# Managing erosion and water quality in agricultural watersheds by small detention ponds

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**Abstract**

Terrace-contouring systems with on-site water detention cannot be installed in areas of complex topography, small parceling and multi-blade moldboard plow use. However, field borders at the downslope end may be raised at the deepest part where runoff overtops to create detention ponds, which can be drained by subsurface tile outlets and act similar to terrace-contouring systems. Four of such detention ponds were monitored over 8 years. Monitored effects included the prevention of linear erosion down slope, the sediment trapping from upslope, the enrichment of major nutrients in the trapped and delivered sediments, the amount of runoff retained temporarily, the amount of runoff reduced by infiltration, the decrease in peak runoff rate and the decrease in peak concentrations of agrochemicals due to the mixing of different volumes of water within the detention ponds. The detention ponds had a volume of 30–260 $m^3$ $ha^{-1}$ and trapped 54–85% of the incoming sediment, which was insignificantly to slightly depleted (5–25%) in organic carbon, phosphorus, nitrogen and clay as compared to the eroding topsoil, while the delivered sediment was strongly enriched (+70–270%) but part of this enrichment already resulted from the enrichment of soil loss. The detention ponds temporarily stored 200–500 $m^3$ of runoff. A failure was never experienced. Due to the siltation of the pond bottom, the short filled time (1–5 days) and the small water covered area, infiltration and evaporation reduced runoff by less than 10% for large events. Peak runoff during heavy rains was lowered by a factor of three. Peak concentrations of agrochemicals (Terbutylazin) were lowered by a factor of two. The detention ponds created by raising the downslope field borders at the pour point efficiently reduced adverse erosion effects downslope the eroding site. They are cheap and can easily be created with on-farm machinery. Their efficiency is improved where they are combined with an on-site erosion control like mulch tillage because sediment and runoff input are reduced. Ponds had to be dredged only after the first year when on-site erosion control was not fully effective.

*Keywords:* Detention ponds; Sedimentation; Flood control; Pesticide; Nutrient enrichment

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## 1. Introduction

Storm water detention and retention ponds or basins (referred to as detention ponds in this paper) are common features in storm water management, to retain storm runoff for a certain time and to reduce peak discharge to a level that is bearable for the drainage system (Verstraeten and Poesen, 1999). Besides the reduction of peak runoff rates, there are several additional purposes, like sediment trapping, prevention of downstream linear erosion, or water quality management, which have been addressed in a variety of detention pond sizes, constructions and storage strategies.

In agricultural areas (dry) detention ponds, which typically hold water only during storms, are used to protect infrastructure and private properties from flooding and damages by muddy floods (Boardman et al., 2003; Verstraeten and Poesen, 1999, 2000). These ponds compensate on-site erosion in the fields, but create high costs for construction, area and maintenance. Especially regular dredging is cost intensive (Boardman et al., 2003). The size of these ponds, for example, in Central Belgium, where they are widely established, reaches volumes of several thousands of $m^3$ (Verstraeten and Poesen, 1999). Besides these flood protection measures, ponds are also constructed to treat agricultural runoff (Rushton and Bahk, 2001). These ponds typically maintain a permanent pool of water between storms to improve water quality by the settling of suspended solids and sediment bound substances.

A similar strategy but with completely different dimensions and layout are terrace-contouring systems with temporary water storage behind the terraces and a controlled, dampened drainage by underground tile outlets (Schwab et al., 1993). This system catches runoff shortly after the source area. Hence, only small volumes of water have to be retained behind each length unit of terrace, which causes little construction costs. A major advantage is that the retention area can still be farmed because water storage will only be shallow and occur during short periods of time, which will not be harmful to the crops as long as sediment input is reduced by additional on-site erosion control measures like mulching. This strategy, however, requires that field layout can be adapted to the landscape morphology. This is only possible in slightly undulated landscapes with large fields. This type of runoff control can hence be widely found in US American and in Australian agriculture, while it cannot be applied in areas where the land is owned by many farmers and with a steep and complex morphology as it is found in Middle Europe and many other areas in the world. In these cases, field borders running perpendicular to the main slope may be reshaped to serve similar purposes as the terrace-contouring systems.

This study investigates the performance of such small dry detention ponds (220–490 $m^3$ in size) established at field borders along the drainage ways of hill slopes. The objectives were to evaluate: (i) the on-site effects on linear erosion in the down slope fields; (ii) the trapping efficiency of sediments and sediment bound pollutants; (iii) the reduction of runoff volumes and peak runoff rates coming from the fields; and (iv) the reduction of peak concentrations of water soluble pollutants by water mixing in the ponds.

