The gravel pit depth was determined at about 3 m based on the 1954 DSM.

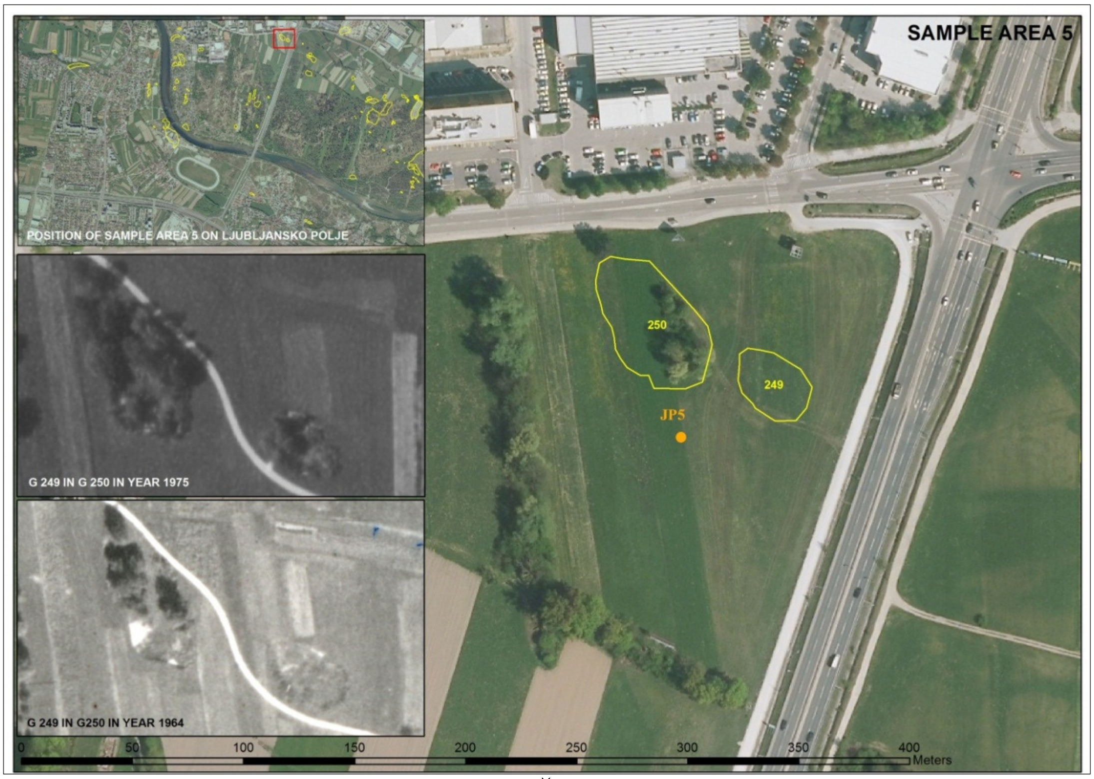


Figure 207: *Location of sample area 5, near Štajerska cesta road, in relation to the two observed gravel pits and a recognition of the gravel pits in the past landscape. The position of the electrical resistivity profile is marked in black.*

Name	Land use	Depth (cm)	Horizons	Anthropogenic parts	Soil base	Vegetation	Soil type
JP5	meadow	50	yes	none	gravel	grass	fluvisol
G 249	meadow	25,27,25, 50	none	construction waste, mixed	loam, gravel	grass	deposol
G 250	forest	35	none	none	gravel	snowbells	fluvisol

Table 24: Results of the pedological sounding in sample area 5.

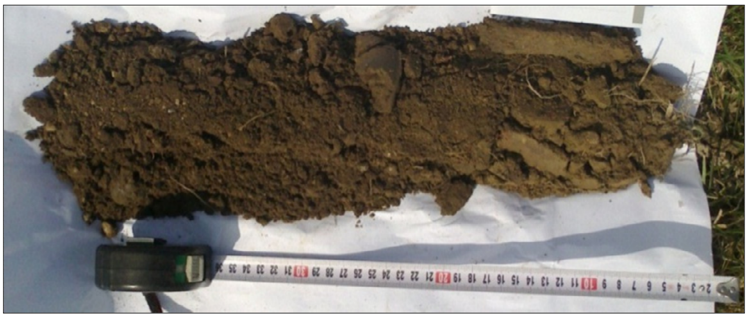


Figure 208: *Referential profile JP5. The sample was taken in a meadow. The profile depth is approximately 50cm.*

The referential profile JP5 (Figure 208) depth is approximately 50 cm, where smaller gravelstones appear. This is a shallow, slightly loamy fluvisol on a gravel.

***Figure 209**: The profile of gravel pit G249 is over 25 cm deep.*

***Figure 210**: Profile of G 250 with very dense and deep roots and without waste or any other anhropogenic parts.*

In addition, the electrical resistivity of G249 was measured (Figure 211). A sectional profile with following characteristics was made: length: 58 m; number of electrodes: 20; distance between electrodes: 3m; tested methods: Schlumberger, dipol / dipol

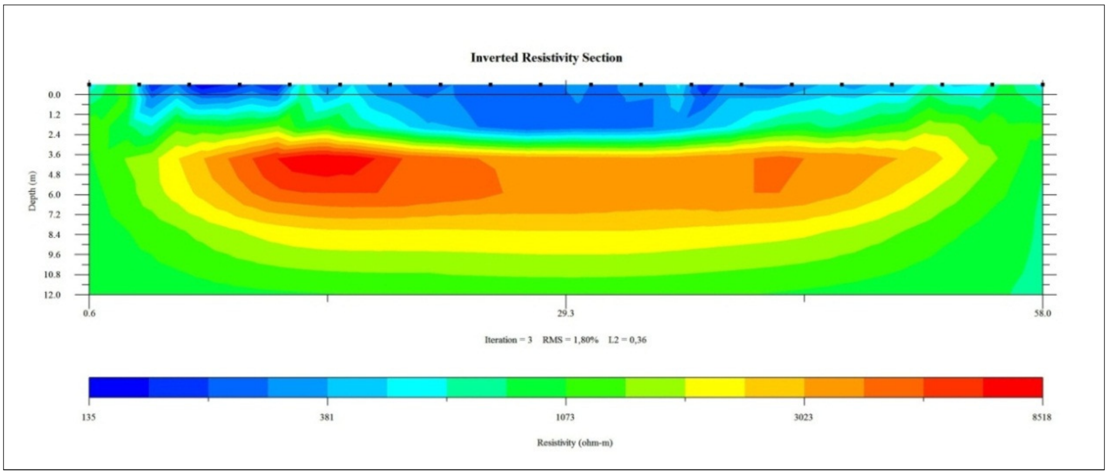


***Figure 211**: Electrical resistivity section of G249, the measurement is based on the Schlumberger method.*

The G249 sampling area is a waste-filled gravel pit, whose depth amounts to approximately 3 meters, which precisely matches the depth that was estimated on the map of gravel pits depth calculated from DSM1964 (Figure 151).

The section is in Figure 211, acquired using the Schlumberger method. The estimated waste depth and the geological layer underneath proved to have an extremely high resistance (over 8000Ω), which may indicate a probable loamy or clay layer.

9.6.2.6 Roje

Sample area 6 (Figure 212) lies on an alluvial plain, 500 m south of the Sava River, with relict riverbeds detectable in the relief as well as on the CIR image. The sample sounding area consists of two potential gravel pits (G0 and G5) that were located with the relief analysis of the recent surface (Lidar) and placed in the highest (G0) or middle (G5) level of probability of a gravel pit being filled.

The available archive aerial photographs (1964, 1975, 1985, 2006) show no changes in the ground use on the areas. According to the results of the pedological sounding (RR1, RR2), the soil is deeper and contains loam; it is more moist and therefore seems cooler (RR1). In contrast, the areas of the shallower, sandy soils (RR2) are drier and appear warmer.

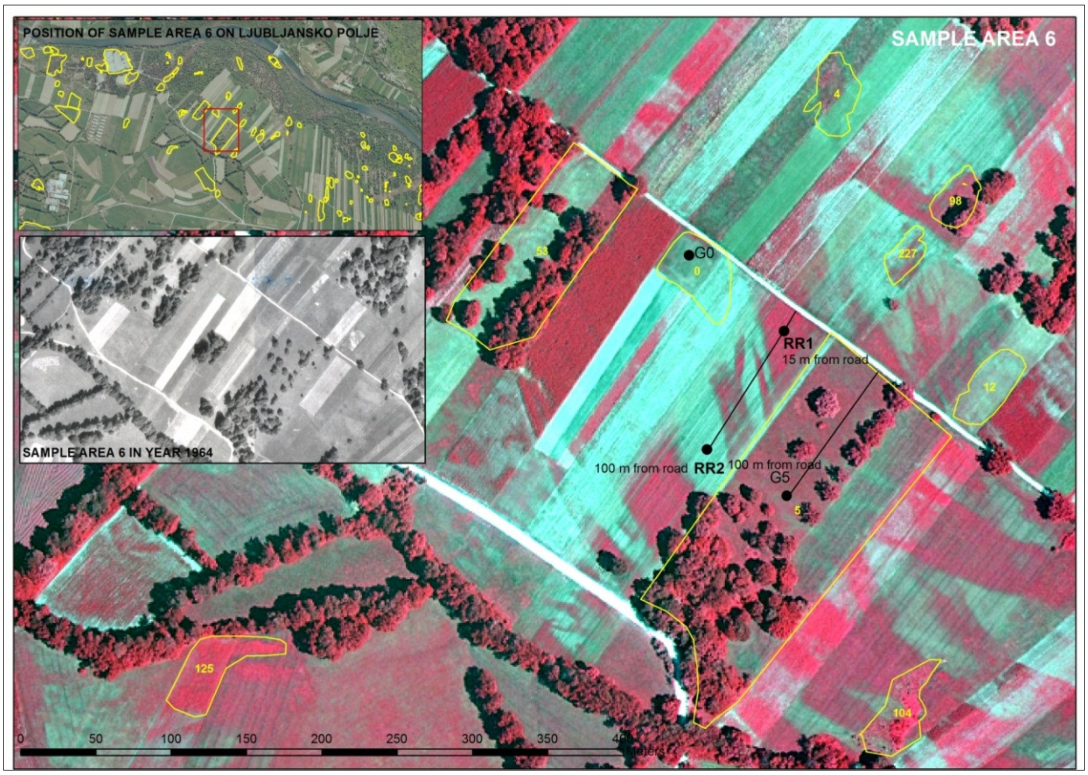


***Figure 212**: The position of pedological sounding profiles on sample area 6.*

Name	**Land use**	**Depth (cm)**	**Horizon**	**Anthrop. parts**	**Soil base**	**Vegetation**	**Soil type**
RR1	meadow	90	yes	none	loam, gravel	grass	soil in relict riverbed
RR2	meadow	25	yes	none	gravel	grass	fluvisol
G 0	meadow	25,27,25	none	construction waste	construction waste	grass	deposol
G 5	meadow, rare trees	35	yes	none	loam, gravel	grass	fluvisol

Table 25*: Results of pedological sounding in sample area 6.*

Figure 213: *Referential profile RR1 is an example of deep and humid loamy soil in a relict riverbed.*

Figure 214*: Referential profile RR2 is, in contrast to RR1, a very shallow natural soil, sampled outside a relict riverbed, only 85 meters away from RR1 on the same meadow.*

Figure 215*: Profile of gravel pit G0.*

Figure 216*: Profile of gravel pit G5.*

Based on the results of the pedological sounding (Figure 216) , it is not possible to claim with certainty that this is a filled gravel pit or other natural basin. It needs to be additionally verified by measuring the electrical resistance. Area G5 is confirmed as a natural area and is not a filled gravel pit. The soil sample represents natural fluvisols.

9.6.3 Field mapping

Field mapping with the intent to control the gravel pit areas that were located using geoinformatic methods, was carried out during March and April 2012. Every accessible, previously located gravel pit area was verified in the field and the following attributes were determined:

Relief attributes:

- The gravel pit can be recognizable in nature by its relief: an expressed concave shape / an expressed convex shape / ridged flat surface / ridged slightly concave surface / ridged slightly convex surface.
- The state of the gravel pit being filled in nature: no signs of filling / partially filled / completely filled.

Vegetation attributes:

- Land cover of the potential gravel pits: active waste disposal site / built-up, partially built-up / fields and gardens / meadow / traditional meadow / sparse trees, overgrowing / overgrowing with bushes / forest / active gravel pit.
- The presence of vegetation / waste: no cover, still visible waste on the surface / completely uncovered / overgrown with natural vegetation / cultural vegetation.
- Mosses: the ground is visibly overgrown with mosses / no present mosses.

The charting data were merged into a digital geoinformatic layer, where the gravel pit locations are presented with ranges that were located using geoinformatic methods. Based on the field research of the relief characteristics and anomalies and the presence of waste on the areas of potential gravel pits, the level of probability that there was deposited waste in the gravel pit was determined (Figure 217). It should be noted that using this method did not confirm the suspicion that the object was actually a gravel pit. It may be a filled relict riverbed or a flaw of the geoinformatic method, which can also mean that a gravel pit never existed there.

Class 1: completely filled convex, flattened, or slightly concave landform with visible waste on the surface (No 82).

Class 2: completely filled convex, flattened, or slightly concave landform with no visible waste on the surface (No 23).

Class 3: partially filled convex, flattened, or slightly concave landform with visible waste on the surface (No 128).

Class 4: partially filled convex, flattened, or slightly concave landform with no visible waste on the surface (No 12).

Class 5: The gravel pit areas that remained unchanged from the aspect of waste dumping are unfilled and are subject to secondary succession (No 7).

