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Article

Modeling the Impact of Ditch Water Level Management on Stream–Aquifer Interactions

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Abstract: Decreasing groundwater levels in many parts of Germany and decreasing low flows in Central Europe have created a need for adaptation measures to stabilize the water balance and to increase low flows. The objective of our study was to estimate the impact of ditch water level management on stream-aquifer interactions in small lowland catchments of the mid-latitudes. The water balance of a ditch-irrigated area and fluxes between the subsurface and the adjacent stream were modeled for three runoff recession periods using the Hydrus-2D software package. The results showed that the subsurface flow to the stream was closely related to the difference between the water level in the ditch system and the stream. Evapotranspiration during the growing season additionally reduced base flow. It was crucial to stop irrigation during a recession period to decrease water withdrawal from the stream and enhance the base flow by draining the irrigated area. Mean fluxes to the stream were between 0.04 and 0.64 ls^{-1} for the first 20 days of the low-flow periods. This only slightly increased the flow in the stream, whose mean was 57 ls^{-1} during the period with the lowest flows. Larger areas would be necessary to effectively increase flows in mesoscale catchments.

Keywords: groundwater surface water interaction; adaption measure; required minimum runoff; ditch irrigation; Hydrus-2D

1. Introduction

The effective use of water and adaption to water scarcity has always been a major challenge of societies [1]. In the 21st century, adaptation to water scarcity as a consequence of climate change will be a major task in many regions of the world [2]. In the mid-latitudes, moderate changes to greater water scarcity are projected as a consequence of more droughts. The focus is placed on adapting water management to sustain minimum runoff [3]. In these regions the mean annual stream runoff will still be sufficient, but there will be increasing periods of seasonal water scarcity as a consequence of the projected precipitation and evapotranspiration patterns [4,5]. On the other hand, sustaining minimum runoff is important to safeguard the ecological functions of the stream systems and sustainable water use. Therefore, seasonal water storage will play a crucial role in mitigating water scarcity in these regions [6]. This requires the consideration of seasonal water yield and demand rather than annual mean values. The majority of processes generating runoff from precipitation are nonlinear. For some catchments changes can be abrupt after a threshold is reached, e.g., due to the decoupling of groundwater from stream water [7]. Adaptation strategies need to take into account changes in the annual runoff cycle, as well as differences between catchments [8].

Recently, adaptation strategies have mainly been developed in arid and semi-arid regions. Nevertheless, in the future similar measures and strategies may be useful in the mid-latitudes. Thomas *et al.* (2011) [9] reviewed measures to sustain minimum runoff in small catchments of the mid-latitudes. Several small measures with relatively small effects can be combined in a catchment to fulfill water management goals. Thomas *et al.* (2011) [9] claim that measures have to be adapted to the conditions in the mid-latitudes and have to be tested under those conditions. In the beginning, existing measures will be implemented which can be optimized by storing water during the wet season and releasing it during dryer periods. Costs are lower and stakeholder acceptance is higher during implementation compared to the introduction of new measures. In wetlands and the vicinity of streams, ditches have been constructed at many places in lowland catchments in order to improve soil water conditions for the agricultural use of these areas [10–12]. It seems worthwhile investigating whether ditch water management can be optimized in order to increase runoff in a stream during low flow in the mid-latitudes. Recharging shallow groundwater close to a stream allows water retention similar to a reservoir which is filled before, and released during, low flow [9]. Such a measure should not be confused with groundwater recharge at recharge areas, which allow at least annual water retention from the winter to the summer months [13].

For evaluation, a suitable model is needed in order to quantify the fluxes which have not been measured, e.g., see [14]. Traditionally, hydrological modeling has focused either on surface water or groundwater processes and only simple theories have been used to describe the interactions. A description of relevant processes and an increased understanding of the interactions between groundwater and surface water remain necessary [15,16], especially for managing water resources in a lowland basin [17]. During recent years, the number of applications of coupled models and corresponding studies has increased [18], particularly with respect to hydrological and biogeochemical processes [15,19]. Modeling vadose zone flow processes on the scale of about a hectare (field scale) with a spatial discretization comparable to soil hydrological modeling is still rare [20], and the same applies to understanding flow dynamics [21] and quantifying water fluxes [15].

In hydrology, modeling approaches are frequently used to extrapolate between point measurements and to estimate unmeasured variables such as actual evapotranspiration and groundwater fluxes, e.g., see [22]. Models are especially valuable if information is limited because required data are not delivered by existing monitoring. Two- and three-dimensional modeling, particularly, have been applied to such problems [17,23–25]. Today a large number of models solving these problems are available. We refer to [26] who reviewed the different modeling approaches.

In Central Europe, mutual ditch irrigation and drainage systems have both been introduced to improve and increase the agricultural uses of wetland areas [27]. Irrigation is possible if the ditch water levels can be adjusted higher than the groundwater level in the wetland area. The wetland area can also be drained by lowering the ditch water levels below the groundwater level, as long as there is sufficient drainage capability. At the moment many ditch systems are used, such that water levels are as high as possible and agricultural use is still feasible, increasing carbon storage and ecological functions. Thus, these kinds of wetlands are mainly water consumers because they have high water levels and increased evapotranspiration losses during drier periods [22,28]. In Northeast Germany, wetlands are often located in the vicinity of streams in groundwater discharge areas and their water balance is often regulated by a ditch irrigation system. Consequently, changes in the water level of the ditches will only affect the ground water level reached by these systems.

The objective is to assess the impact of ditch water level management on stream-aquifer interactions with a modeling study mapping alterations to the management of already existing ditch structures in small lowland catchments of the mid-latitudes. We present the monitoring results of such a system and analyses of different water management scenarios using a hydrological model.

2. Methods

2.1. Study Site

The study site in the federal state of Brandenburg is situated in the Baruther Urstromtal, a postglacial valley in the lowlands of northeast Germany close to the city of Cottbus. It is located in a small lowland watershed (average altitude 65 m.a.s.l.) and represents an agriculturally used riparian area of approximately 13 ha at the western side of the Koselmühlenfließ stream (51.735829 N/ 14.193276 E). The discharge of the Koselmühlenfließ stream (Figure 1) is partly controlled by drainage water from the open-pit lignite mining (Lower Lusatia) located in the headwater catchment.

