

**Ecosystem Development**

**Vol. 1**

**The artificial catchment  
'Hühnerwasser' (Chicken Creek):  
Construction and initial properties**

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Brandenburg University of Technology Cottbus 2010

## Vol. 1

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## 1. Introduction

Established in summer 2007 with financial support from the German Science Foundation (DFG), the Collaborative Research Centre/Transregio 38 involves close cooperation between the Brandenburg University of Technology at Cottbus, the Technische Universität München and the Swiss Federal Institute of Technology. The overall aim of this collaborative interdisciplinary project is to elucidate the role of structures and processes during the initial establishment of an ecosystem (Schaaf et al., 2010, Gerwin et al., 2009). The central hypothesis assumes that initial patterns substantially define and shape both the development and later stages of an ecosystem. The main objectives of this collaborative project are (1) to reveal which abiotic and biotic structures and processes control the initial phase of ecosystem development; (2) to investigate the interactions existing between both abiotic and biotic processes and patterns in the initial phase; (3) to characterize the differences between processes and patterns of initial-phase systems compared to mature ecosystems; (4) to derive and define the different stages occurring during early ecosystem development; and (5) to find indicators that allow the transfer of results to other ecosystems at an initial stage of development.

The most important investigation object for this research is an artificially created watershed in a lignite mine located in Lower Lusatia, Germany. Known as the 'Hühnerwasser' ('Chicken Creek'), this site is seen as a model for the initial stages of an ecosystem. With its 6 ha area and tremendous potential for interdisciplinary ecological research, the site offers globally unique conditions.

In this first volume of the series 'Ecosystem Development', the geographic situation, construction and fundamental structures, as well as an outline of the comprehensive monitoring program are introduced. Established in autumn 2005 thanks to financial support from the Brandenburg University of Technology and the State of Brandenburg itself, the monitoring program was set up in order to document the highly dynamic development of this initial-phase system and describe the newly emerging structures both qualitatively and quantitatively. The data provided by the central monitoring project can also be used as the fundamental basis for a number of other scientific projects. The objective of this series is to document this important research site, including the changes occurring during the ongoing initial stages of ecosystem development. Whereas this volume presents the site itself and the general concept of the monitoring investigations, the following volumes in the series will present the results gathered during each phase of the investigative period.

Data of the central monitoring of the Chicken Creek Catchment are available on request from the BTU Research Center Landscape Development and Mining Landscapes (FZLB). For contact see [www.tu-cottbus.de/fzlb/](http://www.tu-cottbus.de/fzlb/).

## **2. Regional background**

### **2.1 Geographic situation**

The Hühnerwasser ('Chicken Creek') artificial watershed is located in the lowlands of northeast Germany, the name deriving from a former small stream (the Hühnerwasser) destroyed by open-cast mining activities during the 1980s. The site falls within the region of Lower Lusatia in the State of Brandenburg, about 150 km southeast of Berlin close to the Polish border. Situated south of Cottbus (Fig. 1), the area is predominantly affected by both Pleistocene glacial influences and by more modern anthropogenic disturbance including large-scale open-cast lignite mines.

During the Pleistocene, the Elster and Saale ice ages were mainly responsible for the geomorphologic formation of the surrounding natural, i.e. non-mining affected, landscape (Fig. 2). Glaciers from Scandinavia left typical deposits such as terminal moraines and lodgement tills that can be found today on the surface and near subsurface. However, as these glaciers only reached the northern areas during the last glaciation period (Weichsel), the region as a whole was mainly characterized by periglacial conditions. Large glacial outwash plains developed and were covered by sandy sediments transported and deposited by meltwater streams derived from the northern glaciers. These meltwater streams formed large glacial valleys ('Urstromtäler'), parts of which are still exploited by recent rivers and streams. Two main glacial valleys dominate the region: (i) The Breslau-Magdeburg-Bremer valley in the south which developed during the Saale stage, and (ii) The Glogau-Baruther valley along the northern border of the region which formed later during the Weichsel stage. The latter glacial valley is home to the city of Cottbus as well as the Spreewald with its UNESCO Biosphere reserve.

The artificial watershed itself is located between these two major glacial valleys in a landscape originally shaped by a terminal moraine deposited during the Saale stage (Warthe stadial). This hilly landscape is part of the 'Südlicher Landrücken', a large terminal moraine originating in the Lüneburger Heide in the northwest, which is still visible today continuing into the southeast of northern Germany and reaching as far south as southern and central Poland. The sector of this moraine south of the city of Cottbus is known as the 'Lausitzer Grenzwall'. The hills in the area are in general relatively slight, although some of the more prominent small mountains of the 'Steinitzer Alpen' close to the Hühnerwasser site reach heights of up to 160 m a.s.l. (about 60 m above the surrounding landscape).

Sandy Cambisols and Podzols of relatively low fertility are dominant in this landscape, having developed on both moraines and outwash plains. However, smaller areas of the Lausitzer Grenzwall are characterized by more loamy sediments and soils.

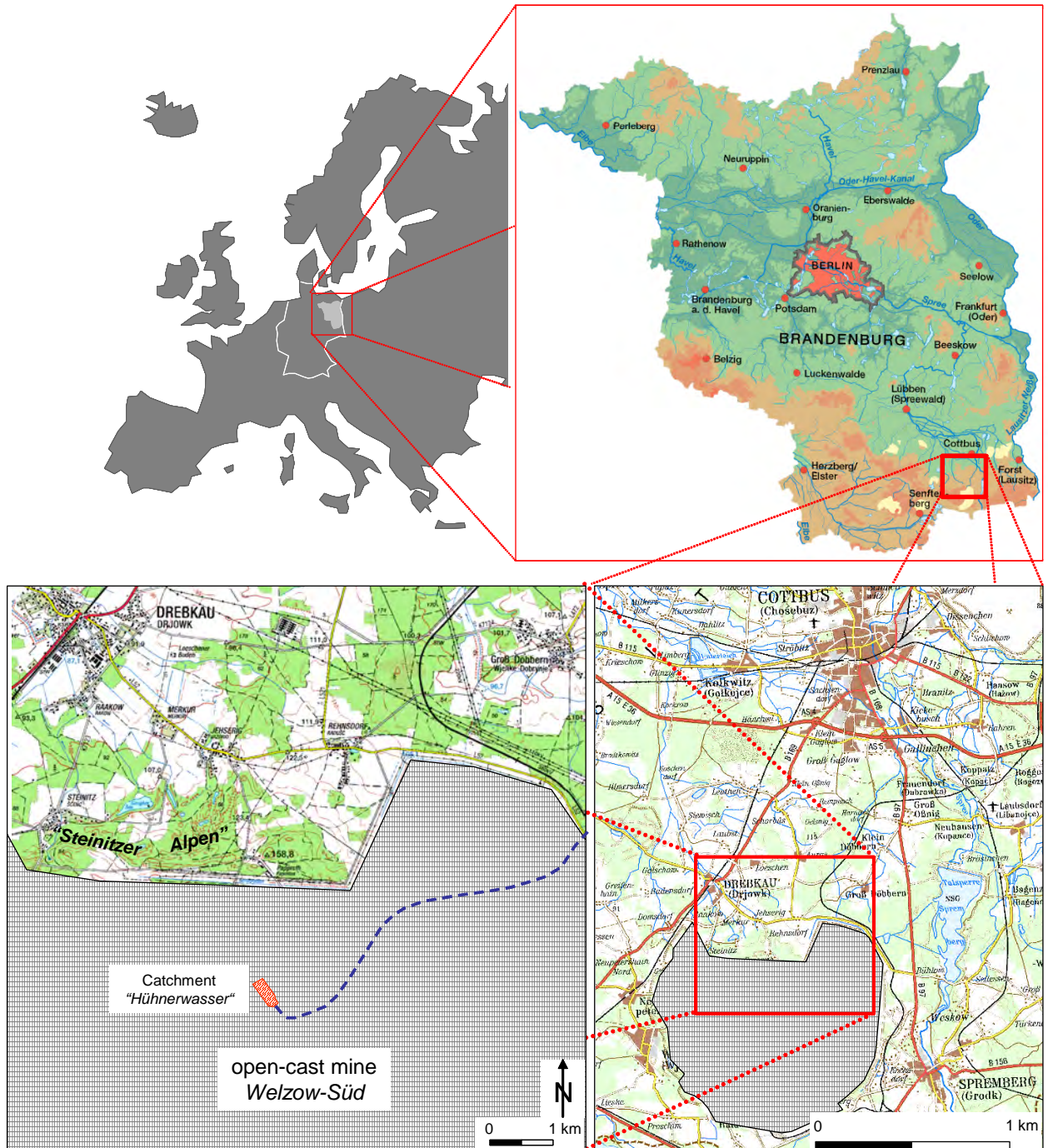


Fig. 1: Location of the Hühnerwasser (Chicken Creek) artificial catchment (Übersichtskarte Brandenburg; TÜK 200 CC4750 Cottbus; TK 50 L4350 Cottbus West, published by Landesvermessung und Geobasisinformation Brandenburg 2007).



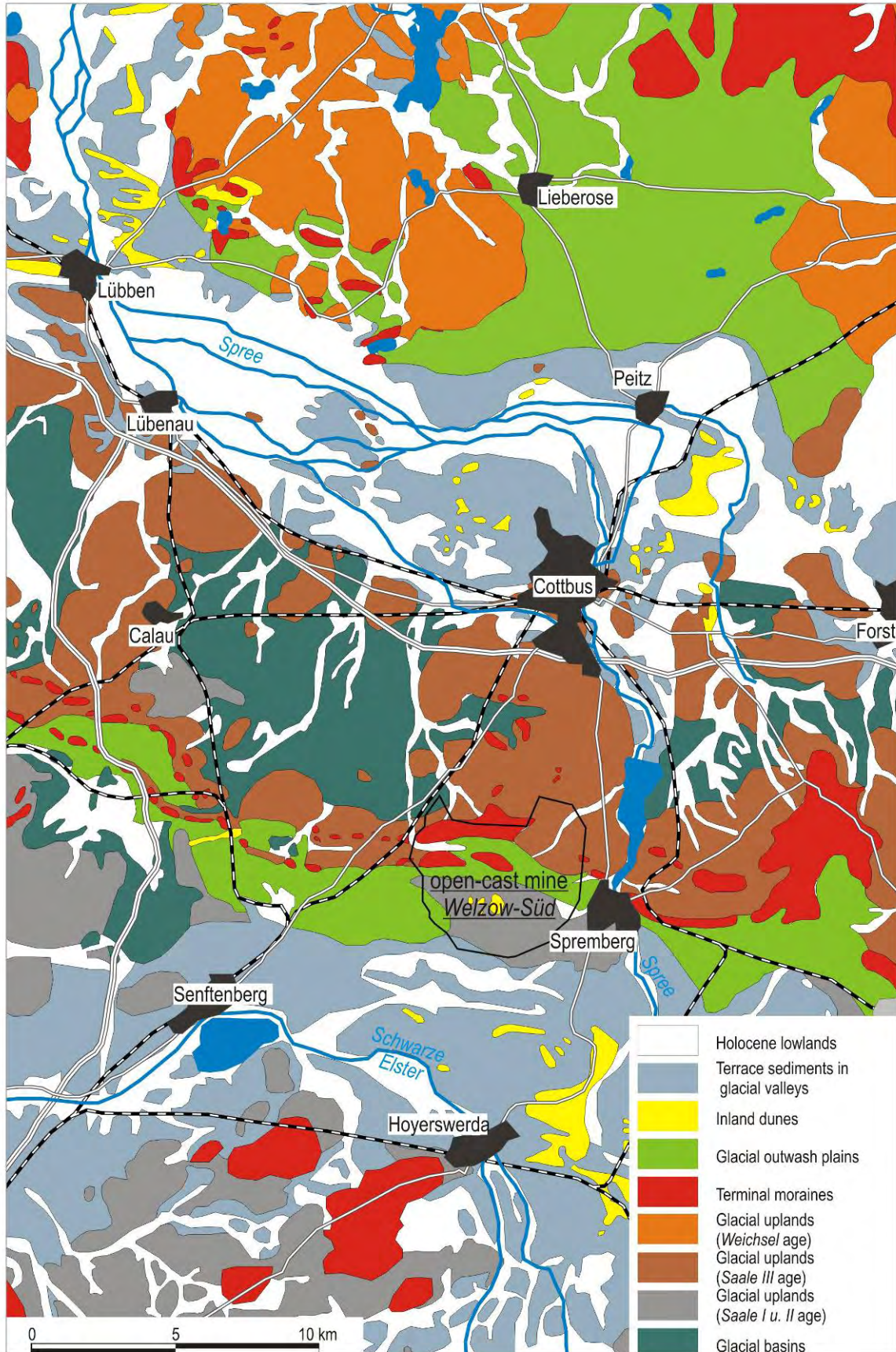


Fig. 2: Geological/geomorphological map of Lower Lusatia (Lausitzer Braunkohle Aktiengesellschaft (1992), modified).



The climate of the region is humid with some sub-continental influence (Fig. 3). Minimum temperatures occur in January with an average of  $-0.8^{\circ}\text{C}$ ; the average maximum temperature of  $18.4^{\circ}\text{C}$  is reached in July (according to 1961-1990 data from Cottbus weather station). Annual total rainfall is comparatively low at only 563 mm, with Lower Lusatia experiencing some of the lowest precipitation levels in the whole of Germany.

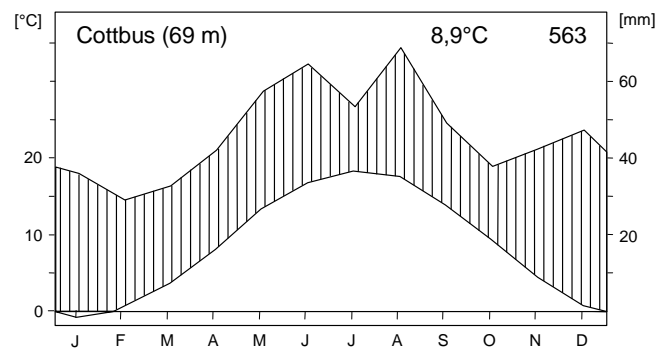


Fig. 3: Climatic chart from the DWD weather station Cottbus (Walter climate diagram for normal period 1961-1990).

Due to the predominantly poor sandy soils and low total annual precipitation, mixed oak-pine forests can be regarded as the potential natural vegetation of the Lower Lusatian landscape outside of the glacial valleys. However, typical of many regions in Central Europe, for centuries the landscape has been used for agriculture and forestry, and as a result the actual vegetation is currently characterized by large pine forest stands and some agricultural sites, as well as a large proportion of grasslands. In addition to this anthropogenic alteration of the natural landscape cover, lignite mining has also influenced and disturbed large swathes of the region. Indeed, with open-cast mining and subsequent restoration activities still ongoing, many parts of the region are in a state of permanent change.

Amongst a variety of influences and disturbances, open-cast mining also results in significant lowering of groundwater levels. Before the commencement of large-scale mining operations in the 1970s, several springs and small streams were present along the Lausitzer Grenzwall which fed tributaries of the river Spree. One of these was the former Hühnerwasser headwater which supplied a small stream flowing into the Spree north of Spremberg (Fig. 4). Today this stream exists only in a few locations running to the Spree water reservoir between Spremberg and Cottbus, and without a functioning headwater is supplied artificially by water pumped from the lignite mine. However, the mining company Vattenfall Europe Mining AG (VEM) is obliged to restore this stream after mining activities have been completed. As the complete restoration of the natural groundwater table of the landscape will take several decades, an artificial spring is needed to ensure a minimum discharge level for this stream in the near future.

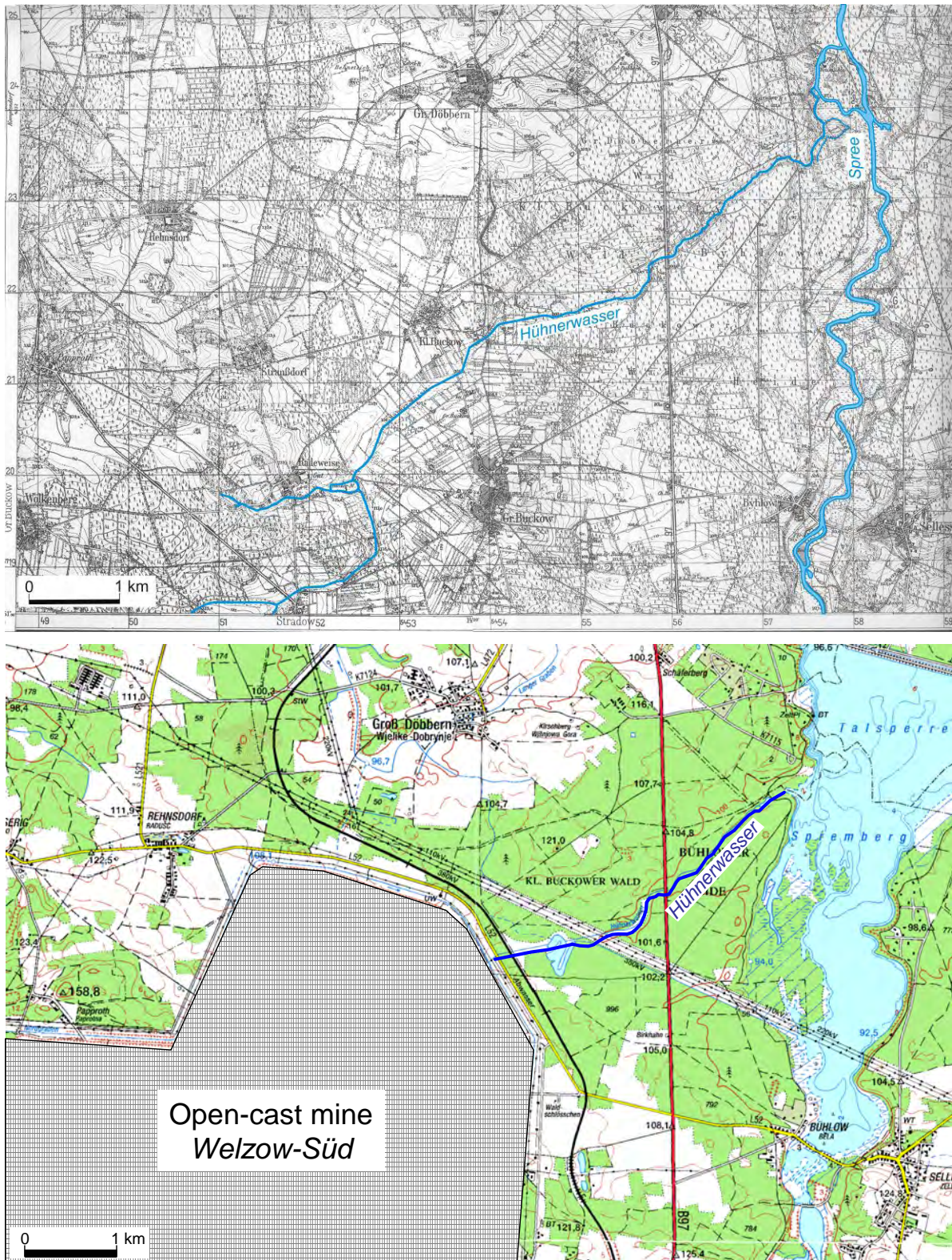


Fig. 4: Maps of the Hühnerwasser stream: Above: Historical map of the region showing the original course of the Hühnerwasser stream before the start of mining operations (map based on: TK25 4351 Drebkau, issue 1943; TK25 4352 Komptendorf, issue 1939); below: Map of the extant Hühnerwasser stream (map based on: TK 50 L4350 Cottbus West; L4352 Cottbus Ost, © Landesvermessung und Geobasisinformation Brandenburg 2007).



Therefore as part of the reclamation and restoration process, a new headwater with a small artificially created watershed was planned by VEM with the aim of developing a local groundwater body with an artificial spring.

## 2.2 Mining activities

The region of Lower Lusatia in the southeast of Brandenburg is shaped by mining activity in the form of the Lusatian lignite mining district (Fig. 5). Beginning in the 19th and early 20th centuries, initial mining activity was minor in scale. In the 1920s however, large-scale open-cast mines were opened to extract lignite, mainly for the production of electricity and briquets. In the following decades more than 20 open-cast mines were operating in the region, but by the time of German reunification only 5 open-cast mines remained active. These mines are operated by VEM, the German branch of the Swedish Vattenfall group.