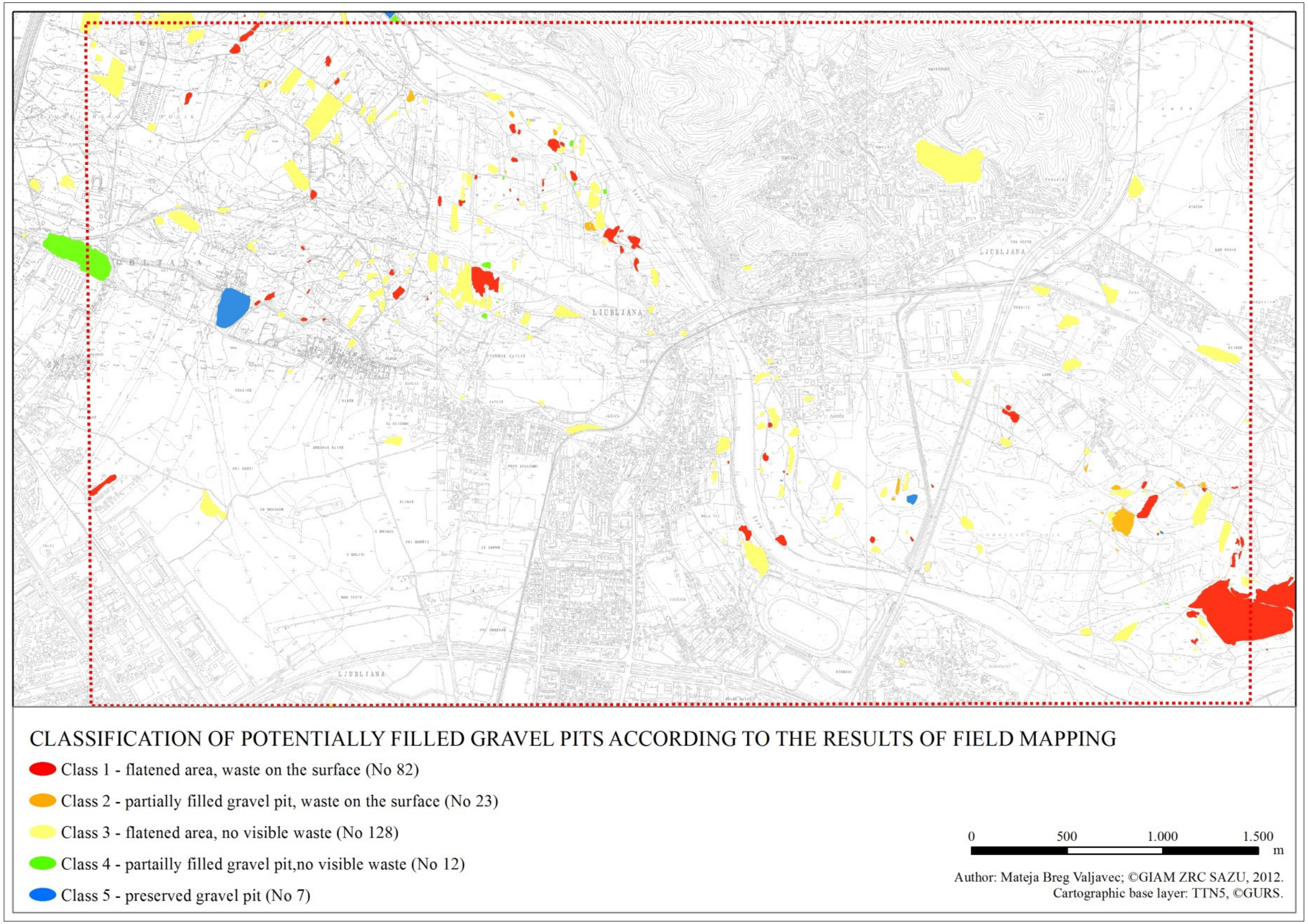


***Figure 217**: Possible validation of the cadaster with the results of field mapping.*

9.7 Conclusive Remarks for Further Geoinformatic Studies

The connections between a certain soil characteristic and the spectral reflection characteristics were determined by analyzing the multispectral aerial photographs and the pedological sounding.

The soil sounding samples only prove deposols but not also the gravel pit existance. Regarding these it must be considered that the deposols can be developed either on a thin layer of waste or on a few meters thick layer of heterogeneous waste filled in a gravel pit. In accordance to the Russian classification (Stroganova et al. 2004), the first could be named deposols and the second depozems. In some case study gravel pits, the results need to be supplemented with methods that allow the estimation of waste “depth”. This either means a 3D past landscape analysis (DSM analysis) or measuring the electrical resistance of the ground in the recent landscape.

Deposols are detectable by geoinformatic methods on FWDS gravel pits that had been “remediated” by covering them. Construction and demolition waste was most commonly used for covering the disposed waste material, along with the material from construction excavations (e.g. G22, G42, G127, G192, G31). Since the gravel from excavations is a useful construction material, it was usually not dumped; however loams and clay excavation material of a poorer quality were. Deposols were formed on layers of allogenic soils or waste. Since they are quite young and unstructured, they usually do not have a developed humus horizon on top. The waste (mostly construction and demolition) is shallow under the surface, so the root zone is shallow as well. Like on the natural bedrock, the pedogenetic factors specific for waste “bedrock” launch pedogenetic processes. The depth and mineral structure of the deposols form the physical characteristics like soil moisture, soil temperature, nutrients, pH that locally affect the vegetation development on deposols. These characteristics of soil and vegetation are reflected most intensively in the infrared parts of the EMS.

Based on the analysis of the sampled sounding profiles it may be discovered that soil moisture as a consequence of mineral structure and depth is elementary for distinguishing between deposols on FWDS from natural soils in the studied area. For the Ljubljansko polje study area, two types of soils are predominant. Shallow fluvisols on carbonate gravel and sand are predominant on Holocene alluvial terraces, while deeper brown eutric cambisols appear on higher Pleistocene terraces. Due to the sandy structure and relative depth (from 10 to 60cm), both soil types are dry. This reflects in the NIR band.

Another important conclusion of the field work are the characteristics of deep soils in relict riverbeds in connection with deposols and other predominantly natural soil types. Due to the convergent surface, water flows in relict riverbeds and the loamy structure soils are moist and have a high reflection in NIR. In contrast, the shallow as well as deeper sandy soils on relict point bars between the relict riverbeds are drier. The referential profiles of areas 6 (RR2) and 3 (KL3) are both deep, but they differ in their mineral composition. The 90cm deep RR2 in the relict riverbed is loamy, while the KL3 is sandy. The differences in the examples are partly a consequence of the differences in the land use. KL3 is sampled on a planted field that was not completely covered with vegetation at the time of the shooting and RR2 was sampled on a traditional meadow. In comparison to that, profiles RR2 and RR1 were both sampled on the same lot, a traditional meadow. The first lies in a relict riverbed and the other outside it, which means a difference in depth 80: 25cm and also in the mineral structure (fine loam). If the spectral sample of the FWDS gravel pits is compared with the spectral reflection of non-degraded surroundings, it may be concluded that the FWDS gravel pit areas are moister than the sandy fluvisols on relict point bars. An extremely uneven image texture in the NIR band is a consequence of a ridged relief, which directs the surface water as well as the heterogeneous waste structure (see Figure 218, gravel pits 22 and 42). Sample areas 6, 2 and 3 illustrate differences between the natural areas and FWDS gravel pits. Even the vegetation indexes that were calculated based on the satellite (GeoEye1, August 2009) and aerial photographs (CAS, June 2006) depict healthy vegetation on the areas of filled gravel pits (G21, G22, G42, G127, G249, etc.). On FWDS gravel pits overgrown with bush or tree vegetation (see sample area 4), the spectral reflection of the soil does not appear, as the tall and thick vegetation enables measurements of the soil reflection.

Areas 1 and 4 represent forested areas on Jarški prod point bars. The soils are shallow sandy, undeveloped fluvisols on carbonate gravel-sandy bedrock. The case study gravel pits on area 1 are mostly not filled with waste. Only smaller piles of very old waste appear, which indicates that they were never premeditatedly filled or remediated. They have retained a concave relief shape and have been overgrown with bushes and low trees in the last fifty years. Shallow profiles (15cm) of the newly-forming soils were sounded on gravel at the basin bottoms. The soils are black, humus. Snowbells (*Galanthus nivalis*) flourished there in March. The filled gravel pits in area 4 (G26, G31, G192) are filled or partly filled with waste and overgrown with sparse forest. Field charting allowed us to locate the visible waste on the surface. Differentiating between the mentioned FWDS overgrown gravel pits on area 4 from the unfilled overgrown gravel pits on areas 1 and 4 is possible with relief analysis. The NIR band does not focus on the consequences of waste disposal in the vegetation, except if dangerous waste is deposited that harms the vegetation (vegetation stress). The natural vegetation on the studied area on the point bars along the Sava River is predominantly very young, sparse, and expresses similar characteristics as the areas of overgrown FWDS gravel pits. However, with the help of off-road gravel pit mapping on sample areas 1 and 4, the differences appear on a micro-level. The FWDS gravel pits on area 4 are overgrown by mosses that also happen to be an indicator of anthropogenous soils.

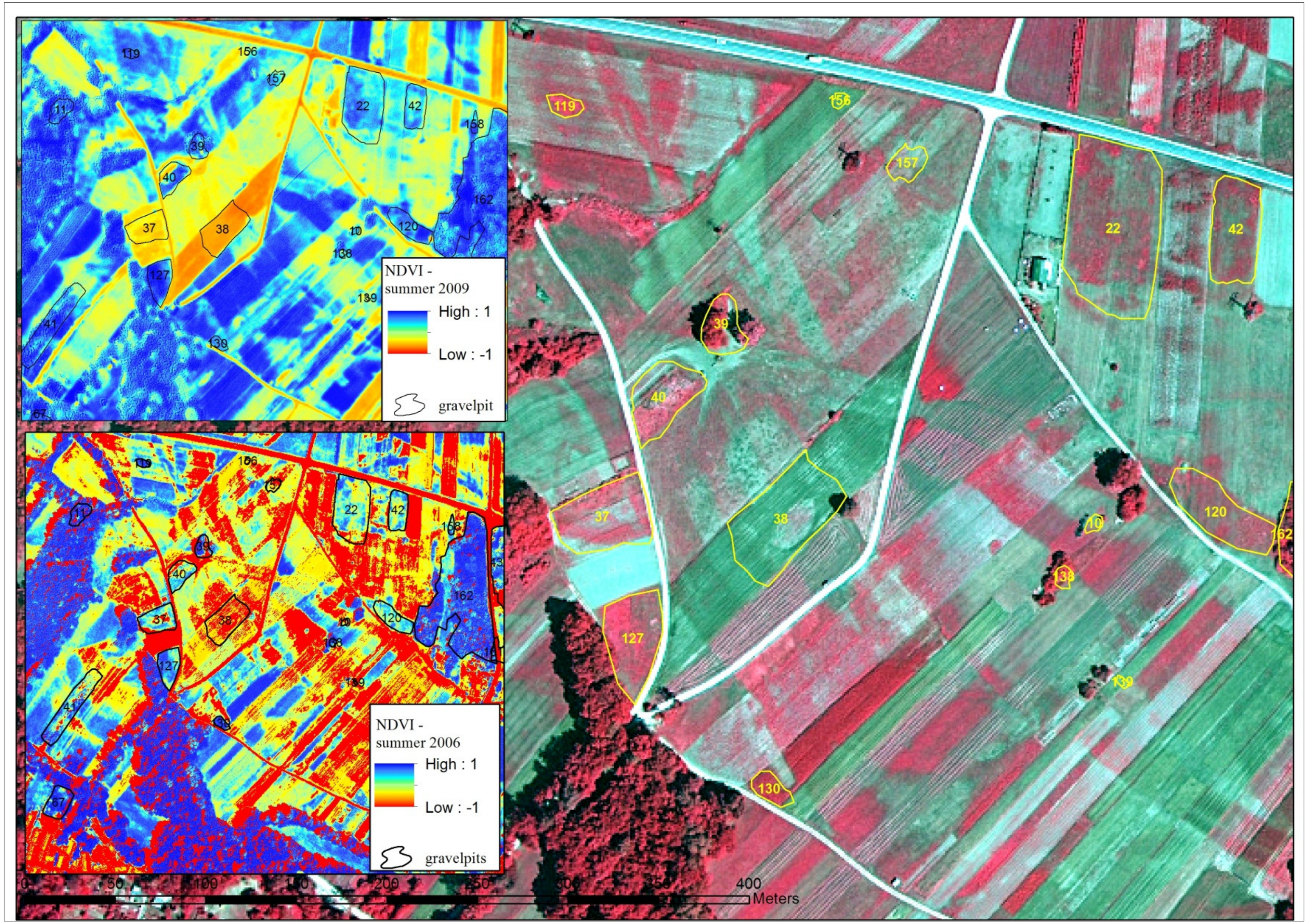


***Figure 218**: Some filled gravel pits (G21, G22, G42, G43, G127) that are confirmed with pedological sounding have a high (blue) NDVI index (healthy vegetation).*

Gravel pit areas G249 and G250 on sample area 5 on meadow areas of fluvisols outside the forest are completely blended with the surroundings. The pedological sounding did not confirm the suspicion of them being filled with waste. Only by measuring the electrical resistance of the ground was the existence of the waste in the filled basin proven, which is of an anthropogenous formation based on its depth (3m).

The areas of FWDS gravel pits and preserved gravel pits may be separated from the natural surroundings based on the pedo and phytogeographical characteristic in the field and using geoinformatic methods for studying soil and vegetation. The pedo and phytogeographical differences between the natural and anthropogenous relief shapes in the fluvial relief of Ljubljansko polje are summarized in the following table

		RELICT RIVERBED	**RELICT BAS POINT**	**OPENED GRAVEL PIT**	**FILLED GRAVEL PIT**
RELIEF	concave	x		x	x
	convex		x		x
	flat		x		x
SOIL	thick loamy soil	x			x
	shallow loamy soil		x		x
	thick or shallow sandy soil		x		x
	shallow humus soil			x	
	No soil			x	x
VEGETATION	Mosses				x
	Hydrofilneous perrenials	x		x	
	Bushes	x	x	x	x
	Tall trees	x	x		

Table 26*: The relations between the relief, soil and vegetation characteristics, identified during field research regarding natural landforms and gravel pits that are important to distinguish between natural and anthropogenic landforms.*

10 DISCUSSION

10.1 Discussion about Methodological Issues

FWDS can be determined using geoinformatic methods that make it possible to identify relief, soil and vegetation changes. Soil and vegetation analyses are based on recent landscape data (multispectral images), while relief analyses are possible in both landscapes and also with a comparison of the past and recent relief (Figure 219). The use and success of the selected methods differ according to the geological characteristics of the studied area, land use type and type of filled waste and cover layer.