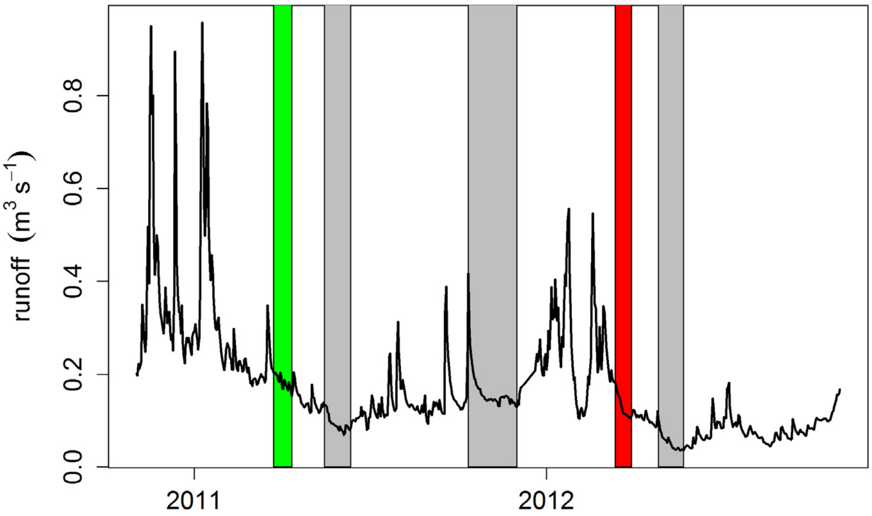


Figure 1. Runoff of the Koselmühlenfließ above the weir at the discharge gauge Q16 and selected time periods for calibration (red, 15 March–2 April 2012), validation (green, 24 March–12 April 2011), and scenario analyses (gray, 16 May–12 June 2011, 12 October–1 December 2011, and 26 April–22 May 2012).

The agricultural area of about 18 ha has an average width of 130 m and a total length of 1400 m. It is located downstream of a weir and is, therefore, continuously drained by the Koselmühlenfließ stream. In order to irrigate the agricultural area, stream water is withdrawn by a ditch upstream of the weir which is combined with a fish pass (Figure 2). The water abstraction takes place more or less continuously depending on the stream water level. After water abstraction, the water is distributed using two ditches; one approximately 10 m away from the stream (Ditch 1) and another approximately 100 m away from Ditch 1 at the agricultural area (Ditch 2). Excess water is discharged downstream. Inflow to Ditch 1 can be controlled by a weir at discharge gauge Q17, and inflow to Ditch 2 is through an underground pipe which cannot be regulated and was below the water table for the whole study period. The part of the study site which is influenced by the irrigation of both ditches extends only to a length of 982 m because Ditch 1 drains to the stream there. The agricultural area is used as pasture. Irrigation is important to increase grass production during summer months (June to August). The farmer managed the pasture irrigation via the weir at Q17 depending on actual soil water conditions. This management was changed to investigate the effects of the ditch water level management on stream-aquifer interactions. In the study periods the weir at Q17 was adjusted to a fixed height to allow flows to be measured. The adjusted height allowed water to flow into Ditch 1 for most of the time, so only Ditch 1 did not receive water for some of the periods of low flow in the stream. Groundwater observation wells were installed along a transect orthogonal to the streambed (Figure 2) to assess the interaction between the groundwater and surface water.

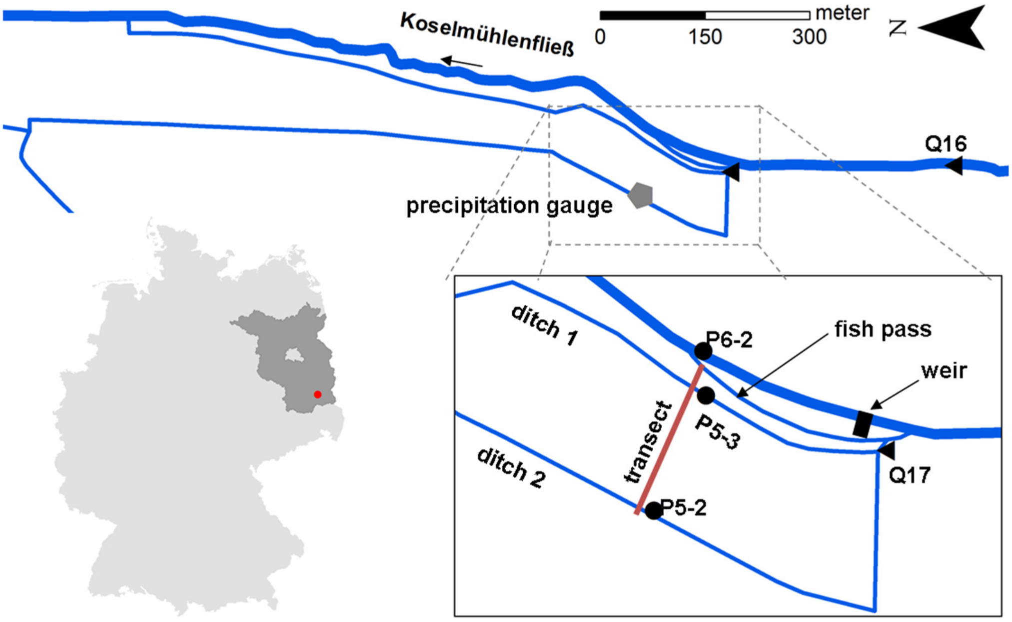


Figure 2. The study site and its location in the federal state of Brandenburg (red dot). Groundwater wells (circles), discharge gauges (triangles), rain gauge (gray pentagon), and the stream and ditch system at the Koselmühlenfließ stream. At the weir the stream is dammed and water is let into the two irrigation ditches. The modeled transect is located between the groundwater well at P5-2 by Ditch 2 and the stream.

The predominant soil type at the study site was gley. It was characterized by sandy layers with primarily medium grain sizes. The sands locally contained clay, fine and coarse sand, and fine gravel. The soil horizons were classified as Ah (mineral soil with humus accumulation), Go (oxidized groundwater horizon), Gr (reduced groundwater horizon), and C (mineral layer less affected by pedogenetic processes) according to the German manual of soil mapping [29]. The FAO soil classification would merge the Go and Gr horizons and classify the horizons as Ah, Bl, and C. The corresponding soil unit is Gleysoil. The soil characterization was carried out based on a soil profile in the center between the two ditches as well as drilling cores from the groundwater wells and two additional boreholes of 3.5 m depth between the ditches and the profile. The 2D profile used for modeling (Figure 3) is based on the interpolation of these data. The vertical extent of the profile is defined by an underlying silt layer with low permeability.

