

# Potential impacts of groundwater conservation measures on catchment-wide vegetation patterns in a future climate

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## Abstract

**Context** In temperate Europe, warming, summer droughts, and increased winter precipitation are predicted to have profound effects on vegetation performance and composition. Especially groundwater dependent vegetation will be affected. These impacts within the landscape may negatively affect the connectivity within ecological networks.

**Objectives** With an integrated surface- and groundwater model and a climate robust traits-based vegetation model, we simulated the implementation of water conservation measures in a stream valley catchment in the Netherlands.

**Methods** We assessed the impacts of conservation measures on groundwater levels, seepage flux, and vegetation composition for the current climate and two

climate scenarios, with a global temperature increase of 2 °C and an increase (+6 %) or decrease (−2 %) in annual precipitation.

**Results** Our model showed that water conservation measures on average increased groundwater levels, although there were large spatial differences. At the same time, water conservation decreased the seepage flux in the stream valley, thereby decreasing the supply of nutrient-poor groundwater. These negative impacts on seepage flux will be amplified in a future climate. Semi-terrestrial vegetation along the streams will benefit from water conservation measures and increasingly so in a future climate. Other vegetation types showed a wide array of responses depending on spatially-differentiated changes in groundwater level and seepage fluxes.

**Conclusion** Our results highlight the importance of integrating spatially-explicit hydrology-vegetation interactions into models that evaluate climate adaptation measures. Customized water conservation

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measures can contribute to minimize negative effects of climate change on groundwater dependent vegetation and ensure the robustness of ecological networks.

**Keywords** The Netherlands · Stream valley · Riparian vegetation · Drought · Climate change · Ecological network

## Introduction

Climate projections and observations indicate that the Earth's climate faces significant changes. The most prominent impact is a predicted change in the global mean temperature, but there is also overwhelming evidence that the hydrological cycle is changing and will continue to change (IPCC 2013). Large scale observations show an increase in mean annual precipitation in the tropics and high latitudes and a decrease in the subtropics (Alexander et al. 2006). Seasonal patterns of precipitation are also likely to change and it is projected that prolonged dry periods will alternate with more intense rainfall events, even in regions where mean precipitation decreases (Alexander et al. 2006; Rajczak et al. 2013). Decreases in summer precipitation are projected to co-occur with increased precipitation events in fall, winter and spring (Rajczak et al. 2013; van Haren et al. 2013; Vautard et al. 2014). These changes will most likely lead to an increase in surface saturation and associated surface runoff, which, together with increased rates of groundwater seepage in streams, increases flood risks in spring and to a lesser extent in autumn (Arnell and Gosling 2013; Rajczak et al. 2013). At the same time, summer droughts (especially in combination with higher summer temperatures) are likely to occur more often (Bakker and Bessembinder 2007; Briffa et al. 2009; Zolina et al. 2013). Besides precipitation, potential evaporation is also subject to change and will, on average, increase due to expected higher temperatures. Increased evaporation combined with less precipitation in summer can lead to lower groundwater tables which may in turn amplify the impact of summer droughts in groundwater fed ecosystems (IPCC 2013).

Water conservation measures are advocated to combat the negative impacts that these changes in the hydrological cycle might have on river flow regimes

(Döll and Zhang 2010) as well as on agricultural yields and nature conservation (Witte et al. 2012; Van Bodegom et al. 2014). Water conservation measures include overhead-irrigation prohibitions during dry periods, increasing the use of groundwater and aquifer recharge by aquifer storage recovery (Lowry and Anderson 2006), damming of gullies, the creation of hydrological buffer zones, retention basins against floods, and increased flexibility of drainage systems, which includes drainage systems that can be turned on or off, within agricultural fields. Each of these measures aims at storing water in times of excess (often during winter and spring) and using the stored water to reduce the negative effects of drought during the dry summer months.