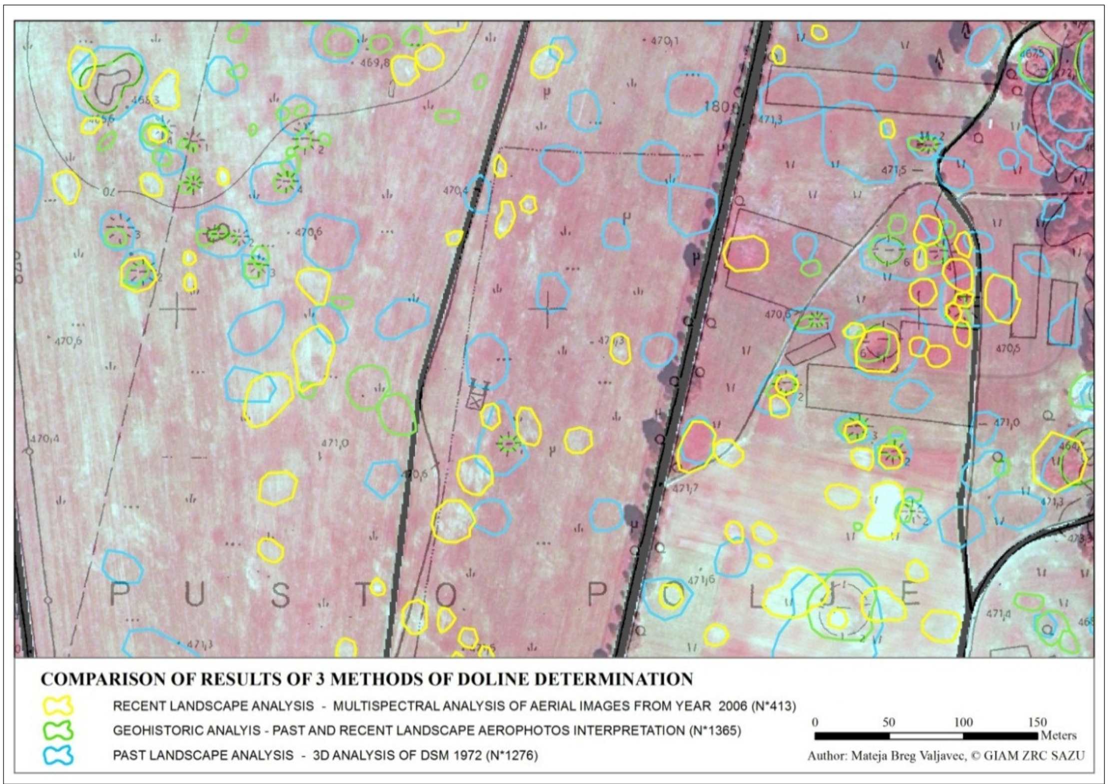


***Figure 219**: The comparison of methods for locating dolines: multispectral analysis of recent landscape in comparison to the results of the 2D and 3D analysis of past landscape.*

The represented 2TL/3E concept started with an analysis of the past landscape by determining the zero state of dolines and gravel pits. The results of all tested geoinformatic methods are merged in Table 27 and presented separately for both landscape types.

It is very time consuming to investigate the recent conditions of approximately 1,200 dolines, which were detected with 2D and 3D analysis of archive aerial photographs from year 1972. Among all, only 20 sites were tested with soil sounding and 5 of them also with electrical resistivity tomography. Field studies, sampling and measurements are very time consuming and could be performed on smaller areas but not for the entire case study area of Logaško polje. This is not a problem in recognition of gravel pits in the past landscape. The number of recognized objects is much lower and could be theoretically all tested with simple field methods.

A more object-based analysis of FWDS in highly karstified areas with a high density of dolines is recommended for further studies that must be oriented into consequences that could be recognized as an impact of waste dumping on relief, soil and vegetation. The large number of dolines makes the study unfocused on the actual FWDS research object. In order to prove the results, many more control case studies would have to be done in the field. The solution could be in recent landscape study if multispectral and relief data of high quality (high spatial resolution below 2m) are available for acceptable price. The study of recent landscape was based on multispectral aerial photographs. The result is 473 locations of potentially filled dolines that expressed soil and vegetation anomalies in comparison to the natural dolines. This are mostly dolines that were filled or covered with alogenic materials that reflect as dry, warm surface in NIR spectre. In contrary, natural soil that is formed on the bottom of dolines is loamy and humid and reflects as colder surface in NIR spectre. The results could be further validated with precise relief data to confirm also the relief anomalies (filled doline).

The final number of FWDS in dolines is 92 and in gravel pits 118. These results were obtained only with synthesis of individual methods (probability maps) and afterwards the synthesis map was compared to the existing old registers.

	GEOINFORMATIC METHOD	LOGAŠKO KARST POLJE				LJUBLJANSKO POLJE ALLUVIAL PLAIN **(CASE STUDY - ROJE)**			
		DATA TYPE AND TIME	ZERO STATE DOLINE	FWDS BY METHOD	**FWDS**	DATA TYPE AND TIME	ZERO STATE GRAVEL PIT	FWDS BY METHOD	**FWDS**
PAST LANDSCAPE	VISUAL INTERPRETATION AND ON SCREEN DIGITALIZATION	Digital archive aerial photos 1972	1,200	/	**92**	Archive aerial photographs 1959	56		118
						Archive aerial photographs 1964	46		
		Topographic map 1:5,000	947			Topographic map 1:5,000 (TTN5)	2		
	STEREO INTERPRETATION	/	/	/		Archive aerial photographs 1959	24		
						1964	19		
	GEOMORPHOMETRIC ANALYSIS	DSM 1972	1,276	/		DSM1959	59		
		DTMTTN5	947	/		DSM1964	28		
RECENT LANDSCAPE	MULTISPECTRAL IMAGE PROCESSING	4-band composition image (DOP 2006)	/	473		4-band composition image (DOP 2006)		26	
						GeoEye1 satellite image (August 17, 2009)		26	
	VISUALISATION OF DTM		/			Lidar 2008		48	
	HYDRO-GEOMORPHOMETRIC MODELING		/			Lidar 2008		31	
COMPARISON OF PAST AND RECENT	COMPARISON OF PAST AND RECENT RELIEF	DSM 1972		566		/	/		
		DMTTN5							
	GEOHISTORICAL LAND USE ANALYSIS	Digital archive aerial photos 1957, 1972 and DOP 2000, 2006		161					

***Table 27**: The results of the individual geoinformatic method in relation to the past and recent landscape study.*

10.1.1 Detection of FWDS According to the Soil and Vegetation Changes

In the chapter Hypothesis (1.4) it was stated that the impacts of waste disposal could be detected in recent soil and vegetation changes, depending on the non-degraded surroundings.

The filled and overgrown gravel pits are not detectable on regular RGB images, while some filled dolines can already be detected on the image in the colors of the visible part of the specter – RGB DOP (red, green, blue). To improve the results **the multispectral analysis** of karstic and nonkartic landscape was based on the aerial photograph analysis (aerial photographs from 2006, ©GURS), where the entire area of Slovenia was recorded in four radiometrical bands (red, green, blue, NIR). The radiometric bands are mosaicked in the RGB and CIR files; as a consequence, they need to be processed to generate a four-band image for automatic image processing. The method cannot be used as an independent method to successfully determine FWDS on Ljubljansko polje, while it gives very good results on Logaško polje, predominantly the alluvial part of studied area (cover dolines). The method enables to exclude the areas with warm / dry vegetation (automatic analysis) and areas with sparser vegetation above the waste (visual analysis) that are typical for FWDS dolines. The multispectral analysis consists of unsupervised image classification (ISODATA) and of the detection of vegetation stress via the calculated vegetation indexes (NDVI, IR/R) of the vegetated surface.

Regarding land use type we conclude that dolines on Logaško polje that are the easiest to detect lie on meadow surfaces. FWDS on predominantly loam alluviums on Logaško polje that have top layers of construction and demolition waste, carbonate tailings from the near-by quarries or of Permo-Carbon slate and are overgrown with meadow vegetation are the most easy to detect using multispectral analysis. The reason for this is the temperature difference between the surrounding soil and the deposols in the FWDS. The FWDS's differences in moisture and consequently surface temperature enable it to be detected on the NIR spectral channel. Such FWDS are also easy to detect on field surfaces.

The multispectral method is successful in detecting dolines being filled with industrial waste (Company Kli doline - profile V 481), filled or at least covered with construction material or tailings from the dolomite quarry (dolomite) (V402). The main reason is the absence of loamy structured soils that are typical for the bottom of natural dolines. Usually there is no soil developed on the top layer or it is a very shallow soil-like layer, dry deposol, and warm in comparison to traditionally cultivated and agrarian dolines in which the soils are deeper, loamy, moister, and reflect cooler in NIR band of specter.

The first exception to this is areas on limestone and dolomite around dolines where shallow soil is usually developed with a similar spectral reflection. An example of this is sample area 2, which lies on dolomite. Based on the multispectral analysis, case study doline V6000 was determined as a potentially filled doline, but pedological sounding showed that this was a case of an natural concave landform in dolomite bedrock. Profiles V6000, RLOG3A, and RLOG3B are typical case studies of soil forming on dolomite bedrock in relation to the geomorphological structure. V6000 and RLOG3B were sampled on a convex relief shape, from which a weathering material is washed into an intermediate concave shape (forming indentation), where the RLOG3A profile was sampled. The first two profiles are extremely shallow, the original foundation is reached at a depth of 20 cm (crushable dolomite), while the middle layer is at least 80 cm deep (deeper sounding was prevented by the dense loam).

Finally, the effect of agromeliorations must be taken into account, as the waste-filled dolines were "remediated" simply by being covered with thicker layers of the surrounding soil in order to ascertain more quality farming surfaces that would be appropriate for motorized cultivation. As a consequence, most of the dolines on Pusto polje were filled with waste and later "remediated" with agromeliorations. The waste does not appear until a greater depth (1 m) and does not have a direct physical effect on the soil characteristics (moisture, temperature) to be recognizable on near infra-red photographs. Also, the vegetation expresses good conditions rather than vegetation stress that could be measured by NDVI. Nevertheless, by field charting the vegetation, anthropogenic soil with nitrifilneous vegetation that is developing above organic waste was proven. A more detailed phytogeographical research will be necessary, oriented towards field charting the grassland vegetation (pioneer, ruderal, invasive, eutrophic species). This could potentially prove the effect of a large amount of waste on the development of the micropedological and microhabitat characteristics that differ from the surroundings. Theoretically, the waste could create special growth conditions due to a lower water content, greater / smaller amounts of nutrients, a smaller electrical resistance, a smaller specific density and other chemically-physical characteristics.

The NDVI index of the FWDS gravel pits that have been overgrown with grassland vegetation is very high, which is a consequence of increased moisture, reflected on the NIR band. The vegetation index of the vegetation damage that overgrows filled dolines depends on the type of covering material. Vegetation stress was not detected on such areas, rather the opposite. No noticeable vegetation differences were detected in comparison to the surroundings during the field vegetation charting. The index is low for the vegetation that overgrows dolines with a hard mineral cover and dolines where the waste is not covered. The low value is predominantly the consequence of shallow, unsaturated, dry deposols. A low value was also expressed on doline areas where organic waste was deposited in alluvial dolines. The area temperature increased with the decay of organic waste and is noticeably higher than the temperature of the surrounding loamy alluvium. The type of waste in the FWDS was not identified with the described geoinformatic analysis in the research. This would require extensive field research as well as invasive research of the ground.

Pedological sounding is an easily and quickly feasible, lightly invasive method that does not leave traces in the landscape but enables god and relaiable results. The soils were sampled on 25 gravel pits and 20 doline locations. Before that the locations were classified regarding the level of environmental risk with already represented geoinformatic methods (synthesis maps and cadaster). The suces of classification is represented in Figure 220. In first column are included FWDS in dolines (green) and gravel pits (blue), which were correctly determined as locations of high environmental risk (1st or 2nd risk level) that was also confirmed with deposol sounding profiles. In the second column preserved dolines and gravelpits are included, which were correctly determined as locations of low environmental risk (3rd and 4th risk level) and confirmed with soil sounding as natural soils or agrarian anthrosols. In third column are dolines or gravel pits that were classified wrong.

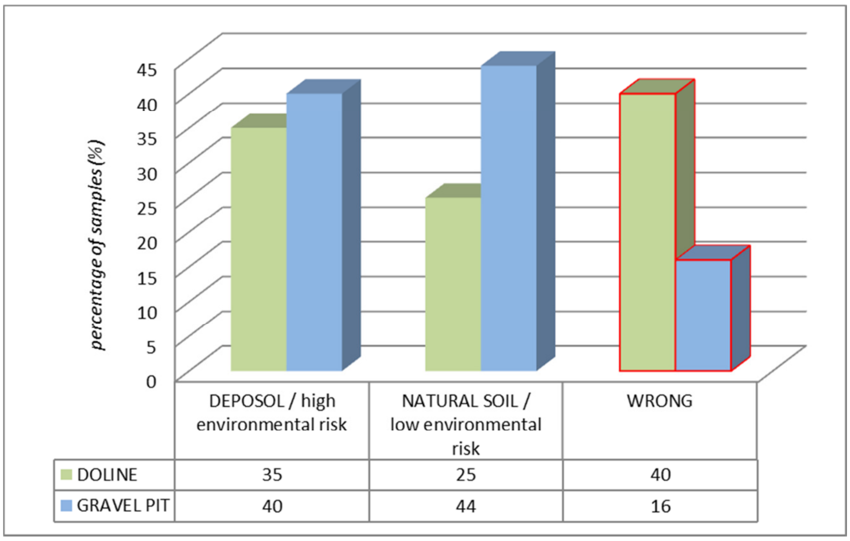


Figure 220*: The figure shows the success of applied geoinformatic methods in accordance to soil sampling testing methods.*

The method of locating FWDS using soil and vegetation anomalies is not usable on the areas that are densely overgrown with forest. On such areas, it is necessary to analyze especially the density and height of the vegetation. Data from the laser scans of the surface are of use here, as the vegetation layer is eliminated. The use of the method is also limited on built-up and partly built-up surfaces.