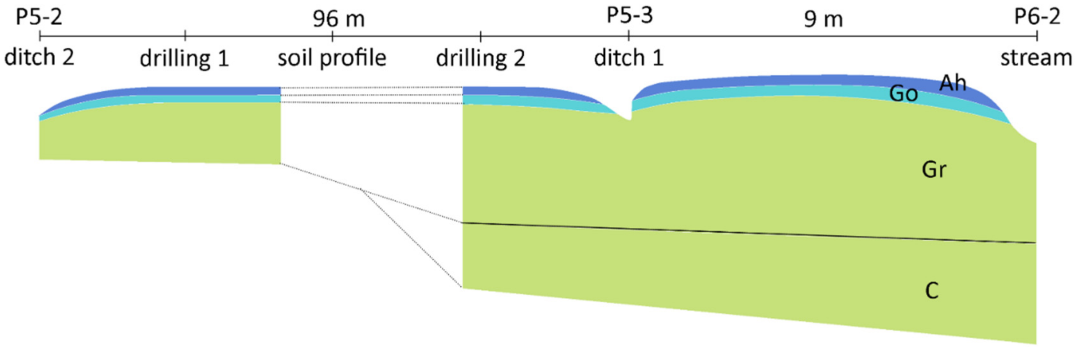


Figure 3. Geometry of the model domain and implemented soil layers. The soil body was divided into three different horizons (Ah, Go, and Gr/C).

2.2. Data

Precipitation was measured along with the groundwater levels at five observation wells and surface water levels at three stream gauging stations. The groundwater observation wells and weirs were equipped with MWAG (Ackermann KG, Berlin, Germany) and MDS Dipper-3 (SEBA Hydrometrie GmbH, Kaufbeuren, Germany) data loggers with 1 mm depth resolution. Hourly water level values were available since 8 July 2010 and were aggregated to daily values. Precipitation measured by a Hellmann RG50 precipitation gauge (Thies Clima, Göttingen, Germany) was corrected for evaporation and wind errors according to [30]. The potential evapotranspiration was calculated using the Penman equation modified by [31]. Further meteorological data, provided by the German Meteorological Service [32], were available from the meteorological station in Cottbus, which is 9.34 km away. The altitude along the transect of groundwater gauges was determined by leveling using the digital tachymeter DiNi 11T (Carl Zeiss, Jena, Germany).

Disturbed soil samples from the horizons Ah (eight samples), Go and Gr (five samples each) and C (two samples) were taken from the soil profile and the two boreholes. The soil textures of the disturbed samples are shown in Table 1. The gravel and sand contents were determined by sieving with mesh sizes of 2000 µm (gravel) and 63 µm (sand). The remaining silt and clay fractions were determined by sedimentation analysis. Additionally, undisturbed soil samples from the horizons Ah (two samples in 8 cm depth), Go (three samples in 15 cm depth), and Gr (two samples in 39 cm depth) were taken from the soil profile using 250 ml sampling rings. The bulk densities (eBD) were determined by drying and weighing the undisturbed samples (Table 1). The soil water retention curve $\theta(h)$ describing the relation between the soil moisture θ and matric head h, and the hydraulic conductivity curve $K(h)$ of the undisturbed samples from the upper three horizons, were analyzed using the simplified evaporation method [33] and the *HYPROP* device [34]. In this way the soil hydraulic parameters of residual and saturated water content θ_r and θ_s, the inverse of the matric head at the air entry point α, the hydraulic conductivity of the saturated soil K_s, and the shape parameter n of the van Genuchten/Mualem model [35,36] were determined:

$$\theta(h) = \theta_r + \frac{(\theta_s - \theta_r)}{\left[1 + |\alpha \cdot h|^n\right]^m} \text{ with } m = 1 - 1/n \tag{1}$$

and

$$K(S_e) = K_S S_e^\tau \left[1 - \left(1 - S_e^{1/m}\right)^m\right]^2 \text{ with } S_e(h) = \frac{\theta(h) - \theta_r}{\theta_s - \theta_r} \tag{2}$$

with the effective saturation S_e and another shape parameter m. The tortuosity parameter τ was set to 0.5 [36] in order to reduce the number of unknown parameters. Resulting parameter sets for each horizon are shown in Table 2.

Table 1. Bulk density (*eBD*) and fractions of gravel, sand, silt, and clay for each horizon. Standard deviations are given in parentheses. Textural classes correspond to the German classification system [29].

Horizon	*eBD*	*Gravel*	*Sand*	*Silt*	*Clay*	*Textural class*
	($g \cdot cm^{-3}$)	*(%)*	*(%)*	*(%)*	*(%)*	
Ah	1.18	1.8 (1.8)	95.1 (1.8)	2.9 (1.0)	<0.1	Pure sand
Go	1.77	1.6 (0.8)	95.6 (0.8)	2.2(1.6)	<0.1	Pure sand
Gr	1.91	6.2 (3.3)	93.6 (3.3)	0.3 (0.2)	<0.1	Pure sand
C	-	2.1	84.9	13.0	<0.1	Slightly silty sand

Table 2. Initial parameter set of the soil hydraulic properties determined using the evaporation method (horizons Ah, Go, and Gr/C). The mean and 2.5% to 97.5% confidence intervals are given.

Horizon	*Confidence Intervals*	θ_r *(-)*	θ_s *(-)*	α *(cm^{-1})*	*n (-)*	K_s *(cm·day^{-1})*	*l (-)*
Ah	2.5%	0.120	0.540	0.0135	1.26	12.11	**0.5**
	mean	**0.198**	**0.546**	**0.0167**	**1.38**	**21.82**	
	97.5%	0.275	0.551	0.0206	1.58	39.32	
Go	2.5%	−0.032	0.329	0.0203	1.29	5.11	**0.5**
	mean	**0.024**	**0.333**	**0.0239**	**1.40**	**8.27**	
	97.5%	0.080	0.337	0.0281	1.54	13.39	
Gr	2.5%	−0.006	0.274	0.0245	1.99	4.88	**0.5**
	mean	**0.000**	**0.278**	**0.0257**	**2.05**	**6.28**	
	97.5%	0.006	0.282	0.0274	2.12	8.10	

2.3. Modeling Framework

2.3.1. Model Set-Up

We used the Hydrus-2D package of [37] because it is suitable to (i) simulate water transport in variably saturated media; (ii) incorporates several time-dependent boundary conditions including evapotranspiration patterns; and (iii) handles spatial domains on the field scale. It is a standard tool to model water and solute transport in the unsaturated and saturated zone. Šimůnek *et al.* (2008) [38] presented examples of various Hydrus-2D applications. Moreover, the Hydrus-2D model provides an optimal tradeoff between computational costs and the accuracy of model simulations. It has already been used before to model groundwater problems at the scale of several hundred meters [20].