The availability of water, and of soil moisture in particular, is one of the most important drivers of plant species composition and species richness worldwide (Weltzin et al. 2003; Wright et al. 2005; Ordoñez et al. 2010; Bartholomeus et al. 2011; Douma et al. 2012a). Average water availability and the temporal and spatial fluctuations therein are important factors shaping plant species composition (Leyer 2005; Katz et al. 2012). Also water quality is an important driver of plant species composition and species richness (Wassen et al. 1990; Tahvanainen 2004; Lucassen et al. 2006; Marini et al. 2008; Kuglerová et al. 2014). For example, species richness is especially high in seepage areas (McNamara et al. 1992), which can be ascribed to the local buffered trophic status and acidity of the groundwater, that is different from that at infiltration sites.

Water conservation measures will influence water quantity and seepage fluxes, and may therefore contribute to the preservation of target ecosystems by maintaining habitat quality. Maintenance of habitat quality is a critical condition for a sustained quality of the ecological network (Gonzalez et al. 2011). In temperate Europe, most nature areas are scattered throughout the landscape. To ensure the integrity of ecological networks, a high quality of habitats and robustness thereof may even gain importance in a future climate, since the likelihood of extreme weather events is expected to increase, which is likely to cause more damage to habitats that are already degraded than to climate robust habitats. Despite ubiquitous impacts of potential changes in habitat quality for ecological networks, the number of comprehensive analyses on whether water conservation measures will

aid combating the negative impacts of climate change is still very limited (Witte et al. 2012).

Here, we provide such a comprehensive analysis for a stream valley catchment in the Netherlands. Like in various other regions of temperate Europe, the most valuable nature reserves in the Netherlands, in terms of biodiversity and number of rare plant species, are located in areas with groundwater-dependent vegetation. Within the European habitat directive, groundwater-dependent habitats are recognized as habitats with a potential high nature conservation value. These groundwater-dependent vegetation types are highly sensitive to changes in the hydrological cycle, e.g. as caused by climate change and water management (Bartholomeus et al. 2011).

With a spatially explicit hydrological model we can analyse the effects of climate change and adaptation measures on groundwater levels and seepage fluxes in a stream valley catchment. The effects of these hydrological changes on vegetation patterns in the catchment can subsequently be analysed with a vegetation model. Thus, to analyse the complete cause-and-effect-chain an integrated hydrology-vegetation modelling approach is needed. However, this has hardly been done so far in a climate versatile manner. Furthermore, since vegetation changes can occur on a small scale, one requires a detailed hydrological model with a high resolution. Therefore, we used a novel approach by coupling a detailed spatially explicit hydrological model to a probabilistic vegetation model (Witte et al. 2014). This allows for detailed modelling of climate change effects on the groundwater level and its fluctuations, and on seepage fluxes, which are translated, through the vegetation model, into probabilities of vegetation type occurrence. Especially the effects of water conservation measures, through hydrology, on vegetation can thus be analysed in more detail, providing added value to our approach. With our integrated hydrology-vegetation modelling approach we aim to answer the following research questions:

1. What are the effects of projected climate change in 2050 (a 2 °C temperature increase and changes in seasonal distribution of precipitation by on average +6 % or –2 %) on groundwater quantity and seepage flux, and how does that influence projected vegetation patterns?

2. To what extent can water conservation measures reduce or compensate for the potential negative effects of climate change on vegetation patterns?

## Methods

### General approach

For our integrated hydrology-vegetation modelling approach we used a spatially explicit hydrology (IBRAHYM; Vermeulen et al. 2007) and vegetation model (PROBE; Douma et al. 2012b; Witte et al. 2014). IBRAHYM is commonly applied by the water managers of our case study region for planning purposes. This hydrology model produced several maps which serve as input for the vegetation model, including: (i) mean groundwater table, (ii) mean highest and lowest groundwater table (respectively the average of the three highest and lowest water tables elevations per year, averaged over a period of eight years), (iii) mean average spring groundwater table (defined as average of the water table elevations at March 14, 28 and April 14, averaged over a period of eight years), and (iv) seepage flux into the saturated zone. We did not distinguish between local and regional seepage. Other inputs for the vegetation model included maps of soil type and land use in order to calculate the probability of occurrence of the various vegetation types in nature areas.