## 2. Materials and methods

### 2.1. Test site

The test site was part of the Scheyern Experimental Farm of the Munich Research Association for Agricultural Ecosystems (FAM), which is located about 40 km north of Munich. The area is part of the Tertiary hills, an important agricultural landscape in central Europe. The test site covered approximately 22 ha of arable land at an altitude of 461–486 m a.s.l. (48°30′50″ N, 11°26′30″ E). The mean annual air temperature was 8.4 °C (for 1993–2001). The average precipitation per year was 834 mm (for 1993–2001) with the highest precipitation occurring from May to July (average maximum 106 mm in July) and the lowest occurring in the autumn and winter months (average minimum 29 mm in October).

The test site consisted of four small adjacent watersheds 1.6–7.8 ha in size (Table 1). The management in the fields followed the principles of integrated farming in combination with an intensive soil conservation system (mulch tillage) (Auerswald et al., 2000). Field sizes ranged from 1.9 to 6.5 ha. The crop rotation consisted of potato (*Solanum tuberosum* L.), winter wheat (*Triticum aestivum* L.),

Table 1
Characteristics of the detention ponds and their upslope watersheds

| Watershed no. | Watershed characteristics: Size (ha) | Mean slope (%) | Shape factor $f_h$[a] (−) | Average annual runoff 1994–2001 (1 m$^2$) | Detention pond characteristics: Pond no. | Location (−) | Maximum dam height (m) | Dam top width (m) | Maximum volume (m$^3$) | Maximum water level (m) | Diameter orifice plate (m) | Volume per watershed area (1 m$^{-2}$) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| W01 | 1.60 | 7.40 | 0.31 | 43.4 | P01 | Field | 1.40 | 4.2[c] | 423 | 1.18 | 0.025 | 26.5 |
| W02 | 3.57 | 6.71 | 1.01 | 62.5 | P02 | Field | 1.49 | 1.8 | 486 | 1.25 | 0.040 | 13.6 |
| W05 | 4.05 | 9.27 | 0.84 | 25.4 | P05 | GWW[b] | 1.66 | 4.5[c] | 335 | 1.44 | 0.040 | 8.3 |
| W06 | 7.81 | 9.43 | 0.47 | 6.4 | P06 | GWW | 1.25 | 5.5[c] | 221 | 1.08 | 0.040 | 2.8 |

[a] fh: watershed size/(max watershed length)$^2$.
[b] GWW: grassed waterway.
[c] Embankment top used as farm road.

maize (*Zea mays* L.), and winter wheat. This rotation allowed planting of a cover crop (mustard, *Sinapis alba* L.) before each row crop. Maize was planted directly into the winter-killed mustard. Potatoes were planted in ridges formed before sowing the mustard which provided winter-killed cover.

## 2.2. Detention pond design

The long sides of the fields were mostly oriented perpendicular to the overall slope. Although field size was small, the complex morphology and the restriction to allow for a use of a moldboard plow made it impossible to align the fields exactly along the contour. Runoff hence, still would be concentrated in slope depressions within the fields and pass the field border at the bottom of these slope depressions. At these locations, the field borders were raised by earth embankments to create small detention ponds. Small earth embankments further extending over the lower field border would additionally prevent runoff from entering the downslope fields and direct runoff into these ponds (Figs. 1 and 2). The height of the pond embankments at the pour point ranged between 1.25 m (P06) and 1.66 m (P05) with a dam top width from 1.8 m (P02) to 5.5 m (P06), where the top was used as farm road (Table 1). The detention ponds were drained by underground tile outlets. They consisted of 15.6-cm-diameter standpipes, which were perforated to prevent blocking by plant residues (Hickenbottom

Fig. 1. Picture of pond P02 after a runoff event in March 2002; in the center of the ponded area the perforated riser pipe and the overflow are located; winter wheat was cultivated in the watershed.

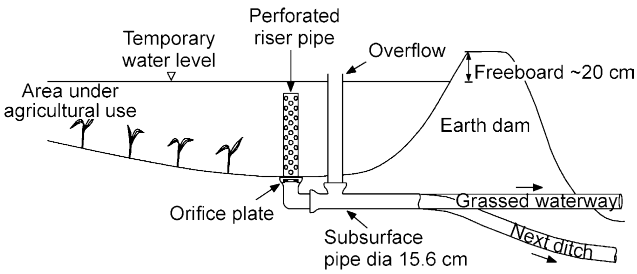


Fig. 2. Schematic diagram of the pond cross-section.

Inc., Fairfield, IA, USA). Depending on watershed characteristics and pond size orifice plates of either 0.025 or 0.040 m (Table 1) dampened the outflow. At the ponds P02 and P05, which were located downslope from the ponds P01 and P06, respectively, emergency outflow pipes with a diameter of 15.6 cm were also installed (Fig. 2). The outflow pipes ended either below the embankment of the ponds in a grassed waterway (P05 and P06) or after 185 and 360 m in the next ditch (P01 and P02).

This pond design should control the runoff during most events without overtopping or using the emergency outflow, and delay runoff and enhance sediment settling time as long as possible without damaging field crops or the waterway grass, which happens approximately after 3–4 days of submergence.