A two-dimensional profile section located between the groundwater observation wells P5-2 (at Ditch 2) and the stream was defined as the model domain (Figure 3). It was implemented as a 105 m-wide and up to 6.2 m-deep vertical plain with an area of 316 m^2. The increase in the depth of the model domain towards the stream is due to the occurrence of an impermeable layer used as the lower boundary. A finite element mesh was generated with the Hydrus tool Meshgen-2D. At the top of the model domain, fine spatial discretization was used to increase numerical stability in the unsaturated horizons. In line with [39], the spatial extent of the finite elements was increased from the top (approx. 4 cm) to the bottom (approx. 60 cm) in order to decrease computation time. The generated finite element mesh consists of 21,879 nodes and 46,285 elements in total. The results were evaluated at intervals of one day, but modeling time steps were specified automatically by the model algorithm.

Three layers were defined in the model to take soil stratigraphy into consideration. The soil hydraulic characteristics of each horizon were described by Equations (1) and (2). The upper two horizons (Ah and Go) were implemented according to the depths found in the soil profile (Figure 3). In these horizons vertical fluxes mainly occur through the unsaturated soil. Thus, the van Genuchten/Mualem parameters measured in the vertically-taken undisturbed samples (Table 2) were used to define the soil hydraulic characteristics of these two layers. The lower two horizons (Gr and C) were mainly saturated and the main direction of water fluxes was horizontal. We merged these two horizons in the model and calibrated the soil hydraulic parameters with measured groundwater level data (see Section 2.3.2). The reasons for this are that (i) measured soil hydraulic parameters were only available for the Gr horizon; (ii) they were based on vertical fluxes; and (iii) the K_s that is most important for saturated flow exhibits large uncertainties when it is determined with the evaporation method [40]. We assumed horizontal homogeneity according to similar stratigraphy found all along the transect. In the case of the merged horizons (Gr/C) we reduced the potential error caused by this assumption by calibrating effective parameters [41].

Measured daily time-series of precipitation and potential evapotranspiration were implemented as atmospheric boundary conditions at the surface of the model domain. We used the root water uptake model developed by [42] to consider the reduction of actual transpiration due to water stress. It is based on empirical relations that describe actual root water uptake as a function of the calculated pressure head. The potential evapotranspiration (ET_p) was separated into potential soil evaporation (E_s) and potential transpiration (E_t) according to Beer's law:

$$E_t = ET_p \cdot SCF \tag{3}$$

$$E_s = ET_p \cdot (1 - SCF) \tag{4}$$

The soil cover fraction $SCF = 1 - e^{-a_i \cdot LAI}$ was calculated from the leaf area index $LAI = 0.24h_{grass}$ and the extinction constant $a_\mathrm{i} = 0.463$ [43]. The whole study site was covered by pasture. Its grass height (h_grass) was uniformly set at 15 cm. Hence, 80% of the potential evapotranspiration was potential transpiration and 20% potential evaporation.

We used the Feddes parameters for grass that were suggested by [44] and [45]. The maximum rooting depth was set at 40 cm and the depth of maximum intensity at 15 cm based on field observations at the soil profile. The actual evaporation rate was lower than the potential only if evaporation capacity was exceeded. Therefore, pressure heads at the soil surface had to be below a threshold of −15,000 cm. Observed groundwater levels were always close to the surface and this threshold has never been reached in the current observation period. Thus, the potential evaporation rate was equal to the actual rate.

The bottom of Ditch 1 and the lateral boundaries, including the bottom of the stream and the bottom of Ditch 2, were specified as variable head boundary conditions. We assigned the measured time series of groundwater heads from P5-2 (Ditch 2), P5-3 (Ditch 1) and P6-2 (stream) to these boundaries. The bottom of the model domain was defined as no-flux boundary. Through drilling, we found an impermeable layer which is also designated in the hydrogeological map of Brandenburg [46].

2.3.2. Model Calibration and Validation

Effective soil hydraulic parameters of the merged lower soil horizons Gr/C were determined by model calibration using the Levenberg–Marquardt parameter estimation algorithm implemented in Hydrus-2D [37]. We only optimized the two parameters K_s and α in order to reduce the number of estimated parameters. We chose these two parameters because (i) K_s controls the lateral water flux over a large distance in the saturated part of horizon Gr/C; and (ii) α defines the extent of the capillary fringe controlling water retention in a substrate close to saturation. Parameter values measured in the undisturbed soil samples from the Gr horizon (Table 2) were used as initial values. Values from the same measurement were assigned to the remaining parameters θ_r, θ_s, and n. Groundwater level data observed at P5-3 from 15 March to 2 April 2012 were used as inverse solution data. The water levels at the other wells could not be used for calibration because they were needed to define the boundary conditions. During calibration, Ditch 1 was defined as a no-flux boundary. In that time period the inflow to the ditches was stopped in the field to initiate a recession event. The initial conditions of the matric heads were generated by simulating the previous 20 days as a model spin-up. After an initial, successful calibration procedure, the model spin-up and calibration were repeated with updated initial parameters in order to reduce the error caused by imprecise α and K_s values that had to be assumed in the first spin-up run. It was not necessary to constrain the parameter space by setting predefined boundaries as the estimated values of α and K_s were plausible, considering the sandy textures found in the field (Table 1).

In order to validate the model we used measurements of the groundwater heads at P5-3 between 24 March and 12 April 2011. During this time there was no inflow of water to Ditch 1. The initial conditions were simulated using measurements from the previous 20 days. During validation, the water level at P5-3 was not used as a boundary condition, so it could serve as independent validation data.

2.4. Scenarios

Scenarios were used to analyze the groundwater-surface water interaction for different means of managing water levels in the irrigation system. Three different periods were chosen: (1) 16 May to 12 June 2011; (2) 12 October to 1 December 2011; and (3) 26 April to 22 May 2012, showing a clear recession in the runoff (Figure 1). The precipitation, potential evapotranspiration, and water levels of the analyzed periods are described in Table 3. The effective parameters resulting from the calibration were used to calculate scenarios.

Table 3. Meteorological conditions and water levels of the Koselmühlenfließ stream (WLS) for the calibration period, validation period, and the three recession events used for scenario analyses.