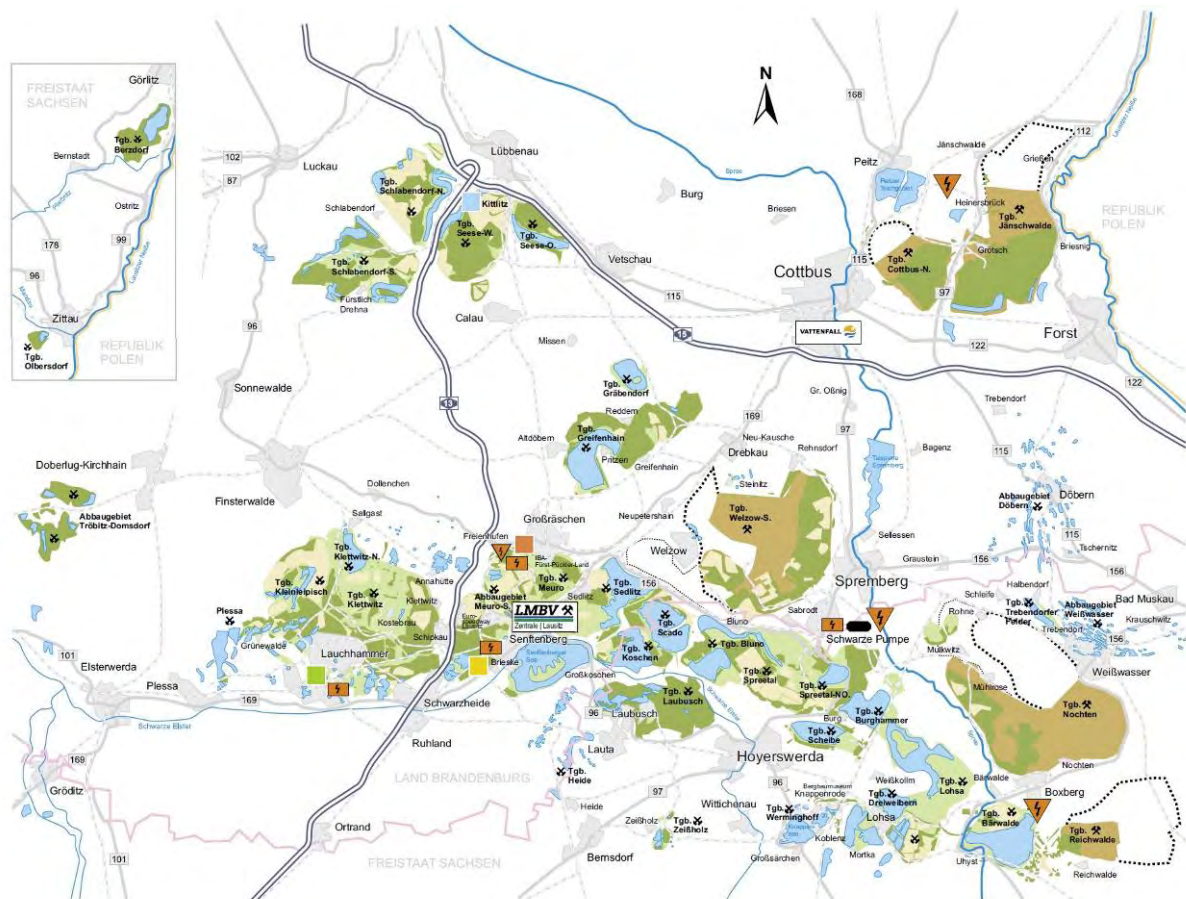


Fig. 5: The Lower Lusatian lignite mining district: reclaimed post-mining landscape (yellow and green) and mining lakes (blue) as well as active mine sites operated by Vattenfall Europe Mining AG (brown) (© Lausitzer und Mitteldeutsche Bergbau-Verwaltungsgesellschaft mbH 2008).

As one of the three most important German lignite mining districts, Lower Lusatia offers geological conditions specifically favorable for large-scale open-cast mining. Lignite is found at a depth of around 60-100 m below the surface, with seams of up to (10-) 15 m in thickness. Most of the lignite layers are in a horizontal position and are undisturbed by tectonic impacts. Therefore conveyor bridge technology is predominantly used and is generally regarded as the typical technique utilized by lignite mines in this region southeast of Berlin. Conveyor bridge technology allows for extremely efficient lignite production, with up to 60 m thick sandy overburden sediments able to be excavated in a single step. These sediments can then be dumped immediately into the worked-out mining area. Only a narrow strip remains open where the coal can be extracted by bucket-wheel excavators. Today, more than 90% of the excavated lignite is used directly for electricity production in one of the adjacent large power plants.

In total, an area of around 80,000 ha has been directly affected by mining activities in Lower Lusatia over the last few decades, often involving large-scale changes in landscape. A challenging issue for the mining companies is therefore the reclamation and restoration of these landscapes after mining activities have ceased. In Lower Lusatia the problem of acid mine drainage is of particular importance, since most of the overburden contains minerals such as Pyrite which often leads to the occurrence of extreme acidification after excavation and aeration. For this reason, more fertile Quaternary sediment overburden is separated in the fore field of the mine. While large quantities of sandy overburden material is removed and directly deposited by means of conveyor bridge technology, the more fertile substrate is excavated separately by bucket wheel excavators and transported by conveyor systems before being dumped by stackers on top of these conveyor bridge spoil heaps to create cultivable land. Immediately after dumping, the surface is flattened and the topography modeled by bulldozers. In general, the new landscape is then ameliorated by the application of lime and fertilizers, and subsequently either afforested or used for agriculture. It is important to note that these typical reclamation measures were not carried out in the case of the Hühnerwasser artificial watershed.

The Hühnerwasser is situated within Welzow-Süd, one of the last remaining active lignite mines in Lusatia, located approximately 20 km south of Cottbus (Fig. 5) and 150 km southeast of Berlin. Mining activities started in the 1960s, and current annual lignite production levels stand at about 20 Mio. t. More than 160 Mio. t of overburden must be removed every year for lignite extraction. Although a large area of this has already been reclaimed, reclamation is ongoing as a result of the continuous dumping of fresh material (Fig. 6).

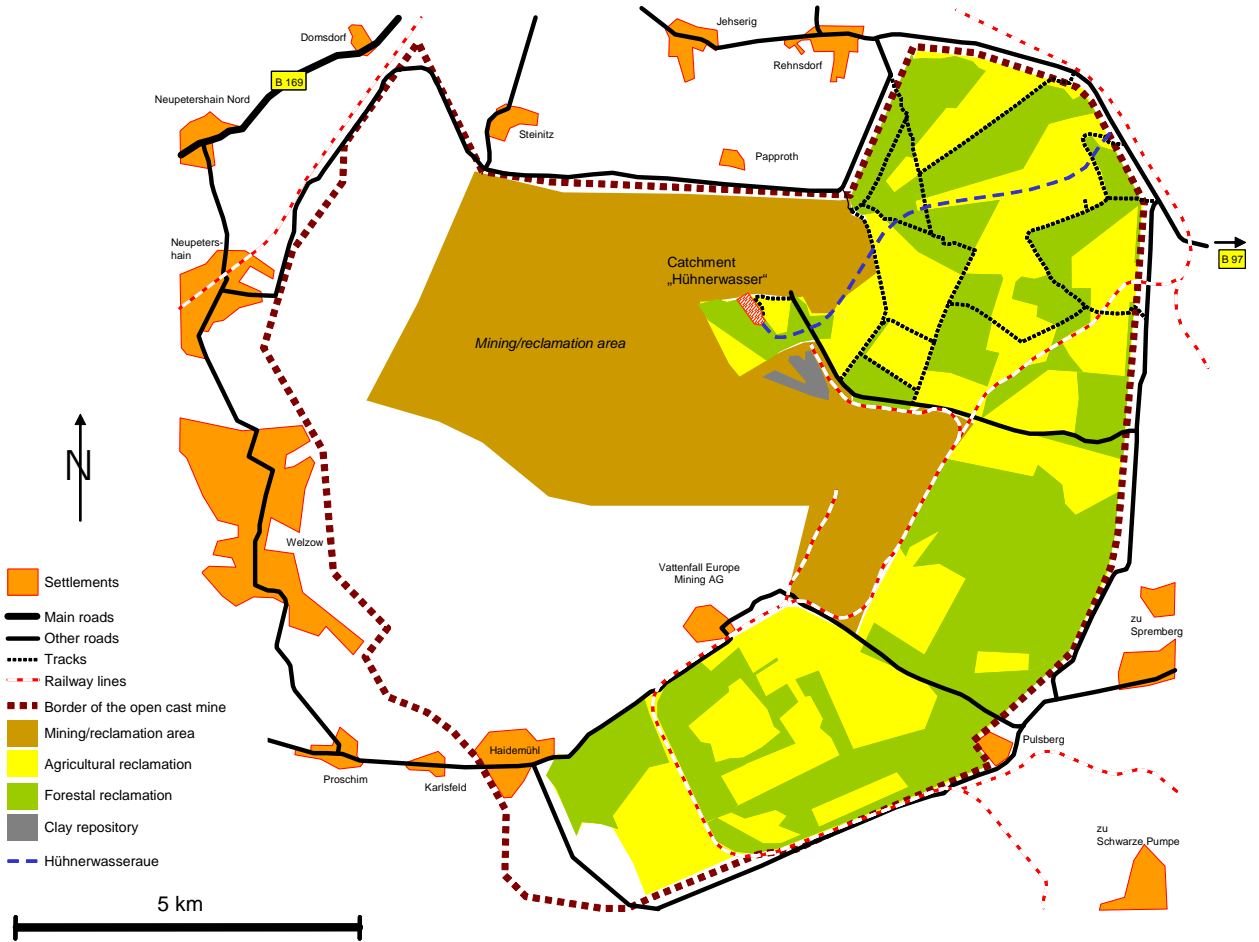


Fig. 6: Map of the Welzow-Süd open-cast mine in 2010 (© Vattenfall Europe Mining AG, modified).



### **3. The artificial catchment**

#### **3.1 Planning of the site and general site description**

Of the variety of potential land uses available, environmental restoration is of particular relevance for the rehabilitation of former mine sites in the Lower Lusatian landscape. The restoration of suitable wetland sites is a central issue for VEM, and therefore planning and construction of the Hühnerwasser artificial catchment was initiated by Beak Consultants GmbH (Freiberg, Saxony). Construction work started in 2004 and the site was finished in September 2005. A general overview of the technical construction work can be found in Kendzia et al. (2008).

The major objective for the mining company in creating an artificial catchment was to ensure a base water supply for the future Hühnerwasser stream which had to be restored after the cessation of mining activities. As the groundwater table in the region had been lowered significantly due to the deep-well pumping which had been carried out in connection with the operation of the mine, it was necessary to construct a watershed in order to establish a local groundwater body fed only by precipitation.

From a scientific point of view, the planned site represents a unique and outstanding research object for ecological studies. As the characteristics of the site were planned in advance, important boundary conditions are well known and the structure of the site was, at least in the beginning, comparatively simple. As a result the catchment is now the central investigation site of the Transregional Collaborative Research Centre (CRC/Transregio 38) and collaboration between the Brandenburg University of Technology Cottbus, the Technische Universität München and the Swiss Federal Institute of Technology (ETH) Zurich. The objective of this research centre is the investigation of the initial phase of ecosystem development, using the Hühnerwasser artificial catchment as a model system which was initiated at 'point zero'. Details of the research program can be found in Gerwin et al. (2009).

With a total area of around 6 ha (400 m x 150 m), the catchment takes the form of a slight hill with a mean altitude difference of 15 m along the main axis and absolute heights ranging from around 125 m a.s.l. at the outlet of the catchment up to a maximum of 140 m a.s.l. The average longitudinal slope is 3.5% and the exposition is SE. The catchment can be divided into the following major sections (Fig. 7):

- (1) The weakly inclined backslope area which covers the main part of the site, subdivided into four sectors (A-D),
- (2) The more steeply inclined footslope,
- (3) The pond basin containing the single outlet

- (4) The spring area: a trapezoidal area in which the originally planned artificial spring is separated from the surrounding parts of the catchment by small lateral sand dams.

Downstream the catchment is hydrologically connected to the new headwater of the Hühnerwasser stream.

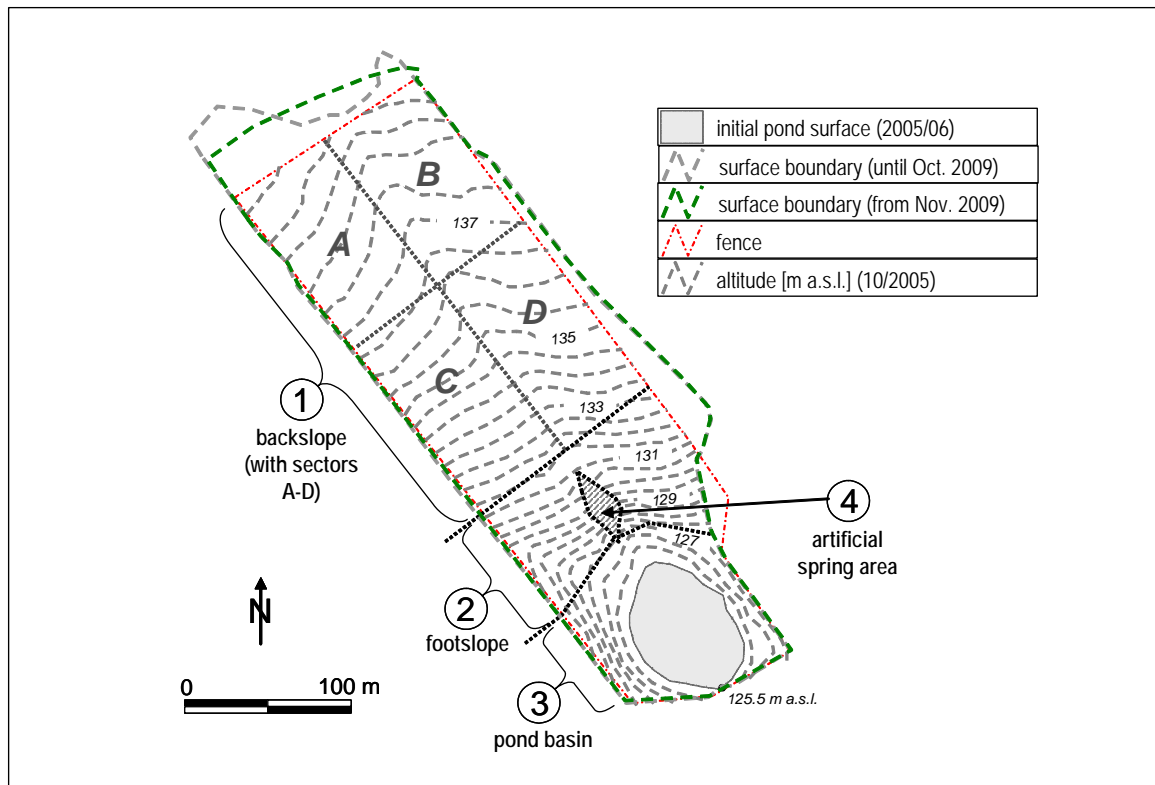


Fig. 7: General map of the Hühnerwasser (Chicken Creek) artificial catchment showing major sectors (1-4) and surface topography at ‘point zero’ (September 2005) (for information on the different surface boundaries see Section 3.3).

### 3.2 Construction of the catchment

The catchment was constructed between May 2004 and September 2005 by large mining machinery, including conveyor belt systems involving bucket wheel excavators and coupled stackers (Fig. 8). In general the erection of the catchment was carried out strip-wise, with four major strips able to be distinguished schematically (Figs. 9/10 and Tab. 1). Of these four strips, only the 2nd and 3rd directly cover the area of the watershed and as such are therefore the only ones relevant to the catchment’s behavior and further development. The two other stages of construction mentioned in the scheme were necessary to build the lateral parts of the hillside. These sections lie largely outside the boundaries of the hydrological catchment and are therefore not part of the ongoing ecological investigations. Aerial photographs taken by VEM in 2004 and 2005 illustrate the progress of the construction work (Fig. 11).

An overview of the work undertaken in terms of the main components of the site: (1) base spoil, (2) clay layer or aquiclude (used synonymously here) and (3) sand layer or aquifer (used synonymously here), is given in Fig. 12. These schematic figures were derived from aerial photographs provided by VEM.



Fig. 8: Technical equipment used in the construction of the artificial catchment: Stacker dumping sandy substrate in Welzow-Süd.

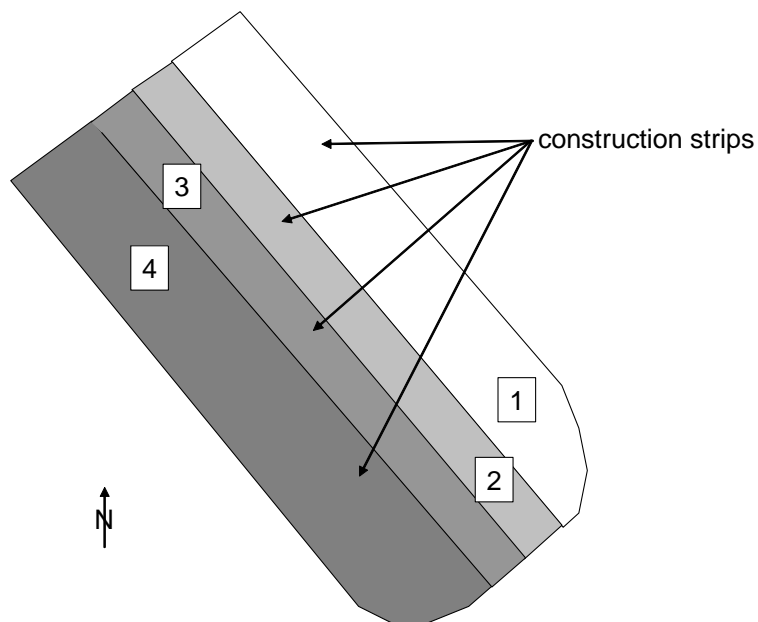


Fig. 9: Schematic illustration of the main construction stages for the Hühnerwasser hillside ('strips' mentioned in Tab. 1) (based on information provided by Beak Consultants GmbH and Vattenfall Europe Mining AG, 2004, modified).



Fig. 10: Strip-wise construction north of the central clay dam can be clearly observed on aerial images (courtesy of Vattenfall Europe Mining AG, 2004).

Tab. 1: General steps taken in the construction of the artificial catchment (information provided by Beak Consultants GmbH and Vattenfall Europe Mining AG).

year/month	2004								2005			
	5	6	7	8	9	10	11	12				
beginning of construction	■											
dumping of base spoil (1 <sup>st</sup> eastern strip)		■										
dumping of clay layer (1 <sup>st</sup> eastern strip)			■									
levelling of clay layer (1 <sup>st</sup> eastern strip)			■									
dumping of sand layer (1 <sup>st</sup> eastern strip)			■									
levelling of sand layer (1 <sup>st</sup> eastern strip)			■									
dumping of base spoil (2 <sup>nd</sup> eastern strip)				■								
dumping of base layer (3 <sup>rd</sup> strip in the centre)					■							
dumping of clay layer (strips 2-4)					■							
levelling clay layer (2 <sup>nd</sup> and 3 <sup>rd</sup> strips)					■							
dumping of base spoil (4 <sup>th</sup> strip, western side)						■						
levelling clay layer (3 <sup>rd</sup> and 4 <sup>th</sup> strips)						■						
dumping of sand layer (3 <sup>rd</sup> and 4 <sup>th</sup> strips)						■						
levelling of sand layer (2 <sup>nd</sup> , 3 <sup>rd</sup> and 4 <sup>th</sup> strips)							■		■	■	■	■

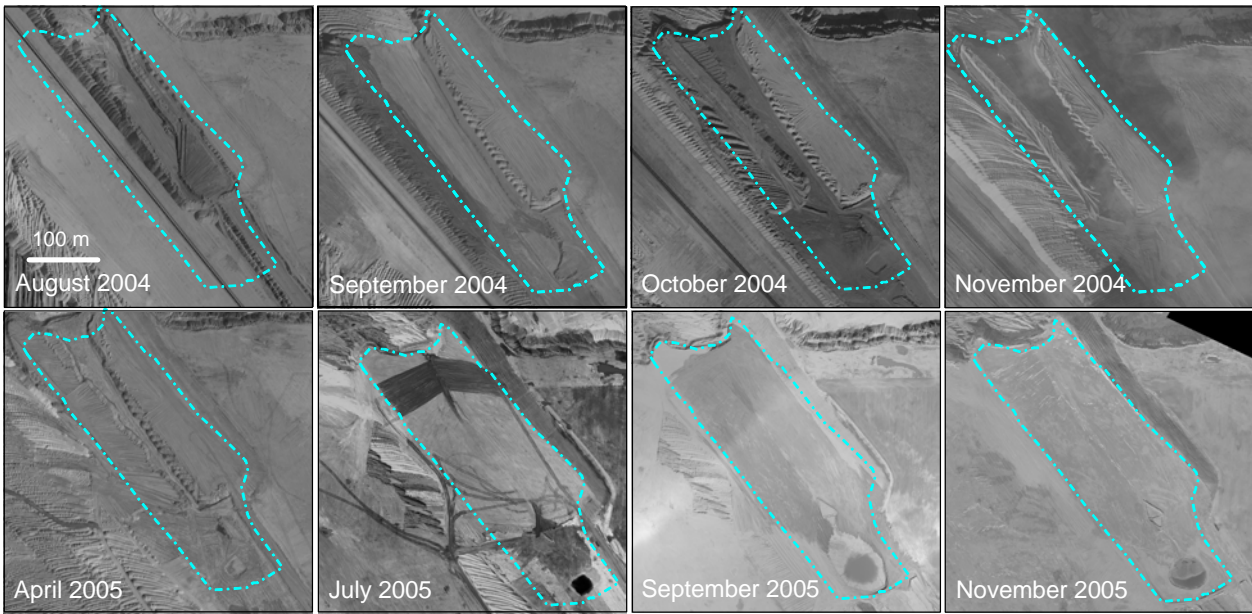


Fig. 11: Construction progress visualized by aerial photographs; the outlines of the later artificial catchment are marked with blue dotted lines (Photographs provided by Vattenfall Europe Mining AG; © Vattenfall Europe Mining AG, 2004 and 2005).