### 2.3. Measuring methods

Linear erosion along the thalweg downslope from the ponds was investigated between 1993 and 2001 by frequent field observations. These observations were compared with the damage created by a large thunderstorm in August 1992 just before pond installation and with results from modeling erosion and deposition of the site assuming that no ponds were established. The soil loss from ephemeral gullies and larger rills during the August thunderstorm was evaluated by determining the length of gullies and rills from aerial photos (scale 1:10,000) and measuring their cross-sections in the field in 25 m steps along the gullies and along transects taken perpendicular to the rills. Eroded volume was converted to eroded mass using measured bulk densities. The used GIS-based model (Mitasova et al., 1996) calculates an erosion and deposition index in a 2-m × 2-m-grid, based on a high-resolution digital elevation model and a detailed K factor (soil erodibility of the Universal Soil Loss Equation, USLE) map of the watershed (Fiener and Auerswald, 2003b).

Outflow volume and rate during runoff events were measured with Coshocton-type wheel runoff samplers, which collected about 0.5% from the total runoff coming from the outflow pipes of the ponds, and lead it to tipping buckets (volume = approximately 85 ml). The number of tips was counted with Delta-T-Loggers (Delta-T Devices Ltd., Cambridge, UK) and runoff samples were taken after defined runoff volumes with an ISCO-Model 3700 portable sampler (Isco, Lincoln, NE, USA). All measuring systems were tested for function at least at the end of each runoff event. A detailed description of the measuring system, including the results of a precision test, can be found in Fiener and Auerswald (2003a). The total sediment delivery of each event was calculated from sediment concentrations determined from subsamples drawn after homogenization and dried at 105 °C. The measuring devices were successively installed after landscape redesign in early 1993.

The sediment trapping in the ponds was evaluated by using a grid of erosion pins laid over the pond bottoms in the beginning of 1993. In the first year severe sedimentation in the ponds was measured because after the landscape-redesign in 1992 the fields and the new structures like the embankments were prone to erosion and produced large sediment amounts. Hence, at the beginning of 1994 all ponds were dredged and the erosion pins were installed again. After dredging no further sedimentation was measured because the soil-conservation system of the farm started to work successfully. Hence, the data of sediment trapping efficiencies of the ponds were calculated averaging the sedimentation in 1993 (15 major events had occurred).

To analyze the trapping of sediment bound substances the average concentration of organic carbon ($C_{org}$), calcium–acetate–lactate extractable phosphorus ($P_{cal}$) and potassium ($K_{cal}$), organic nitrogen ($N_{org}$), and clay (<2 μm) in the pond deposited sediment, the delivered sediment, and the topsoil of the watersheds was determined. A total of 24 sediment samples from the ponds and 50 samples from the largest runoff events in 1993 were taken and compared to data of a soil survey carried out in a 50-m × 50-m-grid in all watersheds in 1992 (Auerswald et al., 2001). To account for the variation between the topsoils of the eroding fields and to allow for an application to other sites, the enrichment ratios of nutrients and clay in pond sediment ($ER_{\mathrm{P}}$) and in the delivered sediment ($ER_{\mathrm{d}}$) compared to the topsoil in the watersheds was calculated, exemplarily shown for $ER_{\mathrm{d}}$ in Eq. (1).

$$ER_{\mathrm{d}} = \frac{\sum_{i=1}^{n} C_i m_i / \sum_{i=1}^{n} m_i}{\sum_{j=1}^{k} C_j / k} \tag{1}$$

$ER_{\mathrm{d}}$ being the average enrichment ratio of nutrients or clay in the delivered sediments, $C_i$ is nutrient or clay content of the $i$th event and $m_i$, is the respective sediment mass while $C_j$ is nutrient or clay content of the $k$ soil samples in the sampling grid.

The peak discharge reduction was determined from the measured outflow rates and the inflow rates calculated according to Eq. (2):

$$Q_{\mathrm{in}}(t) = \frac{\mathrm{d}S}{\mathrm{d}t} P_A(t) + Q_{\mathrm{out}}(t) + I_A(t) + E_A(t) \tag{2}$$

$Q_{\mathrm{in}}$ being the inflow rate ($\mathrm{m}^3\ \mathrm{s}^{-1}$), $S$ is storage volume in the pond ($\mathrm{m}^3$), $P_A$ is precipitation rate on the ponded area ($\mathrm{m}^3\ \mathrm{s}^{-1}$), $Q_{\mathrm{out}}$ is outflow rate ($\mathrm{m}^3\ \mathrm{s}^{-1}$), $I_A$ and $E_A$ are the infiltration and the evaporation rates ($\mathrm{m}^3\ \mathrm{s}^{-1}$) from the ponded area $A$ ($\mathrm{m}^2$), and $t$ is time (s).