Value	*Calibration*	*Validation*	*Scenario Analyses*		
	15 March–2 April 2012	*3 March–2 April 2011*	*16 May–12 June 2011*	*12 October–1 December 2011*	*26 April–22 May 2012*
P (mm)	5	10	18	11	14
pET (mm)	39	42	117	39	95
initial WLS (m a.s.l.)	64.25	64.37	64.28	64.62	64.11
min WLS (m a.s.l.)	64.02	64.22	64.05	64.25	63.79

The aim of the scenario analysis was to quantify the fluxes between the stream and groundwater depending on the different antecedent water levels in the irrigation ditches before a streamflow recession event. Initial conditions were calculated in model spin-up runs using the meteorological conditions of 20 days before the scenario periods. The water levels in the irrigation ditches were defined as constant head corresponding to each scenario. The calculations guaranteed consistent pressure heads in the whole model domain at the end of the spin-ups. Ditch water levels were set to 10, 20, 30, 40 and 50 cm above the bed of the first ditch at P5-3 and those at P5-2 were adapted, respectively (66.4 to 66.8 m a.s.l.). Regarding each scenario, we made the assumption that no water was flowing in the ditches. This was implemented by introducing an exponential recession in pressure heads at the western boundary (P5-2) and defining a no-flux boundary condition at the other ditch (P5-3). During the time period from 15 March to 2 April 2012, the irrigation was stopped and water drained to the Koselmühlenfließ according to the site properties. This experiment was aimed at determining the recession coefficients for the boundary conditions. For the western boundary (P5-2) the recession constant was -0.011 m$\cdot$ day^{-1} (n = 19, r^2 = 0.82).

The five different scenarios were modeled for each time period. The simulated fluxes between the model domain and the stream for the different scenarios were compared to a baseline simulation used as a reference. The measured data on the ditch, stream and groundwater heads were used as boundary conditions for the baseline simulation.

3. Results

3.1. Model Calibration and Validation

The model performance was improved due to the calibration procedure. Obtained effective values of K_s and α of the lower combined horizon (Gr/C) were increased to 30.6 cm$\cdot$ day^{-1} and 0.199 cm^{-1}. These optimized values are more realistic for sandy substrates than the initial values obtained using the evaporation method (Table 2). Groundwater levels simulated at P5-3 with the optimized parameter sets were in good agreement with the measured data for the calibration period (Figure 4). The root-mean-square error (*RMSE*) was 0.003 m and the maximum deviation was 0.03 m. Nash–Sutcliffe efficiency accounted for 0.91 and the Pearson correlation coefficient r^2 was 0.94 (n = 19).

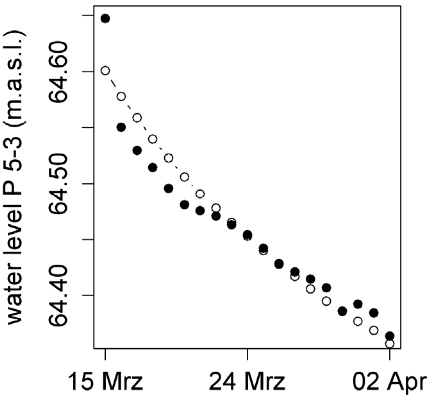
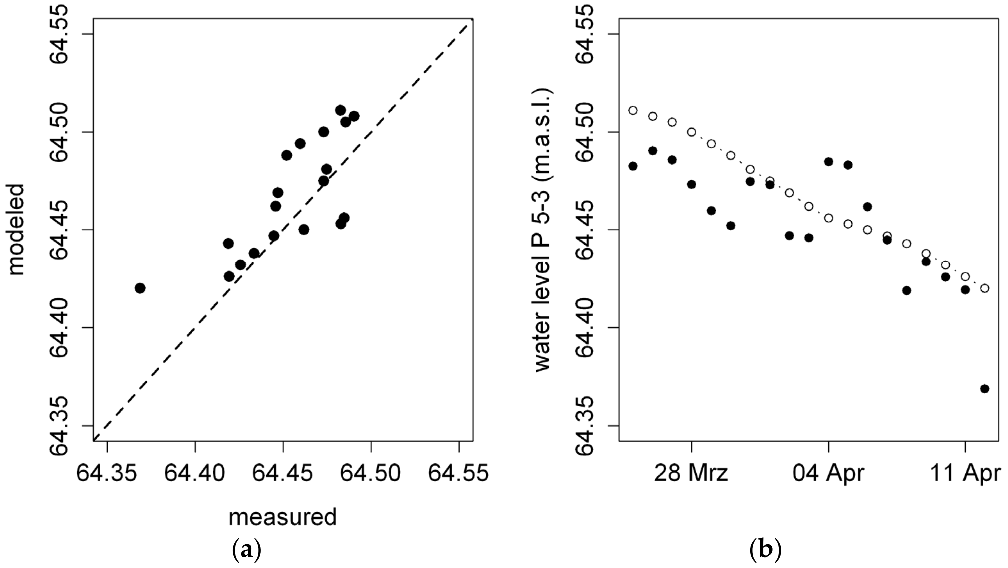


Figure 4. Comparison of observed (filled dots) and calculated (hollow dots) groundwater levels at the groundwater gauge P5-3 for the calibration period (15 March–2 April 2012).

During the validation period, correlation between measured and modeled water levels at P5-3 was $r^2 = 0.58$ and the *RMSE* was 0.012 m. The model was able to simulate the overall recession in water level during the validation period but short time fluctuations could not be reproduced (Figure 5).



(**a**) (**b**)

Figure 5. (**a**) scatterplot and (**b**) comparison of modeled water levels (hollow dots) and measured water levels (filled dots) at P5-2 during the validation period (24 March–2 April 2011). The 1:1 ratio is given by the dashed line.

3.2. Scenario Results

Figure 6 shows the temporal evolution of the groundwater head for the scenario of a 50 cm water level in ditches for one period (16 May–12 June 2011). At Day 0 the water table was controlled by the ditch water levels at the borders of the cross section. Higher water levels in the middle of the cross-section were due to precipitation. The modeled pressure head illustrates ongoing fluxes from the model domain to the stream for the first 20 days after ditch irrigation was stopped. The irrigated area supplied water to the stream for the entire period and water was supplied steadily from the western boundary condition (*i.e.*, the adjacent area). Deviations were due to precipitation.

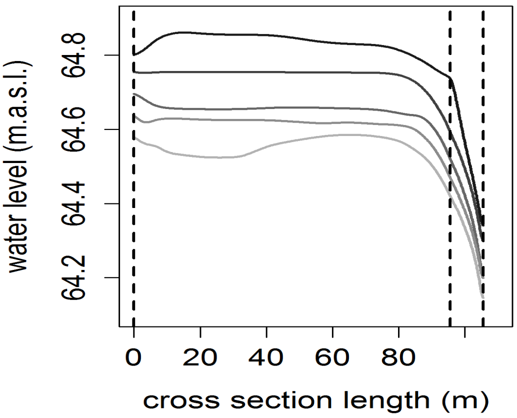


Figure 6. Evolution of groundwater levels for the model domain based on the scenario 50 cm water level in the ditches for the period of 26 April–22 May 2012 (lateral boundaries: right stream and left Ditch 2 at P5-2). The lines correspond to 0, 5, 10, 15, and 20 days of simulation time (from black to light gray). The ditches and stream are given as dashed lines.

The more water that was stored, the longer the system could support fluxes to the stream. Fluxes to the stream increased as ditch water levels controlling the water storage increased before the low-flow period (Figure 7). Additionally, the water level in the stream determined the potential volume of water which could flow towards the stream after irrigation was stopped. During the period with the lowest water levels in the stream, fluxes to the stream were higher.

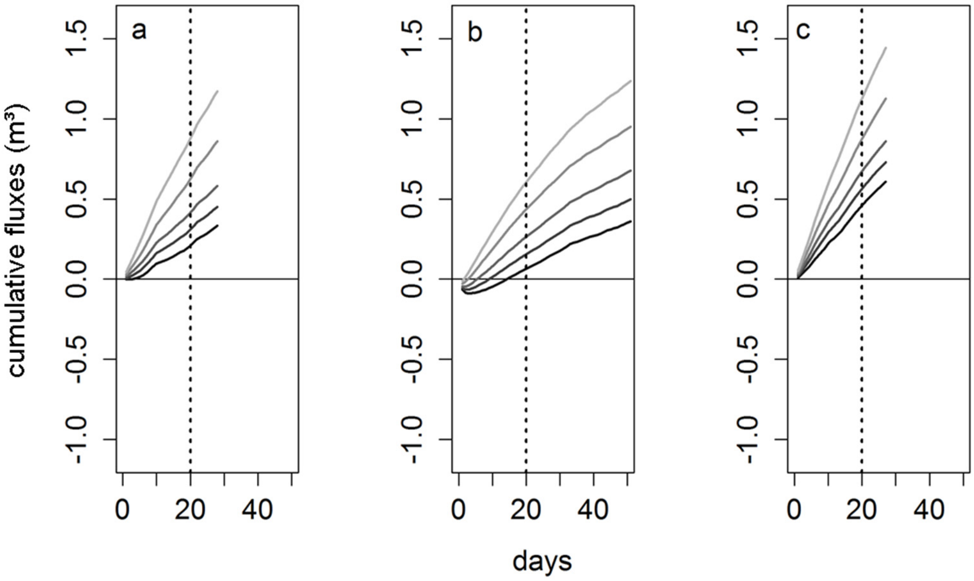


Figure 7. Calculated cumulative fluxes into the stream for the five different scenarios (10 to 50 cm ditch water level, from black to light gray, respectively). Time periods: (**a**) 16 May–12 June 2011; (**b**) 12 October–1 December 2011; and (**c**) 26 April–22 May 2012. Cumulative fluxes are normalized to a width of the 2D-transect of 1 m.

To compare the calculated results we decided to take the first 20 days of the different time periods into account. The results of the baseline and scenario analyses are given in Table 4.

Table 4. Calculated mean fluxes at the model boundaries for the first 20 days of the periods (**a**) 16 May–12 June 2011; (**b**) 12 October–1 December 2011; and (**c**) 2 April–22 May 2012. Positive fluxes lead out of the model domain and *vice versa*. Precipitation (*P*), actual evapotranspiration (*ETa*), western lateral boundary (*Ditch 2*), eastern lateral boundary (*stream*), and fluxes at *Ditch 1*, as well as storage alteration (ΔS, differences in inflow and outflow of the model domain) and mean relative numerical error in the modeled water mass balance, are measured as quality criteria of the numerical solution (*MWatBalR*, [37]).

Scenario	*P*	*ETa*	*Stream*	*Ditch 2*	*Ditch 1*	ΔS	*MWatBalR*
	$(mm \cdot day^{-1})$	$(mm \cdot day^{-1})$	$(mm \cdot day^{-1})$	$(mm \cdot day^{-1})$	$(mm \cdot day^{-1})$	$(mm \cdot day^{-1})$	(%)
(a) 16 May–12 June 2011			Initial Stream Water Level:		64.28 m a.s.l.		
10 cm	0.31	4.12	0.10	−3.29	0.00	−0.62	0.07
20 cm	0.31	4.13	0.15	−3.49	0.00	−0.47	0.06
30 cm	0.31	3.87	0.20	−2.50	0.00	−1.25	0.02
40 cm	0.31	3.11	0.30	−1.99	0.00	−1.12	0.07
50 cm	0.31	2.28	0.42	−1.02	0.00	−1.36	0.47
baseline	0.31	3.69	0.16	−0.09	−0.98	−2.48	0.18
(b) 12 October–1 December 2011			Initial Stream Water Level:		64.63 m a.s.l.		
10 cm	0.42	0.86	0.03	1.13	0.00	−1.60	0.06
20 cm	0.42	0.81	0.07	0.85	0.00	−1.31	0.05
30 cm	0.42	0.73	0.13	0.44	0.00	−0.87	0.03
40 cm	0.42	0.59	0.21	0.33	0.00	−0.71	0.13
50 cm	0.42	0.46	0.29	0.04	0.00	−0.36	0.10
baseline	0.42	0.45	0.33	0.07	−0.30	−0.13	0.25
(c) 26 April–22 May 2012			Initial Stream Water Level:		64.11 m a.s.l.		
10 cm	0.86	3.28	0.22	−2.42	0.00	−0.22	0.06
20 cm	0.86	3.29	0.27	−2.53	0.00	−0.17	0.04
30 cm	0.86	2.98	0.32	−1.81	0.00	−0.63	0.03
40 cm	0.86	2.37	0.41	−1.53	0.00	−0.40	0.12
50 cm	0.86	1.65	0.53	−0.63	0.00	−0.69	0.28
baseline	0.86	3.24	0.38	−0.11	−0.59	−2.07	0.14

All scenarios resulted in positive fluxes from the riparian irrigation system to the river. The highest flow rates to the stream were found for the events when the effective storage was high (*i.e.*, the difference between water levels in the ditches and stream). In spring and summer, higher evapotranspiration, presumably, lowered fluxes and the change in water storage. Evapotranspiration losses were compensated by inflow from the ditches in the baseline. All in all, the irrigation system had a positive influence on fluxes to the stream during low-flow conditions and fluxes increased along with increasing ditch water levels in the scenarios. The mean relative numerical error was below 1% in each case, indicating a sufficient numerical performance.

Irrigation was stopped during the run time of the scenarios preventing withdrawal of stream water during the low flow periods. We calculated the cumulative fluxes over 10 and 20 days as a function of the mean difference between the ditch water level (before drought period) and water level in the stream (Figure 8). Cumulative fluxes in the direction of the stream increased along with increasing ditch water levels and time. Scattering was due to different evapotranspiration and precipitation during the events, but was of minor importance. The general influence of evapotranspiration can be seen by the offset between the values of the period in the fall and those two in the spring.

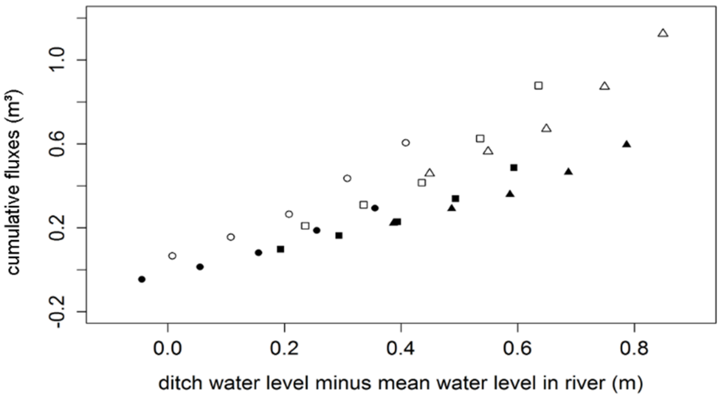


Figure 8. Mean ground water fluxes to the stream depending on the height difference of constant water levels in the ditches before the recession event; mean water levels in the stream for the evaluated recession periods from 16 May–12 June 2011 (squares), 12 October–1 December 2011 (dots), and 26 April–22 May 2012 (triangles). The first 10 days (black filled symbols) and 20 days (hollow symbols) of these time periods were evaluated. Cumulative fluxes are normalized to a width of the 2D-transect of 1 m.

3.3. Water Balance of Low Flow Periods

The simulated fluxes in the direction of the stream were extrapolated to the total length of the irrigation system (982 m, Table 5). The results of the two-dimensional profile section were multiplied with the length of the irrigation ditches; thus, changes in relief were neglected.

Table 5. Mean discharge of the Koselmühlenfließ stream (*Q-Stream*) and mean fluxes from the irrigation system (*IF-Stream*) at a length of 982 m for the first 20 days of the three analyzed periods. Water loss by infiltration to the two ditches is considered for the baseline.

Scenario	*16 May–12 June 2011*		*12 October–1 December 2011*		*26 April–22 May 2012*	
	IF-Stream (ls^{-1})	*Q-Stream* (ls^{-1})	*IF-Stream* (ls^{-1})	*Q-Stream* (ls^{-1})	*IF-Stream* (ls^{-1})	*Q-Stream* (ls^{-1})
10 cm	0.12	97.12	0.04	195.99	0.26	57.64
20 cm	0.18	97.12	0.09	195.99	0.32	57.64
30 cm	0.24	97.12	0.15	195.99	0.38	57.64
40 cm	0.36	97.12	0.25	195.99	0.50	57.64
50 cm	0.50	97.12	0.34	195.99	0.64	57.64
baseline	0.19	95.84	0.39	195.71	0.46	56.81

The mean increase in river flow was between 0.04 ls^{-1} and 0.64 ls^{-1} depending on the period and scenario. However, when there was more water in the storage system, this led to an increased inflow of water into the stream. The comparison between the inflow of water to the stream and its discharge into the stream highlights the fact that much larger areas would be necessary to distinctly increase any low flow at this river section. Compared to the baseline, the streamflow was much higher in the scenario runs because no water was let into the ditch system. The fluxes from the two ditches to the groundwater were higher than the subsurface fluxes to the stream for those periods in spring (see also flows at the ditches in Table 4). Measurements at the inlet to the ditches showed that the proportion of water which was led to the ditch system could be more than 20% of the streamflow. However, the water flow from the ditch system back to the stream was not measured. The baseline scenarios estimate how much water infiltrates in the ditches (Table 4). During the three recession events, infiltration from the ditches was between -1.17 ls^{-1} and -0.36 ls^{-1} (P5-3), and -0.13 ls^{-1} and 0.08 ls^{-1} (P5-2) for the whole irrigated area.

4. Discussion

The selected model proved suitable to analyze the interaction between ditches, the Koselmühlenfließ stream, and the adjacent meadow. We chose this model because groundwater tables were shallow and interaction between the groundwater, ditches, stream, and atmosphere had to be taken into account. Hydrus-2D provided algorithms to implement all of these features and allowed unsaturated flows above the groundwater table to be calculated, as well as saturated flows in aquifers [37]. The soil hydrological parameters had to be calibrated to fit the measured recession in groundwater heads in an experiment where no water was directed to the ditches. The recession in the groundwater level during the calibration period was faster than the one in the model using the measured parameter set. Consequently, the hydraulic conductivity of the groundwater layer was increased.

Some restrictions and uncertainties must be mentioned: (i) regarding annual precipitation in Brandenburg since 1900, the years 2010, 2011, and 2012 ranked 4th, 20th, and 56th [32], showing that conditions were relatively wet. Correspondingly, no extreme low flows were observed. The scenario analyses showed that flows to the stream are higher when the stream water level decreases. Thus, we expect higher flows from the system to the stream during extreme low-flow events; (ii) the vegetation was assumed to be static without change over time and adaptation to the higher groundwater levels in the scenarios. The parameterized vegetation is considered to be typical of pasture [44,45]. Actual transpiration decreased with increasing groundwater levels in the model, despite the fact that more water was available to plants. The productivity of the pasture plants used to define the parameters decreases when groundwater levels are high. Regarding the scenarios with high water levels, in particular, we expect that the species composition would not be sustained over time and hydrophilic species would grow. The groundwater gradient had the largest impact on fluxes between the stream and the subsurface, and evapotranspiration lowered fluxes during the months of the growing season; (iii) at the western boundary, a water level recession constant was introduced during the scenario analysis. It was assumed that no water was let into the ditches for the scenarios and, thus, the measured ditch water levels were incorrect as boundary conditions. The recession constant was derived from the drainage event also used for calibration. The drainage experiment was not repeated; thus, no uncertainties of the recession constant can be given; (iv) comparison of uncalibrated model runs with measured groundwater tables during the calibration period showed that the effective conductivity of the groundwater layer is higher than the measured conductivity at the lowest soil horizon. This shows the necessity to calibrate the respective parameters of the horizon which are mainly responsible for groundwater flows; (v) the focus of this study was on the interaction of a meadow with ditch irrigation and the adjacent stream during the stream flow recession. Parameter and model uncertainties were not analyzed. The analysis of equifinality and different model structures was beyond the scope of this study; (vi) the simulated fluxes from the irrigation system to the stream were multiplied with the length of the irrigation ditches in order to extrapolate the 2D results to a realistic management scale. This might provide only an approximation for the investigated system, since the specific relief along the ditches was neglected. However, the flux estimation allows us to evaluate the general applicability of such ditch systems for water retention.