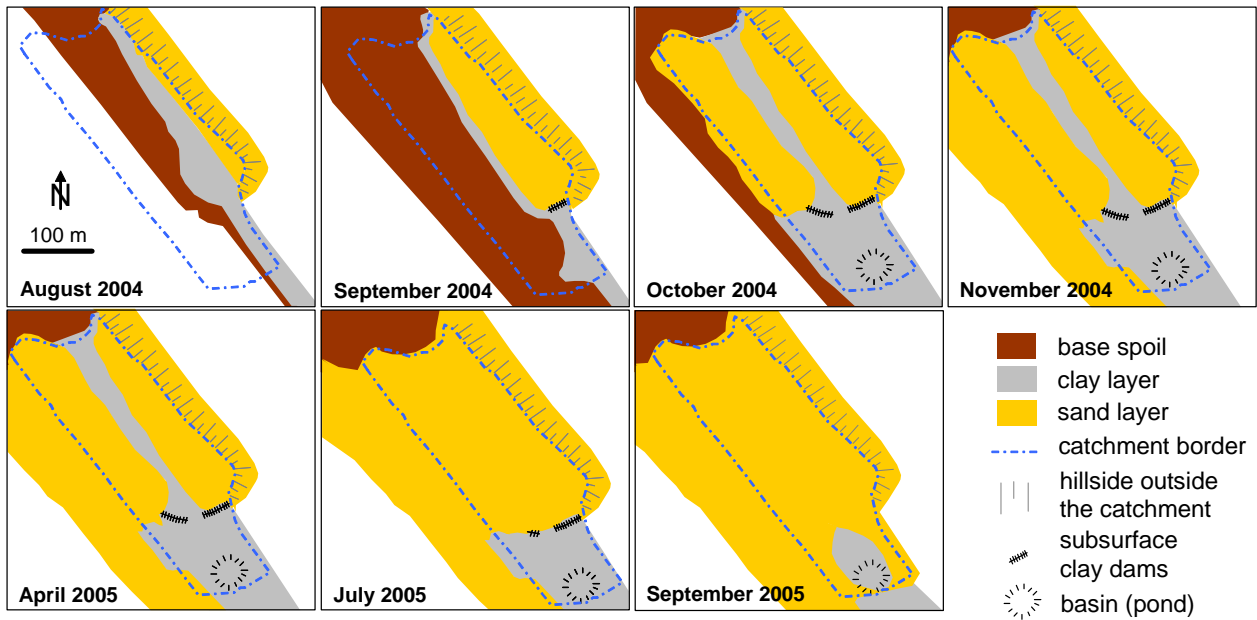


Fig. 12: Schematic maps of construction progress (based on aerial photographs provided by Vattenfall Europe Mining AG, 2004-2005).



### 3.2.1 Aquiclude

The aquiclude was built in the form of a 1-3 m thick layer of Tertiary clay, comprising a total volume of 174,000 m<sup>3</sup> (Kendzia et al., 2008). This clay material derives from local geological layers identified as ‘Flaschenton’ and is supplied as a by-product of the activities of Welzow-Süd open-cast mine. The clay content varies between 24 and 93%, with an average of 53%. The combined clay and silt content is 83% (Tab. 2).

Tab. 2: Texture of clay substrate used for the aquiclude (Flaschentone) (unpublished data from Vattenfall Europe Mining AG, analysis of 49 samples [in % by weight]).

	Clay	Silt	Sand (calculated)*
Mean value	53	30	17
Maximum value	93	65	-
Minimal value	24	2	-
Standard deviation	20	16	-

\* data for the sand content was not available, the mean value was calculated as the difference of the mean sum of clay and silt from 100%

The material was separated from the Tertiary overburden layers by bucket wheel excavators and dumped by a stacker. The clay surface was then leveled by bulldozers - but not compacted, as this material tends to self-seal when considerable swelling occurs. Initially the freshly dumped substrate consisted of large aggregates (Fig. 13), but these vanished when the clay became wet and subsequently swelled, demonstrating the extremely low permeability of the clay layer ( $k_{sat} \sim 10^{-9} \text{ m/s}^{-1}$ ; Kendzia et al., 2008). During construction, the clay layer was dumped across of the site in an east-west direction. Its surface was shaped into a shallow basin ascending from the centre to the edges to form the subsurface boundaries of the catchment. The clay base liner has an average slope of 3% which is parallel to the inclination of the surface area. Fig. 14 shows the morphology of the clay layer.

Belowground in the lower part of the catchment, additional clay dams were constructed on top of the clay layer transverse to the slope. These act as both a stabilization barrier to prevent the sandy substrate from sliding downhill on the clay layer, and as a central groundwater discharge unit for the creation of an artificial spring for the reconstructed creek. The importance of this feature as an initial structure of the system is discussed in chapter 4.1.



Fig. 13: Freshly dumped clay material with large aggregates resulting from the transport by conveyor belts (left, 2004); clay surface after the occurrence of swelling processes (right, 2005).

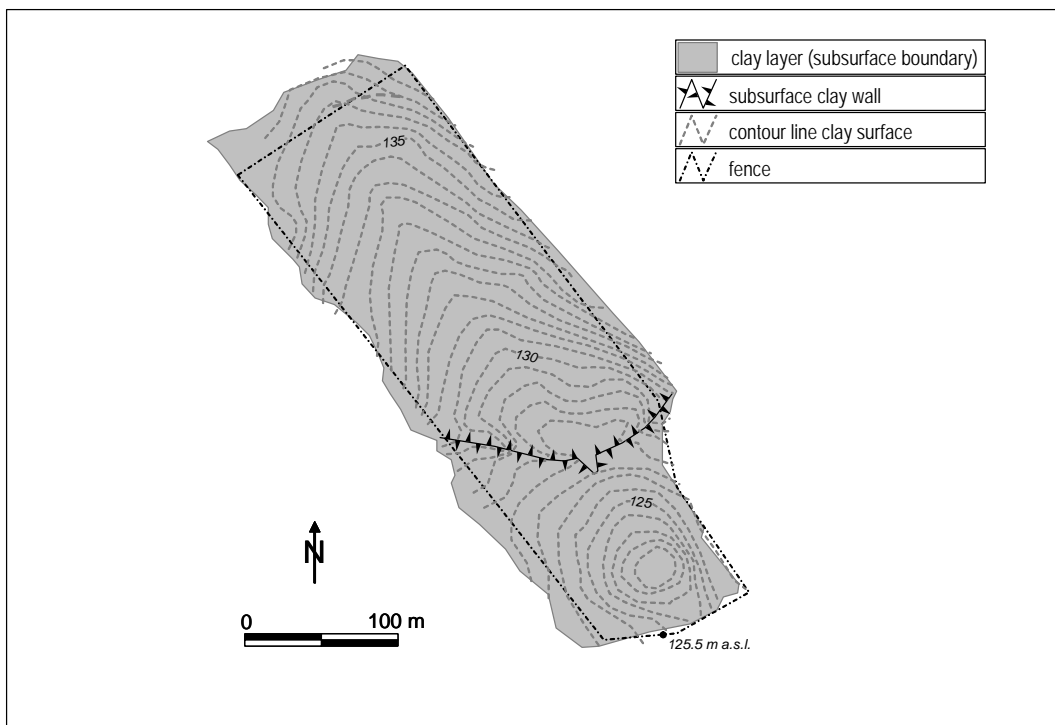


Fig. 14: Topographic map of the clay layer (partially based on different datasets provided by Vattenfall Europe Mining AG).

In addition, a basin with a diameter of around 60 m and a maximum depth of 3.5 m was shaped to allow the establishment of a small pond in the lowest part of the catchment. A clay wall at the southern edge of the pond defines the lower border of the catchment and has a single defined outlet.

### 3.2.2 Aquifer

On top of the clay layer, 117,500 m<sup>3</sup> (Kendzia et al., 2008) of sandy substrate material was dumped, again by stacker in steps with a thickness of up to 3.5 m, with the aim of providing an aquifer for the establishment of a local groundwater body. This mixed sandy material was sourced from a variety of Pleistocene sediments from the fore field of Welzow-Süd, where they had been deposited during the Saale-glacial period as part of a terminal moraine and lodgement till layers. Details of the physical and chemical properties of the substrate are discussed in chapter 5.1.

The construction of the sandy aquifer layer began in August 2004 with the eastern area of the hillside adjacent to the later hydrological catchment, followed by the central parts of the catchment during the next two months. The vertical cross-section presented in Fig. 15 illustrates the fundamental components of the system. The area of the catchment generally consists of three different sections which can be distinguished in terms of the overall construction process. The sandy material in section I (Fig. 15) was dumped during the second phase of construction work in September 2004. During the third construction phase in September/October 2004 the western part of the clay layer was completed and immediately covered with sandy substrate material. This part of the catchment is marked as section II in the profile. Sections I and II are characterized by typical subsurface structures resulting from the dumping process (see chapter 4).

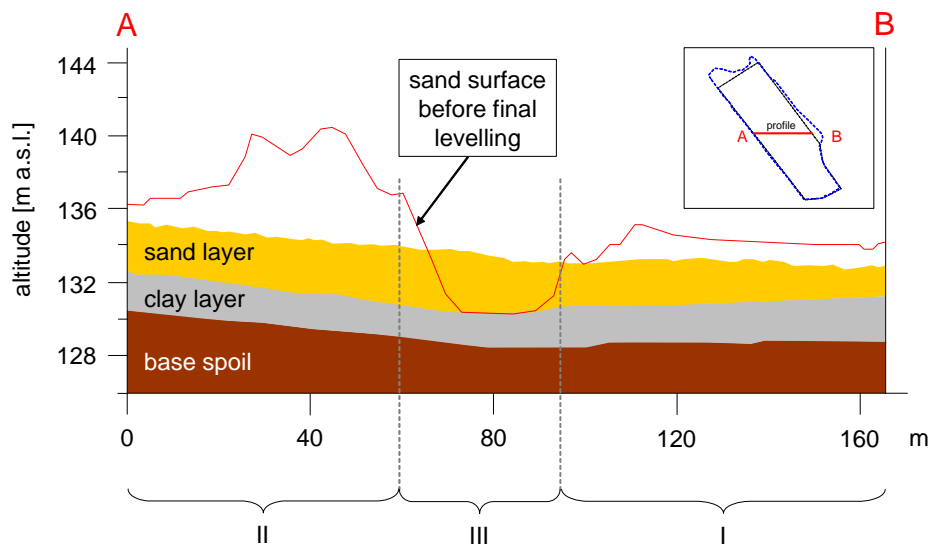


Fig. 15: Cross profiles with the three general construction stages (I - III) showing mass transport during final leveling by bulldozer: (1) red line: surface October 2004; (2) surface of sand layer September 2005 (4x vertical exaggerated, modified after Dominik 2007; based on photogrammetric interpretation of aerial photographs 10/2004 and 09/2005 provided by Vattenfall Europe Mining AG).

The central area, marked as section III in the profile, was left open as a 'central trench' for a period of seven months, before finally being filled in by bulldozers in May 2005 with substrate material from sections I and II. The surface level of the eastern part of the catchment was lowered, as shown in the profile. This lowering was undertaken in order to remove the surface-lying substrate material that had been exposed to the atmosphere for more than one year, restoring the surface to its initial state. The morphology of the catchment was shaped into a shallow basin with the similar aim of defining clear surface boundary conditions.

As a final step, in September 2005 the sandy layer was spread close to the edge of the pond in the lower part of the catchment, with the immediate border of the pond left sand-free. However, sandy material transported by surface runoff was soon deposited around the pond during the following months, and by the beginning of 2006 the entire area of the clay layer was completely covered.

### **3.2.3 Final steps**

In August/September 2005 the whole surface of the site was flattened once more, and the surface shaped into a basin which defined the final surface boundaries of the catchment. In September 2005 the surface was also homogenized using rails pulled by tractors (Fig. 16). This final treatment was undertaken in order to remove surface structures generated by the construction work, such as car and bulldozer tracks, as well as the earliest-emerging features of the already forming ecosystem such as erosion gullies, soil crusts and vegetation. These were removed to ensure as uniform initial surface conditions as possible for the complete catchment. However, it is likely that some bulldozer tracks remained even after this homogenization, hidden only by a thin sandy layer. These tracks must therefore be regarded as having an important influence on the later establishment of surface structures (see chapter 4.2).

In the centre of the footslope area, a trapezoidal sector cut off by small sandy dams was designated as the area for the originally planned artificial spring (sector 4 in Fig. 7). A specific groundwater outlet unit was also built in the centre of this sector and is described in chapter 4.1.1. The lateral dams were positioned to redirect surface water from this area, in order to avoid damage by erosion and sedimentation processes. With natural erosion and sedimentation processes strongly restricted here, this trapezoidal sector was therefore excluded from the ongoing monitoring process and used as the location for the installation of monitoring devices, including a complex weather station (see chapter 5.2).

In September 2005 the main area of the catchment was fenced in completely to avoid disturbance and vandalism, particularly by human visitors but also by the abundant game animals that live in the area. This step marked the completion of the construction process, and September 2005 is therefore defined as 'point zero' of the development of the site. Only a small part of the eastern side of the watershed remains unfenced, and is therefore not included

within the comprehensive monitoring of surface structure development. However, as this area is hydrologically connected to the main part of the catchment within the fenced area, it is taken into account in hydrological investigations.



Fig. 16: Final flattening of the sandy surface and elimination of surface structures such as bulldozer tracks (September 2005).

Since then the site has been left for unrestricted and unmanaged succession. Neither amelioration measures – such as fertilization or liming – nor any artificial re-vegetation has been undertaken, but erosion and other natural surface-forming processes have been allowed to occur without restriction.

### 3.3 Catchment boundaries

During construction the boundaries of the catchment were defined according to the working plans by means of specific modeling of site morphology. Both the surface and subsurface catchments were designed as shallow basins, although due to the site being constructed in multiple stages, some slight differences exist between the boundaries of these two catchments, as illustrated in Fig. 17. In addition, in October/November 2009 some modification of the surface boundaries was necessary in the northern part of the catchment due to construction work being undertaken on the adjacent ‘Wolkenberg’ hill. These changes are also highlighted in Fig. 17.





Fig. 17: Catchment borders: (1) surface boundary, (2) subsurface boundary, and (3) outline of the fenced area for comprehensive monitoring of surface structure development.

A digital elevation model (DEM) of the clay layer was constructed using specific 3D-GIS software (GOCAD) (see Fig. 18) and was partly based on spatial and elevation data provided by VEM. From the DEM of the entire surface of the clay layer, the extension of the subsurface catchment was derived using the D8 algorithm. Within this zone, seepage water accumulates and contributes to the catchment's groundwater body.

### 3.3.1 Subsurface

An example of the visualized GOCAD clay surface model is presented in Fig. 18. According to this model, the underground clay base liner covers an area of 64,631 m<sup>2</sup>, whereas the subsurface catchment area extends to only 60,898 m<sup>2</sup>. The relief map shown in Fig. 18 is based on a digital elevation model of the clay layer derived from the following data:

- (1) Topographical surveys carried out by VEM during construction,
- (2) Photogrammetric surveys also carried out by VEM,
- (3) Information from the first soil sampling campaign as well as from the installation of groundwater gauges,
- (4) Later exploration at additional boreholes on the edges of the catchment (Fig. 19).

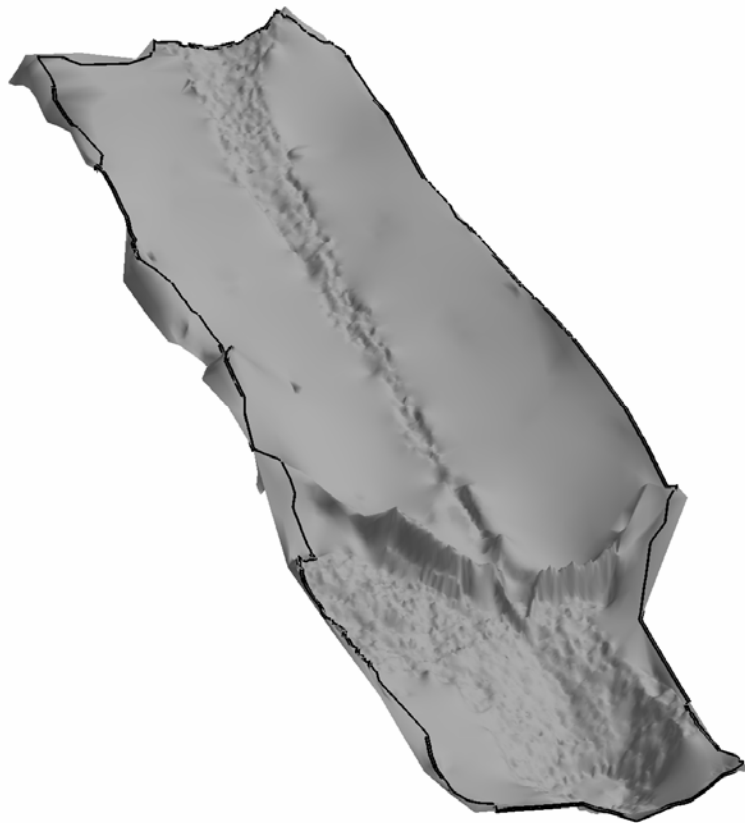


Fig. 18: GOCAD image of the topography of the clay base liner (tenfold vertical exaggeration): The black line marks the subterranean catchment as identified from elevation data using the D8-algorithm in SAGA-GIS. Higher information density is clearly visible in the lower parts of the catchment around the pond as well as along the former ‘central trench’ in the back slope area due to the better availability of data concerning the clay surface (screenshot from the GOCAD model of the catchment, partially based on spatial and elevation data provided by Vattenfall Europe Mining AG).

The available VEM survey data (1 and 2) covered the central part of the catchment (the former ‘central trench’; see chapter 3.2.2) as well as some areas within the pond basin, and are of a comparatively high information density. These areas are clearly noticeable in the digital elevation model due to the high density of grid points. In contrast, information regarding large parts of the clay layer in the backslope area was derived from data gathered during the first comprehensive soil sampling campaign in 2005 and the following installation of groundwater gauges. More comprehensive direct measurement of the clay surface could not be carried out here since the dumping processes proceeded rather quickly. The regularly taken aerial photographs also do not show the uncovered surface of the clay layer in these parts of the catchment for the same reason. In the elevation model these sectors are clearly recognizable by the much lower information and TIN-node density.

As a result, additional borehole investigation became necessary in the borders of the watershed to explore the clay layer and the lateral clay dams in more detail, the latter of which could not be detected from the aerial pictures taken by VEM during the construction phase. Fig. 19 shows all positions where the clay layer was explored, including these additional boreholes.