10.1.2 Detection of Relief Changes

FWDS can be determined using g**eoinformatic methods, which enable relief analyses and determining relief changes.** This hypothesis, posed at the beginning of the research, was proved with relief analyses of the past and recent landscape and also with quantitive comparisons of both surfaces on Logaško polje.

Determination of the anthropogenic relief elements that were formed by dumping waste in nature is based on a geomorphological knowledge and understanding of the natural landforms and processes. Each studied area is very specific from that aspect. The relief changes resulting from improper waste dumping in the past remain in both studied relief types; the only difference being that this anthropogenic process has caused the karst relief today to be much more altered and degraded as a landscape element than the fluvial one. In the case of filling dolines on Logaško polje, this is namely a permanent degradation of a large number of natural karstic landforms, while Ljubljansko polje and filling gravel pits is a case of actual relief returning to its original shape. Of course, the consequences are more visible on other landscape elements, most visibly in the presence of anthropogenous soils called deposols and the ruderal surface vegetation, as well as in the pollution of underground water.

The relief change analyses are based on different digital surface models (DSM), digital elevation models (DEM), or digital terain models (DTM). The identification depends on the surface it represents. DTM depicts the relief, while the DSM depicts elevation; forest, buildings, etc. fall under this category as well. The model quality and their appropriateness for precise relief geomorphometric analyses and possibilities for a quantitive comparison (e.g. excluding the surfaces) can be extremely varying.

We have established that the photogrammetric DSMs (like DSM 1972, DSM 1959, DSM 1964) are appropriate data for studying detailed relief characteristics such as dolines and active gravel pits. From the viewpoint of generating a photogrammetric relief model, the forest floor undoubtedly represents a weak point, as these are areas where the problem is the difficulty of locating the appropriate points (locatable in the earlier and present landscape) and a sufficient number of ground control points.

The digital models of the past surface must be made anew, depending on the quality and preservation of the film or contact copies, the digitalization quality, aerotriangulation quality, and finally, the data interpolation. The end result is a DSM that is very difficult to transform into a precise DTM, because it cannot be verified in the field. It can be controlled using old topographical maps that are also a very good source of elevation data and exist for the entire area of Slovenia. The generation of the current (latest) TTN5 of Slovenia took very long to do, so it is not rare that to encounter current maps that are based on the topographical measurements from the seventies, as it happened on the case of Logaško polje. The dolines on TTN5 are very precisely marked but despite this, some smaller and shallower dolines are lost due to the inevitable data generalization. In the case of detecting gravel pits, especially smaller ones, the TTN5 is much less useful, as smaller gravel pits are almost never marked, but mostly only the biggest ones that were in the excavation period for a longer amount of time. Making a DTM from the contour lines of the TTN5 is much faster an immeasurably less demanding than a DTM or at least a DSM of the archive aerial photographs. The biggest problem with the latter methods (digital photogrammetry methods) is the missing data on the interior and external orientation of the image (camera calibration report). The latest photogrammetric programs have built-in modules and algorithms that make it possible to overcome this problem. The period when the occurrence of illegal waste disposal sites was the largest in size and amount was the period of post-war industrialization and urbanization of Slovenia, which coincides with numerous national infrastructural projects that encouraged aerial shooting. Such special aerial photo shoots (SAS) are an important source of aerial photographs for the period up to 1975, when the period of cyclical aerial photo shoots of Slovenia started (CAS). The special photo shoots covered smaller areas, tied to a project (e.g. freeway construction near Logatec), so the research is limited in that regard. Despite that, the infrastructure objects have also resulted in gravel being excavated in the vicinity (northern bypass in Ljubljana, Obvozna cesta road) or dolines being filled (the southern railway, freeway, pipeline in Logatec), so they are an important source for researching the formation of FWDS. There are also military aerial photographs, made by RAF (1943-44) of a very good quality available for certain areas of Slovenia (areas along the southern railway), but they do nott enable the DSM generation of the past landscape. They are also kept in foreign archives (e.g. RACHMS, Edinburgh, Great Britain) and very expensive (70 €/scaned image 1,200 dpi).

The hydrogeomorphometric method made it possible to independently determine filled gravel pits: this means a very precise determining of the position and shape as well as the spatial extent or the horizontal delineation of the object. It is immeasurably faster compared to the 3D analysis of the past landscape. The problem is the Lidar data, which does not exist for the entire country and is still very expensive. The data is available free of charge for some areas of Slovenia (Dravsko polje, Istria).

The problems of the method are areas covered with forest that have a very high relief potential. People do not interfere in the surface in the forest compared to the cultivated agrarian surfaces and the urban land use. The relief under the forest can be detected as a ridged surface using laser scanning, which is also typical of completely filled gravel pits. This problem can be avoided by determining the tree density and height at a critical location with the help of the orto-photo and the Lidar vegetation layer. When the trees are tall, it means they flourish on a stabile original foundation and natural soils that enable them a stable growth. On the areas of filled gravel pits, lower trees or bush growth flourish, since the undeveloped soils and the inhomogeneous original foundation (waste) does not guarantee a static stability to tall trees (e.g. English oak). This method cannot be used to determine the object formation, excavation period, filling period; not even the type of filling material. The Lidar data is very difficult to process due to its extremely high spatial resolution and demands extremely capable hardware and software to be processed. Of course, the method cannot be used on built-up surfaces either, because the relief has been completely anthropogenously altered.

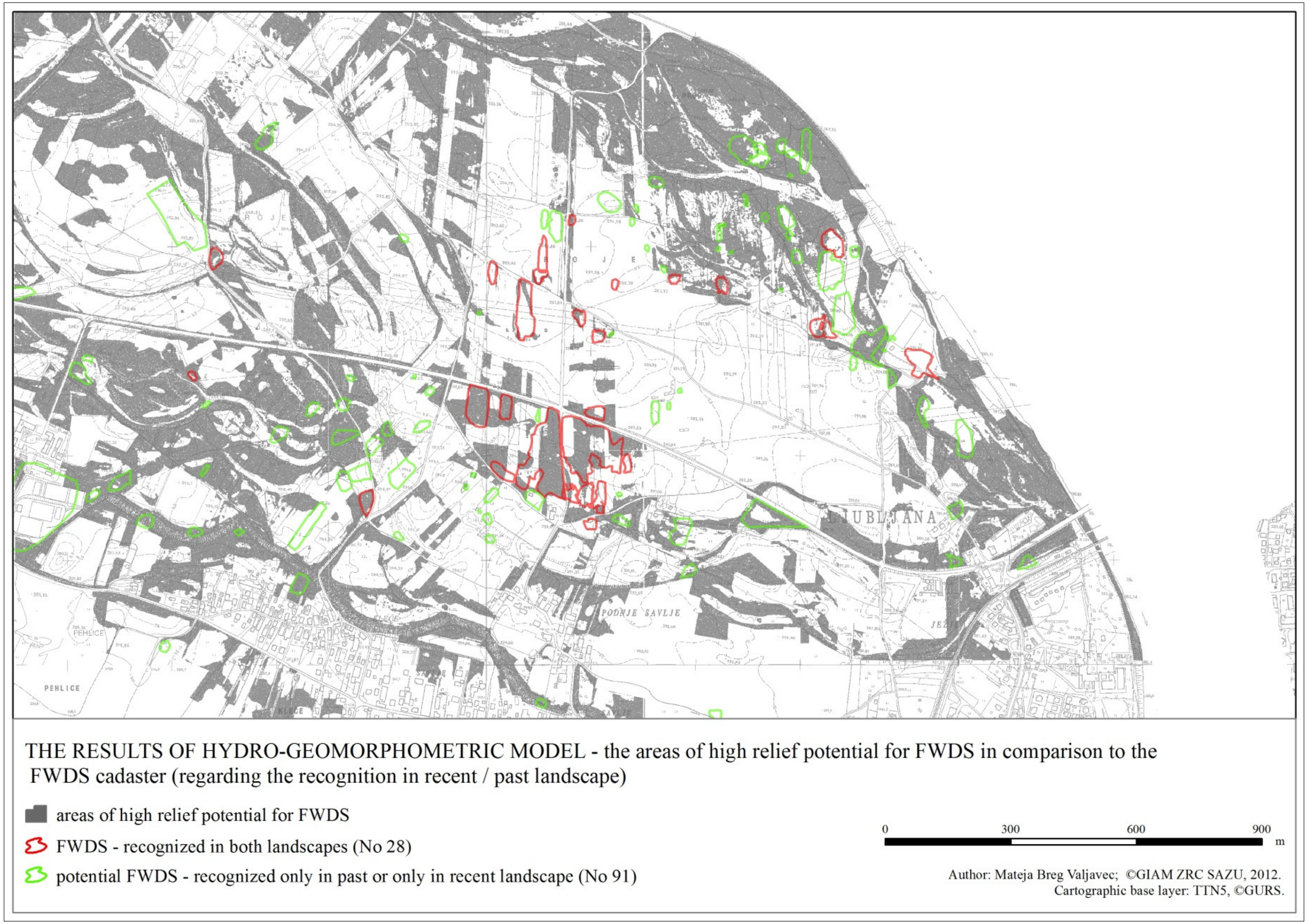


Figure 221: *The success of recognition of FWDS by hydro-geomorphometric modeling (Recent relief study).*

10.1.3 Two Landscape Types – One FWDS Model

The basic research concept presented at the beginning was called 2TL/3E. It consists of methods for studying the past landscape and methods for studying the environmental consequences on three landscape elements: relief, soil and vegetation in the recent landscape. The concept represents a framework and action plan for the research. It is the basis for a general FWDS model that will be executable in identical and similar landscape types in Slovenia.

One of the main issues in developing the final 2TL/3E model (Figure 222) is to decide whether the research should start to provide the most accurate data for the present or the past. However, FWDS are basically a historical object caused by past human activities and have been buried underground. The 2TL/3E FWDS model enables the past or recent landscape to be studied, depending on the available data of the studied landscape.

The basic goal of the 2TL/3E FWDS model is to use automatic geoinformatic methods on the available data on the recent landscape (Lidar and multispectral photographs CAS 2006) to determine potential FWDS, to minimize the past landscape analyses, which are more time-consuming. The past landscape analysis should be used only as a control method in combination with field methods or as additional method for a detailed study of individual FWDS in specific cases for determining the depth of the filled material. The model includes spectral analyses and geomorphometric analyses, which place filled gravel pits in the context of a natural fluvial relief and filled dolines in kartic landscape.

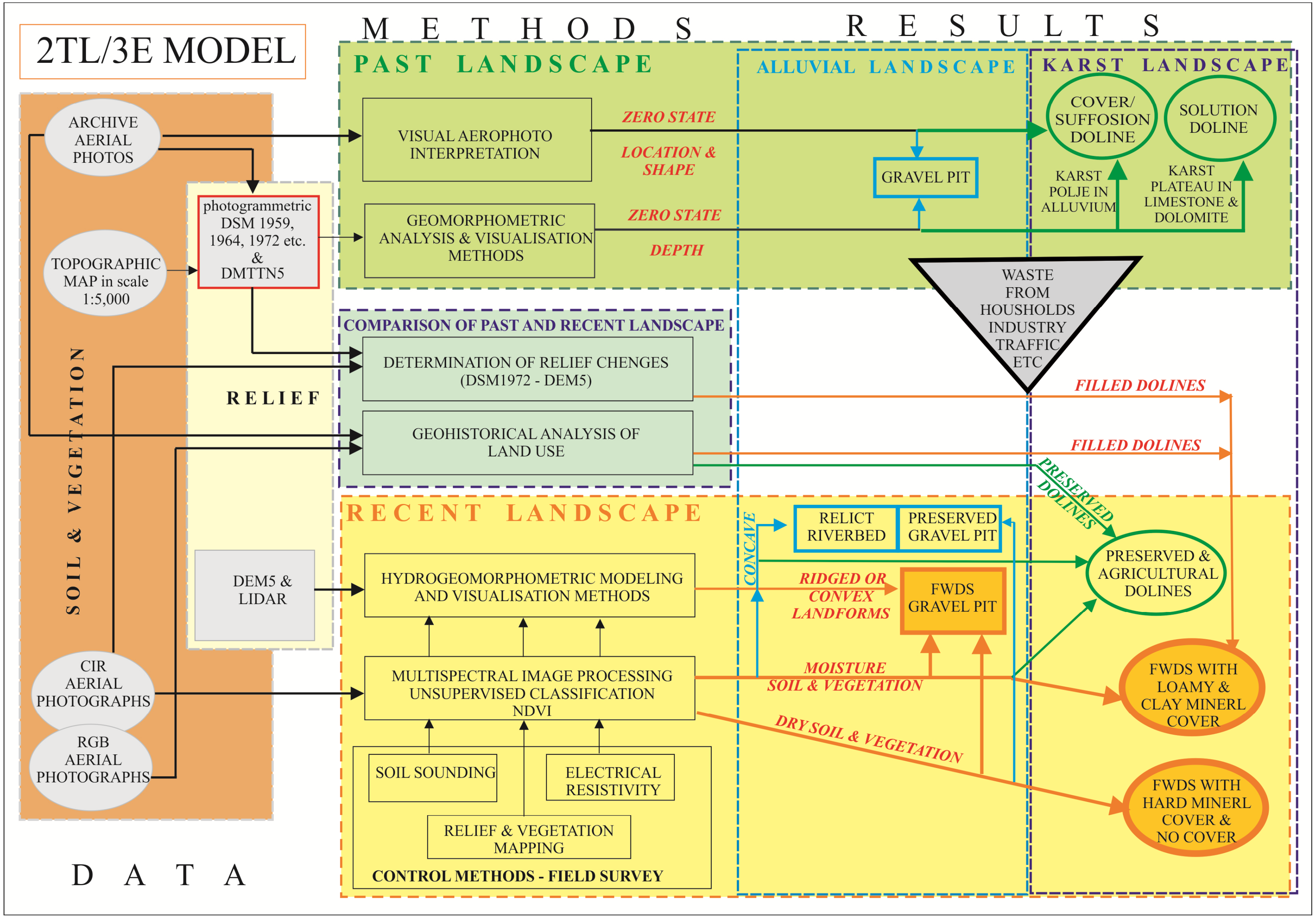


***Figure 222**: The scheme of the 2TL/3E FWDS model for detecting FWDS in dolines and gravel pits.*

10.1.4 The Issue of Dangerous Waste Remains

FWDS present a potential environmental risk in the recent landscape. The term '*potential risk*' is used for FWDS gravel pits and dolines that are confirmed to be filled today and proved to be three-dimensional concave landforms in past landscape. The type of underground deposited buried waste was not detected with the selected geoinformatic methods. Despite of all many previous researches (review in Sloncker et al. 2010) state that geoinformatics are able to discriminate the present real threat to the environment and to human health. The first radiometric research of dangerous waste disposal sites were based on the satellite image analysis of different generations of the Landsat satellites (Landsat MSS sensor, Landsat TM5 sensor, Landsat TM7 sensor). All of these images have a very good radiometric resolution (7 spectral bands, including infrared, thermal, pancromatic) but an insufficient spatial resolution for the Slovenian conditions (over 20 m, most over 30 m).