We analysed two climate scenarios (W and W+; see section on Climate change scenarios below) and one water conservation scenario and compared those to a reference scenario, i.e. the current conditions. By implementing two climate scenarios we could model the impact of seasonal precipitation changes. The water conservation scenario implied using water management measures to ensure sufficient water supply for both agriculture and nature, while preventing flooding of urban areas. This was achieved by increasing the retention time of water in the stream by constructing additional weirs, widening water courses, raising the water level in the water course and/or shallow the water course (see also Appendix 1), which raises the groundwater table around the stream. The climate and water conservation scenarios were combined to create six scenarios: (i) a reference scenario, (ii) climate W scenario, (iii) climate W+ scenario, (iv)

water conservation in the reference climate, (v) water conservation in the W climate, and (vi) water conservation in the W+ climate.

## Model specifications

### *Hydrology model*

IBRAHYM combines a fully coupled model for the saturated and unsaturated zone. For the saturated zone MODFLOW (McDonald and Harbaugh 1988, 1996) was used and for the unsaturated zone and surface water SIMGRO (van Walsum and Groenendijk 2008). The hydrological model has a temporal resolution of days and a spatial resolution of 25 m. Soil physical properties were based on 23 different soil types derived from the Dutch soil map 1:50,000 and surface level elevation was based on the 5 m resolution general elevation database of the Netherlands (AHN) (van der Sande et al. 2010). The hydrogeological schematisation was based on the 100 m resolution geo-hydrological model of The Netherlands REGIS (TNO-NITG 1998). Groundwater recharge for the reference situation was calculated based on measured precipitation and reference crop evapotranspiration, land use, and irrigation (Gehrels 1999). The model calculated the actual groundwater level on a daily basis for the coupled saturated and unsaturated zone. Position of water courses and drainage levels were based on the Dutch topographic map (Top10 vector, scale 1:10,000) and partly on additional data originating from the regional water managers. The accuracy of the groundwater levels of our model results is in the range of 15 centimetres. However, the uncertainty in groundwater level differences between the scenarios will be considerably lower, since most uncertainties were caused by uncertainties in input data (notably surface elevation), which were constant between different scenarios.

### *Vegetation model*

The modeling framework PRObability-Based Ecological target model (PROBE; Douma et al. 2012b; Witte et al. 2014) has been designed to compute the effects of climate change and of water management measures on the occurrence probability of vegetation types. To this end, it utilized available maps (on soil, groundwater levels, upward seepage, and land use) and transfer functions (TFs) derived from mechanistic

models to simulate environmental drivers that directly affect plant performance: drought stress, respiration stress, nutrient availability (approximated by P mineralization rate) and soil pH. With a preprocessor (Bartholomeus and Witte 2013) we generated TFs for the case study catchment, to take the local climate into account. Local data on precipitation, reference evapotranspiration and temperature were obtained from the Royal Dutch Meteorological Institute (KNMI). Subsequently, these environmental drivers are related to vegetation characteristics (defined as by mean plot values of plant traits) by process-based relationships, i.e. relationships that can also be applied outside their calibration range as is required for climate projections. Based on the distribution of vegetation types in trait space, occurrence probabilities of vegetation types were calculated (Witte et al. 2007), thus accounting for the fact that vegetation types may partly share the same habitat requirements and that locally it is hard to predict which vegetation type will be observed. For visualization, we mapped the vegetation types with the highest probability density.

Since species within one vegetation unit may respond differently to climate change, we took a vegetation typology with rather coarse vegetation units, and considered these units as reference points in a multi-dimensional trait space (Table 1). This typology defines vegetation units on the basis of the vegetation characteristics ‘vegetation structure’ (which is an indirect measure for the environmental driver ‘light’), ‘moisture regime’, ‘nutrient availability’ and ‘acidity’ (Witte and Van der Meijden 2000; Runhaar et al. 2004). These drivers are identifiable by their codes, e.g. K27 is a vegetation unit with a short vegetation structure (K) on wet (2) and moderately nutrient-rich (7) soils.