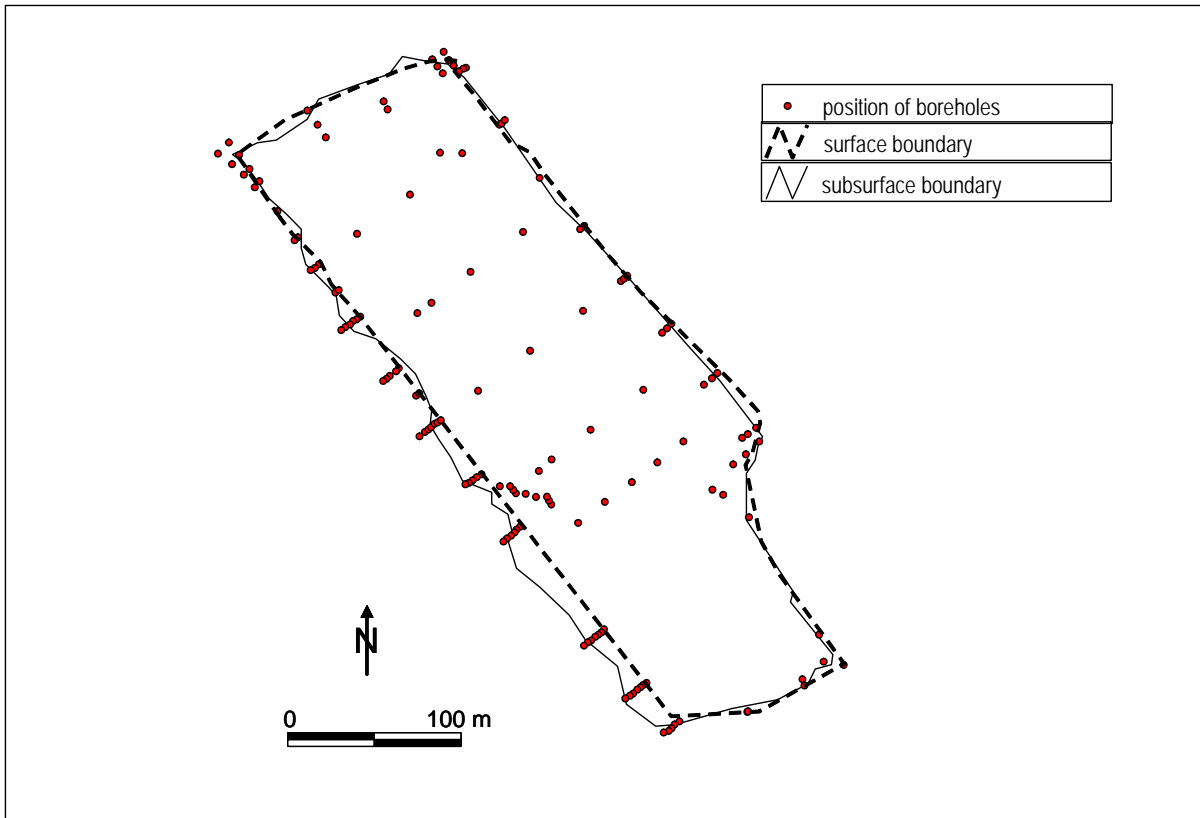


Fig. 19: Position of borehole investigating of the clay layer (drilling for groundwater gauges and additional survey carried out in 2008 and 2009).

The boundary of the subsurface catchment is mainly characterized by small clay dams created during the flattening of the clay surface by bulldozers. Fig. 20 shows sample profiles of the edges of the clay layer in the western part of the catchment revealed by drilling. Obviously, these clay dams have different characteristics in different parts of the site. However despite this limitation, the outline of the underground section of the catchment is generally more clearly defined and understood compared to that of natural watersheds. In future, the edges of models of the clay layer and of the clay dams will be optimized by means of geophysical methods such as Ground Penetrating Radar (GPR).

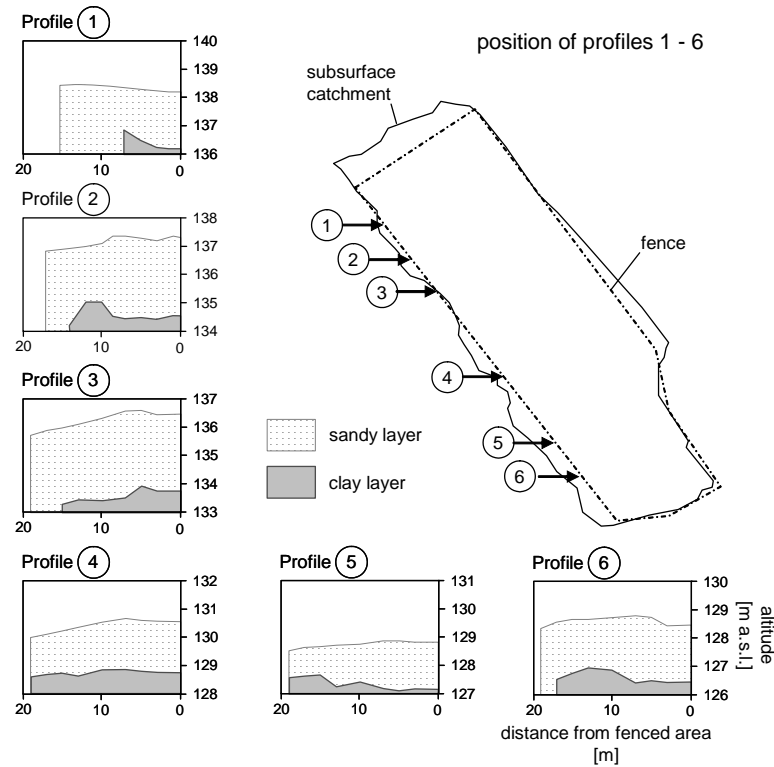


Fig. 20: Sample profiles of the clay border in the western part of the catchment derived from borehole investigations.

### 3.3.2 Surface

Fig. 21 presents a 3D-view of the initial subsurface and surface areas of the Chicken Creek catchment in September 2005, visualized by GOCAD. The data for this 3D-model were obtained from regular surveys carried out by VEM and are based on photogrammetric interpretation of aerial photographs. Both the subsurface clay layer and the surface of the catchment take the form of shallow basins in order to ensure clearly-defined boundary conditions.

The initial surface of the catchment was immediately subjected to processes such as erosion and sedimentation, with the topography rapidly altered by a network of erosion gullies and sedimentation areas. To assist in the comprehension of such rapid structural change, digital elevation models of the catchment surface are regularly constructed based on data provided by VEM and laser scanning. In addition, aerial photographs have been taken of the site by the CRC/TRR 38 since 2008, using a microdrone equipped with a digital camera. These pictures offer a significantly higher spatial resolution of 2-3 cm/pixel at the current standard flying altitude of around 80 m. Overlapping image pairs are analyzed using photogrammetric software to produce digital elevation models of the catchment surface. Also since 2008, laser scanning measurement of the site has been carried out regularly to register any small-scale change in topography resulting from geomorphologic processes.

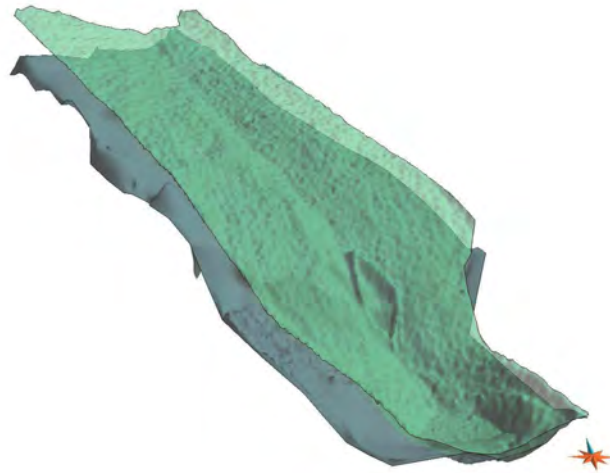


Fig. 21: 3D visualization of the catchment surface in 2005, compared with the surface of the clay layer underground (tenfold vertical exaggeration): screenshot from the GOCAD model of the watershed (partially based on data provided by Vattenfall Europe Mining AG).

A certain level of direct technical intervention was necessary to maintain the clearly defined nature of the surface boundaries of the catchment. In the western part of the site, additional small ramparts had to be constructed parallel to the fence and to the edge of the subsurface clay layer in order to define explicit borders and to prevent potential water flux from outside the watershed into the system. Built using a small excavator in September 2006 one year after the completion of the catchment, the dams have an average maximum height of 30-40 cm and are accompanied by a small parallel trench on their outer side. Construction was completed with the installation of flexible pipes in the westernmost erosion gully inside the catchment, as indicated in Fig. 22. This additional intervention was necessary to prevent water loss from the watershed, since this particular lateral erosion gully had a tendency to incise into the dam on the catchment border and thus endanger the stability of the adjacent fence. The canalization undertaken consequently reduced the extent of erosion to a minimum.

Whereas the area west of the fenced site lies outside the catchment, the entire eastern part of the hill plateau outside of the fenced area is hydrologically connected (the clay layer continues to the edge of the hill, see Fig. 23). This part of the catchment was leveled again in February 2008 by a bulldozer, with the aim of creating clear catchment borders on the edges of the hill. Dams were constructed to prevent water loss and surface runoff from this sub-catchment. The area was finally connected to the fenced site and runoff water allowed to enter the central part of the catchment. As a consequence of these changes, a deep erosion gully developed at the junction of the sub-catchment and the central part of the watershed, with



water channeled from the eastern sub-catchment to the pond. As with the western side of the site, a preliminary dam had been constructed in September 2006 along the eastern fence. This dam still remained after the leveling undertaken in February 2008, but has lost its primary function.

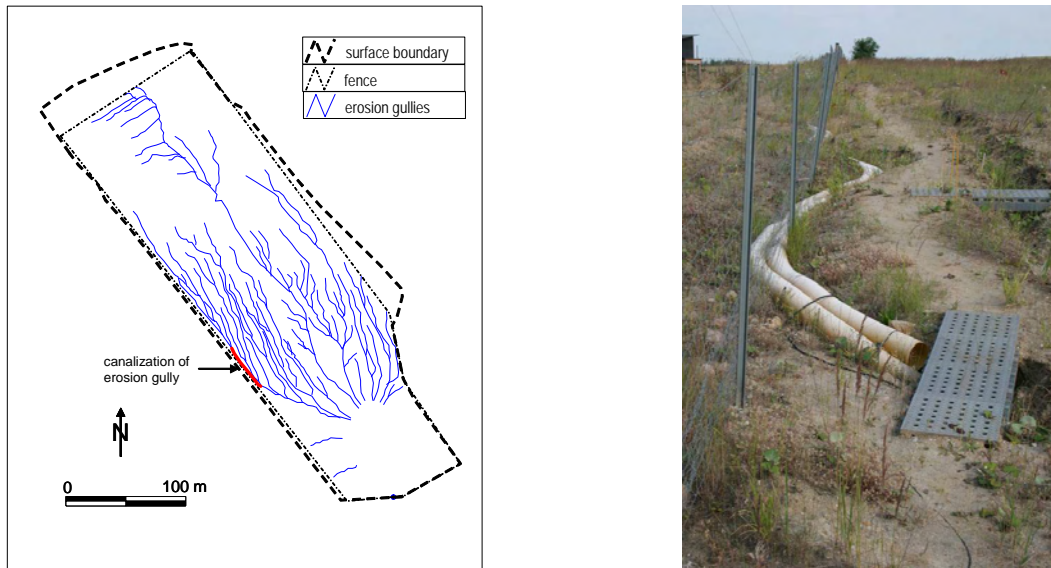


Fig. 22: Canalization of the western erosion gully preventing further incision. Left: location, right: installed flexible pipes (April 2008).

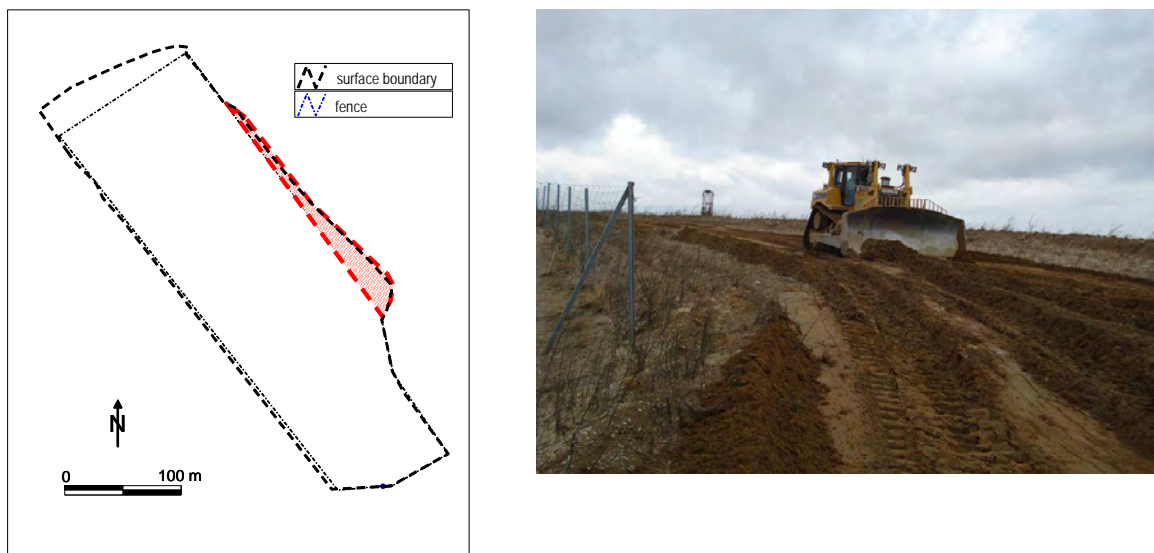


Fig. 23: Sub-catchment outside the fenced area in the eastern part of the catchment leveled in February 2008 (marked in red on the map left hand side). On right: bulldozer leveling the surface (February 2008).

#### 4. Initial structures

In general, the artificially modeled morphology of the site with its specifically designed landforms can be seen as one complex central initial structure that defined the later establishment of new surface structures, of the groundwater body and of other newly emerging ecosystem features. Although significant effort was made to create more or less homogenous starting conditions for ecosystem development, a number of mainly artificially-created structures, both on the surface and underground, were already present at 'point zero'. Such features are often the result of specific construction processes. These initial structures are supposed to play a key role for the further development of the ecosystem and for the establishment of secondary and tertiary structures.

Many initial surface structures were soon transformed or even completely removed by the rapid onset of surface-forming processes. Nevertheless, their existence had a significant role in defining the shape and establishment of subsequent structures. An important example is the downslope-oriented depressions caused by vehicles during the final construction phase, which turned into significant gullies (Fig. 24, see also chapter 4.2). Other depressions with different orientations were soon obliterated by erosion processes.

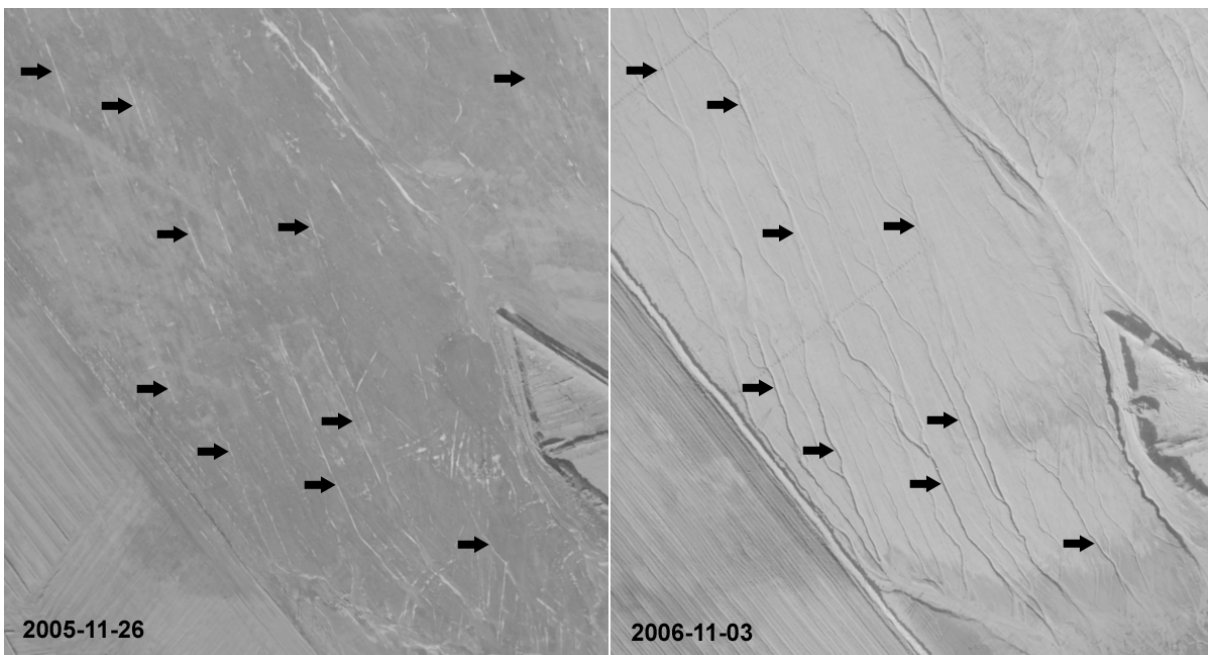


Fig. 24: Initial technogenic surface structures (vehicle tracks) featuring favorable conditions (i.e. small angles with the slope line) were soon transformed into 'gullies' by erosion processes and incorporated in the drainage system (© Photograph by Vattenfall Europe Mining AG, 2005/2006).

Most subsurface structures present at ‘point zero’ of ecosystem development in autumn 2005 have been much more persistent compared to those on the surface. Indeed it is expected that certain structures, especially those resulting from dumping processes, will last for a very long period of time and thus their influence on the system and control of important system structures and processes will continue. In the following chapters selected examples of these structures are introduced and described in detail.

#### 4.1 Internal structures

##### 4.1.1 Aquiclude

The clay dams found in the lower part of the site have a complex influence on the groundwater balance of the system. Constructed as a barrier for both potential slides of sandy material and for groundwater, the dams have a height and diameter of around 1 m and are situated on top of the clay layer and embedded into the sandy layer. The location of the clay dams is shown in Fig. 25. In the central area between the western and eastern sections, a section of the impermeable clay dam has been replaced by one made of coarse rubble. This provides groundwater with a defined outlet and also enables measurement of total groundwater discharge from the catchment. A large weir was installed here shortly before the end of construction.

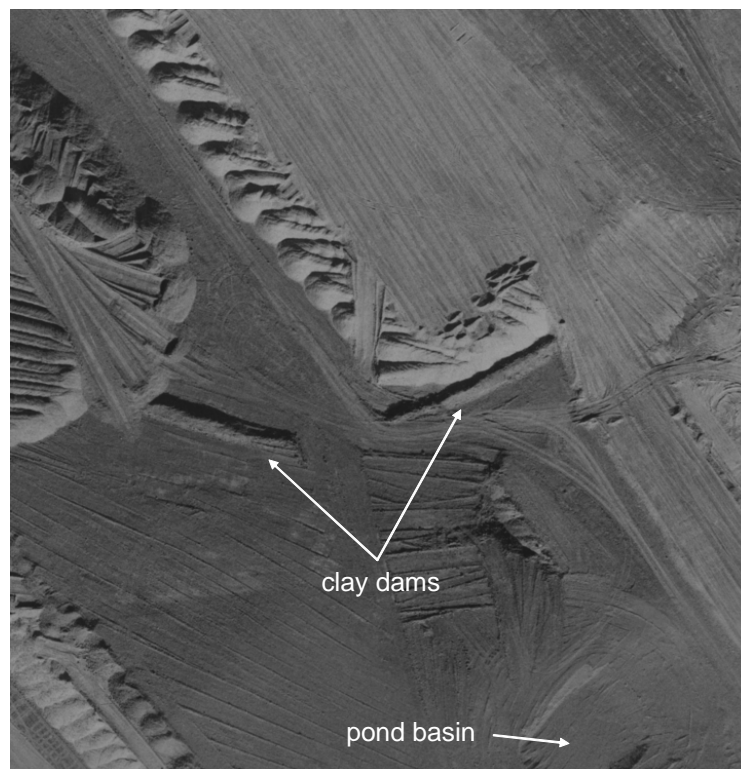


Fig. 25: Subsurface clay dams in the footslope area: Detail of the aerial photograph, October 2004 (© Vattenfall Europe Mining AG).

The interior of this rubble dam was initially protected by geotextile material. However, during the initial months of system development, evidence arose that this geotextile was impeding groundwater exfiltration and, more importantly, that DOC could potentially be dissolved from the material. As a consequence this textile was removed without replacement in May 2006.

With the further development of the system, it also became apparent that groundwater might pass through the internal clay dam at locations other than the central outlet. This was especially visible in the eastern part of the footslope beyond the clay dam, with the surface here exhibiting wetter soil conditions due to the upwelling of groundwater. This phenomenon is also reflected by the presence of fast-growing reed vegetation which is typical of soils with high moisture content.

In March 2005 with the ‘central trench’ between the two main areas of the catchment still open (see chapter 3.2.2), the opportunity of accessing the clay surface was taken and markers deposited to be used in later geophysical measurements. Short stainless steel rods with a length of 30 cm were laid out in two parallel rows over a distance of 20 m. The rods were placed directly on top of the clay surface and were afterwards covered by sandy material. The precise positions of the rods are given in Fig. 26.