$S$ and $A$ for time $t$ were calculated from the storage heights, measured every 10 min between 1994 and 1997 with pressure transducers (UMS GmbH, Munich, Germany) connected to Delta-T-Loggers, and data of a detailed geodetic survey carried out in the ponds after dredging in January 1994 (Fig. 3). $P_A$ for time $t$ was calculated from $A(t)$ and the average of two meteorological stations at the research farm located about 500 m east and west from the ponds. Considering the small contribution of evaporation to the water balance of the pond, $E_A$ was estimated from measurements of the German Meteorological Service (DWD) at the Weihenstephan meteorological station located at a similar situation 25 km southeast of the test site.

The soil moisture at the start of pond filling and the soil silting at the pond bottom is needed to calculate $I_A$. The ponds were filled in two contrasting situations: (i) after long lasting rains in winter with soils close to field capacity; (ii) in case of heavy thunderstorms in summer, when the soils could be initially dry but when pond filling starts after some rain conditions close to field capacity may be assumed as well, even if this may slightly underestimate infiltration in some cases. The macropores, which then will be filled when pond filling starts, were estimated to contribute 70 l $\mathrm{m}^{-2}$ ponded area (Scheinost et al., 1997) to runoff reduction in the ponds. The saturated hydraulic conductivity for the soil at the test site was measured during field surveys (Scheinost et al., 1997), it ranged between $10^{-6}$ and $5.0 \times 10^{-6}\ \mathrm{m\ s^{-1}}$. Due to the distance of 15–20 m between soil surface and ground water we assume that the effect of storage heights (<1.66 m) on saturated hydraulic conductivity could be neglected. Soil sealing may occur by the effect of rain prior to pond filling or by siltation afterwards. Adopting measurements of Schröder and Auerswald

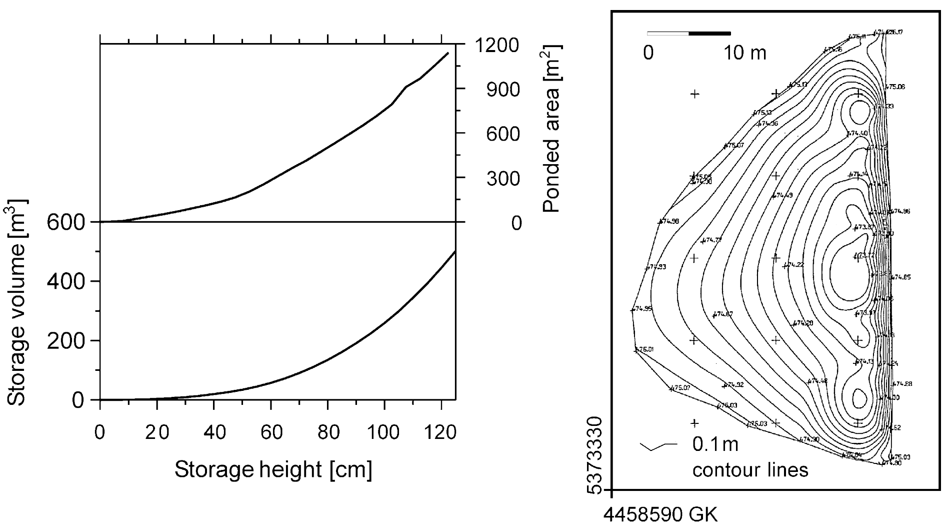


Fig. 3. Storage characteristics and topography of detention pond P02 after dredging at the beginning of 1994.

(2000) at the test site, the saturated hydraulic conductivity was reduced by a factor of about 2.5 to account for sealing, which corresponds to the findings on similar soils by others (e.g., Roth, 1992). Infiltration and evaporation after pond filling then yields the reduction in runoff volume. To separate surface runoff into the components rain and soil water the stable isotope technique was used (Rozanski et al., 2001). This allowed to characterize the individual inflow of a detention pond and facilitates the interpretation of the measured inflow concentrations of soluble agrochemicals. Isotope signatures determined at the GSF Hydrology Laboratory in Neuherberg (Germany) are given relative to standard mean ocean water in commonly used $\delta$ notation:

$$\delta X = \frac{[(R_{\text{sample}}/R_{\text{standard}}) - 1]}{10^3} \tag{3}$$

$X$ being $^2H$ or $^{18}O$ and $R$ being the respective $^2H/H$ or $^{18}O/^{16}O$ ratio.

While deuterium ($^2H$) and oxygen-18 ($^{18}O$) of rainwater followed the local meteoric water line, water taken by suction cups from the soil deeper than 1.0 m showed little temporal variation ($^2H = -62.2 \pm 2.1$ and $^{18}O = -8.7 \pm 0.2$). It was close to the average of all isotopic signatures of rain ($-72.9$ and $-10.0$, respectively) because recharge occurs mainly in winter months, during which rain is slightly more depleted in heavier isotopes and thus compensates for the enrichment of soil water by evapotranspiration left after the growing period. It also corresponded with the isotopic signature of the ground water. In general, rains from heavy runoff inducing storms often deviate considerably from average soil water signature. In this case the contribution of rainwater and exfiltrating soil water or ground water to surface runoff can easily be computed from the average soil water signature and the signatures measured in rain and surface runoff by mass balance calculations (Eq. (4)).

$$\delta_{\text{runoff}} = \delta_{\text{rain}} P_{\text{rain}} + \delta_{\text{soil}}(1 - P_{\text{rain}}) \tag{4}$$

$P_{\text{rain}}$ is being the relative contribution of rainwater to runoff, while $\delta$ is the isotopic signature in runoff, rain, and soil water, respectively.