## Case study

We applied the models to the stream valley catchment of the Tungalroyse Beek in the South-Eastern part of the Netherlands (Fig. 1). Mean annual temperature is 9.8 °C, with mean lowest temperatures in January (2.6 °C) and highest in July (17.5 °C). Mean annual precipitation is 712 mm, distributed evenly over the year. The catchment covers an area of approximately 157 km<sup>2</sup>. Around 1850, the upper part of the catchment consisted mostly of swamp and heath areas, with occasional forest and agricultural lands. Around the

**Table 1** Description of the vegetation types. Only the vegetation types that are modelled in the case study area are included

Vegetation type	Description
A11	Semi-terrestrial vegetation in stagnant, oligotrophic, acid water
A12	Semi-terrestrial vegetation in stagnant, oligotrophic, neutral/alkaline water
A15	Semi-terrestrial vegetation in stagnant, mesotrophic, neutral/alkaline water
A16	Semi-terrestrial vegetation in stagnant, mesotrophic, alkaline water
A18	Semi-terrestrial vegetation in stagnant, very eutrotrophic water
K21	Herbaceous vegetation on wet, oligotrophic, acid soil
K22	Herbaceous vegetation on wet, oligotrophic, neutral soil
K27	Herbaceous vegetation on wet, mesotrophic soil
K28	Herbaceous vegetation on wet, very eutrophic soil
K41	Herbaceous vegetation on moist, oligotrophic, acid soil
K42	Herbaceous vegetation on moist, oligotrophic, neutral soil
K47	Herbaceous vegetation on moist, mesotrophic soil
K48	Herbaceous vegetation on moist, very eutrophic, limy soil
K61	Herbaceous vegetation on dry, oligotrophic, acid soil
K62	Herbaceous vegetation on dry, oligotrophic, neutral soil
K67	Herbaceous vegetation on dry, mesotrophic soil
K68	Herbaceous vegetation on dry, very eutrophic soil
H21	Woods and shrubs on wet, oligotrophic, acid soil
H22	Woods and shrubs on wet, oligotrophic, neutral soil
H27	Woods and shrubs on wet, mesotrophic soil
H41	Woods and shrubs on moist, oligotrophic, acid soil
H47	Woods and shrubs on moist, mesotrophic soil
H61	Woods and shrubs on dry, oligotrophic, acid soil
H62	Woods and shrubs on dry, oligotrophic, neutral soil
H67	Woods and shrubs on dry, mesotrophic soil

For more information about the vegetation type classification system see Witte and van der Meijden (2000)

beginning of the 20th century, a large part of the catchment has been drained for peat extraction. Agricultural activities increased which led to a more intense drainage of the area, and initiated desiccation of nature areas. The canalization of streams increased desiccation further. Nowadays, the catchment consists of agricultural land (ca. 67 %, including grasslands), urban area (ca. 16 %), nature areas (ca. 16 %) and open water (ca. 1 %) (Straatman and Luijendijk 2002).