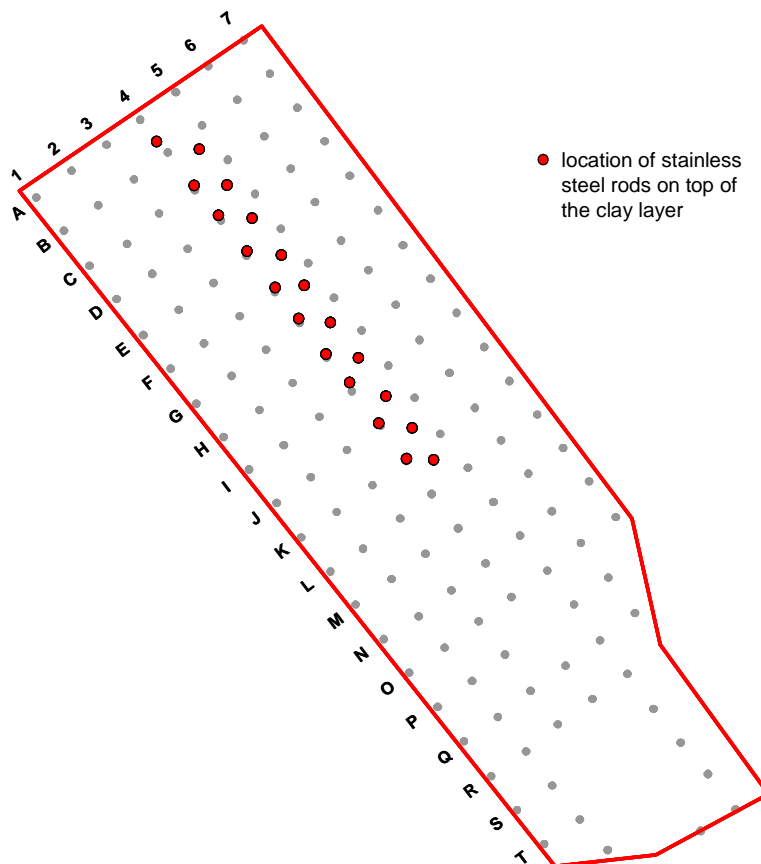


Fig. 26: Position of stainless steel rods on top of the clay layer laid out in March 2005.

### 4.1.2 Aquifer

As a result of the stacker dumping process, the underground sandy layer is structured in the form of cones with a base width of 3-4 m. The edges of these cones are clearly visible on an aerial photograph taken in October 2004 (Fig. 11). A mosaic picture of the eastern longitudinal section illustrating the sequence and extent of the single cones (Fig. 27) was also taken in March 2005 while the central part of the catchment was still open. In this image can be seen the characteristic inner structure of spoils previously described and modeled in other Lusatian post-mining sites with specific soil physical properties (Buczko et al., 2001). Although the upper sections of the cones were cut away and leveled by bulldozers after dumping, the majority of the structures still remain underground.

Even though the orientation of these cones can be partly discerned from aerial photographs taken during construction (see Fig. 11), large parts of the catchment were immediately leveled after dumping, and thus the aerial pictures only show rudimentary parts of the cones under the surface. However as stackers generally produce parallel cones, it is possible to roughly reconstruct the approximate curves of these structures. The results of such an attempt are presented in Fig. 28, based on information derived from the aerial photograph taken in October 2004 and the corresponding digital elevation model.



Fig. 27: Longitudinal section across the catchment during the construction phase in March 2005: internal ripple structure.

At least three regions can be distinguished with regard to dumping structures (labeled A-C in Fig. 28):

- A) The oldest part of the catchment dumped in August/September 2004. The edges of the cones are clearly visible along the 'central trench'.



- B) The western part was covered with sand in September/October 2004. The dumping structures in this sector can also be clearly detected in the aerial picture. Dumped temporarily at two different altitudes, the upper level of material was used to provide sufficient substrate for the later closure of the ‘central trench’.
- C) Leveling of material in this sector was already at an advanced stage when the aerial photograph was taken, and thus dumping structures are no longer visible.

The central part of the catchment, the temporary ‘central trench’ (labeled as D in Fig 28; see chapter 3.2.2), does not contain comparable underground cone structures as substrate material was not dumped here. Sand was moved by bulldozers from the surface of the neighboring sectors into this hollow, and therefore this central region of the backslope area is characterized by other, less regularly-oriented structures. Fig. 29 shows a three-dimensional view of the dumping structures derived from a combination of aerial photographs and digital elevation models.

Due to the characteristics of the applied stacker technology, the spatial distribution of substrate heterogeneity cannot be adequately modeled using only geostatistical methods (see Figs. 36-42). In contrast, process-based structural modeling combined with the available structural information (Fig. 29) can reproduce realistic heterogeneity patterns (Fig. 30).

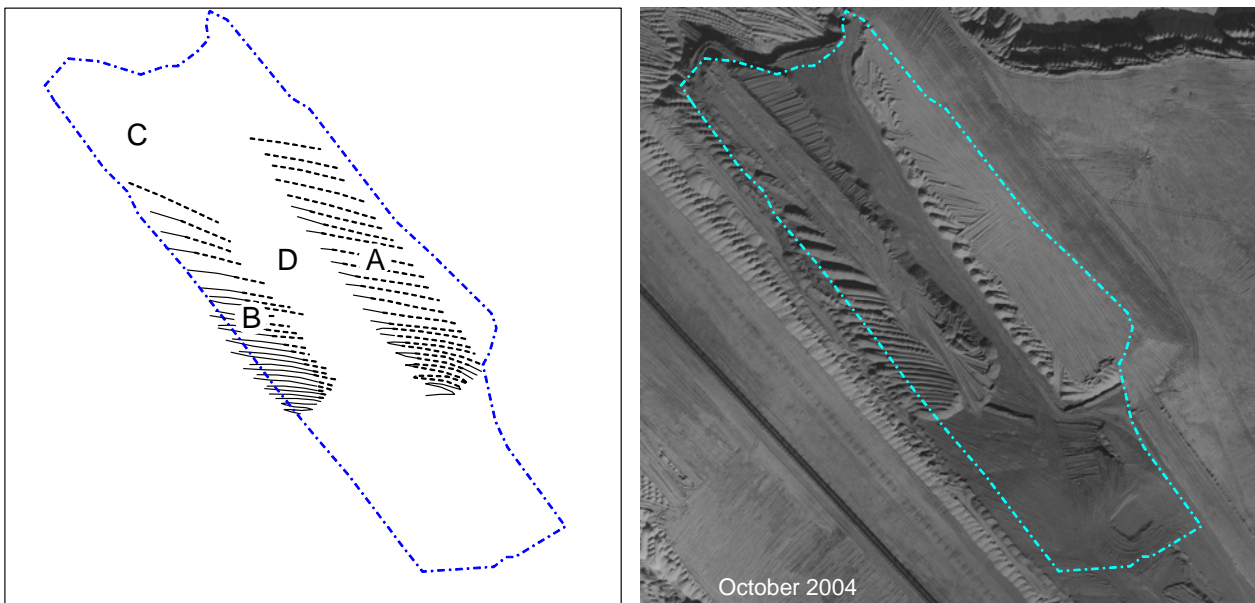


Fig. 28: Orientation of the subsurface cones produced by dumping processes: reconstructed by aerial photographs taken during construction (October 2004, dotted lines: not visible in the photograph), for meaning of the labels A-D see text (© photograph by Vattenfall Europe Mining AG, 2004).

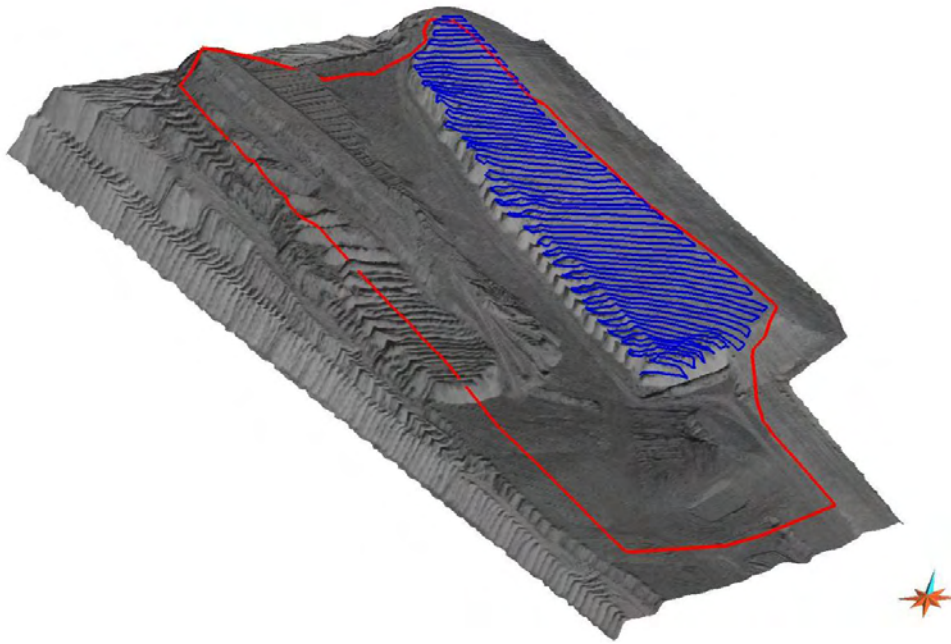


Fig. 29: The course of spoil ridges was derived using a combination of aerial photographs and digital elevation models (GOCAD model; fivefold vertical exaggeration; based on aerial photographs and DTM by Vattenfall Europe Mining AG, October 2004).

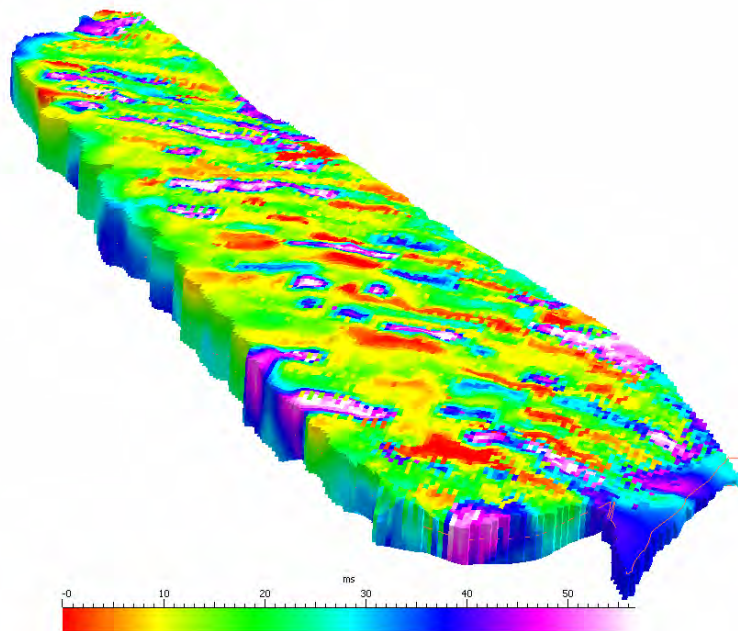


Fig. 30: Model realization of the 3D distribution (fivefold vertical exaggeration) of medium-sized sand in the eastern part of the catchment. Substrate heterogeneity patterns were reproduced using GOCAD and application of a process-based structure generator approach (this model realization does not correspond to actually measured values).



In 2006, gully erosion reached a maximum and a main gully was formed in the central part of the site. This main gully incised into the surface down to the level of the groundwater table near the central trapezoidal spring area. As a consequence, groundwater discharge had already occurred by summer 2006 within these two gullies, and since then has fed small permanent streams. In September 2006 some effort was made to drain these springs and redirect the groundwater back through the originally-planned outlet in the gravel dam. Trenches were dug with a small excavator partly down to the surface of the clay layer in the central trapezoidal spring area and filled with fine gravel (Fig. 31). However, the success of these drainage trenches was limited. The naturally formed springs in the two main gullies were not significantly affected and groundwater discharge in the central weir beyond the rubble outlet of the clay dams did not change appreciably.

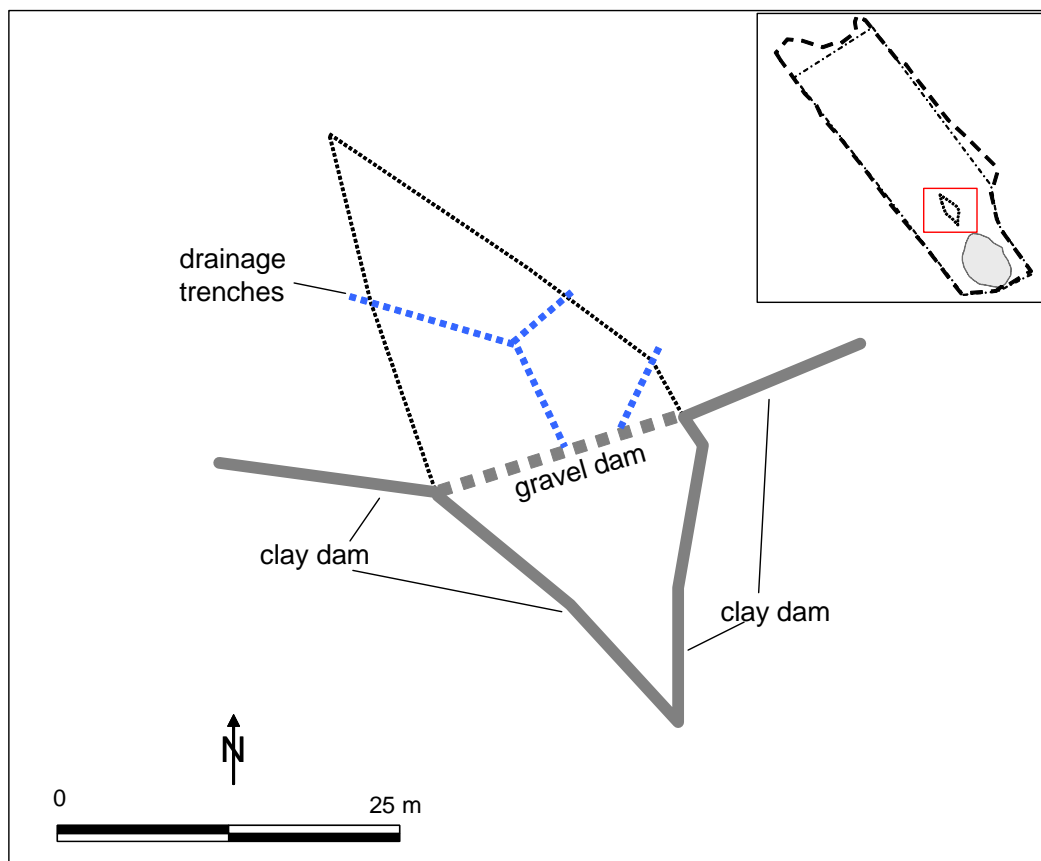


Fig. 31: Position of the drainage trenches in the spring area of the catchment (September 2006).

#### 4.2 Surface structures

The aerial photograph taken in August 2005 shows the catchment only a few weeks before the end of construction. The tracks of the bulldozers are clearly visible and their orientation is highlighted in Fig. 32 (see also Fig. 24).

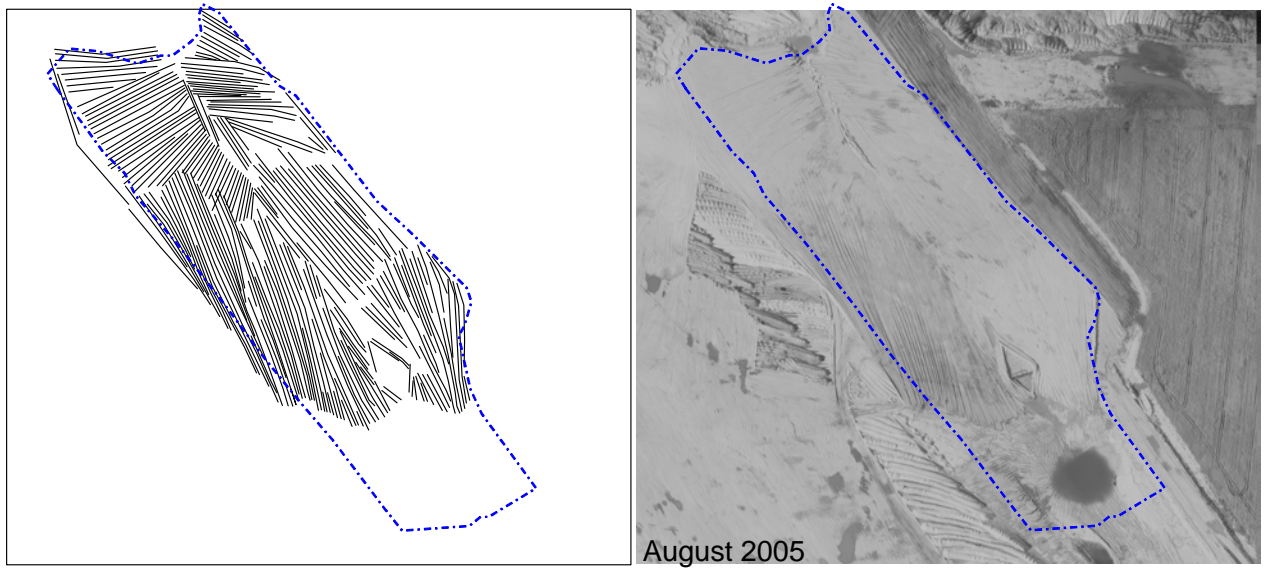


Fig. 32: Bulldozer tracks created during final leveling in August 2005 (superficially removed by final flattening, cf. Fig. 16) (© photograph by Vattenfall Europe Mining AG, 2005).

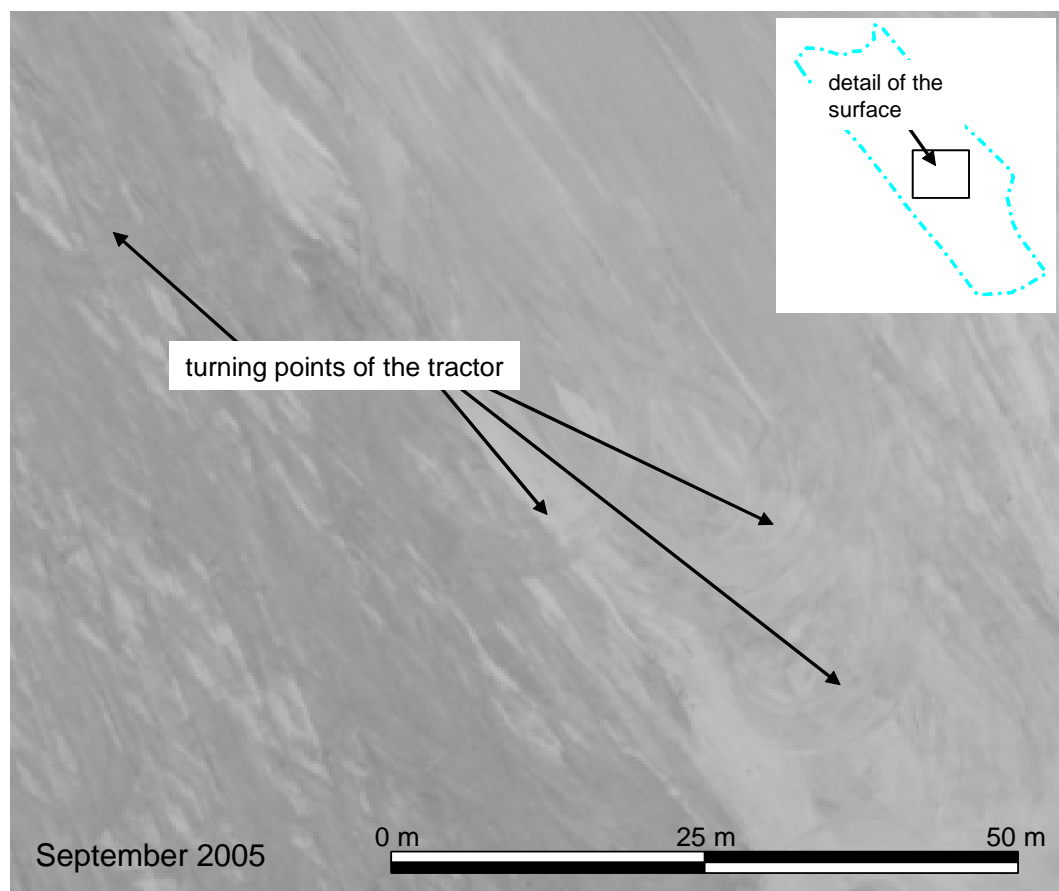


Fig. 33: Zoomed detail of the aerial photograph of the artificial catchment taken in September 2005 showing traces of the final flattening with rails (aerial photograph provided by Vattenfall Europe Mining AG; © (base photograph) Vattenfall Europe Mining AG, 2005).

Most of the bulldozer tracks were removed by pulling rails over the surface (see chapter 3.2.3) and by the end of the construction work the catchment surface was comparatively homogeneous without any obvious initial structures. Even though this final flattening procedure certainly resulted in some artificial surface structures, the photograph taken in September 2005 presents an apparently more or less homogenized sand surface (Fig. 33). However, it is highly likely that some rudiments were conserved below a shallow surface layer of loose sandy material. Such tracks may be of great importance with regard to the fluxes of surface runoff, and the establishment of both erosion gullies and the later stream network.