According to Slonecker et al. (2010), multispectral analyses are a successful way of determining waste disposal sites of hazardous, toxic waste by detecting the vegetation stress. In order to detect vegetation stress, the site must be filled with a large amount of toxic waste, on which unhealthy vegetation develops to such an extent that it can be differentiated from its surroundings. There are a few known larger industrial waste disposal sites of more or less hazardous waste in Slovenia that would be appropriate for testing the spectral analyses and measuring the vegetation stress. An example of this is the red mud disposal site in Kidričevo (Dravsko polje, NE Slovenia), which is a former industrial waste site of the aluminum production plant in the TALUM factory (former TGA). The area is rehabilitated by phytoremediation. It has been covered with an inert layer of soil and planted with tree vegetation in the 80s. Similar cases can be found in Slovenia in the vicinity of larger industrial towns and major production plants (Maribor, Celje, Idrija, Jesenice etc.). However, a special feature of the Slovenian waste disposal sites that were formed in the second half of the twentieth century is that they are small and numerous, so it is almost impossible to adopt the scale of foreign geoinformatic methodologies that were used to determine more extensive waste disposal sites, as they are only comparable to a few known former industrial waste disposal sites in Slovenia.

10.1 Discussion on FWDS Topic

10.1.1 The Need of a FWDS Register for Slovenia

It is necessary to establish a register of FWDS of the entire country. They represent a potential environmental risk, especially to underground aquifers, which are a source of drinking water. Porous alluvial and karst aquifers are the main and almost only sources of drinking water in Slovenia. In Slovenia, karst regions extend over 44% of the country (Gams 2003). Large karst massifs and karst plateaus, intersected by shallow karst areas, poljes and valleys, characterize the Slovene karst (Ravbar 2007). Carbonate rocks are of a very high to medium permeability, the groundwater velocities ranging between 0.02 and 29.6 cm/s, respectively from 0.72 m/h to about 1,000 m/h (Novak 1993a cited in: Ravbar 2007). Half of the national drinking water needs are already covered by capturing karst water sources, but in the dry period of the year, this amount reaches about two thirds of the consumption (Brečko Grubar and Plut 2001; Ravbar 2007). Extensive areas on the western, south-western, southern and south-eastern parts of the country are almost entirely dependent on karst water sources. Therefore karst aquifers are of special economic importance in Slovenia (Ravbar 2007).

The pollutions, detected by regular drinking water monitoring, are often of an unknown origin and do not represent a pollutants that would be formed in the recent industrial processes. The monitoring results are the evidence that recent leakages from FWDS already exist.

The present study showed the main environmental impacts that could be detected in the soil and vegetation, although some results of the ground electrical resistivity provided some inputs to discuss the impacts of pollutant leakage into karts and their flowing through porous alluvium aquifers. The ground resistivity profile of cover doline V75 (Figure 223) shows an interesting funnel-shaped doline, which points to leaking material seeping in the lower lying layers and into the karst underground. In order to unequivocally prove this thesis, it would be necessary to repeat the measurements in different time periods after heavy rainfall, to ‘catch’ the sinking water.

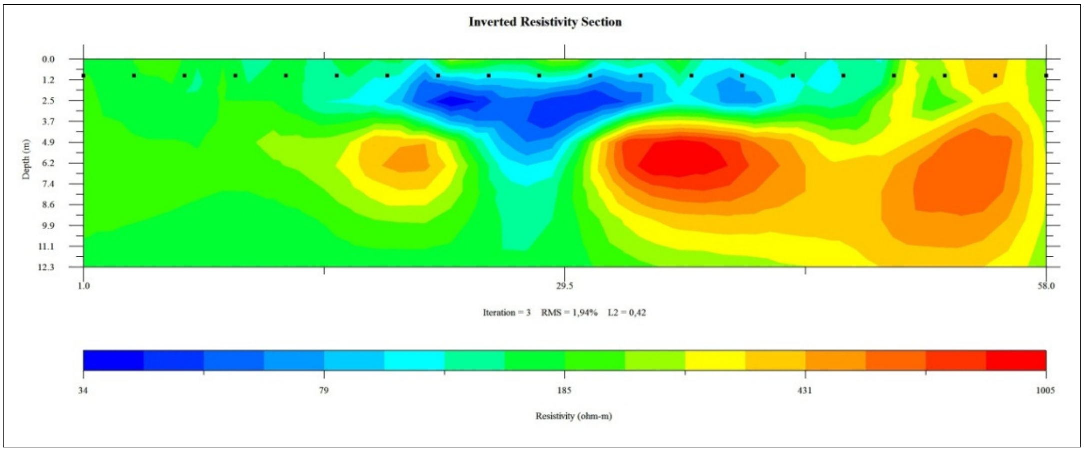


Figure 223: *Sectional profile of FWDS (blue) in a cover doline. The degradation of the waste is resulting in pollutants that are leaching into the karst underground with suffusion processes.*

The Ljubljansko polje aquifer is the main water source for the capital, Ljubljana. The present research proved many FWDS in gravel pits that are above the aquifer (Figure 224). A rise of the groundwater would mean an ecological catastrophe for the capital city. If the groundwater reached and flooded the buried waste, the processes of degradation would speed up and different pollutants could leach in to the groundwater and contaminate the drinking water.

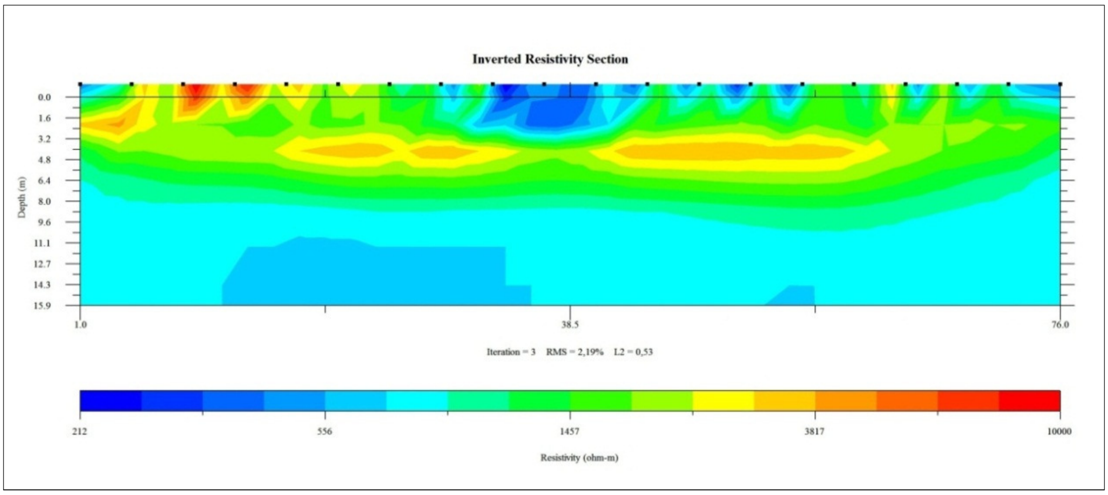


Figure 224: *The electrical resistivity profile of case study FWDS. The light blue indicates a groundwater table at 8 meter depth.*

The trend of a ground water table has been mostly linear in last two decades (Figure 225), with normal oscillations in relation to the amount of rainfall. Also the consumption of drinking water is stable, since the drastic decrease in nineties, when some large industrial water consumers stopped production and others improved production regarding water consumption and pollution. The public consumption is stable and differs in individual areas in Ljubljana - 150-250 l/person/day (©INCOME, 2012).

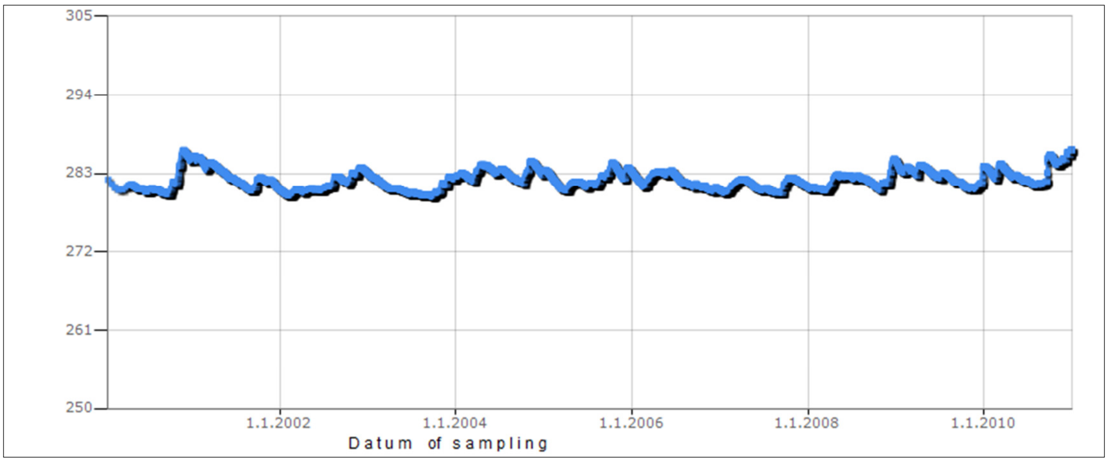


Figure 225: *The groundwater table trend (1992 – 2010) (Source: ©INCOME, 2012).*

Any recent and future spatial planning must consider the FWDS and foresee the environmental impacts of the buried waste. In Ljubljansko polje, the connections between the hydrologic regime of the Sava River and the groundwater table are especially important. The Sava River (with its tributaries) is, beside rainfalls, the main water input for the Ljubljansko polje aquifer. Technical interventions into the riverbed may cause some unpredictable environmental consequences in the groundwater table. The impact of the Mavčiče hydro-electrical power station (built in year 1988) on the groundwater was studied by Horvat (2006). The ground water table in the Kranjsko-Sorško polje alluvial plain has increased. The water table close to lake in the Moše and Breg villages is higher by 9m and is decreasing with distance from lake (Horvat 2006). The same impact can also be predicted on Ljubljansko polje if the Sava River were dammed. For this reason, detailed technical and environmental expertise must be made before any further construction interventions. From that point of view, the establishment of a FWDS registry on the country / region level is very important in order to protect the groundwater.

Another point of view is more spatial than ecological. FWDS areas have some physical constraints for locating some activities. For example, when planning the locations of new residential, commercial or industrial areas that include buildings, the locations of FWDS areas must be remediated before further construction takes place.

FWDS are covered with deposols in most case studies, which have no agricultural quality or economic importance. The deposols are very shallow (average 20 cm) and mixed with hard parts of construction waste that enables ploughing. The predominant agricultural land use is a traditional meadow or the area is simply overgrowing by local flora. In the context of agricultural as well as economic development, the price of the land is very important. The existing classification of agricultural land in Slovenia is the basis for the determination of the agricultural as well as the economic value and price of the land. The classification does not consider lower land quality on the FWDS.

10.1.2 Phytoremediation of FWDS

Phytoremediation systems utilize the potential of the natural or actively managed soil-vegetation system to detoxify, degrade and deactivate potentially toxic elements in the leachate (Jones et al 2005). Walton at al. (1994) has already proposed that plants produce specific signals in response to specific contaminants (in Nagendran et al 2006). Natural or planted vegetation on a landfill has an important role in erosion control and the removal of contaminants and may also be used in leachate treatment (Maurice 1998). Exhaustive information of phytoremediation is available in McCutcheon and Schnoor (2003).

A good starting point for the selection of appropriate plant species for the remediation of dumpsites is to employ endemic species. Although landfills only cover a limited surface, they often offer a large diversity of environmental niches for species. Several fluxes of waste and cover materials with different origins end up at landfills and create microhabitats on which a certain type of vegetation will have a competitive advantage and develop while other species will be rare (Nagendran et al 2006). The age of the cover also accounts for the occurrence of landfill plants. The species diversity decreases with the age of the landfill (Maurice et al 1995, Maurice 1998) and it is influenced by the type of waste, the local flora and the conditions prevailing at the landfill (Nagendran et al 2006). The vegetation cover in the area of the FWDS doline (approximately 100 m²) visibly differs from the surrounding grass vegetation that represents a cultivated meadow. Inside the filled doline, eutrophic species grow that do not appear in the surroundings. Based on the phytocenological list of V75 and the surrounding cultivated meadow, it is possible to conclude that the waste that fills the doline is of an organic origin (wood waste from Valkarton, organic waste from farms and households), topped with a 1m thick layer of soil. Nutrients (nitrogen) are excreted from the decaying waste, which cause the soil to eutrophication and eutrophic plants to flourish (the dolines are grown over by nettles and broad-leafed dock, which are an indicator of over-fertilization).