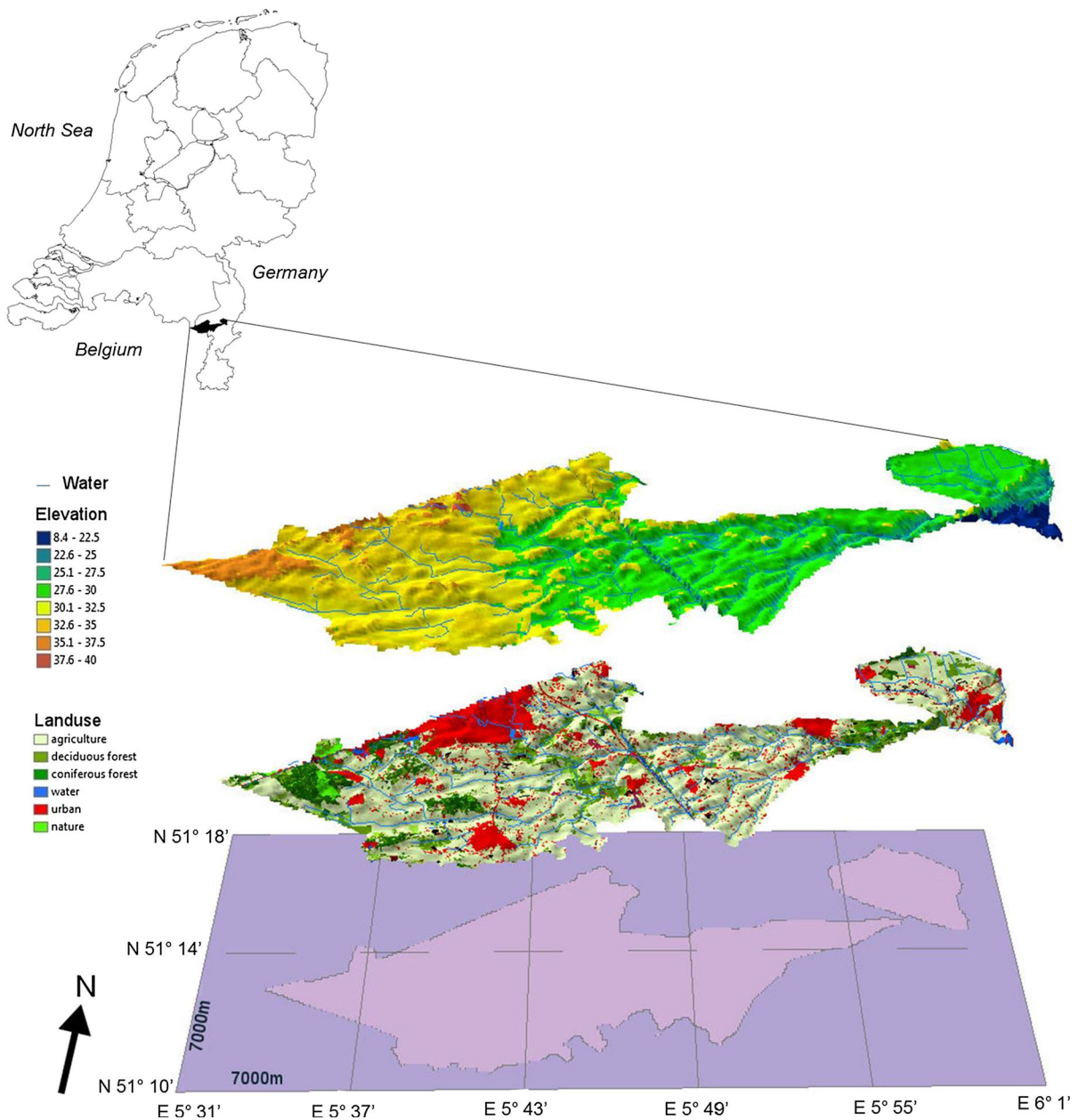
#### Climate change scenarios

For projecting climate change, we applied regional scenarios as developed by the Royal Netherlands Meteorological Institute (KNMI) that are based on General Circulation Model simulations, Regional Climate Model simulations, and local observations. These scenarios have been tailor-made for the Netherlands (van den Hurk et al. 2006) from the ensemble

of global climate models used in IPCC Assessment Report Four (IPCC 2007). The two regional scenarios used in this study are the W and W+ scenarios which are related to the B1, A1B and A2 IPCC scenarios (van den Hurk et al. 2006). The W and W+ scenarios represent a global average temperature increase of 2 °C by 2050 and differ in their projected changes in precipitation amounts. The average precipitation increases in winter with 7 % for W and 14 % for the W+ scenario, compared to 1990. For the W scenario it also increases in summer (6 %), but it decreases in summer for the W+ scenario (−19 %). Summer evaporation increases by 7 % in the W scenario and by 15 % in the W+ scenario.