One of the 10 heaviest rain events, out of 1423 events between 1994 and 2001, fell on June 5th 1995 (43.3 mm) on a runoff-prone maize seedbed in W02 and thus produced the tenth largest among 1097 observed runoff events (reoccurrence time of more than 3 years).

Seven days before the storm, 1.5 l ha$^{-1}$ of Gardoprim 500® was applied, containing 0.47 kg l$^{-1}$ 1 of the herbicide Terbutylazin. The outflow concentration of Terbutylazin was determined according to standard procedures (Schülein, 1998). Assuming a homogeneous Terbutylazin concentration within the pond (total mixing) and neglecting changes by precipitation, evaporation and infiltration, we calculated the pond inflow concentrations from Eq. (5):

$$C_{\text{in}}(t_{n+1}) = \frac{\begin{array}{c}\{[C_{\text{out}}(t_{n+1})(V_{\text{pond}}(t_n) + V_{\text{in}}(t_{n+1} - t_n))] \\ -C_{\text{out}}(t_n)V_{\text{pond}}(t_n)\}\end{array}}{V_{\text{in}}(t_{n+1} - t_n)} \tag{5}$$

$t$ being the time, $C_{\text{in}}$ and $C_{\text{out}}$ being Terbutylazin inflow and outflow concentration, respectively, $V_{\text{pond}}$ pond volume, $V_{\text{in}}$ being inflow volume between the two time steps $t_n$ and $t_{n+1}$;

## 3. Results and discussion

The ponds were created with on-farm machinery with almost no costs. Only the inlet raiser and the transmitting pipes had to be purchased. Damage of the crops occurred only during the first year, when heavy siltation was induced (up to more than 0.5 m), because on-site erosion control was still not fully effective. Even in this year the damage was restricted to an area of less than 100 m$^2$ per pond at the deepest part of the pond. A damage of the crops by flooding was never observed, even not for potatoes. Dredging was necessary only after the first year and could also be done with on-farm machinery at low costs. In total, the costs remained below 100 € ha$^{-1}$ year$^{-1}$ averaged over the entire study period and all ponds. However, the dams had to be inspected regularly to identify problems like weaknesses created by burrowing animals or clogging of the orifice. Moreover, such low maintenance costs are only possible if regularly siltation of the ponds is prevented due to an effective soil-conservation in the watersheds.

No linear erosion along the thalwegs downslope the ponds was observed between 1994 and 2001, although those thalwegs were heavily prone to erosion before establishing the ponds. The principal vulnerability of the thalwegs, where runoff from two opposite slopes converges, was shown by modeling (Mitasova et al., 1996) and also impressively demonstrated by the thunderstorm in August 1992. This event, with a rainfall intensity of up to 160 mm $h^{-1}$ and a total rainfall of 60 mm, created ephemeral gullies along the thalwegs were the ponds were installed later, which were up to several meters wide and 80 cm deep. The prevention of linear erosion results not only from the ponds itself, but from their combination with a drainage via a grassed waterway or pipes to the toe slope.

In 1993 the four tested ponds trapped between 54 and 85% (Fig. 4) and in total between 1.0 and 15.3 t $ha^{-1}$ $year^{-1}$. Event-based measuring was possible for 15 major erosion events during that year. Neither relative (54–85%) and total sediment trapping (1.0–15.3 t $ha^{-1}$ $year^{-1}$), nor sediment trapping and watershed or pond characteristics were related (Table 1, Fig. 4). Given the large variation in watershed conditions and storm characteristics of the individual events we concluded that the long-term trapping efficiency was independent from the total sediment input and the characteristics of the tested ponds and ranges between about 50 and 80%.

After 1993 erosion control by reduced-tillage techniques in the watersheds became more effective, and hence, the input into the detention ponds decreased to less than 1.0 t $ha^{-1}$ $year^{-1}$ with only little coarse sediments being transported. The deposited sediment could then not be measured due to the small deposition depth. Even though, similar sediment trapping efficiencies can be assumed given that small erosion events may result in little retention because only clay is transported, or alternatively complete retention if no runoff leaves the pond.