As many dumping sites are located in rural, agricultural and wooded areas, spray or trickle irrigation of untreated or partially treated leachate onto vegetated land has been considered as a potential remediation option (Haarstad et al. 1999). In many cases, using trees (including short rotation coppice) or grassland, the phytoremediation of leachate has been successful. However, there are significant numbers of examples where phytoremediation has failed. Typically, this failure can be ascribed to excessive leachate application or poor management due to a fundamental lack of understanding of the plant – soil system (Jones et al 2005). Generally on landfills, plants with short root length are preferred so as not to interrupt the underlying geomembrane. In unorganized dumpsites without a bottom membrane, it is essential to use the appropriate plants to control the movement of the pollutants to the groundwater (Nagendran et al 2006).

Simmons (1999) discussed the possibilities of a fhytoremediation of landfill sites for ecological diversity. The opportunities for increasing biodiversity should be used wherever possible. The techniques for the creation and aftercare of a species-rich grassland, heathland, wetland habitats as well as the planting of trees could be applied. On many waste sites, the lack of suitable soils for restoration may make successful agricultural restoration difficult if not impossible. Agricultural restoration should be evaluated in the light of the current and anticipated demand for a restored agricultural land within communities. There is no need for further agricultural land in many areas, especially if that land is of low productivity and requires significant inorganic fertilizer applications each year to maintain productivity. Landfill sites are often located in areas where alternative after-uses are most welcome (Simmons 1999).

11 GENERAL CONCLUSIONS AND FURTHER WORK

Two Slovenian landscapes were researched and studied: Ljubljansko polje and Logaško polje, which represent two of the main relief types in Slovenia, fluvial and karstic. A methodological objective was set to establish the locations of former gravel pits and dolines that are no longer recognizable in the landscape in the present due to filling with waste and covering them with a mineral cover and vegetation, but can be detected using geoinformatic analyses. The latter methods were used to determine the relief, the pedogeographical and phytogeographical consequences, differences and anomalies and the results were partially controled with the extensive field research findings.

Regarding the caracteristics of FWDS in Slovenia it may be concluded that none of the existing and established foreign methods of detecting FWDS are completely transferrable to Slovenia, as our waste disposal sites are not comparable to those abroad in relation to:

- Size – they are very small, tied to the cadaster delineation of the lots, which reflects the fragmentation of land ownership (small lots);
- Gravel excavation was accelerated after WWII on agrarian lots of poorer quality, due to the stifling of agrarian development and the need for construction material for continuing construction in the capital;
- Number – very large number due to the polycentric settlement system;
- It is presumed their character is of a mixed type and cases with a completely industrial character that point to a larger concentration of very hazardous waste are rare.

In comparison to the past researches of waste disposal sites and FWDS, the present research is innovative regarding the following ways:

- the application of different relief data and selected geomorphometric analyses in the determination of FWDS that enable relatively good results;
- the combination of laboratory (multispectral) and field results (soil sampling) and in addition to that some new pedogeographical findings about the characteristics of deposols that should be the input for further research;

- Some basic findings about vegetation on FWDS (eutrophic plants, ruderal plants, invasive plants, etc) in relation to natural vegetation;
- The application of different field methods.

The developed 2TL/3E FWDS model is oriented towards automatic use of geoinformatic methods on the available data on the recent landscape (Lidar and multispectral photographs CAS 2006) to determine potential FWDS, to minimize the past landscape analyses, which are more time-consuming. The past landscape analysis should be used only as a control method in combination with field methods or as additional method for a detailed study of individual FWDS in specific cases for determining the depth of the filled material. The model includes spectral analyses and geomorphometric analyses, which place gravel pits in the context of a natural fluvial relief.

Based on the lidar relief data, the geomorphometric elements may be very precisely detect and the direction of the old relict riverbeds gotten. The concave shapes outside the riverbeds and convex shapes inside the riverbeds may be assumed to be suspicious objects of an anthropogenous origin. In order to distinguish between smaller interrupted relict riverbeds (due to the intense land use they do not stand out – deep tilling) and smaller slightly concave relief shapes, the near infra-red aerial photographs are used, where areas of filled gravel pits stand out with very high values (white) and coincide with dry warm objects on the Earth's surface that have higher values in the near infra-red channel. A heterogeneous texture is typical of filled gravel pits, where higher values predominate (marked in white), or have higher values on the gravel pit edges.

Relief modeling is an appropriate method for detecting filled gravel pits on areas of agrarian land use and on open surfaces with no significant higher vegetation cover. The anthropogenous level of the relief alterations of the two mentioned types of land use allows for natural relief characteristics as well as relief anomalies to be detected that are a consequence of waste disposal and filling gravel pits. The microrelief shape of the forest floor on a leveled gravel plain is completely preserved and is reflected in the non-leveled (anthropogenously uncultivated) ridged surface. Areas of overgrowing, areas of extensive agrarian land use, where there are no physical interruptions in the surface (no tilling, mowing, etc.) express similar microrelief characteristics as well as where the relief is not altered and areas of waste-filled gravel pits that have not been rehabilitated by removing the waste or by covering them with a thick layer of soil.

The areas of high relief potential overlap with 8 gravel pits. All 8 were determined in past and recent landscape and proved as FWDS with field methods. An additional 17 gravel pits that were originally determined only with one type of analysis coincides with the areas of high relief a potential.

The main advantage of 3D past landscape analysis is that beside the object location and object surface / area, it also enables the determination of the doline and gravel pits depth (important for determining the quantity of landfilled waste) in a certain year of the aerial survey. Transforming the imagery into 3D spatial data involves several processes commonly associated with digital photogrammetry. Through various processing steps, 3D spatial data can be automatically extracted and collected from oriented imagery.

This method of relief modeling in combination with visualization technics enables an independent gravel pit determining, a very precise determining of the position and shape as well as the spatial extent or the horizontal delineation of the object. It is immeasurably faster compared to a 3D analysis of the past landscape. The problem is the Lidar data (© GURS 2012), which does not exist for the entire country and is still very expensive. The data is available free of charge for some areas of Slovenia (Dravsko polje, Slovenian Istra).

The problem of the method are areas covered with forest that have a very high relief potential. People do not interfere in the surface in the forest compared to the cultivated agrarian surfaces and the urban land use. The relief under the forest can be detected as a ridged surface using laser scanning, which is also typical of completely filled gravel pits. This problem can be avoided by determining the tree density and height at a critical location with the help of the orto-photo and the lidar vegetation layer. When the trees are tall, it means they flourish on a stable original foundation and natural soils that enable them a stable growth. Lower trees of bush growth flourish on the areas of filled gravel pits, as the undeveloped soils and the inhomogeneous original foundation (waste) does not guarantee a static stability to the tall trees (e.g. English oak). This method cannot be used to determine the object formation, excavation period, filling period; not even the type of filling material. The Lidar data is very difficult to process due to its extremely high spatial resolution (e.g. a spot on 2 cm) and demands extremely capable hardware and software to be processed. Of course, the method cannot be used on built-up surfaces either, because the relief has been completely anthropogenously altered.

Regarding the hydromorphological backgrounds, on which the relief modeling method and determining FWDS are based, the FWDS model is useful for studying FWDS in alluvial plains (gravel, loamy) along larger rivers (Sava, Savinja, Drava, Mura), where FWDS gravel pits can be put into the context of relict riverbeds. In Slovenia, these areas are Kranjsko-Sorško polje, Kamniško-bistriška ravan, Krško-brežiško polje, Spodnja Savinjska dolina, Dravsko polje, Ptujsko polje, Ormoška dobrava and Murska ravan.

The FWDS concept can also be transferred to a karst area in order to determine filled dolines. In accordance with the hydrographical starting points, it is necessary to determine the geomorphometric parameters, based on which the areas with a high relief potential, typical of filled dolines can be located. A karst polje with cover dolines and karst meadows with prevailing underground water current are appropriate areas on which to test the karst relief modeling.

There are undoubtedly many more options for determining FWDS in the hydro-morphometric relief modeling and some innovative relief analyses that could appear with very precise Lidar data. Most foreign and domestic research, oriented towards distant illegal waste disposal site detection, is based on determining vegetation anomalies, like vegetation stress based on radiometric spectral analyses. There are few studies (Pacina et al. 2011) that would be based on relief analyses. However, numerous geomorphologists are researching anthropogenous relief.

Multispectral photograph analysis is very effective for detecting waste-filled dolines on a loamy alluvium, since a very noticeable contrast appears in NIR between the moist and dry ground. It is substantially more difficult to determine filled dolines on limestone or dolomite rocks where the soils are shallow and skeletal. FWDS dolines clearly express a concentric shape and a homogenous spectral reflection inside it (warmer surface).

One of the methodological objectives in this research was to orient the process of studying FWDS towards identifying the landscape consequences in the recent landscape using the effective geoinformatic analyses. These are often sophisticated methods, mathematical algorithms, included in the computer program modules for GIS analyses. The results can be produced very quickly if the appropriate quality data in the right format is available. The spatial data on Slovenia's surface exists for the recent landscape in different formats and enables various analysis types. The past landscape analysis is generally tied to spatial data of a poorer quality and new data modeling; however, it does allow acquiring information on depth, which is impossible with the geoinformatic analysis of the recent landscape.

The described and verified geoinformatic methods cannot be used to determine the type of waste if it is not hazardous waste, which would result in measurable consequences on the vegetation via vegetation stress. The waste type can be determined with invasive field methods like the pedological sounding that was used in this research. The method is very physically taxing, especially when sounding deep karst loamy soils, where profiles could be sounded up to 2 m deep. Measuring the electrical resistance of the ground is a more time-consuming method, where most of the work consists of setting up the probes and cables before the measurement itself. The measurement results depend on the ground moisture. The resistance on Ljubljansko polje was measured in March (2012) after a long-lasting dry period. Consequently, the waste was drier and its average resistance was greater than on Logaško polje, where the measurements were carried out in late-April (2012) after a month-long rainy period. Further research should be upgraded by laboratory soil analyses to determine the basic biochemical (ecological) soil characteristics (pH, concentration of nutrients, concentration of heavy metals, etc.).

The first and simplest field method is field charting of the relief and vegetation characteristics of the object. The areas of potentially filled dolines and gravel pits were determined with geoinformatic methods beforehand, then the vegetation and relief was verified in the field. Almost all the objects (about 300) were included in the charting on Ljubljansko polje, while the number of potential dolines on Logaško polje exceeded the time available for field research. In addition to the relief shape, the presence of mosses on Ljubljansko polje was documented, which are indicators of undeveloped soils and deposols. Phytogeographical research was carried out on sample dolines on Logaško polje that expressed vegetation anomalies (V75, V2000, V3000, V5000, V402). V75 is an instructive case and proof that nature takes care of cleaning itself. There are naturally planted eutrophic plants in the doline that remove increased unnatural nourishments from the ground. The self-cleaning abilities of a filled waste disposal site increased with the process of second succession, which also represents a way of rehabilitating using phytoremediation. Phytoremediation is a process of rehabilitating a degraded area by planting the appropriate plants that need certain substances to flourish, or are unaffected by some substances. Certain plants have an increased ability to absorb and bind toxic substances, like nitrogen, phosphorous, heavy metals, etc. A doline is a good platform for studying plants and planning rehabilitations with phytoremediations.

Despite numerous appropriate geoinformatic methods and quality spatial data that enables distant detection and landscape research, the greatest truth that science can reveal, prove, and verify still lies in the landscape itself – *in situ*. The knowledge a researcher–geographer obtains through a tangible, direct, physical contact with the studied object or phenomenon with the field survey is essential for the interpretation of the geoinformatic analyses results.

12 POVZETEK (SUMMARY)

Osrednje področje raziskave so nekdanja neurejena in nedovoljena, danes nedelujoča in opuščena odlagališča odpadkov, ki predstavljajo staro okoljsko breme. Glede na rezultate predhodnih terenskih študij (Bricelj 1988, Šebenik 1994, Smrekar 2007 itd.) je razvidno, da so pogosto locirana v naravnih (vrtačah, mrtvih rokavih) in antropogenih reliefnih kotanjah (gramoznice, glinokopi, peskokopi, kamnolomi itd.). Pokrajinski tipi v katerih so te reliefne oblike prisotne so dinarska podolja in ravniki ter ravninski pokrajinski tip, zato predstavljajo vzorčno območje te raziskave Logaško kraško polje in prodna ravnina Ljubljanskega polje.

Nekdanja odlagališča, ki so nastala z odlaganjem odpadkov v vbočene reliefne oblike so danes nepoznana in nenatančno locirana, kar onemogoča ugotavljanje njihovih vplivov na okolje. Problem je tudi nepoznavanje količine in sestave odloženih odpadkov. Kljub temu, da so nekatera komunalna odlagališča imela uradno dovoljenje tedanjih oblasti, je bilo zanje značilno strokovno nenadzorovano in neustrezno odlaganje odpadkov. Nevarni industrijski odpadki so se odlagali na komunalnih odlagališčih skupaj z nenevarnimi gospodinjskimi odpadki (Orožen Adamič s sodelavci 1978). Večina odlagališč ni imela vododržnih zaščitnih plasti, zato še danes ogrožajo kakovost okolja in zdravje ljudi saj je *"…izločanje različnih razgradnih snovi v atmosfero, prst in podzemno vodo je dolgotrajno (Allgaier, Stegmann 2005)…"*. *"…Problem je, da se odpadki v odlagališčih ne kompostirajo ampak prej mumificirajo. Vsekakor poteka proces biodegradacije odpadkov ampak hitrost le-te se izraža v stoletjih in ne desetletjih. Celo organski odpadki, kot so ostanki hrane, ostanejo nespremenjeni po tridesetih do štiridesetih letih…"*(Rathje 1991).

Potencialne lokacije nekdanjih odlagališč odpadkov v vrtačah in gramoznicah lahko določimo z geoinformacijskimi metodami, ki temeljijo na analizi in primerjavi različnih prostorskih podatkov (satelitski in aeroposnetki, kartografsko gradivo, digitalni model višin) iz različnih obdobij z ugotavljanjem in lociranjem fizičnih sprememb v naslednjih pokrajinskih sestavinah:

- relief,
- prst,
- rastje.