#### Water conservation scenario

The water conservation scenario which we implemented was based on the Dutch Administrative



**Fig. 1** Overview of the Tugelroyse beek catchment. The location of the catchment in the Netherlands is shown on the *top left* (indicated by the *black area*). The *top figure* of the *lower panel* is the height of the soil surface above sea level, with the streams indicated by *blue lines*. The legend on the *left* of the

*figure* is in meter above sea level. The *figure below* shows the land use in the catchment, the legend is on the *left*. *Nature* are all non-forest nature types. The *bottom figure* shows the actual size and location of the catchment

Agreement for Water Affairs (Ministry of Infrastructure and the Environment 2011). Based on this agreement, regional targets for groundwater and surface water regimes were derived which have to be implemented before 2020. The main purpose of these

target regimes is the realisation and maintenance of a sustainable water system that offers sufficient stability and robustness to support allocated functions. This is achieved by raising the water tables, thus increasing water availability for agriculture and nature. An extra

set of water conservation measures is envisioned to raise groundwater tables in especially the lower areas of the catchment even further. Most water conservation measures apply to stream valleys as the effectiveness of water conservation ( $\text{m}^3$  water stored per ha) is bigger in floodplains with surface waters than in the subsoil of infiltration areas. Such measures include the enlargement of the stream valley zone, which is the area around the stream where the groundwater levels in winter are higher than 70 cm below soil surface (i.e. the area where agricultural yields decrease due to high groundwater levels). By allocating more land area to this stream valley zone, the natural functioning of the streams can be improved. The amount of extra land was based on explorative model calculations, which included an increase of the groundwater table in the stream valleys without taking land use (agriculture, urban, nature) into account (i.e. groundwater table increase was not constrained by land use based restrictions). All areas too wet for agriculture were added to the stream valley zone. Multiple measures were simulated for agriculture, urban areas, nature areas, and natural stream valleys for the (enlarged) stream valley zone, respectively (see Appendix 1 for details on the measures and for details on how these measures were implemented in the groundwater model).

#### Validation of vegetation distribution predictions

To validate the output of the vegetation model, we compared the output of the reference scenario to observed vegetation management types. Note that a single modelled vegetation type can be represented by multiple management types. For example, herbaceous vegetation on wet mesotrophic soil (K27) is represented by the management type *swamp* and by *moist nutrient poor grassland*. Eventually, sixteen modelled vegetation types were represented by 14 management types. Nine modelled vegetation types could not be represented by management types (for example the semi-terrestrial vegetation) and could therefore not be validated. Semi-terrestrial vegetation includes vegetation types that root below the water surface, but have leaves above the water surface. We considered the model to be successful when the modelled vegetation at a certain location corresponded to the representative management type (see Appendix 2 for the analysis).