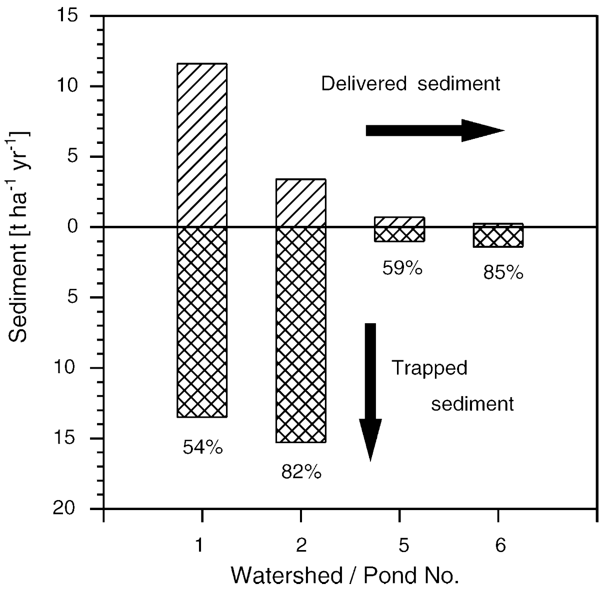


Fig. 4. Sediment trapping of the detention ponds in 1993.

No significant enrichment was found in the pond sediments for the fractions $C_{org}$, $P_{cal}$, $K_{cal}$ and $N_{org}$. Only the clay fraction was depleted with an $ER_P$ of 0.74 (Table 2). In contrast, all measured fractions in the delivered sediment were enriched, most pronounced in case of $K_{cal}$ ($ER_d = 2.7$), $N_{org}$ ($ER_d = 2.4$) and clay ($ER_d = 2.4$). From these measurements two conclusions can be drawn: (i) The sediment in the inflow into the ponds was already enriched compared to the topsoils in the watersheds by a factor of 1.3 as calculated from the total amount of deposited and delivered sediments in 1993 and the enrichment ratios $ER_d$ and $ER_P$; (ii) The ponds increased the enrichment due to a selective sedimentation of the coarse incoming sediments and a preferential loss of the dispersed fines. Residence time within the ponds (roughly 1 d) and water column height (roughly 1/3 of the maximum water level, 0.4 m) allows only for a complete settlement of particles >2.3 μm if Stokes law is applied under the assumption of negligible turbulences. Hence, due to this enrichment of fine particles in the delivered sediments, the sediment trapping of the ponds was more efficient (54–85%) than nutrient trapping (35–70%).

Table 2
Average enrichment as compared to the watershed topsoil for pond deposited sediment ($ER_P$) and delivered sediment ($ER_d$) measured in 1993

| | $ER_P$ | | $ER_d$ | |
|---|---|---|---|---|
| | Avr | S.D. | Avr | S.D. |
| $C_{org}$ | 0.92 | 0.36 a | 1.73 | 0.53 A |
| $P_{cal}$ | 0.96 | 0.33 a | 1.74 | 0.57 A |
| $K_{cal}$ | 1.05 | 0.35 a | 2.66 | 0.99 B |
| $N_{org}$ | 0.91 | 0.34 a | 2.39 | 0.76 C |
| Clay | 0.74 | 0.23 b | 2.35 | 0.71 C |

Significantly different groups within each column are marked with different letters (*n* is 24 for ponded and 50 for delivered sediment). $C_{org}$: organic carbon; $P_{cal}$: calcium–acetate–lactate extractable phosphorus; $N_{org}$: organic nitrogen; $K_{cal}$: calcium–acetate–lactate extractable potassium; Avr: average enrichment; S.D.: standard deviation.

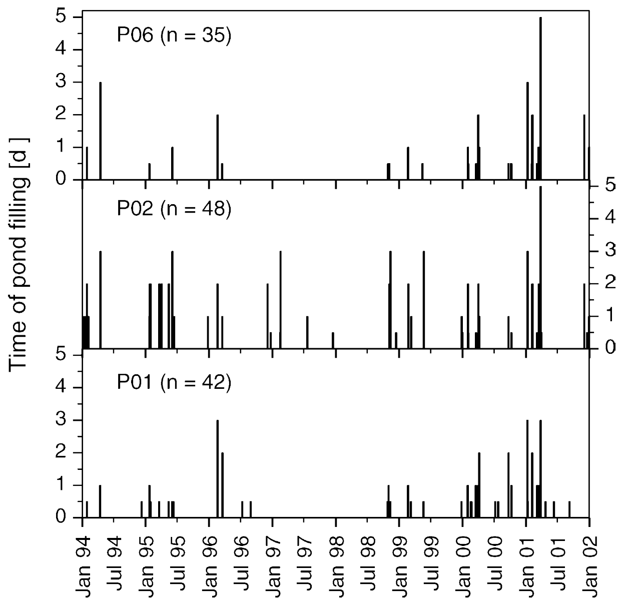


Fig. 5. Pond filling in ponds P01, P02 and P06 between 1994 and 2001. P01 represents the pond with a smaller orifice plate (=2.5 cm) than the others (=4.0 cm); P02 represents the pond with the highest, P06 with the smallest inflow rates.