Uspešnost posamezne geoinformacijske metode se razlikuje glede na vrsto in kakovost uporabljenih podatkov, glede na pokrajinski tip preučevanega območja ter glede na sedanjo in preteklo pokrovnost (gozd, grmovje, travnik, njiva, pozidano,…) na območju nekdanjega odlagališča odpadkov. Z geoinformacijskimi metodami dobljeni rezultati so do določene stopnje preverljivi v recentni pokrajini s terenskimi metodami.

Raziskava je regionalno omejena na dve vzorčni preučevani območji, ki predstavljata dva ravninska pokrajinska tipa (Dinarske planote, Alpske ravnine (Perko 2008) za katera so značilne različne reliefne kotanje. V izbranem kraškem pokrajinskem tipu so bile izpostavljene degradaciji predvsem vrtače. Na nekraških, prodnih ravninah pa so odpadke odlagali predvsem v opuščene in nesanirane gramoznice (Šebenik 1994):

- preučevano območje 1 (Dinarske planote): kraško območje, ki vključuje Logaško polje;
- preučevano območje 2 (Alpske ravnine): nekraško območje, ki vključuje prodno ravnino Ljubljanskega polja.

Izbrana ravninska pokrajinska tipa sodita med tradicionalno gosteje poseljene pokrajinske tipe. Na obeh območjih so v obdobju po drugi svetovni vojni pa vse do danes delovali številni proizvodni obrati. Zaradi neurejenega ravnanja in gospodarjenja z odpadki so se tudi nevarni industrijski odpadki (galvane, lesna industrija, kemična industrija,…) odlagali na odlagališča komunalnih odpadkov in v naravne oziroma umetne kotanje.

Na preučevanih območjih smo si zastavili cilj, ugotoviti, kje so nekdanje gramoznice in vrtače, ki jih zaradi zasipavanja z odpadki in prekritja z mineralnim pokrovom in / ali rastjem, danes v pokrajini ne zaznamo več, so pa določljive z izbranimi geoinformacijskimi analizami. S slednjimi smo določali reliefne, pedogeografske in fitogeografske posledice, razlike in anomalije, rezultate pa podprli z ugotovitvami obsežnega terenskega raziskovanja.

Glede na starost površja, predstavljenega na prostorskih podatkih, ločimo geoinformacijske analize nekdanje pokrajine (arhivski aeroposnetki, stari zemljevidi) in geoinformacijske analize recentne pokrajine (večspektralni satelitski in aeroposnetki, digitalni modeli površja). Teoretično je recentna pokrajina obdobje po

zasutju, nekdanja pokrajina pa obdobje nastanka gramoznice ali naravne vrtače, pred obsežnejšim zasipavanjem kotanj z odpadnim materialom, ko lahko z različnimi geoinformacijskimi metodami dobimo podatke o legi, površini, obliki in globini gramoznice ali vrtače. Pomeni ničelno stanje, ki ga opredelimo časovno z izhodiščnim letom (vezano na leto aerosnemanja), v katerem naredimo presek čez stanje pokrajine. Ničelno stanje je teoretično nemogoče določiti, lahko se mu le čim bolj približamo. Potrebno je narediti časovni presek stanja pokrajine v več različnih letih na obeh vzorčnih območjih.
Območja vrtač na Logaškem polju smo določili v nekdanji pokrajini na aeroposnetkih iz leta 1944, 1957 in 1972. Za posamezno leto smo izdelali digitalni model pokrajine (DMP) in podrobneje analizirali DMP za leto 1972. Z 2D in 3D analizo aeroposnetkov iz leta 1972 smo določili vsa potencialna območja vrtač (No 1.364), njihovo obliko, površino, rabo tal in globino. Analiza nekdanje pokrajine Ljubljanskega polja je zasnovana na arhivskih posnetkih iz petletnih obdobij, s poudarkom na letih 1959 in 1964, za katera smo izdelali digitalne modele nekdanjega površja in izvedli 3D analizo površja. Analize nekdanje pokrajine so bistvene za določitev lokacije preučevanih objektov in izhodiščnega, ničelnega stanja. Analize nekdanjega stanja so zelo omejene z razpoložljivimi podatki in njihovo kakovostjo. Pomemben podatek so poleg kartografskega gradiva tudi arhivski aeroposnetki, ki omogočajo dvodimenzionalno analizo (2D) slikovnih objektov (npr. gramoznic) kakor tud tridimenzionalno analizo (3D) in preučevanje objektov na zemeljskem površju. Oboje smo uporabili v preučevanju nekdanje pokrajine v sedanji pokrajini in pri primerjavi obeh. Reliefne analize smo izvedli tudi na podatkih za sedanjo pokrajino.

Analiza sedanje pokrajine je zasnovana na določanju sprememb v treh naravnogeografskih prvinah: reliefu, prsti in vegetaciji. Reliefno modeliranje temelji na lidar reliefnih podatkih, ki niso na razpolago za celotno Slovenijo, zato smo izdelali metodo le na podlagi značilnosti fluvialnega reliefa aluvialne ravnine. Območja visokega reliefnega potenciala, ki so glavni cilj modeliranja, sovpadajo z območji gramoznic, ki so bile določene z geoinformacijskimi metodami nekdanje in recentne pokrajine. Podatke smo ovrednotili s podatki obstoječega registra vidnih divjih odlagališč odpadkov (Smrekar in sodelavci 2006) in rezultate preverili na terenu. Model je primeren za določanje zasutih gramoznic z grbastim uravnanim ali rahlo izbočenim površjem. Vbočene gramoznice, kamor spadajo delno zasute in nezasute gramoznice, z modeliranjem izločimo iz nadaljnje analize nekdanjih odlagališč odpadkov in s tem zmanjšamo število podatkov. Nekdanja odlagališča odpadkov, ki smo jih potrdili s terenskimi metodami se ujemajo z območji visokega reliefnega potenciala. To so naprimer gramoznice G22, G42, G162, G43, G127 (Poglavji 9.6.2.2 in 9.6.2.3).

Metoda reliefnega modeliranja v kombinaciji z vizualizacijo reliefa omogoča samostojno določanje nekdanjih odlagališč odpadkov, saj zelo natančno določi lego in obliko ter prostorsko razširjenost oziroma horizontalno omejitev objekta. Je neprimerljivo hitrejša v primerjavi z analizo nekdanjega površja. Problem so Lidar podatki, ki ne obstajajo za celotno Slovenijo in so še vedno zelo dragi. Podatki za nekaj območij Slovenije so dostopni brezplačno (Slovenska Istra, Dravsko polje).

Problem metode so območja pokrita z gozdom, ki imajo zelo visok reliefni potencial. Človek v gozdu ne posega v tla in jih najmanj preoblikuje v primerjavi z obdelovalnimi kmetijskimi površinami in urbano rabo tal. Relief pod gozdom je s pomočjo laserskega skeniranja zaznan kot grbasto površje, ki je značilno tudi za povsem zasute gramoznice. Problemu se izognemo tako, da določimo gostoto in višino dreves na kritični lokaciji s pomočjo ortofota in lidar vegetacijskega sloja. Kadar so drevesa visoka, pomeni, da uspevajo na statično stabilni matični podlagi in naravnih prsteh, katere jim omogočajo stabilno rast v višino. Na območjih zasutih gramoznic uspevajo nižja drevesa grmovne rasti, saj nerazvite prsti in nehomogena matična podlaga (odpadki) ne zagotavljajo statične stabilnosti visokim drevesom (npr. hrast dob, lat. *Quercus robur*). Z metodo ne moremo določiti obdobja nastanka objekta, časa izkopavanja, časa zasipavanja; niti vrste zasipnega materiala. Lidar podatki so zaradi zelo visoke prostorske ločljivosti zelo zahtevni za obdelavo in zahtevajo izjemno zmogljivo strojno in programsko opremo. Metoda je seveda neuporabna tudi za pozidana zemljišča, kjer je relief antropogeno povsem spremenjen.

Glede na hidrogeomorfološka izhodišča, na katerih temelji metoda reliefnega modeliranja in določanja nekdanjih odlagališč odpadkov, je metoda uporabna za določanje pojava le-teh na podobnih tipih fluvialnega reliefa, torej na aluvialnih ravninah (prodnatih, ilovnatih). V Sloveniji so to aluvialne ravnine ob večjih rekah

(Sava, Savinja, Drava, Mura) , kjer so ohranjene suhe struge. Ta območja so v Sloveniji Kranjsko-Sorško polje , Kamniško-bistriška ravan, Krško-brežiško polje, Spodnja Savinjska dolina, Dravsko polje, Ptujsko polje, Ormoška dobrava in Murska ravan.
Koncept reliefnega modeliranja je prenosljiv tudi na kraška območja za določanje zasutih vrtač. Skladno z reliefnimi in hidrografskimi izhodišči bi bilo potrebno določiti geomorfometrične parametre, na podlagi katerih bi določili območja z visokim reliefnim potencialom, značilnim za zasute vrtače. Območja, kjer bi lahko preizkusili modeliranje kraškega reliefa so kraška polja z aluvialnimi vrtačami in kraški ravniki, kjer prevladuje podzemni vodni odtok.
Nedvomno je v reliefnem modeliranju in v opisanih reliefnih analizah še veliko možnosti za določanje nekdanjih odlagališč odpadkov. Večina tujih in domačih raziskav, usmerjenih v daljinsko zaznavanje divjih odlagališč, temelji na določanju vegetacijskih anomalij, naprimer vegetacijskega stresa na osnovi radiometričnih spektralnih analiz. Podrobnejše analize, ki bi temeljila na določanju reliefnih posledic, v tuji in domači strokovni literaturi nismo našli. Se pa številni geomorfologi ukvarjajo z antropogenim reliefom.

Spektralne analize so zelo uspešen način določanja odlagališč nevarnih, strupenih odpadkov. Da zaznamo vegetacijski stres je potrebna velika količina strupenih odpadkov, na katerih se razvija nezdrava vegetacija, v tolikšni meri, da jo lahko razlikujemo od okoliške. V Sloveniji imamo nekaj znanih večjih industrijskih odlagališč bolj ali manj nevarnih odpadkov, ki bi bila primerna za preizkušanje spektralnih analiz in merjenje vegetacijskega stresa. Takšno je naprimer odlagališče rdečega blata na Kidričevem (Dravsko polje), ki je industrijski odpadek proizvodnje aluminija v tovarni TALUM (nekdanji TGA). Območje je sanirano in prekrito z neinertnim slojem zemljine ter zasajeno z drevesno vegetacijo. Tovrstne primere imamo v Sloveniji v bližini večjih industrijskih krajev in pomembnejših proizvodnih obratov. Posebnost slovenskih odlagališč, ki so nastajala v drugi polovici 20. Stoletja pa je majhnost in številčnost, zato je skoraj nemogoče povzeti tuje geoinformacijske metodologije, s katerimi so določali obsežnejša odlagališča, primerljiva le z redkimi industrijskimi odlagališči v Sloveniji.

Prve radiometrične raziskave odlagališč odpadkov so temeljile na analizi satelitskih posnetkov različne generacije satelitov Landsat (Landsat MSS senzor, Landsat TM5 senzor, Lansat TM7 senzor). Vsi ti posnetki imajo zelo dobro radiometrično ločljivost (7 spektralnih kanalov) in za slovenske razmere preslabo prostorsko ločljivost (nad 20 m, večina nad 30 m). Skladno s tem smo v raziskavi opisane večspektralne analize obeh pokrajin zasnovali na analizi aeroposnetkov iz leta 2006, kjer je površje celotne Slovenije posneto v štirih delih elektromagnetnega spektra. Podatki so za raziskovalno delo brezplačno dostopni na Geodetski upravi Republike Slovenije. Radiometrični sloji so združeni v RGB in IRRG datotekah, zato je potrebna predobdelava podatkov, da sestavimo štirislojno – štirikanalno sliko za avtomatske obdelave. Večspektralna analiza, temelji na nenadzorovani klasifikaciji (ISODATA) 4-kanalnih satelitskih ali aeroposnetkov (modra, zelena, rdeča, bližnjeinfrardeča) in določanju vegetacijskega stresa preko vegetacijskih indeksov (NDVI, IR/R). Kot samostojna metoda ne zadostuje za strokovno določanje nekdanjih odlagališč odpadkov na Ljubljanskem polju, medtem ko na Logaškem polju (predvsem naplavinski del) daje zelo dobre rezultate. Z metodo lahko določimo območja s toplo /sušno vegetacijo (avtomatska analiza), območja z redkejšo vegetacijo nad odpadki (vizualna analiza), ločimo območja vlažnih in suhih prsti in odziv le-teh na travnati in grmovni vegetaciji (avtomatska analiza).

Z multispektralno metodo nismo izločili območij s poškodovano vegetacijo, ki bi kazala na strupene odpadke. NDVI indeks površja zasutih gramoznic, preraščenih s travniškim rastjem, je zelo visok, kar je posledica povečane vlažnosti, ki se odraža v bližnjeinfradečem spektralnem kanalu. Na takšnih območjih ni prisoten vegetacijski stres ampak ravno nasprotno. Tudi pri terenskem kartiranju vegetacije nismo zaznali bistvenih vegetacijskih razlik z okolico. Vegetacijski indeks poškodovanosti vegetacije, ki prerašča zasute vrtače se razlikuje glede na tip nasipnega materiala. Indeks je zelo nizek za vegetacijo, ki prerašča vrtače z trdim mineralnim pokrovom in vrtače, kjer odpadki niso prekriti. Nizka vrednost je v prvi vrsti posledica nizke vlažnosti tal in prisotnosti deposolov. Nizka vrednost se je pokazala tudi na območju vrtač, kjer so v aluvialnih vrtačah odloženi organski odpadki. Temperatura območja se z razpadanjem organskih odpadkov poveča in je določljivo višja od temperature okoliške ilovnate naplavine. Tovrstna nekdanja odlagališča odpadkov (V75) so določljive z večspektralno analizo in uvrščene v 2 stopnjo degradacije prsti. Vrsta odpadkov v nekdanjem odlagališče odpadkovi z v raziskavi opisanimi geoinformacijskimi analizami ni določljiva. Potrebno je izčrpno terensko raziskovanje površja, kakor tudi pod površjem. Pedološko sondiranje je zelo hitroizvedljiva, blago invazivna terenska metoda, ki ne pušča posledic v pokrajini.