## Results

### Hydrology

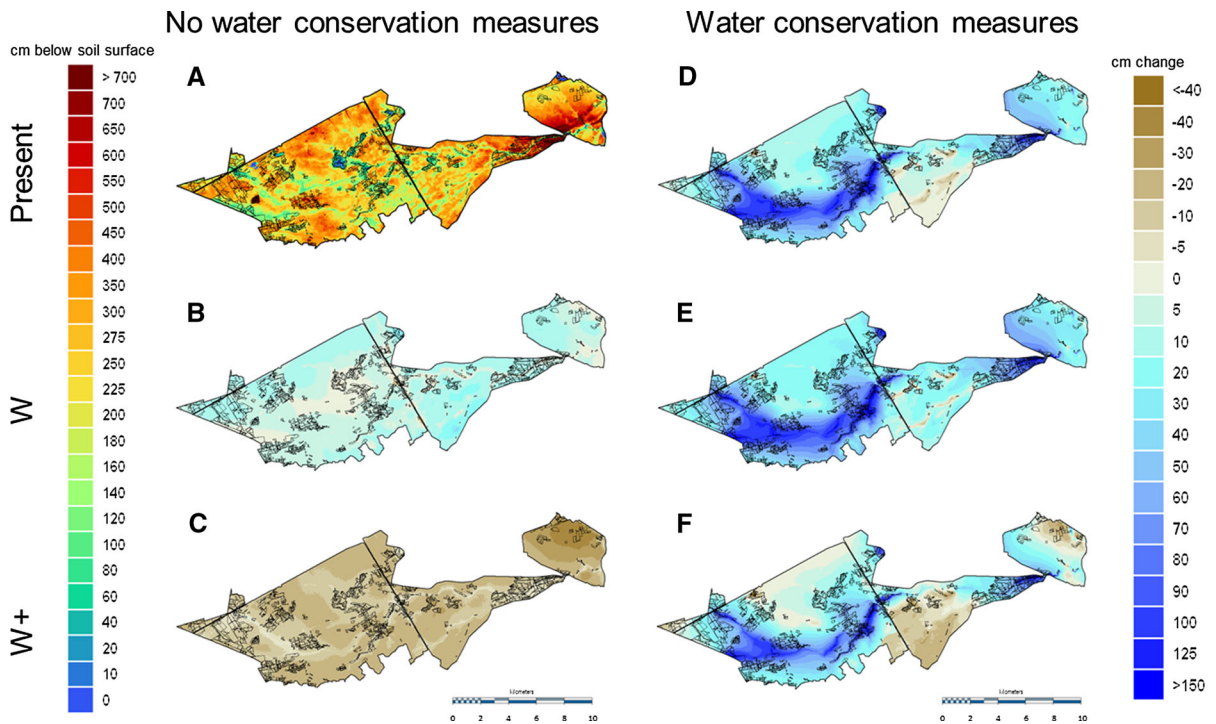
#### *Climate change effects*

In the W scenario (scenario ii), the mean lowest water table increased on average with 9 cm compared to the reference scenario in almost the entire catchment (median increase is 8 cm, 1st and 99th percentiles are 26 and 0 cm, respectively) (Fig. 2b). The mean highest water tables increased on average with 15 cm compared to the current climate (median of 14 cm, 98 % of the increase is between 0 and 38 cm). The average seepage flux in seepage areas increased with  $0.11 \text{ mm day}^{-1}$  and the size of the seepage area increased by 4.6 % (Table 2; Fig. 3b).

The W+ scenario (scenario iii), in which summer precipitation decreased, showed the exact opposite effect (Fig. 2c). The mean lowest water table dropped on average with 12 cm in the entire catchment (median decrease is 11 cm, 1st and 99th percentiles are 2 and 36 cm). The mean highest water tables changed little in most part of the catchment (median of 1 cm, 1st and 99th percentiles of +5 and -25 cm). The average seepage flux and the size of the seepage area decreased as well ( $-0.16 \text{ mm day}^{-1}$  and -2.2 % respectively) (Table 2; Fig. 3c).

#### *Water conservation effects in the current climate*

Under the current climate, water conservation measures (scenario iv) were a successful method to increase the mean lowest and highest water tables especially around the stream. The average increase for the mean lowest water table equaled 41 cm (median increase of 32 cm, 1st and 99th percentiles are +134 and -5 cm, respectively) (Fig. 2d). The mean highest water table increased on average with 49 cm in the catchment (median increase of 39 cm, 1st and 99th percentiles are 158 and 0 cm, respectively) and the seepage flux decreased by  $0.4 \text{ mm day}^{-1}$  (Table 2). Due to the water conservation measures and the associated rise of the groundwater table, the dominant flux in almost the entire upper part of the stream changed from seepage to infiltration. However, a tributary stream in the catchment increased its seepage flux (Fig. 3d), resulting in a very minor (0.4 %) total reduction in seepage area.



**Fig. 2** Effects of climate change and the water conservation measures on the mean lowest groundwater table. From *top to bottom* are the present climate, the W and the W+ climate. *Left* figures are without water conservation measures, while the *right* includes the implementation of water conservation measures. The *black lined areas* within the catchment are the nature areas.

*Panel A* shows the mean lowest groundwater table in cm below soil surface in the present climate, without water conservation measures (legend of *Panel A* is on the *left*). *Panels B–F* depict the differences in water table (in cm) compared to *Panel A* (legend on the *right*)

**Table 2** The hydrological changes for the five (ii–vi) scenarios compared to the reference scenario

Scenarios	Lowest (cm)	Highest (cm)	Seepage flux (mm day <sup>-1</sup> )	Seepage area (%)
W (ii)	+9	+15	+0.11	+4.6
W+ (iii)	-12	-3	-0.16	-2.2
Measures (iv)	+41	+49	-0.40	-0.4
Measures W (v)	+48	+63	-0.33	+5.5
Measures W+ (vi)	+27	+46	-0.53	-2.2