Obviously, a number of initial structures controlled the onset of surface formation. The overall topography and morphology of the site with its specific slope conditions and lateral boundaries can itself be seen as a complex overriding initial structure. In addition, the previously mentioned trapezoidal spring area in the footslope of the site (see Fig. 7, chapter 3.1) was crucial in the development of the main erosion gully network. Lying in the centre of the site, it prevented water running at the surface from taking a direct route to the pond, and hence the central erosion gully split into two branches above this area (see chapter 3.2.3). Originally, both gully branches followed the lateral dams in the trapezoidal area. In April 2007 a barrier was temporarily built into the central gully, diverting the surface water flow into the western branch of the channel (Fig. 34). The aim of this intervention was to concentrate surface water into the western channel to enable measurement of run-off, a device for which was installed there (see Section 5.2 below). Although the barrier was removed soon after the eastern branch was permanently disconnected from the main gully, since then run-off water has been concentrated in the remaining western branch which as a consequence has incised rapidly.

The pond basin was seen as necessary for the establishment of the small pond in the lower part of the catchment. The basin filled with water for the first time in winter 2004/05, but by spring 2005 most of the water had disappeared as the formation of the clay layer had not been finished with the necessary density not yet reached. For that reason, the clay layer of the pond basin was finally compacted by bulldozers in May 2005, and with the consequent accumulation of rain water, the pond began to fill once more in summer 2005. During the following winter of 2005/06, a prolonged spell of low temperatures resulted in deeply frozen soil covered by snow. A short melting period at the beginning of February 2006 with some additional rainfall triggered an extreme surface runoff event and, as a consequence, a rapid rise in pond water level. During the following years the pond level was subject to regular seasonal fluctuations due to rainfall and evaporation. However a certain minimum level is maintained, so that any occurrence of significant seepage losses through the clay layer can be widely excluded.

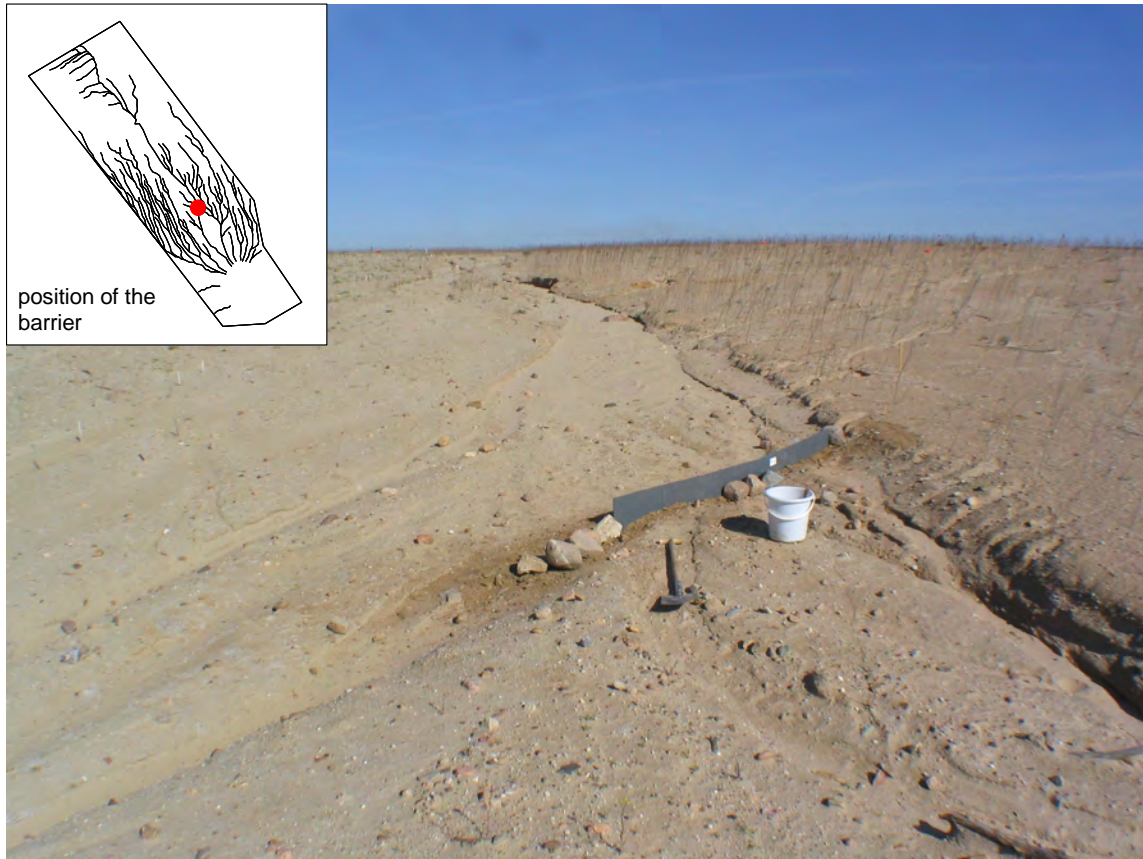


Fig. 34: Temporary barrier at the bifurcation of the central erosion gully close to the central trapezoidal spring area, constructed to direct surface water in the central erosion gully into the western branch of the system (April 2007).

## 5. Determination of initial conditions and ecosystem evolution

### 5.1 Assessment of initial site conditions

The first samples of substrate material were taken in January 2005 from eleven of the dumped cones. After completion of the catchment, area-wide soil samples were taken between October 2005 and April 2006 in a regular 20 m x 20 m grid at two depths (0-30 cm and 30-100 cm). Additional samples were taken in a 40 m x 40 m grid at depths of 100-150 cm, 150-200 cm and >200 cm, i.e. from 2 m depth down to the clay layer.

Samples were analyzed for pH (water extract), electrical conductivity (EC), texture, total carbon nitrogen and sulfur content, organic carbon content and lime content. In addition, the first set of cone samples were also analyzed in terms of actual cation exchange capacity (CEC), oxides and hydroxides of iron and aluminum extracted using dithionite ( $Fe_d$ ,  $Al_d$ ) and oxalate ( $Fe_o$ ,  $Al_o$ ), total Fe and Al ( $Fe_T$ ,  $Al_T$ ) content measured using high temperature and pressure digestion with  $HNO_3$ , and composition of the clay fraction (via XRD analysis). Surfer mapping software Version 8.0 (Golden Software, Golden, Colorado, USA) was used to create maps of substrate properties.

Further undisturbed soil samples were taken in October 2007 using 100 cm<sup>3</sup> cylinders at 4-5 depths during the excavation of four permanent soil pits at grid points C5, F2, I5, and L2 (see chapter 5.2). Retention curves were measured in the laboratory for samples taken from pits F and I. Measurements were conducted in two or three replicates per depth. After wetting, cores were placed on ceramic plates where the following matric potentials were applied: -10, -20, -30, -50, -80, -160, -300 and -1,000 hPa. Finally the samples were dried at 105° C for 24 hours to determine bulk density.

Tab. 3 provides an overview of the main soil parameter values. Catchment substrates can generally be characterized as sands to loamy sands containing low amounts of carbonate, although there are textural differences between the western and eastern parts of the catchment (Fig. 35) due to the substrates in these locations being dumped in two separate periods during the construction process. The NE part of the catchment is dominated by pure sands, while in the SW the sands are more loamy (Figs. 36, 37). Textural composition varies only a little with depth (Tab. 3), with gravel content ranging between 7.8 and 14.5 % down the entire profile. Clay mineral analysis revealed a composition dominated by illite (41–60 %) and mixed layer illite/smectite (12–38 %; <50 % illite). Kaolinite and vermiculite were only found in small amounts (9–16 % and 3–4 %, respectively). In accordance with the sandy texture and composition of the clay fraction, CEC is low (20–68 mmol<sub>(c)</sub> kg<sup>-1</sup>). Base saturation is 98–100 % for all samples. Due to the low carbonate content pH values are mainly weakly alkaline or neutral (Fig. 38, 39). Only in a few spots were lower pH values (down to pH 4.1) identified. Total carbon content is uniformly very low, as expected, with inorganic carbonate

making up around two thirds of the total. The low organic carbon content (1.6–2.2 mg g<sup>-1</sup>) typifies the overall initial state of the soil (Fig. 40). Total nitrogen and sulfur contents are 0.1 and 0.2 mg g<sup>-1</sup> or below, respectively. Spatial variation of nitrogen and sulfur is shown in Figs. 41 and 42, respectively. Total and dithionite-extractable iron contents (Tab. 4) are higher in the Hühnerwasser catchment compared with levels in soils developed on Quaternary substrates at other mines in the region (Neumann, 1999; Weiß, 2005), although total and extractable aluminum content is in the same range as that found at these sites. The very low Fe<sub>o</sub>/Fe<sub>d</sub> ratio of 0.19 emphasizes the weak formation of pedogenetic iron oxides, being even lower than that observed in the C horizons of naturally developed soils in the region (Schaaf et al., 1999).

Tab. 3: Mean values (*m*) and standard deviation (*sd*) of soil parameters from grid sampling (number of samples at 0-30 cm depth: 124, 30-100 cm: 120, 100-150 cm: 29, 150-200 cm: 28, >200 cm: 18).

depth	pH	EC	gravel	sand	silt	clay	C <sub>T</sub>	C <sub>org.</sub>	N <sub>T</sub>	S <sub>T</sub>	CaCO <sub>3</sub>
m	(H <sub>2</sub> O)	μS cm <sup>-1</sup>	%	%	%	%	mg g <sup>-1</sup>	mg g <sup>-1</sup>	mg g <sup>-1</sup>	mg g <sup>-1</sup>	%
0-0.3											
<i>m</i>	8.05	207.4	14.5	84.8	9.1	6.1	2.7	1.6	0.1	0.2	0.87
<i>sd</i>	0.43	293.6	6.6	5.4	3.4	2.1	1.5	1.0	<0.01	0.1	0.66
0.3-1											
<i>m</i>	8.02	187.8	10.7	82.4	10.3	7.3	3.3	2.2	0.1	0.2	0.94
<i>sd</i>	0.46	131.8	5.8	5.7	3.5	2.5	1.7	1.2	<0.01	0.2	0.62
1-1.5											
<i>m</i>	7.82	238.9	7.8	82.2	9.9	7.9	3.4	2.1	0.1	0.2	1.09
<i>sd</i>	0.49	99.4	3.4	5.4	2.7	2.5	1.7	1.2	<0.01	0.2	0.85
1.5-2											
<i>m</i>	7.73	231.8	12.4	82.9	9.6	7.5	3.0	2.0	0.1	0.2	0.89
<i>sd</i>	0.66	111.0	3.2	4.8	2.5	2.2	1.6	1.2	<0.01	0.2	0.63
>2											
<i>m</i>	7.8	257.2	9.3	83.8	8.9	7.3	3.1	1.9	0.1	0.2	1.0
<i>sd</i>	0.45	111.0	4.3	4.4	2.0	1.9	1.2	0.9	<0.01	0.1	0.6
total											
<i>m</i>	7.87	247.9	12.2	83.4	9.7	6.9	3.1	1.9	0.1	0.2	0.93
<i>sd</i>	0.72	12.1	6.0	5.6	3.3	2.4	1.6	1.2	<0.1	0.2	0.67



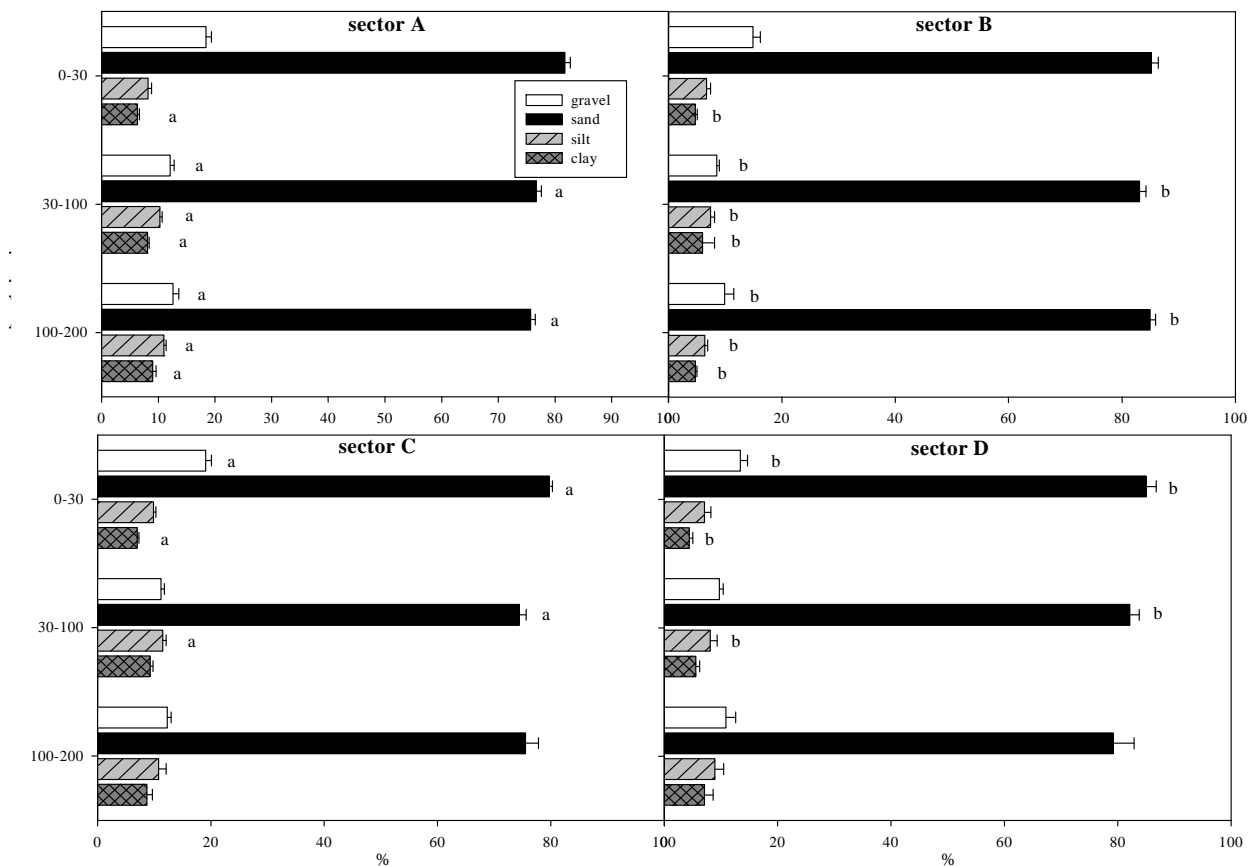


Fig. 35: Soil texture profiles of the four main catchment sectors (mean values and standard error ( $n=18$  for depths 0-30 cm and 30-100 cm,  $n=6$  for 100-200 cm), different letters (a, b) denominate significant differences ( $p<0.01$ ) between the sectors). For the location of sectors A-D see Fig. 7 (Chapter 3.1).

Tab. 4: Mean values ( $m$ ) and standard deviation ( $sd$ ) of total ( $Fe_T$ ,  $Al_T$ ), dithionite ( $Fe_d$ ,  $Al_d$ ) and oxalate ( $Fe_o$ ,  $Al_o$ ) extractable iron and aluminum contents of cone samples (all values in  $mg\ kg^{-1}$ ;  $n=26$ ).

	$Fe_T$	$Fe_d$	$Fe_o$	$Al_T$	$Al_d$	$Al_o$	$Fe_o/Fe_d$	$Fe_d/Fe_T$	$Al_o/Al_d$
$m$	8.599	2.814	545	11.280	385	267	0.192	0.345	0.692
$sd$	2.976	669	190	4.433	91	77	0.042	0.082	0.111

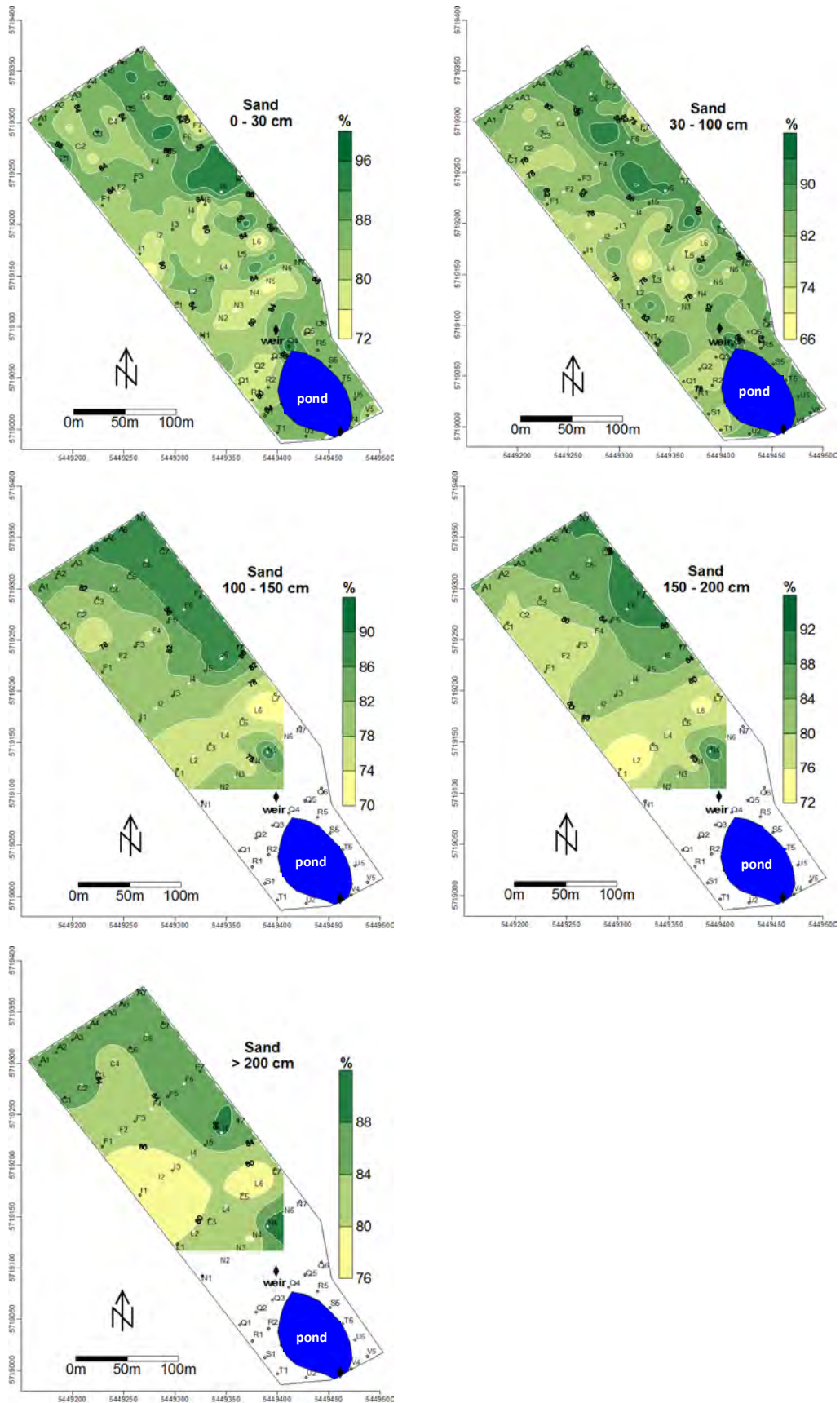


Fig. 36: Spatial pattern of sand content in different soil layers based on the default exponential kriging model of Surfer.

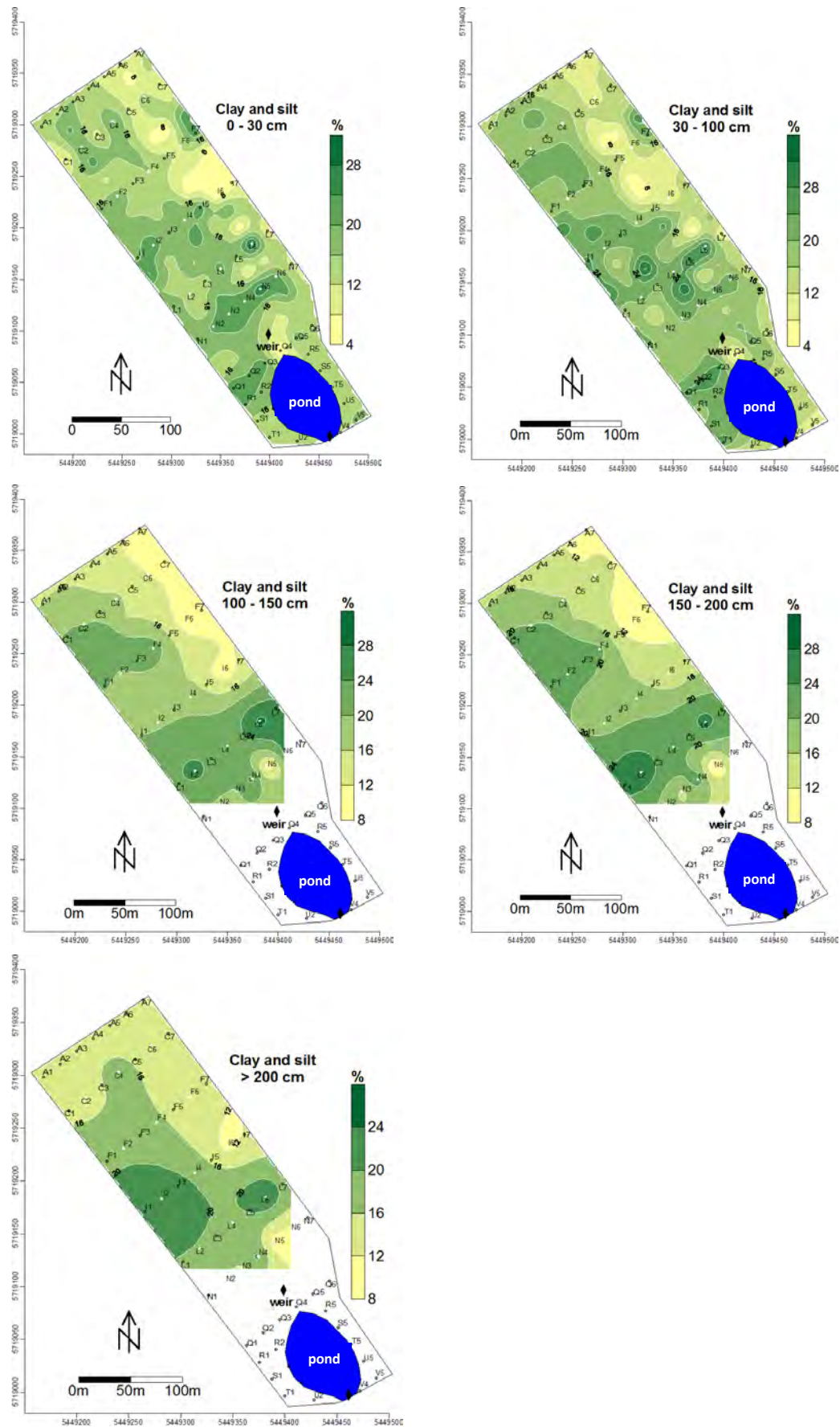


Fig. 37: Spatial pattern of clay and silt content in different soil layers based on the default exponential kriging model of Surfer.