Analiza večspektralnih posnetkov je zelo učinkovita za določanje zasutih vrtač v ilovnati naplavini, saj se v NIR pojavi velik kontrast med vlažnimi in suhimi tlemi. Zasute vrtače dosti težje določamo na apnenčastih ali dolomitnih kamninah, na katerih so prsti plitve in skeletne. Pri zasutih vrtačah je dobro razvidna koncentrična oblika, in znotraj nje homogen spektralni odboj (toplejše površje).

Eden od metodoloških ciljev, ki smo jih želeli doseči v raziskavi je usmeriti proces preučevanja nekdanjih odlagališč odpadkov v določanje pokrajinskih posledic v recentni pokrajini z uporabo učinkovitih geoinformacijskih analiz. Slednje so pogosto sofisticirane metode, matematični algoritmi, ki so vključeni v module računalniških programov za GIS analize. Rezultate lahko dobimo zelo hitro, če imamo na razpolago kakovostne podatke v primerni obliki. Prostorski podatki o površju Slovenije obstajajo za recentno pokrajino v različnih oblikah in omogočajo različne vrste analiz. Analiza nekdanje pokrajine je vezana praviloma na prostorske podatke slabše kakovosti, na modeliranje novih podatkov a omogoča pridobivanje podatkov o globini , kar je z geoinformacijsko analizo recentne pokrajine nemogoče.

Z opisanimi in preizkušenimi geoinformacijskimi metodami ne moremo določati vrste odpadkov, če ne gre za nevarne odpadke, katerih posledice so merljive na vegetaciji z vegetacijskim stresom. Vrsto odpadkov lahko določimo z invazivnimi terenskimi metodami, kot je v raziskavi uporabljeno pedološko sondiranje. Metoda je fizično zelo naporna, še posebej sondiranje globokih kraških ilovnatih prsti, kjer smo izvrtali tudi do 2 m globoke sondažne profile. Merjenje električne upornosti je časovno bolj potratna metoda, kjer je največ dela in časa potrebnega za postavitev sond in kablov, pred samo meritvijo. Rezultati meritev so odvisni od vlažnosti prsti in tal. Na Ljubljanskem polju smo merili upornost v mesecu marcu (2012) po dolgotrajnem sušnem obdobju. Odpadki so bili bolj suhi in zato je bila njihova povprečna upornost večja, kakor na Logaškem polju, kjer so meritve potekale konec aprila (2012), po celomesečnem deževju.

Prva in najpreprostejša terenska metoda, je terensko kartiranje reliefnih in vegetacijskih značilnosti objekta. Območja potencialno zasutih vrtač in gramoznic, smo predhodno določili z geoinformacijskimi metodami in na terenu preverili vegetacijo in relief. Na Ljubljanskem polju smo v kartiranje zajeli skoraj vse objekte (okrog 300), medtem ko je število določenih potencialnih vrtač na Logaškem polju presegalo čas, ki smo ga imeli na razpolago za terensko delo. Na Ljubljanskem polju smo poleg reliefne izoblikovanosti, določali prisotnost mahov, ki so pokazatelj nerazvitih prsti in deposolov. Fitogeografske raziskave, smo opravili na Logaškem polju, na vzorčnih vrtačah, ki izražajo vegetacijske anomalije (V75, V2000, V3000, V5000, V402). V75 je poučen primer in dokaz, da narava sama poskrbi za čišenje. V vrtači naravno zasajene evtrofilne rastline, skrbijo za odstranjevanje povečanih nenaravnih vsebnosti hranil v tleh. Samočistilne sposobnosti zasutega odlagališča so se povečale s procesom sekundarne sukcesije, ki predstavlja tudi način sanacije vrtače s fitoremediacijo. Fitoremediacija je proces sanacije degradiranega območja z zasaditvijo ustreznih rastlin, ki za svoj razvoj potrebujejo določene snovi, oziroma jim ne-škodujejo. Določene rastline imajo povečano sposobnost absorbcije in vezave strupenih snovi, nekatere dušika, fosforja, težkih kovin itd. Vrtača je dobro izhodišče za študij rastlin in načrtovanje sanacij s fitoremediacijami.

Nedvomno bo v prihodnosti potrebno vzpostaviti kataster nekdanjih odlagališč odpadkov, starih bremen za celozno Slovenijo. Ker so njihove lokacije nepoznane, ker ne poznamo nevarnosti odloženih (skritih) odpadkov, predstavljajo potencialno okoljsko tveganje, predvsem za podzemne vodonosnike. V Sloveniji so porozni medzrnski in kraški vodonosniki glavni vir pitne vode. Onesnaženja, ki jih zaznava redni monitoring pitne vode, so pogosto neznanega izvora in predstavljajo odpadne snovi, ki ne nastajajo v recentnih proizvodnih procesih, ki ne izvirajo iz aktivnih virov onesnaženja ampak se izločajo iz starih okoljskih bremen.

Kljub mnogim, dobrim geoinformacijskim metodam in kakovostnim prostorskim podatkom, ki omogočajo daljinsko zaznavanje in preučevanje pokrajine, je največja resnica, ki jo znanost lahko odkrije, dokaže in preveri še zmeraj v pokrajini sami – '*in situ*', na terenu. Znanje, ki ga raziskovalec – geograf – dobi na podlagi otipljivega, neposrednega, fizičnega stika s preučevanim objektom ali pojavom, je bistvenega pomena za interpretacijo rezultatov geoinformacijskih analiz.

A TERMINOLOGY

The enclosed table contains the more important technical terms in this doctoral dissertation, which have been explained for clarity and understanding purposes. Due to the interdisciplinary nature of the dissertation, the list features terminology from different scientific fields, where each field has its own definition of a certain term. The field of geoinformatics most notably dwells on the terms concerning relief models, like digital relief model, digital elevation model, etc.

ENGLISH TERM	*SLOVENE TERM*	*DESCRIPTION*
Aerotriangulation	Aerotriangulacija	The orientation of aerial photographs is called aerotriangulation. Several overlapping photographs are tied into a block and the block is oriented in space, a coordinate system.
Cyclic Aerophoto Survey (CAS)	Ciklično aerofoto snemanje (CAS)	A cyclic aerophoto survey is aerial shooting where the entire area of Slovenia was photographed in 3-5 years intervals.
Digital elevation model (DEM)	Digitalni model višin (DMV)	This is a simple way of inputting relief points, generally in raster form, a regular net of square cells. A DEM is narrower than a DTM in that it only contains information on point elevation.
DEM5	DMV5	A model completed in 2007. The point elevation data was acquired from stereo pairs of aerial photo shoots.
Digital orthophoto (DOP)	Digitalni ortofoto (DOF)	A photograph or image of the Earth's surface. The image is geometrically modified using control points and the DTM. The ortophoto can be used similarly as a map for direct measure.
Digital surface model (DSM)	Digitalni model površja (DMP)	A model depicting the surface and the objects on it (buildings, vegetation). A DSM is a DTM complete with buildings.
Digital terrain model (DTM)	Digitalni model reliefa (DMR)	DTM is a continuous surface that, besides the values of height as a grid (known as a digital elevation model, DEM), also consists of other elements that describe the topographic surface, such as slope or skeleton .

Doline (sinkhole)	Vrtača	The term is derived from *dolina,* an everyday Slovenian expression for a valley. It is a typical karst landform, a medium-sized enclosed depression. Dolines are usually circular to subcircular in plan form, and vary in diameter from a few meters to 1 km. They form by various processes including dissolution, collapse and subsidence. Dolines are called sinkholes in engineering and North American literature.
DTM 100	DMR 100	Generated during 1973-84 by manually inserting the point elevations from map materials.
DTM 25	DMR 25	Generated during 1995-2003. The point elevations were acquired from stereopars of aerial photographs.
DTM 12.5	DMR 12,5	Generated in 2001 with a special method of summing up sets of existing spatial data. The value 12.5 means the size of a model cell.
External image orientation	Zunanja orientacija slike	Orientation of the aerial camera in space.
Fiducial marks	Robne marke	Fiducial marks on an image are indirect elements used to define the coordinate system. They are marks in the corner of the aerial photograph (4 marks / mage), sometimes in the middle of the image's side (8 marks / image).
Focal length	Gorišćna razdalja (gorišćnica)	The distance from the lens to its focal point.
Ground Control Points (GCP)	Oslonilne točke	Points with known geographic coordinates and elevations in the coordinate system that serve as the basis for determining the external image orientation of the aerial photographs during the process of aerotriangulation.
Geographic information system (GIS)	Geografski informacijski sistem (GIS)	A system for the collection, upkeep, maintenance, processing, analysis and presentation of geocoded spatial data. GIS consists of hardware, system and specific software, user applications, an integrated collection of spatial data, maintenance and user aspects of the information system.

Gravel pit	gramoznica	A gravel pit is the term for an open pit used for the extraction of gravel.
Hill shading (shaded relief)	Senčenje površja (senčen relief)	A plastic method of depicting the surface in shades of grey, reflecting the surface depending on its exposure. One of the most realistic demonstrations of the surface.
InSar DEM 25	Insar DMV 25	A model, generated in 2000 using radar interferometry.
Internal image orientation	Notranja orientacija slike	Determined by the camera (sensor) parameters: focal length, fiducial mark coordinates, the principal point.
Lidar	Lidar	Light Detection and Ranging – a general abbreviation for a system of data and products produced by aerial laser scanning technology.
Normalized DEM (nDEM)	nDMV	A layer of differences between two elevation layers. Generated by subtracting two elevation models.
Normalized DSM (nDSM)	nDMP	Generated by subtracting two surface models.
Old Environmental Burden	staro okoljsko breme	Degraded areas that are a consequence of previous activities not considering its negative effects.
Photogrammetry	Fotogrametrija	Photogrammetry is the manner of acquiring metrical data from photographs.
Phytoremediation	Fitoremediacija	Phytoremediation utilizes the potential of the natural or actively managed soil-vegetation system to detoxify, degrade and inactivate potentially toxic elements in the leachate.
Pixel (picture element)	Piksel (slikovni element)	The smallest element of a digital image or raster, usually square-shaped, illustrating a single tone value or color (wave length). Its size depends in the recording device's resolution.

Remote sensing	daljinsko zaznavanje	Remote sensing encompasses a body of non-contact monitoring techniques that measure energy-matter interactions to determine the characteristics of a target surface or medium.
Resolution	Ločljivost (resolucija)	Number of points per certain unit.
Stereopar	Stereopar	A stereopar are two photographs recorded under specific conditions. This is generated when the same area is photographed from two perspectives that are a certain distance apart. Such generated images are moved into the correct mutual position in order to be viewed with the stereo effect: they must be vertically and horizontally aligned. The aligned images are placed so that one eye sees one image and the other eye the other image. This creates a virtual image depth – a stereo effect.
Stereoeffect	Stereo učinek	A three-dimensional image generated by a stereopar.

B LIST OF ABBREVATIONS

ENGLISH	***SLOVENSKO***	**MEANING OF THE WORD**	***POMEN BESEDE***
CAS	*CAS*	Cyclic Aerial Survey (recording)	*Ciklično aerofoto snemanje*
CIR	*CIR*	Color Infrared image	*Barvna infrardeča slika*
DEM	*DMV*	Digital Elevation Model	*digitalni model nadmorskih višin*
DLM	*DPM*	Digital Landscape Model	*digitalni pokrajinski model*
DOP	*DOF*	Digital Orthophoto	*digitalni ortofoto*
DTM	*DMR*	Digital Terrain Model	*digitalni model reliefa*
DSM	*DMP*	Digital Surface Model	*digitalni model površja*
D48	*D48*	Datum of Slovene Coordinate System from 1948	*datum slovenskega koordinatnega sistema iz leta 1948*
EMS	*EMS*	Electromagnetic Specter	*Elektromagnetni spekter*
FWDS	*NOO*	Former Waste Disposal Site	*Nekdanje odlagališče odpadkov*
GIS	*GIS*	Geographic Information Systems	*Geografski informacijski sistemi*
GURS	*GURS*	The Surveying and Mapping Authority of the Republic of Slovenia	*Geodetska uprava Republike Slovenije*
GZS	*GZS*	Slovenian Geodetic Survey	*Geodetski zavod Slovenije*
Landsat MSS		Landsat Multi Spectral Sensor	*Senzor satelita Landsat*
Landsat TM		Landsat Thematic Mapper	*Senzor satelita Landsat*
LIDAR	*ZLS*	Light Detection and Ranging	*Zračno lasersko snemanje*
	UL RS	Law Gazette of the Republic of Slovenia	*Uradni list Republike Slovenije*
MGI	*VGI*	Military Geographical Institute (Belgrade)	*Vojnogeografski inštitut (Beograd)*
MKGP		Ministry for Agriculture, Forestry and Food	*Ministrstvo za kmetijstvo gozdarstvo in prehrano*
MrVBF		Multiresolution Index of Valley Bottom Flatness	*Indeks ravninskosti dolinskega dna*
NASA		National Aeronautics and Space Administration	*Vesoljska agencija Združenih držav Amerike*
NDVI	*NDVI*	Normalized Vegetation Index	*Normaliziran vegetacijski indeks*
NIR		Near Infrared	*Bližnje infrardeči*

PCA	*MGK*	Principal Component Analysis	*Metoda glavnih komponent*
RAF		Royal Air Force	*Kraljeve letalske sile*
RCAHMS		Royal Commission on the Ancient and Historical Monuments of Scotland	*Kraljeva komisija za zgodovinske spomenike Škotske*
RGB		Visible colors image composited of Red Green Blue image	*Kompozitna slika iz rdeče, modre, zelene barve EMS*
SAS	*PAS*	Special Aerophoto Survey	*Posebno aerofoto snemanje*
TIR		Thermal Infrared	*Termalna infrardeča*
TTN5	*TTN5*	Topographic Map in scale 1:5,000	*Temeljna topografska karta*
			1 : 5.000
WWII		World War II	*Druga svetovna vojna*

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