The ditch-irrigated area slightly increased the flow in the adjacent stream during periods of runoff recession. Fluxes to the stream increased along with the height difference between the water level in the ditch system prior to the stream flow recession and the mean stream water level during the recession period. Fluxes were highest during the first few days, but sustained for more than 25 days during the scenarios. Regarding the lower water levels in the ditches, it is possible to reverse the flows (from the stream to the pasture) at the beginning of the period in the fall because gradients are generally low and can be temporarily reversed. Despite the fact that evaporation lowered fluxes to the stream, storage depletion due to evapotranspiration is estimated to become more important for periods of low flows lasting longer than the 20 days analyzed in this article. Still, the influence of evapotranspiration decreased fluxes to the stream for the two events in spring (Figure 8). Stopping irrigation during streamflow recession was important to lower water abstraction from the stream which is partly lost by evapotranspiration and to guarantee that fluxes to the stream result from storage change (Table 4). At Ditch 1 (P5-3) infiltration was −0.98, −0.30, and −0.59 mm day^{-1} and fluxes to the stream were 0.16, 0.33, and 0.38 mm· day^{-1}, for the three investigated periods, respectively. Measurable low flow mitigation for the investigated stream would require a much larger area because flows to the stream of this approximately 13 ha system delivered less than 1 ls^{-1} for the studied recession periods. For the first 20 days mean fluxes to the stream were between 0.04 ls^{-1} and 0.64 ls^{-1} per 982 m length of the ditches, depending on the period and scenario.

More extreme low flows are expected considering trends in other streams of central Europe [47]. Additionally, runoff will decrease at the investigated stream because dewatering of the adjacent lignite mine will be stopped in the future. Measures to increase the base flow and stabilize the water balance during low flows must be developed. An existing ditch irrigation system was tested using different scenarios of adjusted groundwater levels before a low flow event. However, [28] showed that natural wetlands often decrease downstream discharge. Riverine fens with ditch systems generally have to be considered as water consumers, but the temporal dynamics of the water balance and fluxes also depend on the water management [9,12,22]. Although the evapotranspiration of such systems is high, lowering the water table during low flows results in a decrease in storage and some increase in fluxes to the stream or ditches. Our results from monitoring and modeling showed that managing the ditch water levels before a low-flow period and stopping water inflow to the ditches during low flows increased fluxes to the stream. Regional modeling of groundwater recharge with the ABIMO model [48] estimated a mean runoff of 114 mm per year (3.6 $\text{ls}^{-1}\cdot \text{km}^{-2}$) for Brandenburg between 1976 and 2005. Considering 13 ha of ditch-irrigated area and a flow to the stream of 0.5 ls^{-1} (comparable to some of the scenario calculations), the contribution of the area would be 3.9 $\text{ls}^{-1}\text{km}^{-2}$. It must be taken into consideration that, depending on the situation, the real contributing area may be larger than the area between the ditches because water is allowed to enter the western boundary of the model domain.

The general results can be transferred to the whole region despite the uniqueness of every place. Within the lowland of the Elbe catchment, [11] identified 35 wetlands with respective areas between 1200 and 40,000 ha and mutual water regulation systems. It is conceivable that certain areas totaling 3840 km^2 are suitable for the intended application, or even more since small catchments (<1000 ha) were not included. The practical applicability has to be examined in each individual case.

High and fluctuating groundwater levels can conflict with land use or environmental protection. Compromises are necessary for areas which could potentially be managed in the way suggested here. Future studies need to estimate the potential of such measures on the catchment scale and integrate compromises with current land use and environmental protection.

5. Conclusions

Water fluxes between a ditch-irrigated pasture and the adjacent Koselmühlenfließ stream in Northeast Brandenburg were examined for different scenarios of ditch water level management during the recession of water levels in the stream. The benefit of adapting the water management of ditch-irrigated areas in order to sustain minimum runoff in streams was examined. On the one hand, the current management results in higher water consumption by the ditches than fluxes from the pasture to the stream during periods of low flow (up to tenfold depending on the period). On the contrary, it demonstrates that the water management of the ditch system has a positive effect on flows during low flows, but managed areas have to be increased in order to obtain a significant increase in low flows for the investigated stream. However, a similar irrigation system would be sufficient to sustain flows at a smaller stream in a headwater catchment. Thus, it appears that such decentralized systems could help stabilize a catchment's water balance and increase low flow, but it must be taken into account that a measure of this kind has relatively low efficiency compared to surface water reservoirs with higher storage capacity for the same area and more precise regulation possibilities. The magnitude of flows shows that numerous such or similar measures are needed to obtain observable effects for mesoscale catchments. Corresponding measures will only be effective as long as the main flow direction is towards the stream. An increase in the base flow can only be achieved if the ditches are regulated, water levels are as high as possible before low flow, the gradient to the stream water level is high, and no water is let into the ditches during low flow.

Finally, all of these results point at potential conflicts with other land uses. Having reached a certain height, increased groundwater levels will conflict with agricultural use. Strong fluctuations in the groundwater table could be problematic for the environmental protection of species adapted to moist conditions or forestry. As a next step, it will be important to examine the constraints caused by land use and environmental protection to finally decide the feasibility of similar measures to stabilize the water balance and increase low flows in small catchments in Brandenburg.

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Author Contributions: Steffen Gliege carried out the field investigations including soil sampling and laboratory analyses, the model setup, the model calculation, the result evaluation and presentation, and wrote relevant sections. Björn Thomas developed the model approach, supported the field sampling, evaluated and interpreted the results and wrote relevant sections. Jörg Steidl developed the design of this study, evaluated the database and interpreted the model results. Tobias Hohenbrink evaluated the soil analyses, the water movement model approach, its parametrization and results and wrote relevant sections. Ottfried Dietrich evaluated the evapotranspiration model approach, supported its parametrization and evaluated and interpreted its results.

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