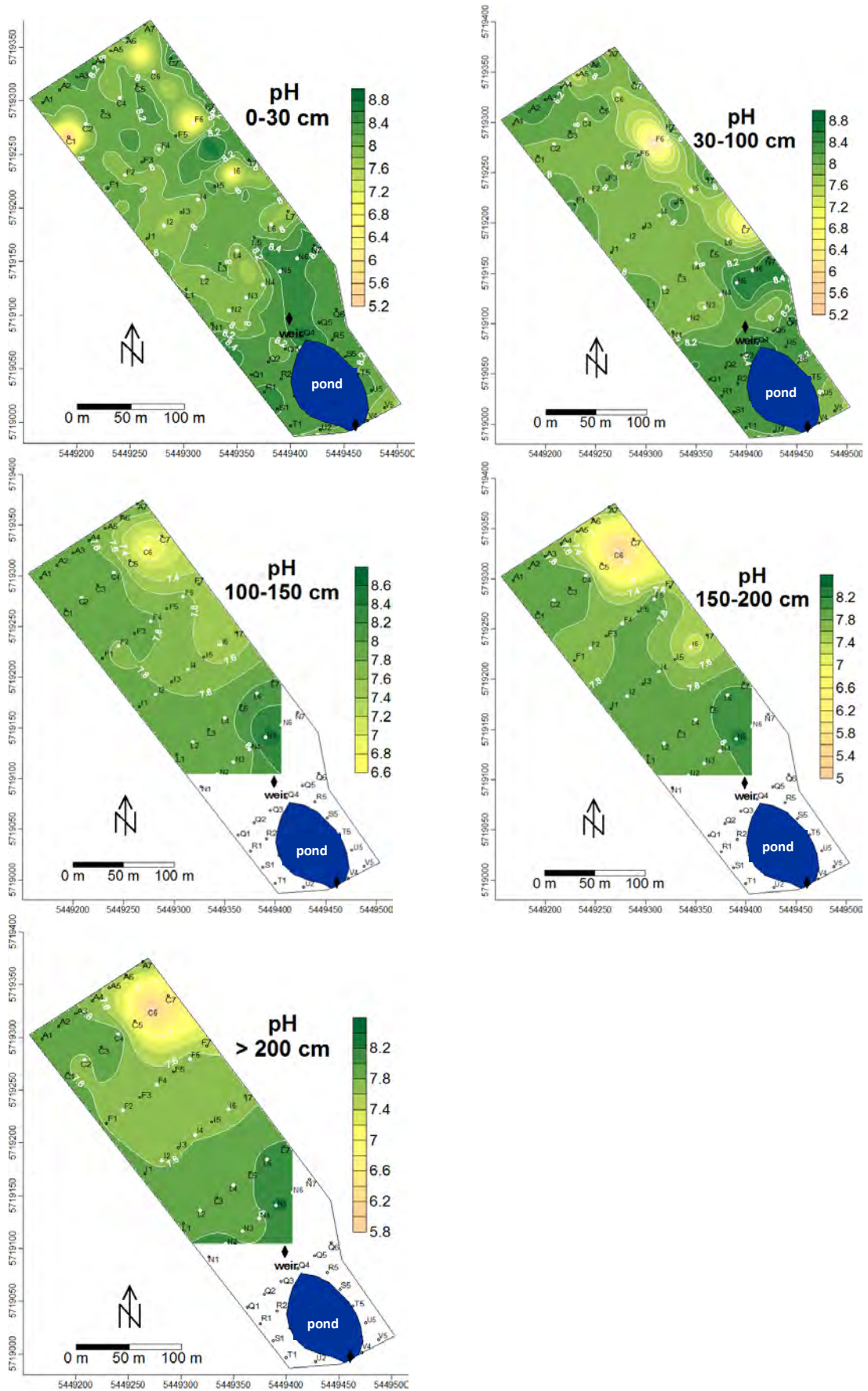


Fig. 38: Spatial pattern of pH values in different soil layers based on the default exponential kriging model of Surfer.



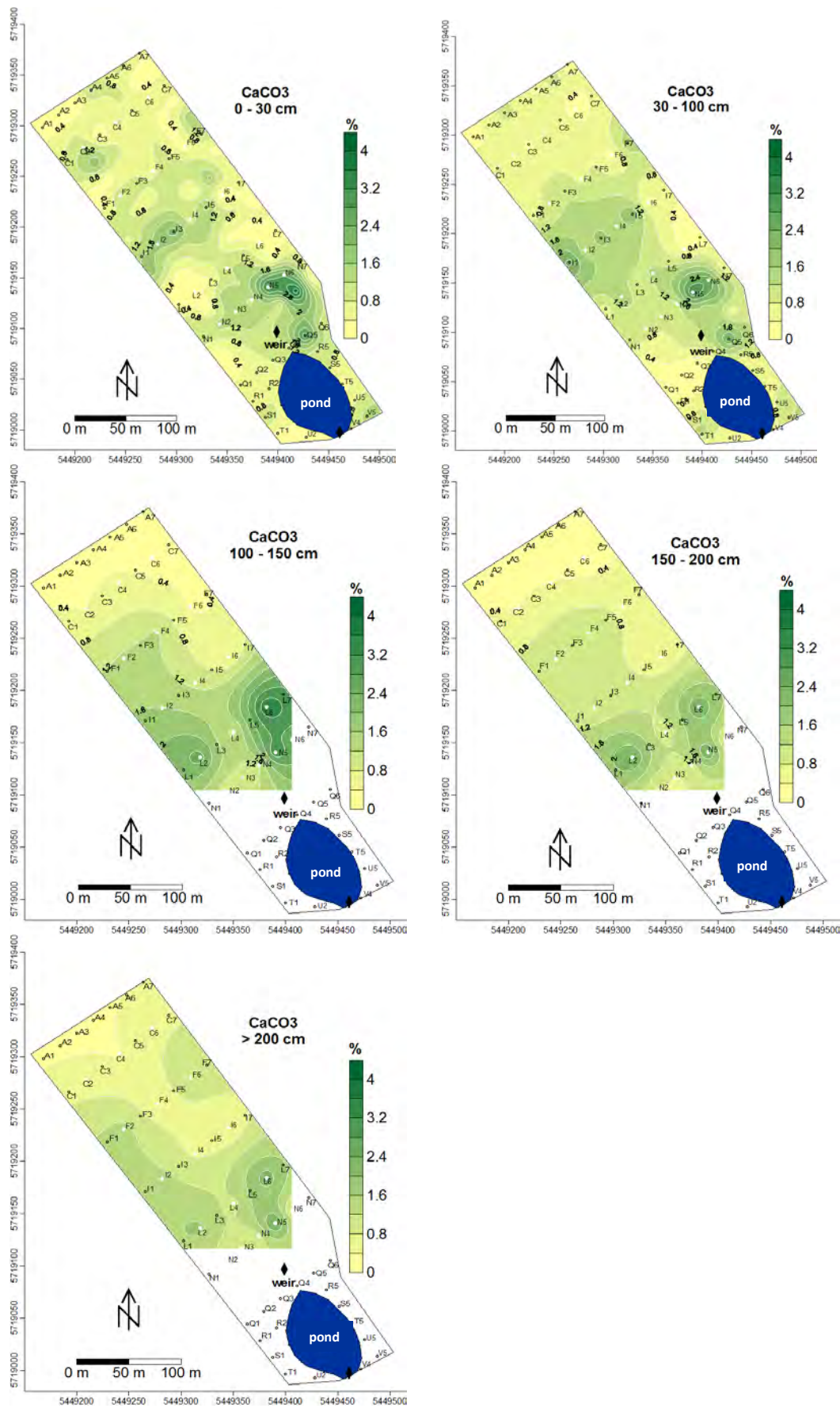


Fig. 39: Spatial pattern of  $\text{CaCO}_3$  content in different soil layers based on the default exponential kriging model of Surfer.

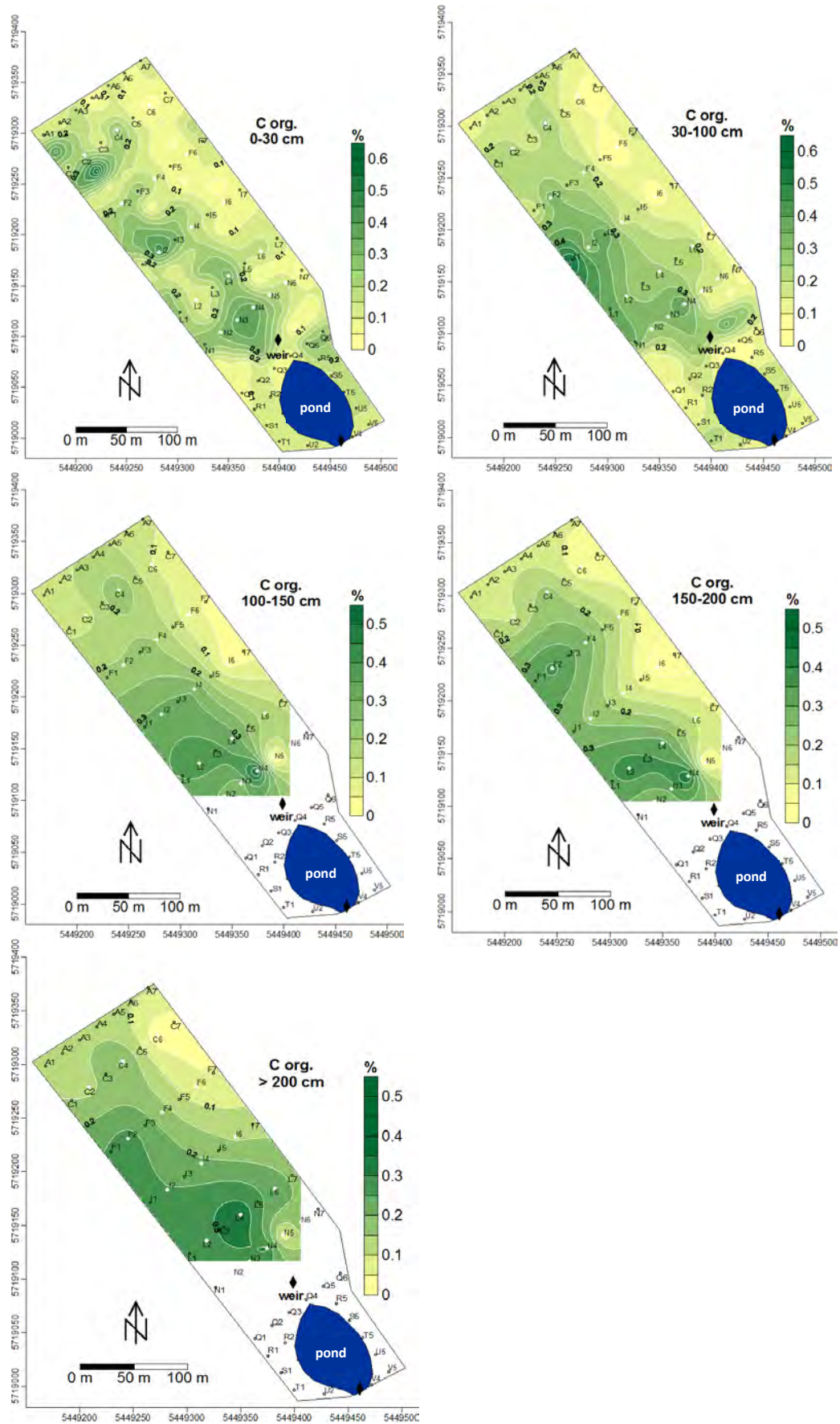


Fig. 40: Spatial pattern of  $C_{org}$  content in different soil layers based on the default exponential kriging model of Surfer.



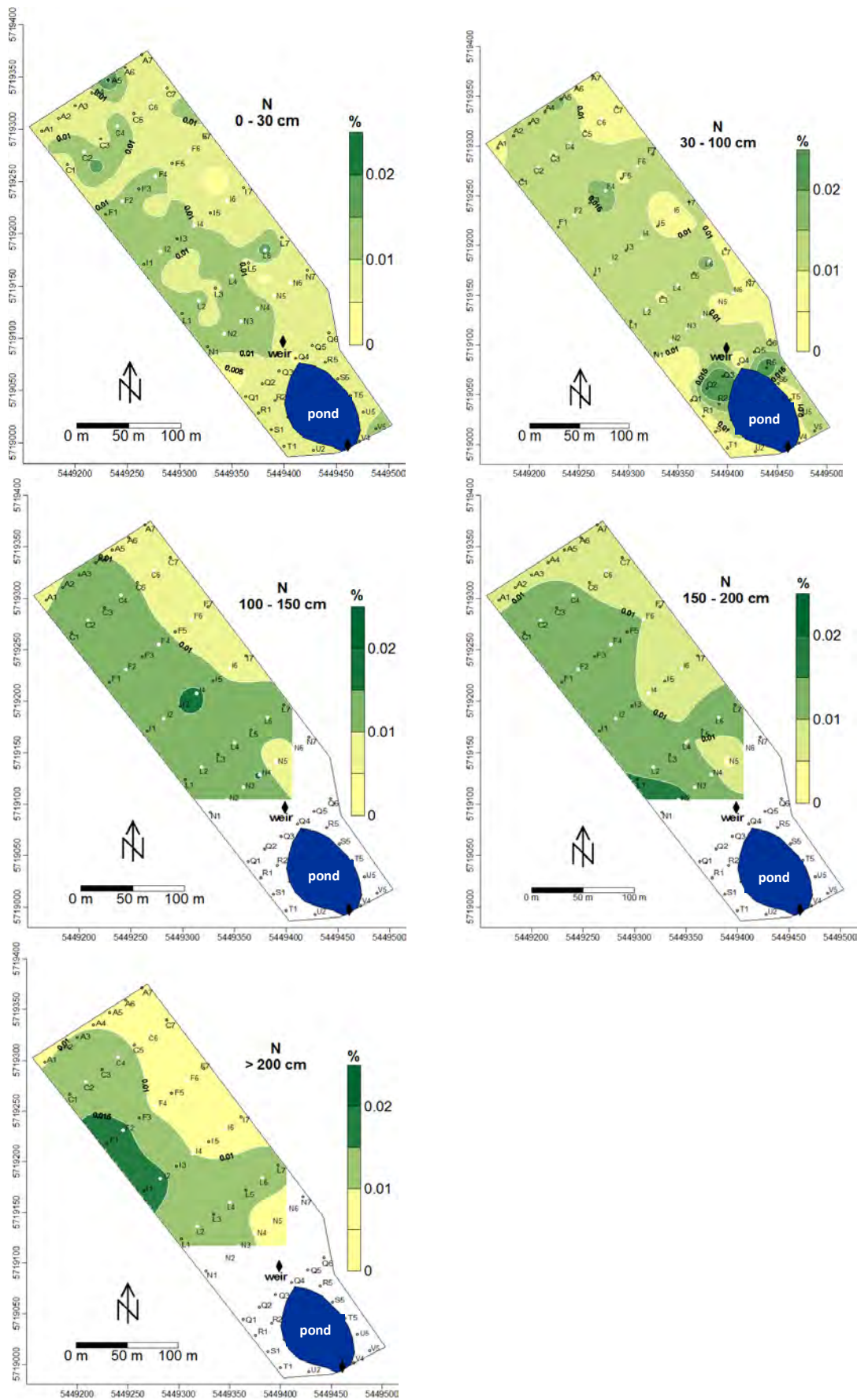


Fig. 41: Spatial pattern of nitrogen content in different soil layers based on the default exponential kriging model of Surfer.

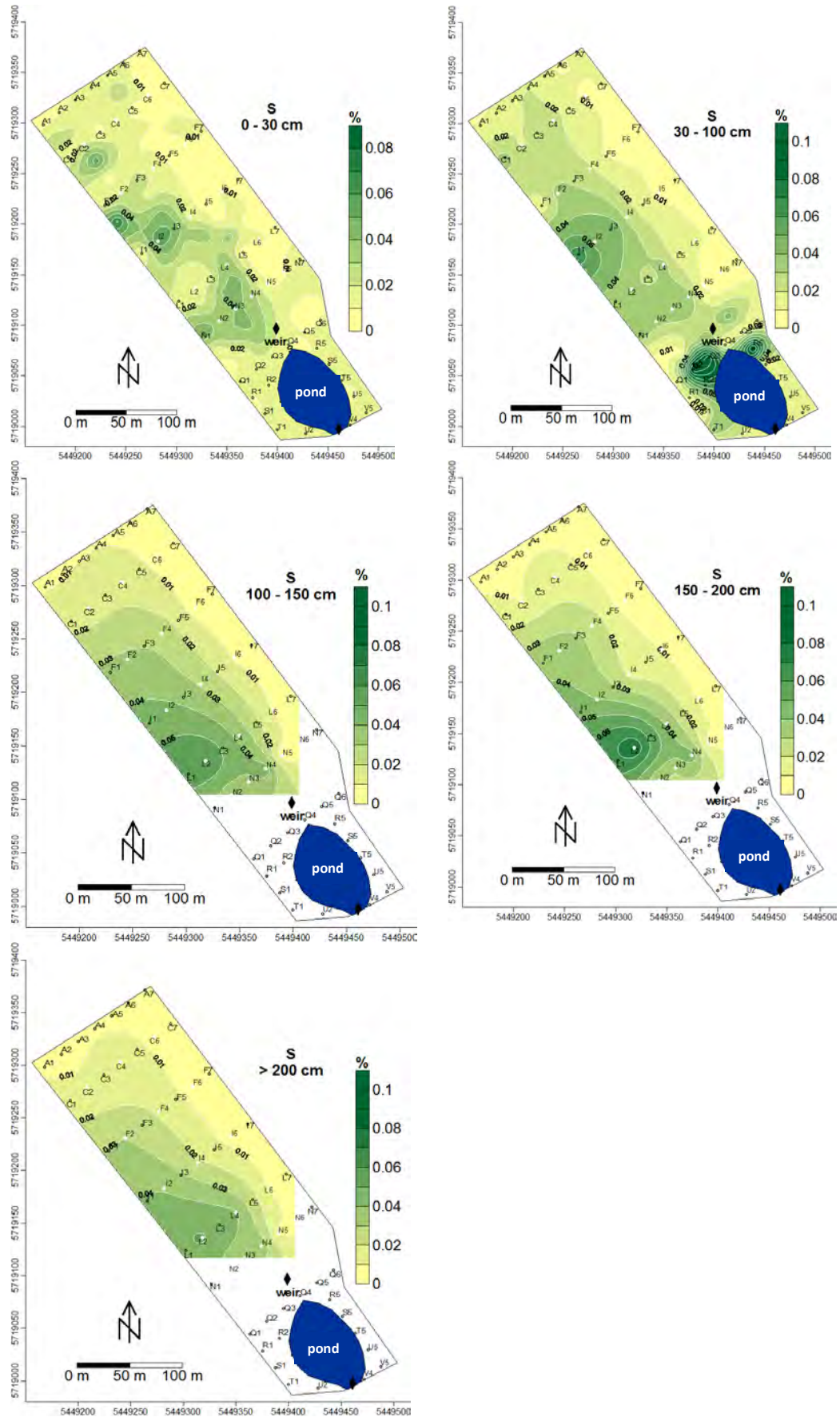


Fig. 42: Spatial pattern of sulfur content in different soil layers based on the default exponential kriging model of Surfer.