During the observation period (1994–2001) approximately 36 runoff events occurred per year and each pond was filled for at least 1/2 day on average 5 times a year (Fig. 5). Overtopping of dams or draining via the emergency overflow (Fig. 1) was not observed. Pond filling reached its highest values and lasted longest (maximum 5 days) at the end of winter and the beginning of spring, when rain and snow melt in combination with partly frozen soils resulted in long-lasting inflow at high rates. In later spring and summer pond filling occurred only after heavy thunderstorms and filling time was in almost all cases <1 day, hence, crops and grasses were not damaged by ponded water (Fig. 5). For single (summer) events the relative filling of the four ponds varied greatly, depending mainly on the type of field crop in the individual watershed and their stage of development. This variation is exemplarily shown for the 43.3 mm storm at the beginning of June 1995 (Fig. 6). The relative maximum pond filling (=measured storage height/maximal storage height) ranged from 22% in case of P06 with winter wheat growing in the watershed to 83% in P02, where maize was planted within the watershed. The time of runoff retention varied between 22 h (P06) and 68 h (P02) for this event (Fig. 6).

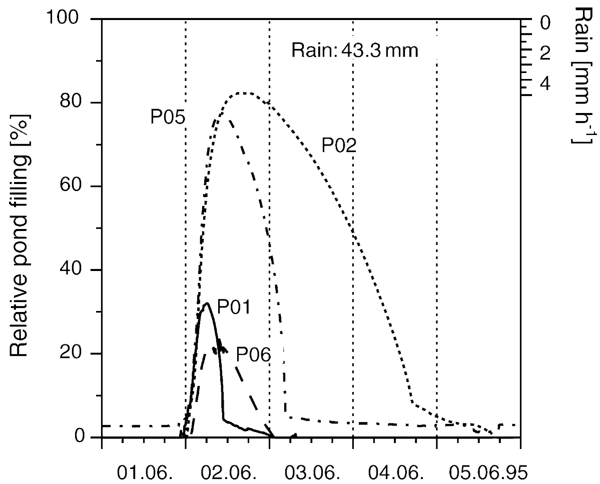


Fig. 6. Relative pond filling (=measured storage height/maximal storage height) of the ponds P01 to P06 for a thunderstrom in early June 1995.

The runoff inflow rate and runoff volume reduction calculated with Eq. (2) is exemplarily given for pond P02 (Fig. 7). Peak runoff rate was reduced from 15.1 to 4.9 l $s^{-1}$, a typical reduction in case of short heavy rains that initiate a rapid pond filling. The dampening effect was smallest during snowmelt runoff events with a broad runoff peak, where dampening may approach zero. This condition could also be observed for this event due to unique characteristics of the specific watershed with an exfiltration of shallow groundwater following shortly after the surface runoff. The contribution of both sources of runoff to total runoff could be clearly distinguished by the isotope

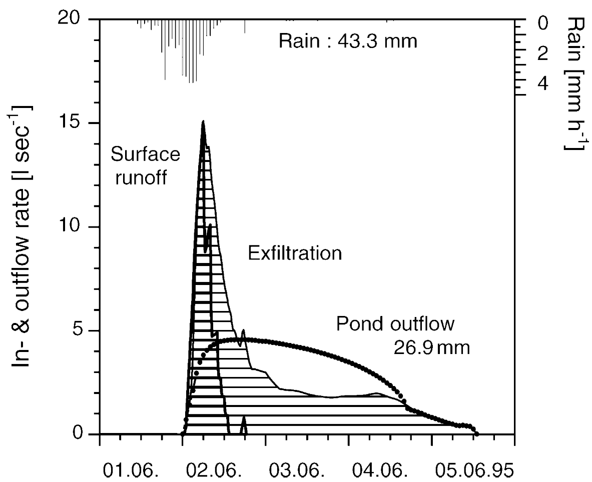


Fig. 7. Rain, inflow and outflow hydrograph of pond P02 for a thunderstorm in early June 1995.

technique (Fig. 7). Exfiltration lasted for more than 3 days with a more or less constant exfiltration rate. Under these circumstances of a steady runoff the effect of the pond on the outflow rate becomes small. This is not true, however, for other substances than runoff, which will be treated below.

The total outflow volume of 894 $m^3$ was reduced by 10% calculated by integrating the infiltration and evaporation rates of Eq. (2) after the end of inflow. This is the maximum runoff reduction, which can be expected for all ponds, because the pond P02 had the longest time of runoff retention (Figs. 5 and 6), caused by the prolonged inflow due to extensive exfiltration in the watershed measured with the isotope technique. In general, it can be concluded that runoff reduction by infiltration and evaporation is small in such ponds because of the small ponded area, the short runoff retention (maximum 5 days) and the rain and sedimentation induced sealing of the pond bottoms.

Due to the small runoff volume reduction by infiltration it can be expected that the amount of dissolved substances will not change too. The decrease in peak concentrations was evaluated for the rain event at the beginning of June 1995, where Terbutylazin was applied in watershed W02 seven days before. The inflow started with a concentration of 25.8 $\mu g\ l^{-1}$ and decreased within 3 h to an absolute minimum of 6.1 $\mu g\ l^{-1}$ (Fig. 8) due to the ongoing depletion of the soil surface, which corresponds with the expectations for a fairly soluble pesticide. The outflow concentration started on the same level as the inflow concentration (negligible ponding at the beginning) and decreased slower to a relative constant level of about 19 $\mu g\ l^{-1}$ due to water mixing in the pond. This demonstrates that a large part of the high-concentration runoff was retained by the pond although the very first runoff passed without mixing. The early unmixed outflow will be small due to the fast rising runoff hydrograph in many cases. After about 3 h of runoff the inflow concentration increased again due to the onset of exfiltration runoff identified by the isotope technique (Fig. 7) and reached its maximum level of 41.6 $\mu g\ l^{-1}$ after about 48 h, while the outflow concentration of the well-filled pond stayed relatively constant (Fig. 8). The Terbutylazin peak concentration thus decreased from 41.6 $\mu g\ l^{-1}$ in the inflow to 19.8 $\mu g\ l^{-1}$ in the outflow. The exfiltration runoff contained even higher concentrations than direct runoff because it contained water from early infiltration stages when the percolating water was still highly charged with the pesticide. Although this behavior is due to the unique constellation of the specific site, it provides prove for our hypothesis of a dampened peak concentration for two different situations. The effect can be clearly seen during early runoff stages (<3 h), when only surface runoff occurs. This effect should show up in most watersheds. It was also shown, however, for the more complicated situation of exfiltrating groundwater (2 and 3 days) and may hence, be expected for a rather wide range of conditions.

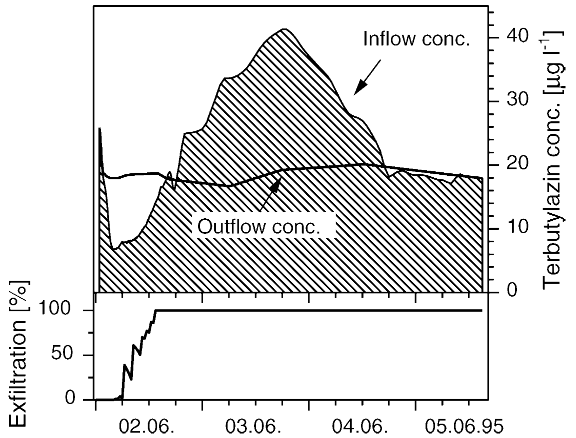


Fig. 8. Pond effects on Terbuthylazin concentrations in the inflow and outflow of pond P02 for a thunderstorm in early June 1995 (upper graph) and proportion of exfiltration to total pond inflow (lower graph).

Even with soil conservation this type of pond is still useful for sediment and nutrient trapping because some periods of the year may still be vulnerable to erosion, e.g. after potato harvest, while ponds remain throughout the year. Furthermore, during the study period no events with a re-occurrence time >5 years were observed. It can be expected that without soil-conserving crop management ponds would decrease in efficacy for larger events, which are the events for which protection is most necessary. The combination of both measures thus allows to extend flooding protection to a wider range of events at low costs for installation and maintenance.

## 4. Conclusions

In this study several purposes of small, earth dammed detention ponds, established at field borders, were discussed according to a 9-year watershed experiment. Prevention of linear erosion in downslope fields, trapping of sediments and sediment bound nutrients, effects on runoff and water-soluble agrochemicals as well as costs were analyzed. The results indicate that: (i) small ponds can prevent linear erosion in downslope fields if outflow is routed to the toe slope via a grassed waterway or a pipe; (ii) they trap 50–80% of the incoming sediments; (iii) if the ponds are combined with effective soil conservation in the fields, total sediment trapping is small, and hence, costs due to crop damages or necessary dredging operations incurre only in case of severe erosion events; (iv) the ponds can remarkably reduce peak runoff rates. At the test site even for one of the largest runoff events occurring during the study period of 32 watershed years and in case of the pond with the most unfavorable runoff to pond volume ratio, peak runoff rate was reduced to one third; (v) according to the sealing of the pond bottom, the short ponding time and the small ponded area no significant reduction of runoff volume can be expected; and (vi) the ponds can also significantly reduce peak concentrations of agrochemicals, exemplarily shown for the Terbutylazin concentration, which approximately dropped to the half.

In general the efficiency of the ponds can be improved by appropriate upslope and downslope measures. An effective erosion control upslope will reduce the loading of the ponds with runoff and sediments and decrease maintenance costs. The combination with a flat-bottomed grassed waterway downslope will make best use of the high infiltration capacity, which can be established on a grassed waterway (Fiener and Auerswald, 2005) fed with runoff over a prolonged time.

This type of pond can easily be installed in many complex landscapes and has almost missing restrictions on arable use, if combined with an effective soil-conservation system in the fields. Therefore, due to its multiple services it should deserve more attention in conservation planning.

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