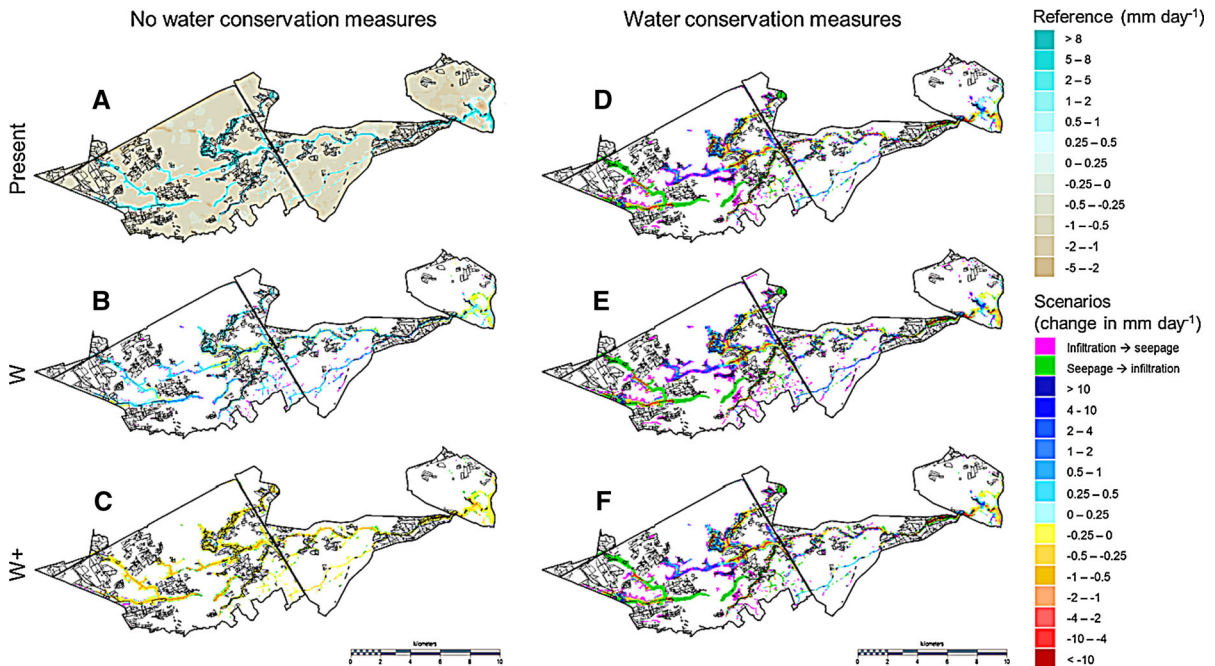
The change in mean lowest (Lowest) and highest (Highest) groundwater tables, the average change in seepage flux for seepage cells (Seepage flux) and the change in extent of the seepage area (Seepage area) for the five (ii–vi) scenarios, compared to the reference scenario (i). The increase in seepage area is in percentages (percentage of the change in number of seepage cells compared to the reference scenario). The “Measures” scenarios stand for the water conservation measures scenarios, see the Methods section for details on these scenarios. Although these are average values for the entire catchment and despite the large spatial differences, these values indicate the overall effects on catchment hydrology

*Climate change and water conservation*

In the W scenario, water conservation measures (scenario v) led to an additional 9 cm increase (amounting to 48 cm on average) in the mean lowest water table compared to the current climate (median of

38 cm, 1st and 99th percentiles are 137 and 0 cm, respectively) (Fig. 2e). The average increase of the mean highest water table was 14 cm higher (amounting to 63 cm) than in the current climate (median of 52 cm, 1st and 99th percentiles of 163 and 9 cm, respectively). The seepage flux decreased less than in





**Fig. 3** Effects of climate change and the water conservation measures on the seepage flux in the saturated zone. From *top to bottom* are the present climate, the W and the W+ climate. *Left* figures are without water conservation measures, while the *right* ones include the implementation of water conservation

measures. The *black lined areas* within the catchment are the nature areas. *Panel A* shows the seepage flux in the saturated zone (legend on the *top right* in  $\text{mm day}^{-1}$ ). