Environ Monit Assess
DOI 10.1007/s10661-012-2998-x

# Monitoring the formation of structures and patterns during initial development of an artificial catchment

**Wolfgang Schaaf · Michael Elmer · Anton Fischer · Werner Gerwin · Rossen Nenov · Hans Pretzsch · Stefan Seifert · Susanne Winter · Markus Klemens Zaplata**

Received: 2 September 2011 / Accepted: 31 October 2012


**Abstract** The objective of this paper is to present observations, results from monitoring measurements, and preliminary conclusions about the development of patterns and structures during the first 5 years of development of an artificial catchment starting from point zero. We discuss the high relevance of initial system traits and external events for the system development and draw conclusions for further research. These investigations as part of a Collaborative Research Center, aim to disentangle and understand the feedback mechanisms and interrelationships of processes and their co-development with spatial and temporal structures and patterns by studying an initial, probably less complex ecosystem. Therefore, intensive measurements were carried out in the catchment with regard to the development of surface structures, hydrological patterns, vegetation dynamics, water chemistry, and element budgets. During the first 5 years, considerable changes within the catchment were observed. Both internal and external factors could be identified as driving forces for the formation of structures and patterns in the artificial catchment. Initial structures formed by the construction process and initial substrate characteristics were decisive for the distribution and flow of water. External factors like episodic events triggered erosion and dissection during this initial phase, promoted by the low vegetation cover, and the unconsolidated sandy substrate. The transformation of the initial geosystem into areas with evolving terrestrial or aquatic characteristics and from a very episodic to a more permanent stream network and discharge, together with the observed vegetation dynamics increased site diversity

W. Schaaf (✉)
Soil Protection and Recultivation,
Brandenburg University of Technology,
Cottbus, Germany
e-mail: schaaf@tu-cottbus.de
URL: http://www.tu-cottbus.de/fakultaet4/de/bodenschutz

M. Elmer · W. Gerwin · R. Nenov
Research Centre Landscape Development and Mining Landscapes, Brandenburg University of Technology,
Cottbus, Germany

A. Fischer · S. Winter · M. K. Zaplata
Geobotany, Technische Universität München,
Munich, Germany

H. Pretzsch · S. Seifert
Chair of Forest Growth and Yield Science,
Technische Universität München,
Munich, Germany

S. Seifert
Department of Forest and Wood Science,
Stellenbosch University,
Stellenbosch, South Africa

Published online: 29 November 2012

and heterogeneity with respect to water and nutrient availability and transformation processes compared with the more homogenous conditions at point zero. The processes and feedback mechanisms in the initial development of a new landscape may deviate in rates, intensity, and dominance from those known from mature ecosystems. It is therefore crucial to understand these early phases of ecosystem development and to disentangle the increasingly complex interactions between the evolving terrestrial and aquatic, biotic, and abiotic compartments of the system. Long-term monitoring of initial ecosystems may provide important data and parameters on processes and the crucial role of spatial and temporal structures and patterns to solve these problems. Artificially created catchments could be a suitable tool to study these initial developments at the landscape scale under known, designed, and defined boundary conditions.

**Keywords** Ecosystem development · Soil formation · Vegetation succession · Hydrology · Surface structures

## Introduction

The structure, mutual interdependencies, and feedback controls of mature natural systems are usually utmost complex (Jørgensen et al. 2000), which makes it difficult or impossible to clearly define the system boundaries. Even the simple case of predicting discharge from a catchment is highly uncertain (Grayson et al. 2002). However, it is a fundamental prerequisite to recognize and understand the dominant ecosystem processes when we want to forecast the response to changing external controls, such as climate change, atmospheric deposition, land use changes, and other driving forces of environmental shifts (e.g., Arndt 2006). The increasing complexity of environmental problems, scientific challenges, and the demand for information and prediction for decision makers and society resulted in large efforts to understand and predict ecosystem functions and services. The reactions of natural systems to such disturbances may become more predictable if we are able to identify and possibly separate the influences of fundamental controls. Studies of terrestrial systems have been carried out in forest, agricultural, and natural ecosystems from the plot scale to the scale of landscapes (e.g., Campbell et al. 2007; Ellenberg et al. 1986; Fränzle et al. 2008).

The transport and cycling of water and elements integrates all the many abiotic and biotic compartments of an ecosystem over scales and relates processes and patterns to the overall ecosystem functioning (e.g., Jørgensen 2009; Schaaf et al. 2011). The analysis of water and element cycling plays a key role in understanding the functioning, stability, elasticity, and resilience of ecosystems. Clearly outlined budget areas are critical for this kind of studies. Catchments and watersheds are therefore frequently used as natural, fundamental spatial landscape units (Likens 1999) offering the opportunity to quantify input parameters as well as the output from the system and to calculate water and element budgets (Neal et al. 2003; Schleppi et al. 1998). Catchments integrate complex processes over several scales and can be treated as dynamic systems (Kirchner 2009) functioning as "a mirror of the landscape" or as an organism (Likens and Borman 1995).

However, natural catchments are typically characterized by a huge complexity and heterogeneity that developed over long-term periods. Boundary conditions are, therefore, often widely unknown and only explored by indirect or punctual methods. Most integrating studies have been carried out in mature systems carrying a long memory of site history (e.g., Pennisi 2010).

Therefore, the study of initial, artificially created ecosystems at a landscape scale could be an appropriate alternative to overcome many of these disadvantages since boundary conditions, and internal structures as well as initial site conditions can be better defined compared with naturally evolved systems (Gerwin et al. 2010). Whereas individual components of ecosystems have been studied in detail during ecosystem development, less attention has been directed to the complex interaction of biotic and abiotic ecosystem components during co-development and the interacting effects of spatial patterns and processes on the development of ecosystem functions and stages (Amundson et al. 2007; Chadwick and Chorover 2001; Groffman et al. 2006; Kelly et al. 1998; Lambers et al. 2009; Roering et al. 2010; Schaaf et al. 2011; Torrent and Nettleton 1978; van Breemen et al. 2000). Current research indicates the importance of hot spots and patches as starting points of initial development (Ludwig et al. 2000; McClain et al. 2003).

In this context, the value of high-quality long-term monitoring data has been recognized as essential for understanding the functioning of ecosystems (Likens and Haeuber 2007; Lindenmayer and Likens 2009; Lovett et al. 2007; Nisbet 2007). Long-term monitoring of ecosystems has proven to be an important tool to understand the complex interactions and feedback mechanisms of different processes and patterns within the systems and to predict their future development (Parr et al. 2002; Schaub et al. 2011). The International Long-Term Ecological Research Network was established with more than 20 countries contributing a large number of monitoring sites (Waide et al. 1998). Recently, several new networks are emerging, such as the National Ecological Observatory Network (Pennisi 2010), the Critical Zone Exploration Network (Brantley et al. 2006), the WATERS network in the USA, or the Biodiversity Exploratories and the Terrestrial Environmental Observatoria (Bogena et al. 2006) in Germany.

The objective of this paper is to present observations, results from monitoring measurements, and preliminary conclusions about the development of patterns and structures during the first 5 years of development of an artificial catchment starting from point zero. Since July 2007, the catchment is the main research site of the Collaborative Research Center (CRC/TR 38) “Structures and processes of the initial ecosystem development phase in an artificial water catchment” a joint initiative of the BTU Cottbus, TU München, and ETH Zurich. Our approach aims to disentangle and understand the feedback mechanisms and interrelationships of processes and their co-development with spatial and temporal structures and patterns by studying an initial, probably less-complex ecosystem (Schaaf et al. 2011). Structures and patterns in this context are biotic and abiotic properties of an ecosystem with explicit spatial, physical, and/or chemical distributions that influence the extent, direction, and duration of processes of ecosystem development. Structures are interacting with processes, and initial structures are influencing the system development as well as the evolution of resulting new structures. Colonizing species during succession are defined as biotic structures. The spatial composition of biotic structures results in patches.

As part of the CRC/TR 38, intensive measurements are carried out in the catchment with regard to the development of surface structures, hydrological patterns, vegetation dynamics, water chemistry, and element budgets.

## Materials and methods

The artificial catchment “Chicken Creek” was constructed in the post-mining area of the Lusatian lignite-mining district in eastern Germany. The region is characterized by temperate seasonal climate (559 mm mean annual precipitation, 9.3 °C mean annual air temperature). The site is located in the middle of the still-active open-pit mine “Welzow-Süd” 30 km south of Cottbus. The catchment consists of a clay layer (174,000 $m^3$, 1–3 m thickness) at the bottom as an aquiclude covered by a layer of post-glacial sediments (117,500 $m^3$, up to 3.5 m thickness) composed of sandy to loamy sandy substrate as aquifer. Details of the construction process and initial site conditions are given by Gerwin et al. (2009) and Kendzia et al. (2008). The catchment size is 6 ha with a SE exposition and a mean slope of 3.5 % (Fig. 1). The site was prepared to allow for the formation of a small pond (0.4 ha) in the lower part of the catchment. No additional restoration measures like fertilization, planting, or seeding were carried out, and the site was left to natural development.

Immediately after construction was completed in September 2005, initial monitoring installations were set up oriented along a 20×20-m grid that covers the whole catchment (Fig. 2). This setup was continuously complemented with additional measurements and installations to cover developing surface structures and patterns. More details on the monitoring program and analytical methods are described in Schaaf et al. (2010), Elmer et al. (2011), and Gerwin et al. (2011).

Since the Pleistocene sediments were dumped in two main phases, substrate characteristics differ slightly within the catchment (Gerwin et al. 2010). Whereas the eastern part is composed of almost pure sands (>80 % sand), in the western part loamy sands dominate (70–80 % sand). Gravel content in both parts is 8–15 %. All substrates are slightly calcareous (0.6–1.1 % $CaCO_3$) with high pH (7.7–8.1). Organic carbon contents are very low (1.6–2.2 mg $C_{org}\,g^{-1}$). Grid sampling at 124 grid points showed no differentiation of these parameters with soil depth.

A microdrone (MD4-200 by microdrones GmbH, Germany) equipped with a optimized commercial digital camera (Pentax Optio A40 with 4,000×3,000 pixels) is used for the documentation of surface structures in the catchment. The system allows GPS waypoint navigation and programming of flight routes. The

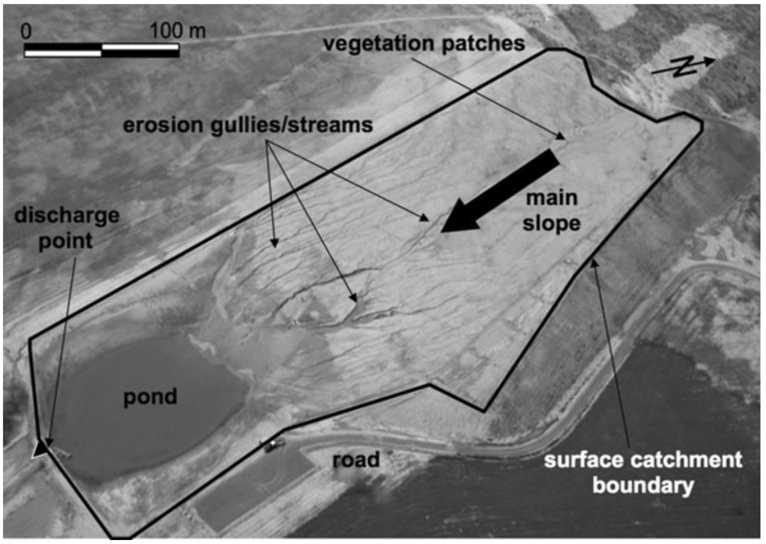


**Fig. 1** Aerial view and main features of the artificial catchment "Chicken Creek" near Cottbus, NE Germany in May 2007, 18 months after finishing of the construction works

specified camera settings in combination with the defined flight plan resulted in a maximum terrain resolution of about 0.03 m/pixel at a flying altitude of 80 m. Camera triggering was executed at defined photo-stops integrated in the programmed flight route. The drone-based aerial photos were georeferenced using 178 ground control points (GCPs) including the 20×20 m grid points and additional GCPs in the pond and along the surface boundary of the catchment using WGEO software. The complete aerial photo of the total catchment is composed of a mosaic of approximately 130 georeferenced image blocks. The aerial maps were created using ArcGIS.

The development of the erosion gully network was documented through manual digitalization from the high-resolution aerial maps in ArcGIS. The extent of the network was documented (digitized from the respective aerial map) for five successive years of development (2006 to 2010). Only those surface structures containing a stream wall and a streambed clearly discernible in the aerial maps were assumed to be part of the erosion gully network. Furthermore, erosion gullies covered by dense vegetation were assumed to be inactive. These assumptions were confirmed by field observations at the site. The length and area of the whole gully network as well as of individual network segments were computed in ArcGIS.

From September 2008, regular laser scans of the whole site where done with a terrestrial laser scanner (Riegl LMS-Z420i) from 13 scan positions inside the catchment mounted on a 6-m-high mobile tower. The effective measured horizontal projected point densities where increased over time to account for the increasing vegetation density. The ground surface was extracted from the combined scans by a grid based minimum filter using the lowest measured point in every 0.5×0.5 m grid cell. Table 1 shows the point densities per grid cell before the filtering. For each grid cell, a local plane of neighboring cells within a 6-m radius was fitted. If the cell height was more than 5 cm below the plane at the same position, it was assumed that the cell belongs to a gully. The height differences of these selected cells between the years 2008, 2009, and 2010 were used as an indicator of active erosion.

To analyze the vegetation succession, the 20×20-m grid (Fig. 2) was used to implement a systematic net of permanent plots with the grid mark in the plot center. Each plot has a size of 5×5 m. On the plots, all vascular plant species were recorded and the cover per species was estimated (for details see Zaplata et al. 2010). Recording started immediately after the construction work had been finished (October 2005) and was repeated each summer (July/August).

Two weather stations were installed in the catchment (Fig. 2). Station 1 is located in the upper part of the catchment recording wind speed and direction, air temperature and humidity, and global radiation in 2 m height and precipitation in 1 m height in hourly intervals since September 2005. A second station was added in February 2008 in the lower part of the catchment with three recording levels (0.5, 2, and 10 m) and higher temporal resolution. Measured precipitation values are corrected according to the method

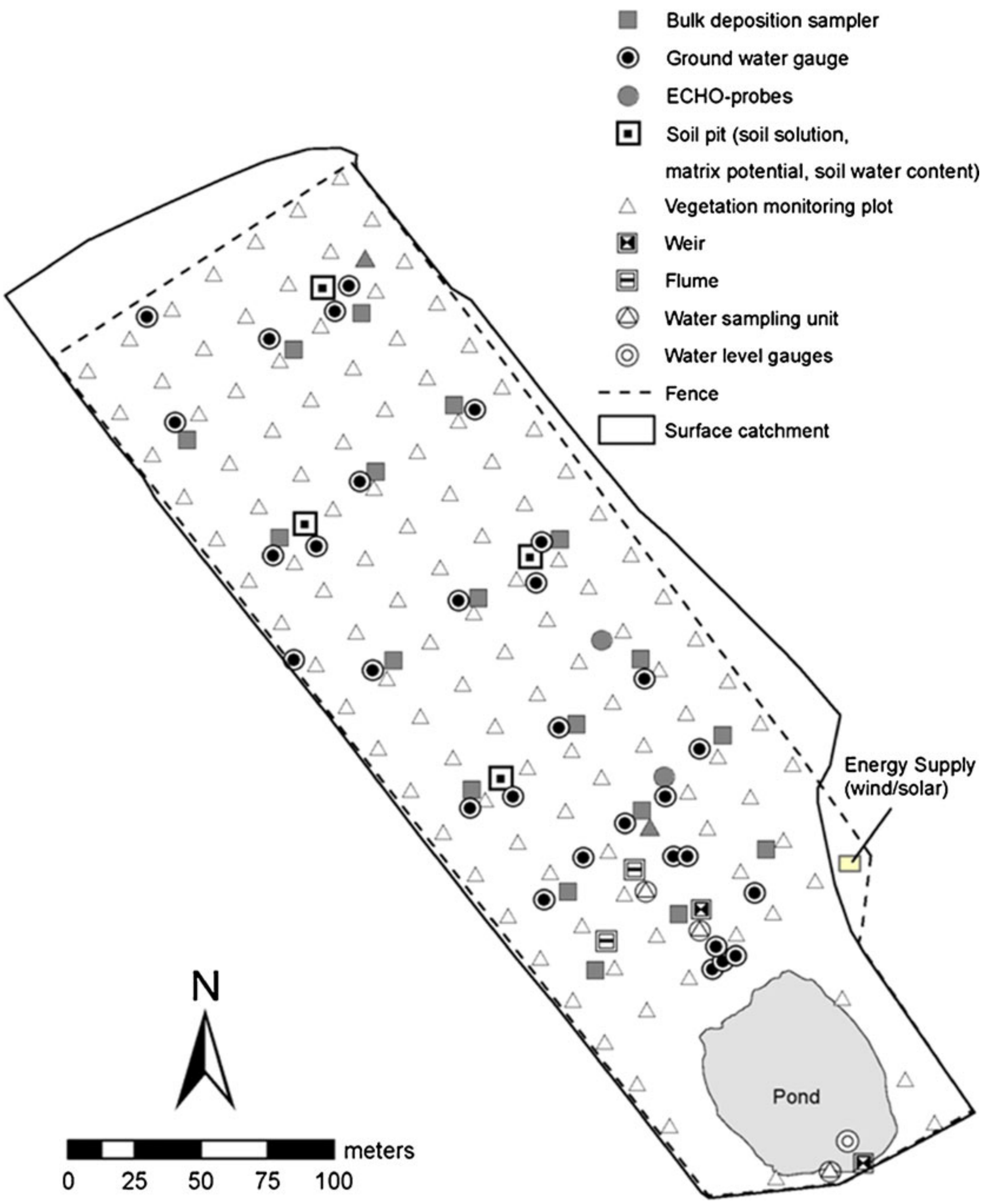


**Fig. 2** Overview over grid points and monitoring installations at "Chicken Creek"

**Table 1** Point densities (pts. $m^{-2}$) per grid cell of 3D terrestrial laser scanner data and number of measured cells of 0.5×0.5 m size

| | September 2008 | August 2009 | October 2010 |
|---|---|---|---|
| Median (pts. $m^{-2}$) | 29 | 1,543 | 2,167 |
| Max (pts. $m^{-2}$) | 2,611 | 47,620 | 202,012 |
| Total No. of cells | 218,096 | 226,120 | 227,001 |

developed for the German Meteorological Service network (Rudolph and Rubel 2005; Wagner 2009).

Within the catchment, 30 observation wells were installed to record groundwater levels (Fig. 2). Seventeen of them were installed along the grid points immediately after the completion of the Chicken Creek catchment. The boreholes were drilled manually down to the clay layer. The gauges were constructed using 2-in. polyethylene (PE) pipes. The lower part of the pipes (1 m) is perforated with 0.3 mm slots, and the lower ends were placed some centimeters into the clay. Both ends of the pipes were screwed with caps. The groundwater wells were not embedded with gravel. Nine gauges were equipped with water level loggers (pressure transducers). The groundwater level in the remaining wells was measured manually at least monthly.

Total discharge was measured in the clay dam at the bottom end of the catchment as discharge from the pond (Fig. 2) using a V-notch weir combined with a tipping bucket to account for a large variation in discharge amounts. In September 2006, this weir had to be reconstructed resulting in a lowering of the discharge level by 37 cm (cf. Fig. 15). In addition, water levels in the pond were recorded using three pressure transducers. A second weir was installed in the subsurface clay wall above the pond running transversal to the main groundwater flow direction. This weir also consists of a V-notch weir and a tipping bucket. In two of the main erosion gullies stainless steel H-flumes equipped with ultrasonic sensors and tipping buckets to account for low flow rates were installed (in January and June 2007, respectively). Both weirs and one of the flumes were equipped with automated water sampling units (ISCO 6712 and ISCO 3700) taking daily water samples that were taken back to the laboratory every 2 weeks.

Bulk deposition was sampled with 18 samplers in 1 m above ground (Fig. 2). The samplers were made of two 2-l receptors and PE collectors (115 $cm^2$). The bottles were mounted in a PVC pipe topped by a metal bird perch. The samples were collected at two weekly intervals. Bulk deposition was calculated by multiplying element concentrations with the rainfall amount per sampler (Schaaf et al. 2010).

In summer 2010, additional soil moisture sensors (ECH2O-EC5, Decagon Devices) were installed in two transects where consistent surface color differences were identified from aerial images. Four sensors each were horizontally installed in depths of 3 and 10 cm along transects of 1.5 m.

Four permanent soil pits were installed in the catchment (cf. Fig. 2) to allow installation of tensiometers, TDR probes, and soil solution sampling in different depths. The pits were excavated by hand in October 2007 down to 2.0–2.5 m depth and stabilized with PE rings (∅ 1 m). Boron silicate glass suction plates (∅ 10 cm) with permanent pressure of −10 kPa in three depths were installed from these pits for soil solution sampling. Samples were taken every 2 weeks. Due to the increasing groundwater table, only the upper two depths (30 and 80 cm) could be sampled from 2009.

All solution samples were analyzed for pH (Beckmann pH34 glass electrode and WTW pH537) and electrical conductivity (EC; Hanna HI 8733 and WTW LF537). Subsamples were filtered (0.45 μm) and stored at −18 °C until further analysis. The samples were analyzed for concentrations of cations (Ca, Mg, K, and Na using ICP-OES Unicam 701 and Thermo Scientific iCAP 6000), anions ($NO_3$, $SO_4$, and Cl using IC Dionex 5000), $NH_4$ (Rapid Flow Analyzer Alpkem), and DOC, TOC, TIC, and TN (Shimadzu TOC-5000 and VCPH+TNM-1).

## Results and discussion

### Surface structures

The comparison of aerial images from 2006 and 2010 reveals the development of several patterns and structures at the catchment surface (Fig. 3). Whereas the image from 2006 shows a relatively homogeneous surface with mainly structures resulting from the construction process itself (e.g., caterpillar tracks, weir construction above the pond), in 2010 vegetation patches, surface, and gully erosion developed over the first 5 years are visible. A delineation of the channel network from the 2006 image indicates that the structures left from the construction works triggered the initial channel network formed after heavy thunder storms on the unvegetated surface in spring and summer 2006 (Fig. 4). This is most pronounced for the perpendicular channel courses in the upper part and for the narrow parallel channels in the lower western part of the catchment. Starting from this initial network, the further development of erosion channels over time was influenced by topography, substrate

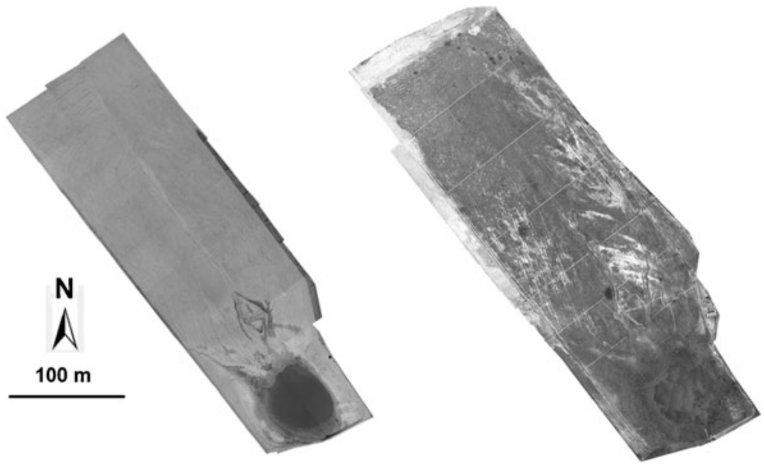


**Fig. 3** Comparison of aerial images of the “Chicken Creek” catchment from microdrone pictures in September 2006 (*left*) and July 2010 (*right*)

characteristics, and vegetation dynamics. Clear differences were found for the two main parts of the catchment (E vs. W part). The overall stream length as derived from aerial images was higher in the western part compared with the eastern part. In both parts, the length of active erosion channels increased until 2007 and then decreased (Fig. 5). The total area of the channel network was initially higher in the western part but showed similar values for both parts in the following years. In 2007, the total area of the erosion channel network reached its peak, covering about 2 % of the surface catchment area. As a result, the ratio of stream length/stream area remained different for the two main parts throughout the years indicating that the gullies in the eastern part with dominating pure sandy substrate are wider and shallower, whereas in the western part with more loamy sands the channels are narrower but incised deeper. After 2007, the reduction in active channel length and area is most probably due to invading vegetation and stabilization of the streambeds (Fig. 6).

These results were confirmed by the laser scan measurements. The height difference of the gully grid cells decreased from 2008 to 2009 by 4.9 cm (median). The same cells changed from 2009 to 2010 by only −0.3 cm (median). Vegetation height in the gully cells as derived from the topmost point in every grid cell was 0.40 m in 2008, 0.41 m in 2009, and 0.51 m in 2010, respectively, indicating vegetation growth. Comparing the average point density of the gully grid cells with the average point density of all grid cells per year revealed an increase in relative density from 1.13 in 2008 to 1.17 in 2009 and 1.34 in 2010 indicating increasingly denser vegetation in the gullies.

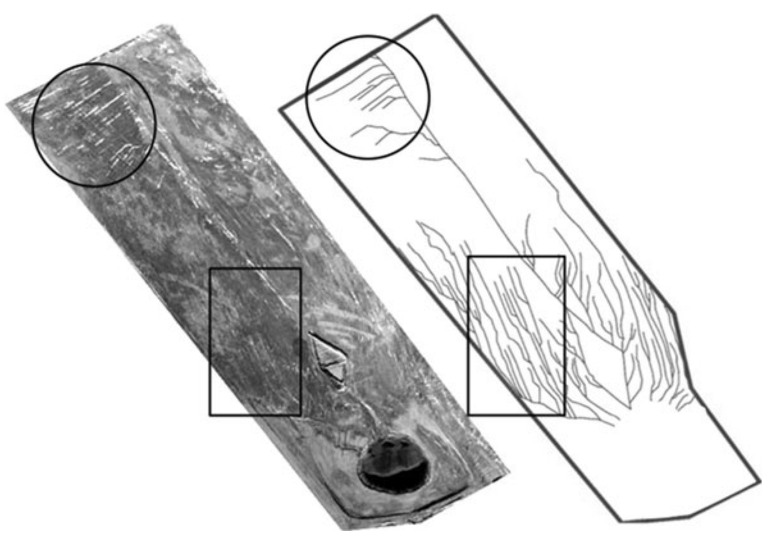

**Fig. 4** Initial network of erosion channels derived from an aerial image of the catchment in November 2005 (photo by Vattenfall Europe Mining AG). *Circles* mark the perpendicular erosion channels in the *upper part* and *rectangles* the parallel channels in the *lower western part* of the catchment corresponding to caterpillar tracks

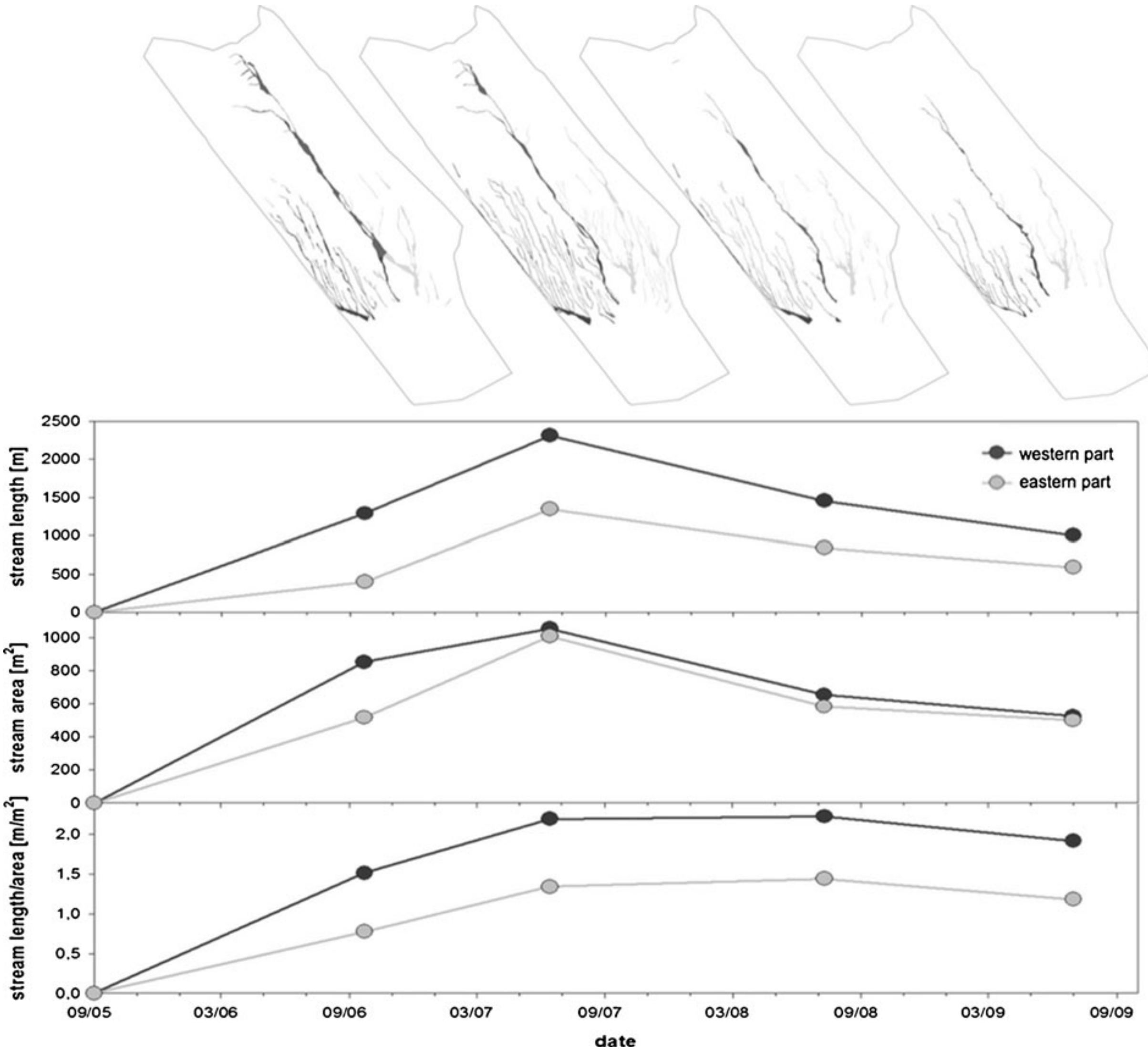


**Fig. 5** Development of the active erosion channel network and derived length and area parameters

Vegetation dynamics

In the beginning, the catchment area was an enclave surrounded by a landscape either without any vegetation (active zone of the mine) or with a very sparse recolonizing vegetation similar to the one developing in the catchment, mainly with typical pioneer species. During the first 5 years, the overall vascular plant cover increased substantially during the first years and reached a maximum value of 38.5 % in 2009 (Fig. 7). The total number of vascular plant species increased quite continuously from 18 in 2005 to 150 in 2010. The number of woody species rose from 1 (the nitrogen-fixing *Robinia pseudoacacia*) to 14 in 2010 with highest frequencies for *Pinus sylvestris* (31.9 %), *Betula* cf. *pendula*, and *R. pseudoacacia* (13.4 % each). Nitrogen-fixing plant species rapidly became a major component of the established vegetation (Fig. 8). Considerable colonization started in 2007 close to the central gully, which was mainly fed by tributaries from the loamier western part of the catchment (Fig. 4). In 2007, Fabaceae (legumes) covers were significantly higher in plots in the western part (Table 2). Although increasing, non-legumes did not keep pace with the increase of Fabaceae in 2008 and 2009. In 2009, legumes cover was dense throughout

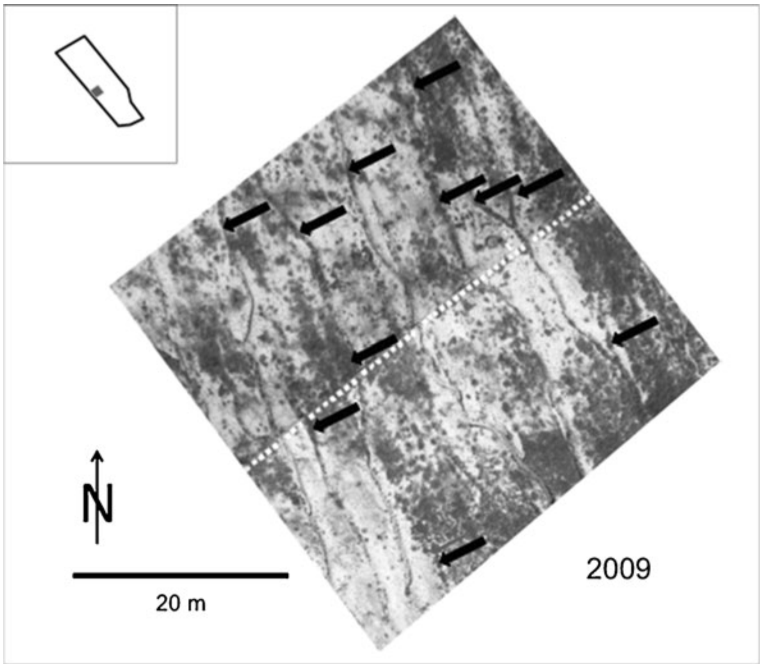


**Fig. 6** Example of the erosion channel network at one 40×40 m plot with linear vegetation development along stabilized former streambeds (*arrows*); aerial image from microdrone flight in July 2009

the catchment and significantly higher compared with the sum of all other vascular plants (Table 3). In 2010, a general decline in legume cover was observed but more pronounced in the western part resulting in a changed dominance pattern (Figs. 8 and 9; Tables 2 and 3). Also, the number of Fabaceae species developed in accordance with the west-east cover pattern. In the eastern part, species numbers increased moderately (one, four, seven, eight, and ten species, respectively, in the years 2006–2010) compared with the initial fast increase in the western part (0, 8, 10, 11, and 11 species, respectively, in the years 2006–2010). Thus, the example of Fabaceae clearly demonstrates that, due to differing substrate properties, the processes of colonization and space occupation were asynchronous.

However, there is no plausible explanation for the decline in total vascular species cover (Fig. 7) besides a marked downturn of the—at this time by far dominant—single species *Trifolium arvense* in 2010. Such dependency in total cover on one leguminous species is in line with the succession series at Mount St. Helens (USA) where vegetation cover initially increased but then fluctuated due to changes in the cover of the legume *Lupinus lepidus* (del Moral 2009). To provide a conceptual understanding, we consider it as failure of the system in compensating for an occurring cover reduction. This low resilience strongly indicates a still early state of succession. Whereas at the beginning of succession species individual numbers were low, later the number of species and especially the

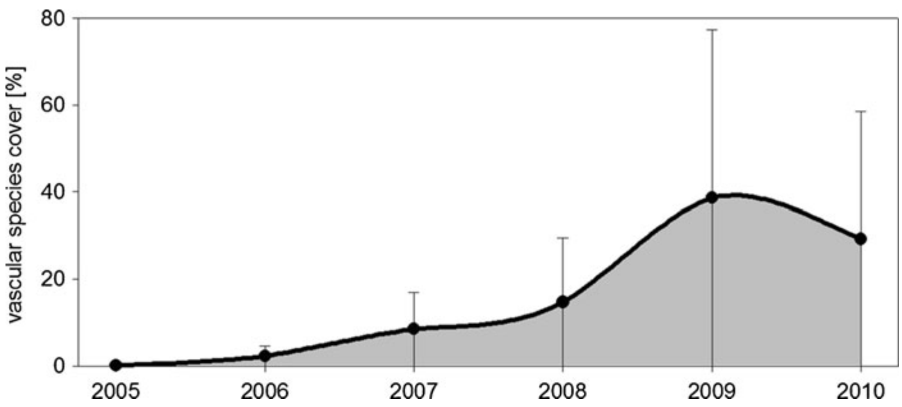


**Fig. 7** Total vascular species cover (in percent) in the catchment (mean value and standard deviation of 120 grid plots, cf. Fig. 2)

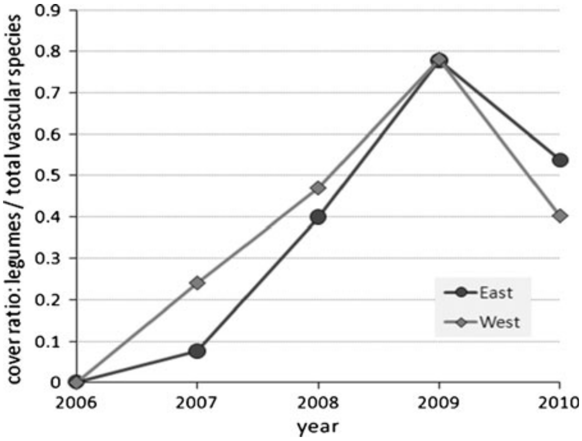


**Fig. 8** Relation of the cover degree of legumes (Fabaceae) to the cover degree of other vascular species within the catchment between 2006 and 2010

number of individuals per species increased. However, individual numbers of other species apparently were not high enough to balance the decline in the cover of *T. arvense*. Moreover, such an extensive and simultaneous diminution of a single plant species in a larger area may substantially contribute to the delimitation of early succession phases as subunits of succession stages (Zaplata et al. 2012). Therefore, the significant cover decline of a single species can be regarded as a characteristic feature of early succession.

After the dominance phase of *Conyza canadensis* in 2006 and 2007 (Zaplata et al. 2011), a development started leading to certain pattern formation whereby the patterns more matched the physical conditions (Baasch et al. 2009). For water-limited regions in a global perspective, the following types and order of vegetation patterns with increasing precipitation levels were classified: bare soil>spots>bands>vegetation with holes>uniform vegetation (Deblauwe et al. 2008; Sun et al. 2010). There, vegetation patterns are induced mainly by the positive feedback between vegetation and water availability. A certain biomass may contribute to the allocation of higher amounts of water (e.g., by promoting infiltration) and plants may facilitate their own growth (Tietjen et al. 2010; van de Koppel and Rietkerk 2000). This process may be enhanced by hysteresis effects, resulting in quite stable vegetation patterns in water-limited regions in the long term.

In the "Chicken Creek" catchment, we observed all types of vegetation patterns listed above. But these patterns appeared not to be stable and the transitions between spotted patterns, vegetation with holes, and uniform vegetation occurred rapidly (Fig. 10). Pattern emergence appeared to be species driven and was largely assigned to *T. arvense*.

In disfavored areas of the catchment, we generally found slower colonization rates and a clearer formation of vegetation patterns. Some sub-areas in the eastern part very hardly were inhabited by vascular plants forming vegetation bands between bare soil. We expect that these relatively small-scale patterns become increasingly blurred with further development, e.g., due to rhizomatous species.

## Hydrological patterns

Precipitation at the site was clearly higher compared with the long-term annual mean except for 2006 (Table 4). Especially in 2010, precipitation inputs were 140 % higher compared with the 30-year mean for Cottbus (1971–2000, see also Fig. 11). This may be partly due to the exposed setting within the post-mining landscape. Also, air temperature exceeded the long-term mean in all years by up to 2.6 °C. Since comparably high values for precipitation and temperature are also reported for the city of Cottbus in these years by the German Meteorological Service effects of climatic change cannot be excluded. Within single years large variations in seasonal distribution of precipitation were observed (Fig. 12).

Starting already during the construction period (2004/2005) precipitation accumulated on top of the bottom clay layer and formed a saturated zone as a new structural hydrologic element of the catchment. At the beginning of the monitoring measurements the

**Table 2** Comparison of the vegetation covers in the eastern and western part of the "Chicken Creek" catchment for the years 2006 to 2010 (*p* values resulting from *t* tests of mean cover for both parts; entries set in italics indicate significant differences)

| | 2006 | 2007 | 2008 | 2009 | 2010 |
|---|---|---|---|---|---|
| Cover of Fabaceae | 0.323 | *0.014* | 0.170 | 0.774 | *0.009* |
| Cover of other vascular plants | 0.872 | 0.692 | 0.595 | 0.767 | *0.011* |

**Table 3** Average cover (in percent) of the Fabaceae species and other vascular plants in the western and eastern part of the "Chicken Creek" catchment for the years 2006 to 2010

| | 2006 | 2007 | 2008 | 2009 | 2010 |
|---|---|---|---|---|---|
| Eastern part | | | | | |
| Cover of Fabaceae (%) | 0 | 0.5 | 5.1 | 30.1 | 16.1 |
| Cover of other vascular plants (%) | 1.7 | 6.3 | 7.6 | 8.8 | 13.9 |
| Difference between Fabaceae and other vascular plants | * [a] | * [a] | ** [a] | [b] | n.s. |
| Western part | | | | | |
| Cover of Fabaceae (%) | 0 | 2.1 | 7.0 | 31.9 | 11.0 |
| Cover of other vascular plants (%) | 1.8 | 6.5 | 7.9 | 9.0 | 16.4 |
| Difference between Fabaceae and other vascular plants | * [a] | * [a] | n.s. | [b] | * [a] |

*n.s.* not significant

*$p<0.001$, highly significant; **$p<0.01$, significant difference (*t* tests)

[a] The cover of Fabaceae is lower compared with the cover of other vascular plants

[b] The cover of Fabaceae is larger compared with the cover of the other vascular plants;

groundwater table varied throughout the catchment between 0.3 and 1.0 m above the clay layer. In the following years, groundwater levels generally showed a clear seasonal pattern with higher levels in winter and decreasing levels in summer (Fig. 13). But all groundwater gauges showed a consistent trend of increasing groundwater levels over the years. Especially the very wet summer and autumn 2010 resulted in raising groundwater levels close to the surface in the upper part of the catchment. The only exception to this trend was found for gauges close to erosion gullies in the lower part of the catchment (marked with a number sign in Fig. 13) that inclined deep enough to cut into the saturated zone so that groundwater could drain through these channels. These unexpected high groundwater levels may be explained by several conditions of the initialized hydrologic system: the cone-like subsurface structures caused by the dumping process of the aquifer sediments run almost perpendicular to the main hill slope and the expected main flow direction of the groundwater. This may have caused un-isotopic conditions in hydraulic conductivity (Mazur et al. 2010). The measured (vertical) saturated conductivity ($5\times10^{-6}$–$5\times10^{-5}\,\mathrm{m\,s^{-1}}$) was lower than expected from the textural composition of the substrate, which again may be caused by sorting of the material during the dumping process. In addition, the subsurface clay dams above the pond, which were constructed to direct groundwater flow to the central upper weir and to prevent downhill movement of the sandy substrates on top of the clay layer, obviously contributed to an increased groundwater level in the upper part of the catchment.

But also other biotic and abiotic factors may have contributed to both the high surface runoff and the high groundwater recharge. The low vegetation cover during the first years made the bare unconsolidated substrate surface prone to wind and water erosion and

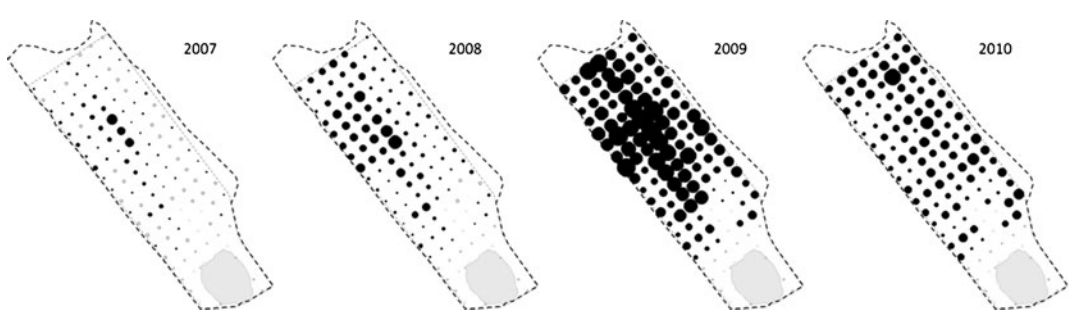


**Fig. 9** Distribution and cover of all legumes from 2007 to 2010 within the catchment. Size of the dots depicts cover classes (≤0.1 %; >0.1–0.5 %; >0.5–1 %; >1–2 % in 1 % steps up to 10 % and in 5 % steps up to 80 %)

**Fig. 10** *T. arvense* in spotted patterns (*left*, photo: M. Veste, May 2008) and in a pattern classified as between "vegetation with holes" and "uniform vegetation" (*right*, photo: M. Zaplata, July 2009)

caused only low transpiration losses. Soil crusts were found very soon within the first years at the soil surface. Abiotic mineral crusts (mainly from gypsum precipitation, cf. Schaaf et al. 2010), physical crusts as a result of rain splash (puddle erosion) as well as different types of biological soil crusts (BSC) were described (Fischer et al. 2010). Depending on type and composition, both physical crusts (e.g., Bresson and Boiffin 1990) and BSC are known to positively or negatively influence infiltration rates and surface runoff processes (Littmann et al. 2000; Yair et al. 2008).

Soil moisture close to the surface (3 cm depth) was consistently higher below BSC compared with adjacent sites with bare soil (Fig. 14). Soil texture analysis from samples taken at the installation sites of the moisture probes revealed higher silt and clay contents below the crust (13.3 % silt and 5.3 % crust) compared with the bare soil (7.5 % silt and 1.4 % crust). All sensors reacted quickly to precipitation events with higher amplitudes below the crusts. These results indicate higher infiltration and water holding capacity below the crust and/or faster surface runoff on bare soil. The lower silt and crust contents at the bare soil surface may be a result of preferential depletion of fine material by lateral water erosion. Water repellency that is often reported for BSC could not be detected for the soil crusts at the catchment (Fischer et al. 2010).

The pond filled very rapidly already few months after construction was finished (Fig. 15). High snowfall accumulated in winter 2005/2006 in the catchment and melted quickly in February 2006. Most of the water released by this snowmelt was discharged as surface runoff on still frozen soil and filled the pond to its maximum level. The fast reaction of the pond level to precipitation events indicates that surface runoff is the dominating input flux to the pond. Both water-table rises in the pond and discharge at the weir occurred during or immediately after precipitation or snowmelt events. During dry periods with high evaporation, the pond level declined indicating that groundwater inflow during these periods is lower than evaporation losses from the pond surface.

Output from the discharge weir occurred for the first time at the beginning of 2007, almost 1.5 years after construction was completed (Fig. 16). Discharge remained quite episodic after precipitation events in 2007–2009. Only then discharge started to be more continuous except for drought periods in summer 2010. Total discharge from the catchment considerably increased over the subsequent years accounting for 14 % of total precipitation inputs in 2007, 12.2 % in 2008, and

**Table 4** Total annual precipitation and mean air temperature at the "Chicken Creek" catchment (data from weather station 1, cf. Fig. 2)

| Hydrological year[a] | 2006 | 2007 | 2008 | 2009 | 2010 |
|---|---|---|---|---|---|
| Precipitation (mm) | 430.7 | 634.9 | 679.3 | 621.7 | 782.0 |
| Air temperature (°C) | 10.3 | 11.9 | 10.7 | 10.3 | 9.5 |

[a] Hydrologic year, e.g., 2008=1st November 2007-31st October 2008)

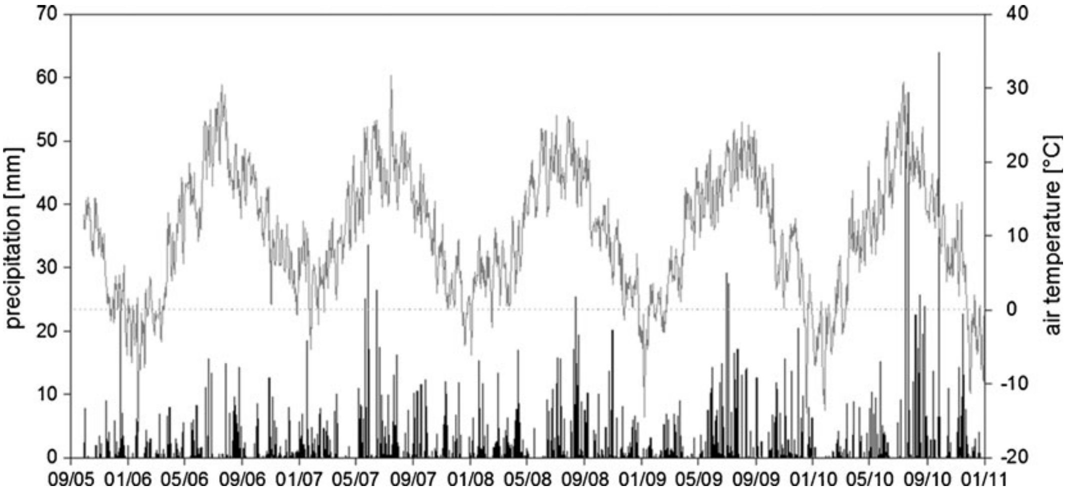


**Fig. 11** Precipitation and air temperature at the catchment (daily sums and mean values, respectively, recorded at weather station 1, cf. Fig. 2)

19.7 % in 2009. In the extremely wet year 2010, total discharge almost equaled precipitation (95.7 %).

These data indicate that during the initial years surface runoff processes dominated catchment hydrology inducing severe surface and gully erosion. At the same time, groundwater built up on top of the aquiclude to very high levels increasing the storage within the catchment. The special meteorological conditions in 2010 finally led to an almost complete saturation of the sediment body. Surface runoff and gully runoff that also drained the groundwater then resulted in high discharge rates. Nonlinear behavior in catchment discharge was also described by Hofer et al. (2011), who could simulate this behavior by modeling the connectivity of pathways and contributing areas.

## Water chemistry and element budgets

Soil solution composition varied considerably between the four soil pits at the beginning of the observation period. Compared with these spatial variations, differences in soil depth were less pronounced. Main

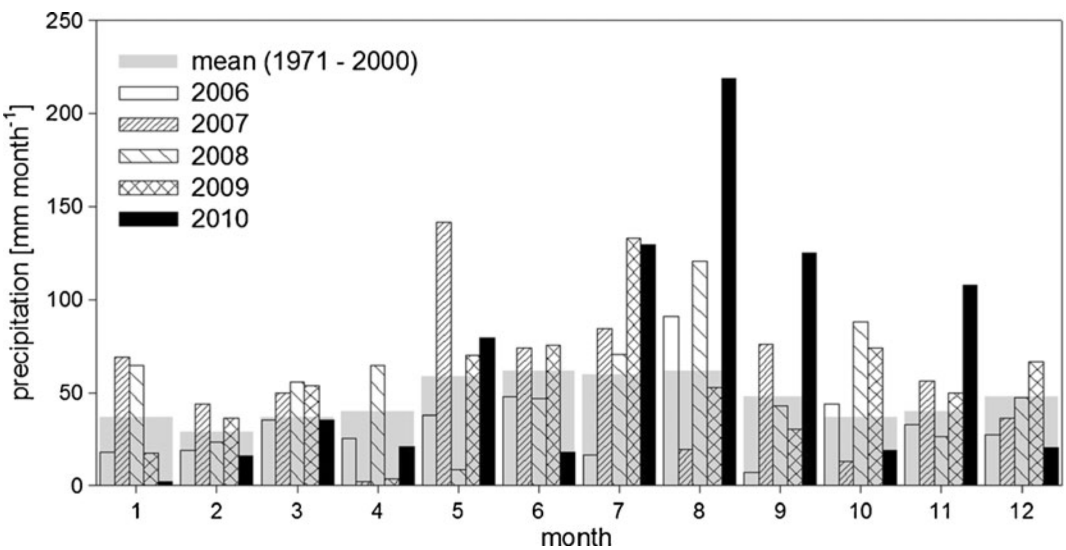


**Fig. 12** Sums of monthly precipitation at the catchment for the years 2006–2010 compared with the long-term mean values for the period 1971–2000

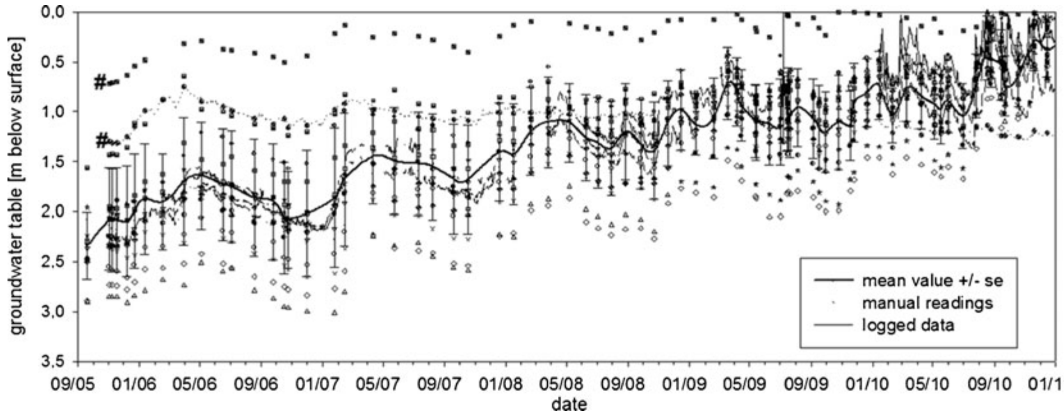


**Fig. 13** Groundwater levels below surface at 17 sites throughout the catchment (cf. Fig. 2; *symbols* mark groundwater gauges with manual readings, *lines* are gauges with logged readings; mean±standard error (SE) gives the mean value of all gauges with *error bars* indicating SE; # marks the two gauges draining groundwater mentioned in the text)

components of all sampled soil solutions were Ca, Mg, $HCO_3$, and $SO_4$ (Fig. 17). Due to the carbonate content of the substrates, mean pH values varied between 7.0 and 8.4 in all samples.

The two parallel samples of each pit in 30 cm depth showed similar composition indicating that spatial heterogeneity was small at the scale of ~1 m. In general, ionic concentrations increased with soil

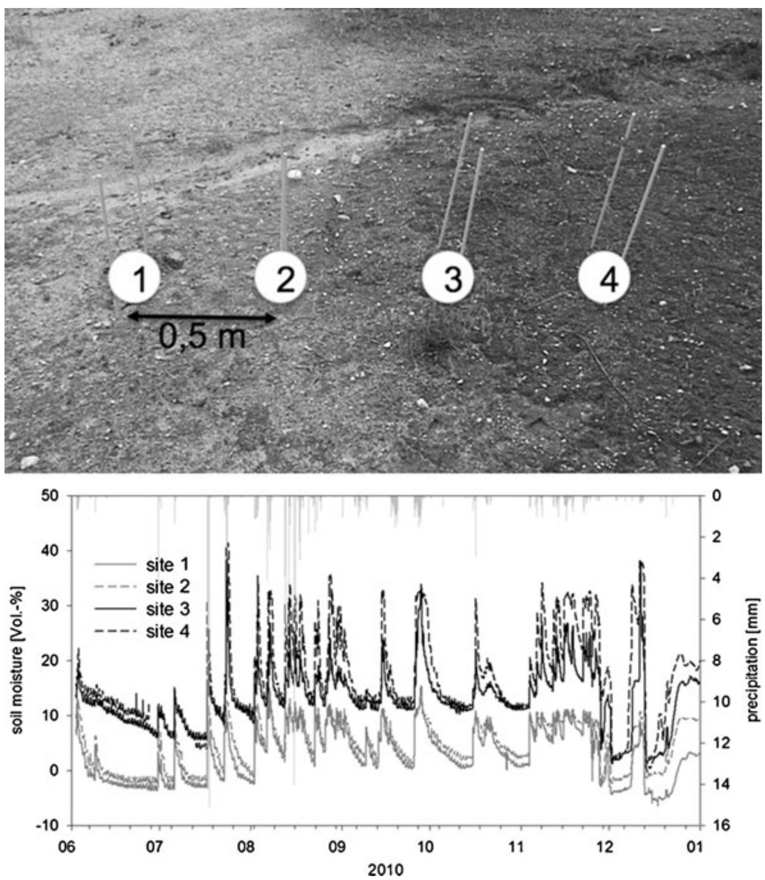


**Fig. 14** Soil moisture content in 3 cm depth along a transect from bare soil to BSC (*top*, picture of the sensor transect; *bottom*, soil moisture at the four sites and precipitation)

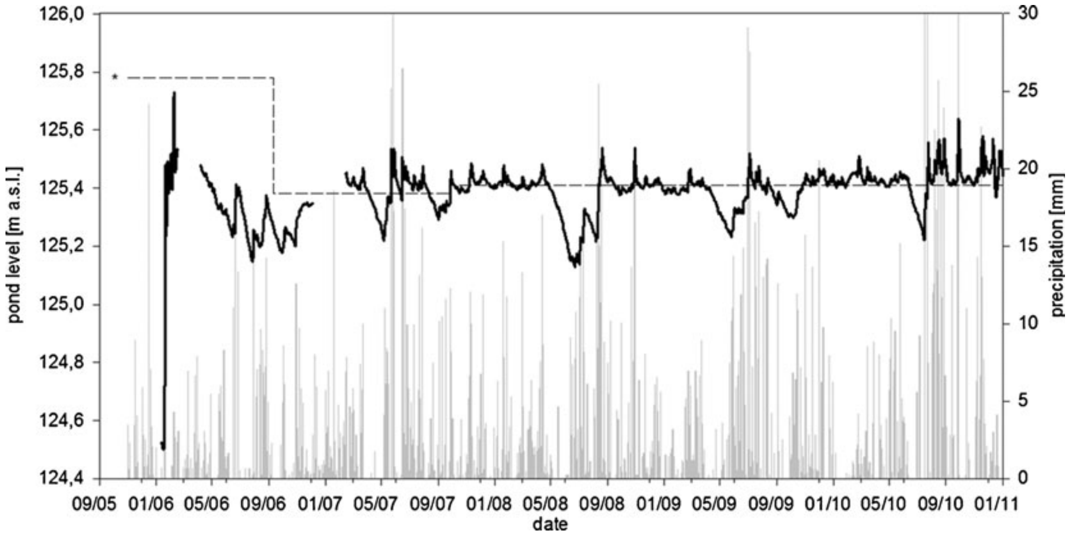


**Fig. 15** Water level of the pond and daily precipitation (*, the *dashed line* indicates the level of the pond outlet that was lowered in 2006 due to weir reconstruction)

depth. Concentrations of Ca (Fig. 17c), Mg (not shown), and $SO_4$ (Fig. 17d) decreased over the first year of measurements as reflected also in the EC (Fig. 17b) and especially the spatial variability between the four pits decreased as shown by the error bars in Fig. 17. Traces of gypsum in the substrates may be a source for both Ca and $SO_4$ in the initial phase of leaching. Thin white precipitations found at soil surfaces especially during dry periods were described as gypsum crusts (Schaaf et al. 2010). In contrast bicarbonate concentrations showed an overall trend of increasing values indicating decalcification (Fig. 17f). Compared with the very low $C_{org}$ contents in the substrates, DOC concentrations were at a high level (Fig. 17e) indicating a potential to mobilize this inherited organic carbon in the substrates.

PH values in all water samples from the two weirs and the flume varied between 6.8 and 8.4. Abrupt drops and increases in pH values of up to 1 pH/day could be observed (Fig. 18). This was most pronounced for the flume samples, but also the weir samples followed similar trends. In general, ion concentrations in water samples from the three sampling sites were in the order flume>upper weir>lower weir as indicated by EC (Fig. 18). Whereas EC values

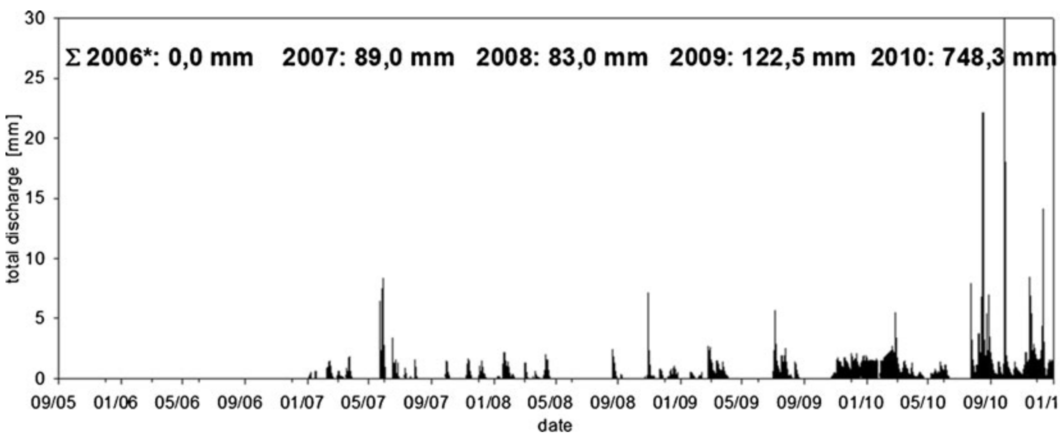


**Fig. 16** Discharge from the catchment as measured at the lower end of the pond (cf. Fig. 2; *, annual sums are given for hydrologic years, e.g., 2008=1st November 2007–31st October 2008)

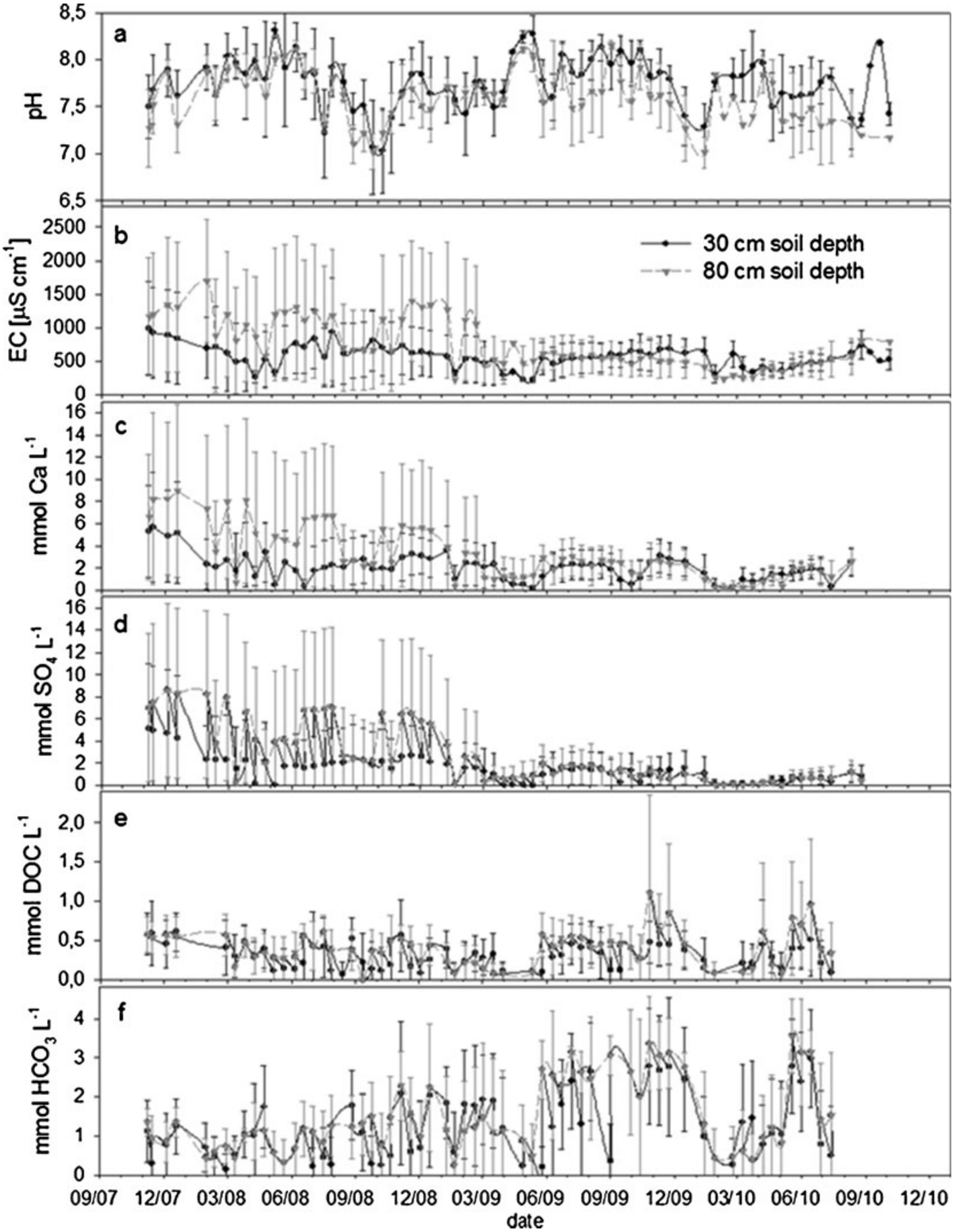


**Fig. 17** Soil solution composition in two soil depths (*symbols* represent mean values of the four soil pits; *error bars* indicate standard deviation)

at the lower weir (pond discharge) showed only little temporal variation, considerable short-term peaks in EC of up to ±1,500 $\mu S cm^{-1}$/day were observed in samples from the upper weir and the flume. EC values of samples from the upper weir showed typical temporal patterns with increasing values during drought periods and sharp drops after precipitation events.

As in soil solutions, the main components in all water samples collected at the different weirs were Ca, Mg, $HCO_3$, $SO_4$, and DOC. Generally, no distinct temporal trends could be detected during the observation period, except for a decline in Ca, Mg, and $SO_4$ concentrations in the upper weir and flume samples, reflecting the same trends as observed for the soil solutions.

Based on the element concentrations measured in bulk precipitation and pond discharge, element budgets were calculated for the catchment (Table 5). Bulk deposition inputs varied relatively little over the years and were very well within the range reported by other authors for the region (Gast et al. 2001; Schaaf and Hüttl 2006; Wellbrock et al. 2005). Output rates indicate that the catchment acted as a net source for Ca, Mg, S, and inorganic carbon released by carbonate weathering and gypsum dissolution, but as a strong sink for nitrogen. Output rates between the years varied considerably, mainly due to the changes in discharge rates as reflected by the chloride budget (Table 5). Increase in TIC output was a result of both discharge and bicarbonate concentrations increase.

## Formation of structures and patterns

During the first 5 years, we observed considerable changes within the catchment, some of them were unpredicted or unexpected, at least in its rate of development, e.g., the fast colonization of the site by vegetation, the formation of a large saturated zone, or the high extent of surface runoff in the early stage (Holländer et al. 2009; Hölzel et al. 2011).

Both internal and external factors could be identified as driving forces for the formation of structures and patterns in the artificial catchment during the first 5 years of development (Fig. 19). Initial structures formed by the construction process (e.g., catchment morphology, subsurface structures like clay dams and dumping cones, and caterpillar tracks on the surface) and initial substrate characteristics (e.g., texture and geochemistry) were decisive both for the distribution and flow of precipitation water and for vegetation succession. External factors like episodic events (e.g., heavy thunderstorms) triggered erosion and dissection during this initial phase and were largely promoted by the low vegetation cover and the unconsolidated sandy substrate. These processes resulted in the transport and redistribution of water and sediment within the catchment, mainly along the main slope, and the formation of new structural elements like gullies and channels, a sedimentation fan above and sediments within the pond. During this initial phase, internal factors imposed by the construction and design of the catchment clearly dominated processes. As a result, we observed an overall differentiation of the site, e.g., with respect to water availability

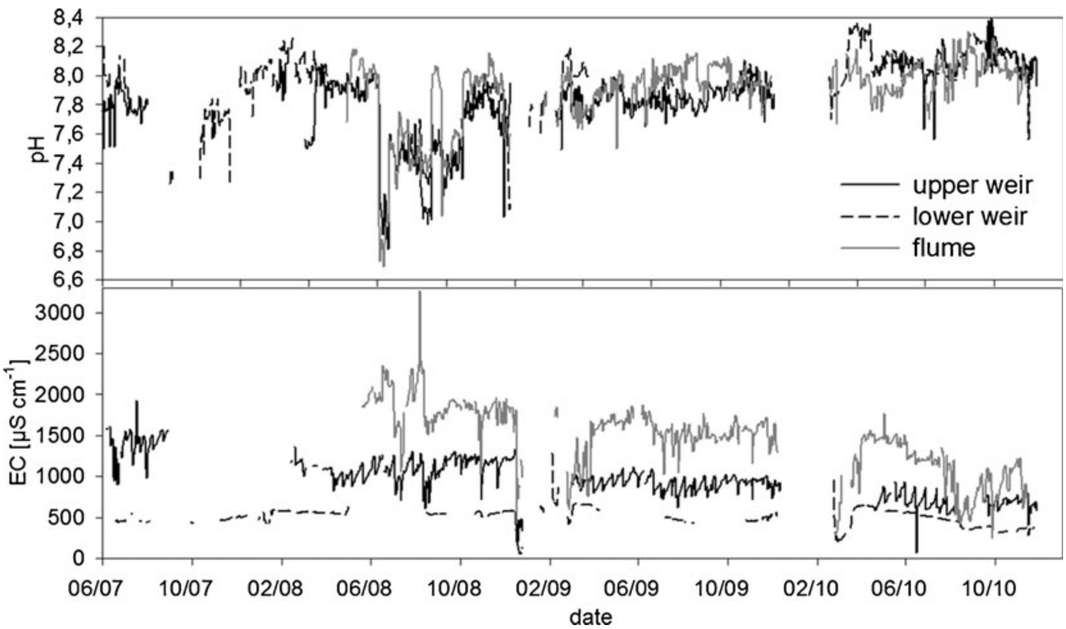


**Fig. 18** Daily values of pH and EC in water samples from the two weirs and the flume

**Table 5** Element budgets of the catchment (values in kilograms per hectare per year) calculated from bulk deposition (IN) and pond discharge (OUT)

| | Ca | Mg | K | Cl | $SO_4$–S | $NH_4$–N | $NO_3$–N | DOC | TIC |
|---|---|---|---|---|---|---|---|---|---|
| 2008[a] | | | | | | | | | |
| IN | 7.2 | 1.2 | 3.9 | 11.4 | 16.1 | 13.5 | 8.7 | 18.2 | 3.5 |
| OUT | 76.5 | 8.2 | 1.1 | 1.9 | 61.3 | 0.3 | b.d. | 5.0 | 12.6 |
| 2009[a] | | | | | | | | | |
| IN | 6.4 | 0.9 | 2.1 | 9.4 | 8.8 | 8.1 | 7.0 | 15.1 | 4.7 |
| OUT | 115.9 | 13.0 | 1.1 | 2.4 | 80.7 | 0.3 | b.d. | 9.2 | 30.4 |
| 2010[a] | | | | | | | | | |
| IN | 7.5 | 0.8 | 2.3 | 5.3 | 10.2 | 10.7 | 6.8 | 14.6 | 7.6 |
| OUT | 290.5 | 33.2 | 4.5 | 9.3 | 107.4 | 0.7 | b.d. | 29.8 | 110.5 |

*b.d.* below detection limit

[a] Hydrologic year, e.g., 2008=1st November 2007–31st October 2008

and texture redistribution, into areas with abrasion or accumulation processes dominating and areas with stable surfaces. External factors like the restoration activities around the catchment influenced the development of the site. For example, besides the initial soil seed bank (Zaplata et al. 2010), the surrounding environment of the catchment clearly affected species invasion, e.g., by anemo- and zoochory. The dissection and stability of surfaces may be an important factor for the establishment of plants and habitats as well as for the formation of vegetation patterns and BSC. After 5 years, several areas of the catchment still remained free of vegetation. Initially established structures like soil crusts obviously influenced vegetation patterns by altering soil hydrological and physical properties and by promoting surface runoff and erosion. Particularly, sedimentation is of importance with respect to plant and animal colonization as the repeated re-establishment of initial site conditions frequently resets colonization processes. In addition, it is assumed that sediments in former erosion gullies offer better site conditions for plants, so that vegetation establishment preferentially started along these linear structures.

The transformation of the initial geosystem into areas with evolving terrestrial or aquatic characteristics and from a very episodic to a more permanent stream

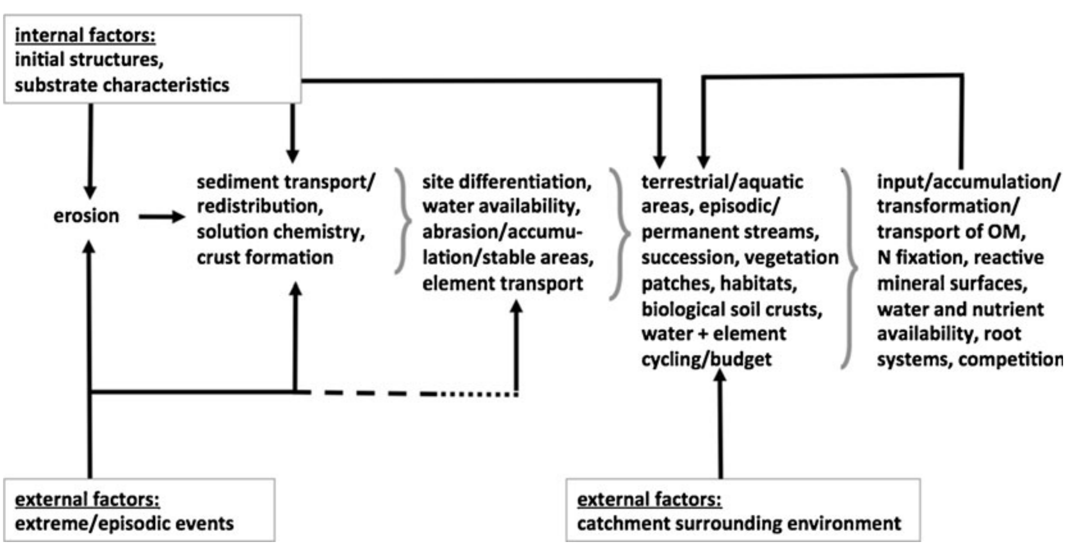


**Fig. 19** Driving factors for the formation of structures and patterns in the "Chicken Creek" catchment

network and discharge, together with the observed vegetation dynamics increased site diversity and heterogeneity with respect to water and nutrient availability and transformation processes compared with the more homogenous conditions at point zero. We expect that these more permanent structures and patterns established after 5 years will greatly influence the future development of the catchment with respect to, e.g., input and accumulation of soil organic matter, nitrogen input and availability by symbiotic microbial N-fixation, development of root systems and soil food webs, weathering and soil formation, element cycling, and the water and element budget at the catchment scale.

Furthermore, we expect that feedback mechanisms between the abiotic and biotic components will intensify with the number of effective structures in the system. For example, the increasing density of plant cover will certainly affect the further groundwater development, as transpiration rates will significantly increase. This should influence the observed trend of increasing groundwater tables into more pronounced seasonal fluctuations, which in turn may have consequences for the composition of the vegetation cover. The focus of further investigation therefore will concentrate on these feedback loops.

## Conclusions

The results from our monitoring data on the initial development of an artificial catchment underline the high dynamics in differentiation of newly exposed land surfaces. The processes and feedback mechanisms in the initial development of a new landscape may deviate in rates, intensity, and dominance from those known from mature ecosystems. It is therefore crucial to understand these early phases of ecosystem development and to disentangle the increasingly complex interactions between the evolving terrestrial and aquatic, biotic, and abiotic compartments of the system. Most time series of the monitoring reflect the strong influence of the initial system structure (internal effects) and the stress events in the very early phase (external effects) on the system development in the first 5 years. The compounding effect of such early initial structures or pulses may be of higher relevance for the understanding and modeling of such systems than all later system attributes. While in later phases external effects may modify system development continuously, steadily, and slowly, early structures and events may lead to chaotic system development and bifurcations, e.g., in the water drainage, soil erosion, or vegetation spread trajectories. Improved understanding, modeling, and predictions of system behavior in such unstable phases require both a detailed monitoring of system development as well as of internal and external drivers.

The synopsis of the monitoring data reveals the crucial role of the initial system structure at point zero and any events like heavy rain, storm, or abrupt snow melting for the pattern and processes in the following geophase of the system. Initial structures and events trigger a long-lasting compounding effect on nearly all monitored time series. Due to their overwhelming effects, future research should strive for an even better recording of initial internal system traits and external drivers. A specifically designed variation of initial structures and external events might clarify their important role in temperate ecosystems.

Compared with tropical and arid systems, the temperate ecosystems we analyzed represent a medium period length from point zero to continuous vegetation coverage. The slower the vegetation development and the more frequent external events as cloudburst, sandstorms, or drought periods, the more relevant and lasting become the system traits in the very early stage of the system. Implications of this understanding of initial ecosystem development could be, e.g., improved forecasting ecosystem behavior, stability, and functioning using models. Experiences with the application of hydrologic models to the Chicken Creek catchment resulted in large variability and discrepancies between model results and measured data (e.g., Bormann 2011; Bormann et al. 2011; Holländer et al. 2009; Hölzel et al. 2011). The effect of surface crusting on infiltration and surface runoff, the buffer effect of the pond zone, and the effect of dumped belowground sediment structures were identified as main problems in modeling this comparably simple system. In addition, the applicability of pedotransfer functions derived from natural soils may be problematic in the early phase of soil development (Badorreck et al. 2010; Buczko et al. 2001; Krümmelbein et al. 2010). Therefore, long-term monitoring of initial ecosystems may provide important data and parameters on processes and the crucial role of spatial and temporal structures and patterns to solve these problems. Artificially created catchments could be a suitable tool to study these initial developments at the landscape scale under known, designed, and defined boundary conditions (Schaaf et al. 2011).

**Acknowledgments** The Transregional Collaborative Research Centre (CRC/TR) 38 "Structures and Processes of the Initial Ecosystem Development Phase in an Artificial Water Catchment" (www.tu-cottbus.de/sfb_trr) funded by the Deutsche Forschungsgemeinschaft (DFG) and by the Brandenburg Ministry of Science and Research was established in July 2007 as an initiative of three universities (BTU Cottbus, TU München, and ETH Zurich). The artificial catchment "Chicken Creek" was constructed with the technical and financial support provided by Vattenfall Europe Mining. We thank Silvio Vogt, Gunter Bormann, Uwe Enke, Patrick Willner, Ralph Dominik, and Marin Dimitrov for their help with the fieldwork, microdrone programming, routine sampling, and maintenance. Many thanks to Gabi Franke, Regina Müller, Helga Köller, Evi Müller, and Anita Maletzki for the analyses of the samples together with Nonka Markova, Natasha Beltran, Ina Hovy, Carmen Schulze, and Tsvetelina Dimitrova. Detlef Biemelt (Hydrology and Water Resources Management, BTU Cottbus) provided the meteorological and hydrological data. Thomas Seiffert carried out the georeferencing of the drone images.

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