Fig. 43 presents the grain-size distribution curves of soil samples taken during drilling for ground water pipes close to the soil pits (see chapter 5.2). At pits F and L loamy sand was found at all depths, while at pits C and I the texture was pure sand. These results correspond with those of grid sampling discussed above and also illustrate the fact that the substrate in the eastern parts of the catchment has a higher sand content than those in the west. Grain-size analysis showed no vertical differences in soil texture at three pits (F, L, I), which correlates with observations made during the installation of the observation pit sensors. While drilling boreholes for the groundwater gauge located close to pit C, vertical layering of different colors (Fig. 44) and textural properties was found.

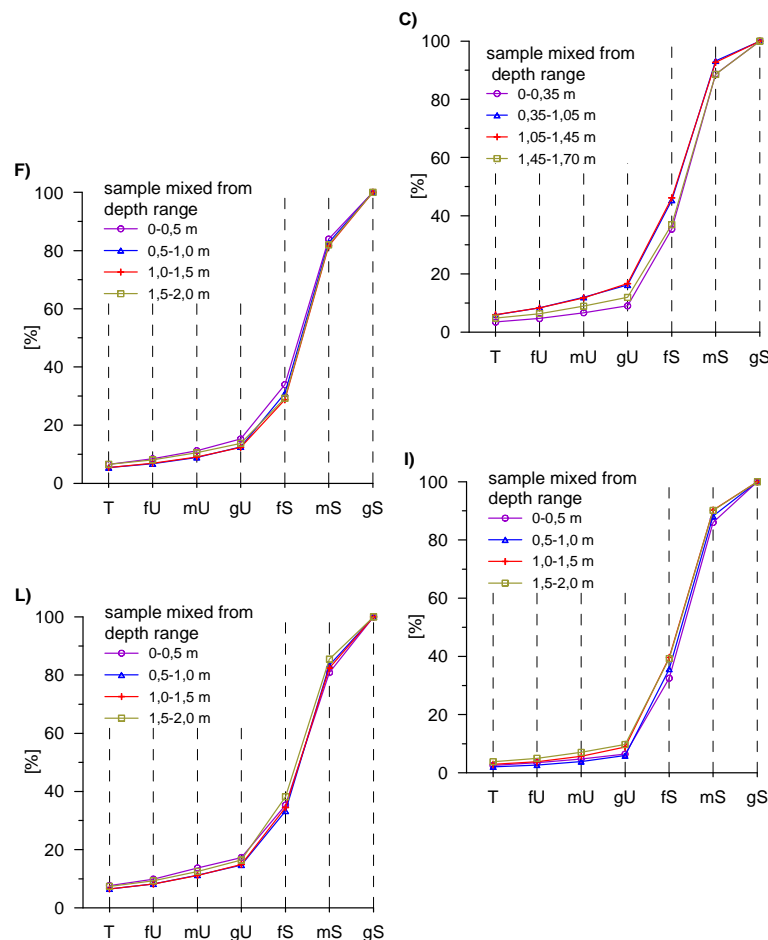


Fig. 43: Sieving curves from sediment sampled during the installation of groundwater level pipes (after DIN 19683: T: clay < 0.002 mm, fU: fine silt 0,002- 0.0063 mm, mU: medium silt: 0.0063-0.02 mm, gU: coarse silt 0.02-0.063 mm, fS: fine sand 0.063-0.2 mm, mS: medium sand 0.2-0.63 mm, gS: coarse sand 0.63-2 mm).

With the exception of 1.50 to 1.54 m depth, the retention curves for pit I are typical of sandy substrates (Fig. 45). Despite the similarity of the sieving curves, the differences in the retention curves from each depth indicate the occurrence of compaction of layers during the

construction of the catchment. Although substrate conditions show some small-scale variation, soil data in general present relatively little horizontal and vertical heterogeneity compared to more developed soils. In summary, the composition of the clay fraction,  $Fe_o$  and  $Fe_d$  data,  $C_{org}$  as well as nitrogen content all underline the fact that the substrate forming the main body of the catchment is composed of fairly unweathered material with little pedogenetic development, and is thus very much suitable for the creation of the initial conditions very close to the ‘point zero’ of ecosystem development.



Fig. 44: Sediments from drilling of groundwater level pipe.

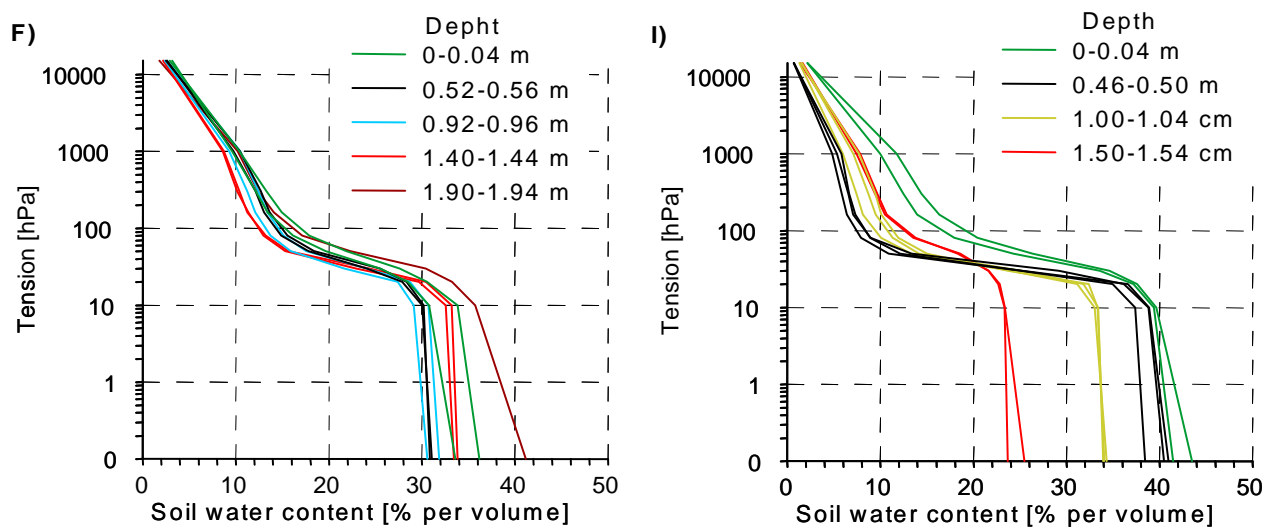


Fig. 45: Laboratory water retention curves for soil pits F (left) and I (right).



**5.2 Monitoring installations (2005-2010)**

Immediately after completion of catchment construction, ecological monitoring techniques were applied to track the development of newly emerging structures. With the surface of the site made as homogeneous as possible, monitoring took the form of a regularly oriented 20 m x 20 m measuring grid, with each grid point precisely positioned using a Differential GPS technique. This involved marking each grid point with a small flag for permanent easy orientation within the catchment, with rows in the NE-SW direction numbered from 1-7 and rows in the NW-SE direction labeled A-V (Fig. 46).

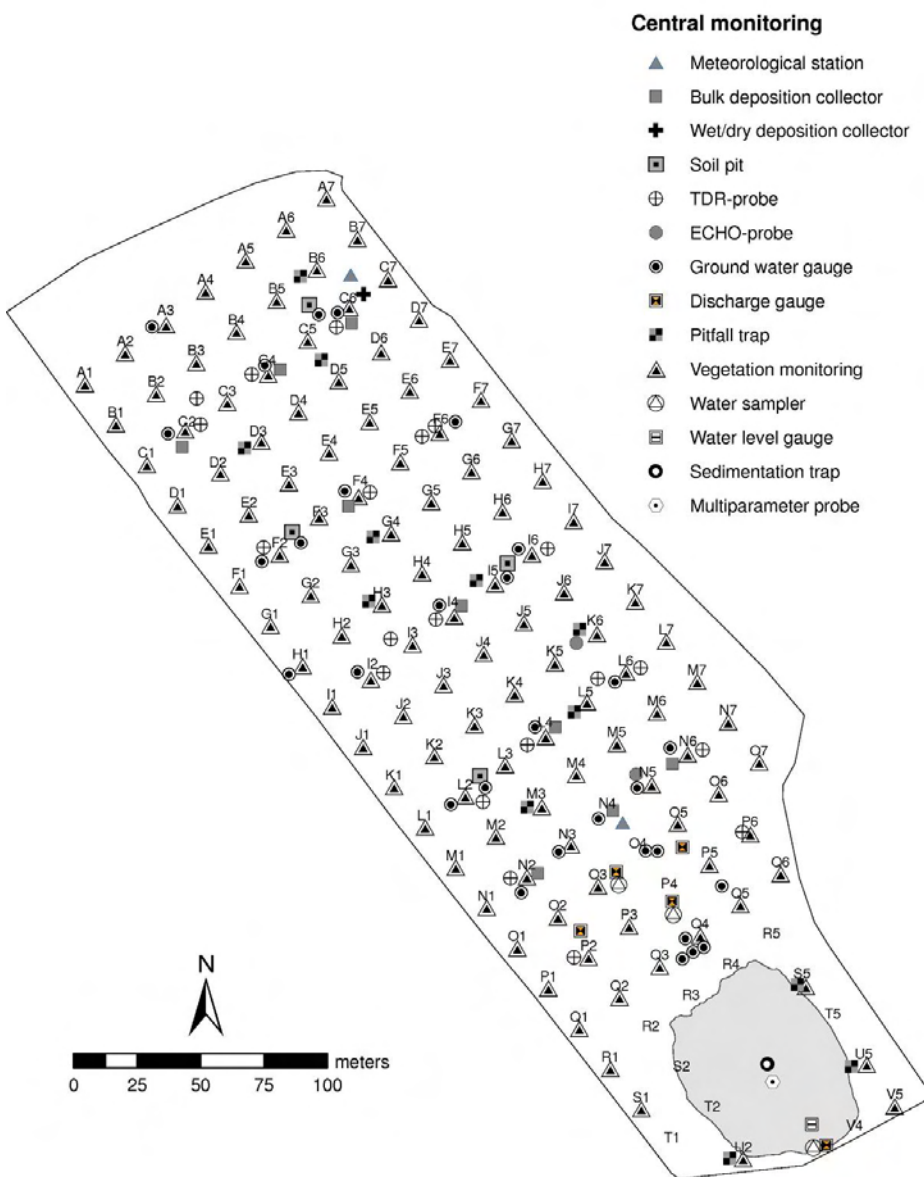


Fig. 46: Grid points, pathways and monitoring installation in the Chicken Creek catchment (November 2010).



To prevent damage being caused to evolving surface structures such as soil crusts or herbaceous vegetation patches, strict site access regulations were established. In general, access is only allowed via pathways positioned between grid points, the most important of which lead to monitoring installations requiring permanent support. These pathways are paved with synthetic pads to avoid deterioration caused by regular site inspection and also to allow permanent access to parts of the site independent of weather conditions. Several small bridges also had to be constructed to cross deeper erosion gullies along these pathways.

As the first phase of soil sampling proved the local Quaternary substrate to be relatively homogenous, both horizontally and with depth (see Tab. 3), all further work was undertaken along the same basic 20 m x 20 m grid. Fig. 46 presents an overview of the installed monitoring devices, while Tab. 5 summarizes the measured parameters and sensors in use.

Two weather stations are currently operating in the catchment. Weather station 1, located in the upper part of the back slope area, is used for the hourly registration of basic meteorological data, while weather station 2 is located in the foot slope area and provides more detailed data regarding wind speed, air temperature and humidity at three different altitudes. Downward- and upward-directed as well as short-wave and long-wave radiation are measured separately, while soil temperature and heat flux are also recorded. As atmospheric deposition may be an important source of nutrient input, bulk deposition is sampled using 18 samplers positioned in a grid pattern across the catchment area. The gathered data are then used to calculate annual element inputs (Schaaf, 2004) that can be integrated into element flux models.

Groundwater levels are recorded at 30 locations within the catchment, 11 of which are equipped with automatically registering pressure transducers (divers). Two main weirs were installed during catchment construction in order to measure water fluxes. The first weir is located at the outlet of the subsurface clay walls above the pond, and mainly registers groundwater flow on top of the subsurface clay layer by means of a tipping counter and a V-notch profile. The second weir was placed at the outlet of the pond which represents the point of discharge for the entire catchment. In order to reduce measurement inaccuracy across the whole measuring range, a variety of different procedures are applied at this second weir. Generally regarded as an important part of the water balance, very low discharge flow rates of up to  $1 \text{ L s}^{-1}$  are registered by means of a tipping counter. Higher fluxes of up to approx.  $4 \text{ L s}^{-1}$  which accompany increasing pond water levels are measured via an adequate V-notch weir. Finally, two additional larger rectangular profiles allow measurement of discharge rates of up to  $110 \text{ L s}^{-1}$  and  $120 \text{ L s}^{-1}$ , respectively. Flumes have been installed in two main erosion gullies to register both continuous base flow from groundwater discharge and episodic run-off events. Both the weirs and one of the flumes are equipped with automated water sampling units taking daily samples for water quality analyses.

Soil solution is sampled from four soil pits that were excavated by hand down to the saturated layer at 2-2.5 m depth and stabilized with a lining constructed of 1 m diameter PE rings. In these pits, boron silicate glass suction plates (diameter 10 cm) were installed in the soil at 2 and 3 m depth, respectively. Soil solution is collected using a permanent pressure head of -10 kPa and sampled biweekly. Automated TDR probes and tensiometers were also installed in these soil pits to measure soil moisture conditions, at the same depths as the suction plates. Data are logged automatically. Soil moisture is additionally monitored by means of 14 permanently installed pipes for a PR2-profile probe and 20 tensiometers.

Aerial images are taken regularly in order to monitor changes in surface structures at 'Chicken Creek' artificial catchment. The first aerial photographs were taken from a helicopter in 2006 and 2007, but since spring 2008 a micro-drone equipped with a digital camera has been used. A characteristic feature of the microdrone is its navigation by GPS, which not only allows way-point-navigation and programmed flights to be carried out, but also enables the microdrone to hold its position. The altitude of the flights varies between 40 m and 80 m depending on the purpose of the monitoring. An aerial photograph of the complete area of the catchment is composed of a mosaic of approx. 20 images, which have to be geo-referenced and rectified for further use in GIS (Fig. 47). Since 2009 the drone has been used to take at least three aerial photographs of the site per year (April, July, September). Additional flights can be made rapidly after significant weather events to detect any effects on surface structures.

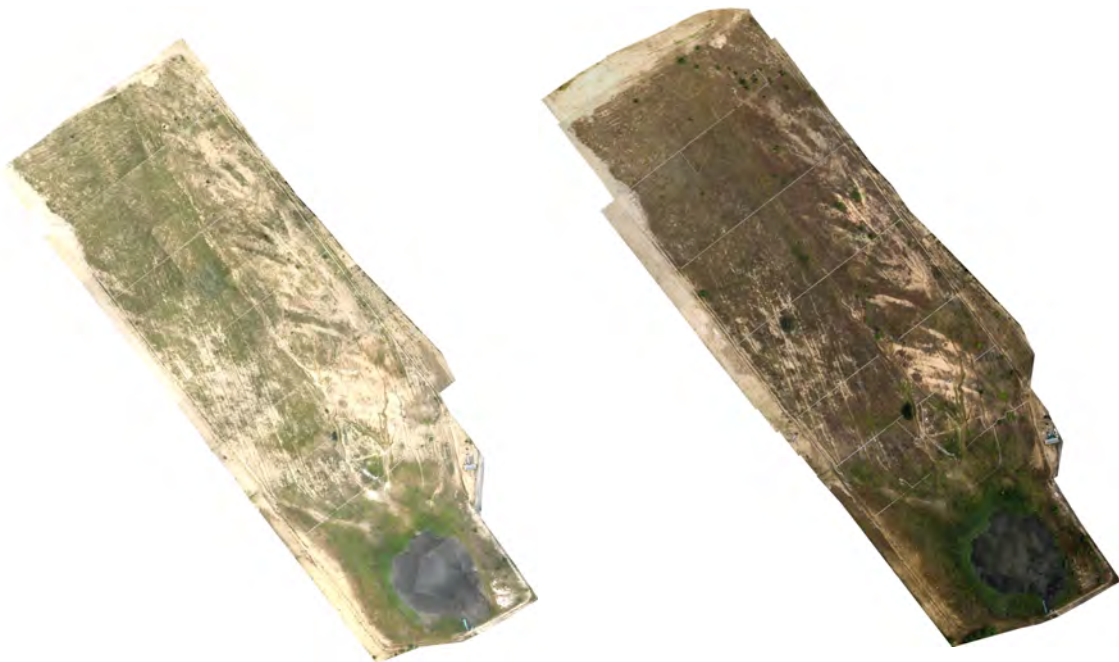


Fig. 47: Sample aerial mosaic photographs taken by microdrone in July 2009 (left) and July 2010 (right).

Tab. 5: Monitoring installations and measured parameters.

Quantity	Instrumentation	Number	Operating mode	Installation level	Comment
meteorological data	weather station (1)	1	automatic, hourly recorded data sets	air temperature, wind, humidity and radiation in 2 m, precipitation in 1 m, soil temperature in -0.05 m and -0.1 m	installed since September 2005
	weather station (2)	1	automatic, data sets recorded every 10 min	air temperature, wind, humidity in 0.5 m, 2 m, 10 m, net radiation in 2 m, precipitation in 1 m and 0 m, soil temperature in -0.05 m and -0.1 m, soil heat flux in -0.2 m	installed since February 2008
deposition	bulk precipitation sampler	18, reduced to 9 in August 2009	manual sampling every 14 days	1 m	installed since July 2007, samples are analyzed for pH (Beckmann pH34 glass electrode and WTW pH 537), electrical conductivity (EC; Hanna HI 8733 and WTW LF537) and concentrations of $\text{Ca}^{2+}$ , $\text{Mg}^{2+}$ , $\text{Na}^+$ , $\text{K}^+$ , $\text{Fe}^{3+}$ , $\text{Al}^{3+}$ (ICP-OES Unicam 701 and Thermo Scientific iCAP 6000), $\text{NO}_3^-$ , $\text{SO}_4^{2-}$ , $\text{Cl}^-$ (IC Dionex 5000), $\text{NH}_4^+$ (Rapid Flow Analyzer Alpkem), DOC, TOC, TIC and TN (Shimadzu TOC 5000 and VCPH+TNM-1)
	groundwater level	30	manual measurement once a month; 11 gauges with automatic hourly measurement	drilled down to the clay layer	installed in a 40 m x 60 m grid since September 2005, additional gauges installed in the following months/years for specific questions
soil water	PR2 probes	14	manual measurement every 14 days	0.1 m, 0.2 m, 0.3 m, 0.4 m, 0.6 m, 1.0 m soil depth	installed in a 40 m x 60 m grid close to the groundwater gauges since April 2008
	TDR probes (pits)	12	automatic hourly measurement	0.1 m, 0.3 m, 0.5 m, 0.8 m soil depth	installed in four permanent reinforced soil pits since July 2008
	TDR probes	16	automatic measurement every 20 minutes	0.15 m, 0.3 m, 0.5 m, 0.8 m soil depth	installed since July 2010
	ECHO probes	16	automatic measurement every 10 minutes	0.03 m and 0.1 m soil depth	installed since July 2010
	tensiometers	12	automatic hourly measurement	0.3 m, 0.5 m, 0.8 m, 1.5 m soil depth	installed in four permanent reinforced soil pits since July 2008

Tab. 5: Monitoring installations and measured parameters (cont.).

Quantity	Instrumentation	Number	Operating mode	Installation level	Comment
soil solution	boron silicate glass suction plates	14	automatic suction control, sampling over a period of 14 days	0.3 m, 0.8 m, 1.5 m soil depth	installed in four permanent reinforced soil pits since November 2007; sample analysis according to bulk precipitation samples above
discharge	weir (1)	1	combined weir geometry with tipping counter, pressure transducer for measuring water level	installed above pond at the outlet of the subsurface clay dam	installed since November 2005; measuring groundwater discharge
	weir (2)	1	combined weir geometry with tipping counter, pressure transducer for measuring water level	installed at the outlet of the pond	installed since November 2005; measuring discharge from the total catchment at the outlet of the pond
	flumes	2	ultrasonic sensor (measurement of water level) combined with tipping counter (1 flume)	installed in the main erosion gully and in one further gully (west)	installed since January 2007 (main) and June 2007 (west); measuring base flow in gullies and surface runoff events
	drainage gutter	1	tipping counter	installed in one eastern gully	installed since June 2009; measurement of continuous base flow
water chemistry	water samplers	3	automatic water sampling once a day	installed at the two weirs and the flume in the main erosion gully	installed since June 2007 and May 2008 (flume); daily samples analyzed for pH and EC; biweekly mixed samples analyzed according to bulk precipitation samples above

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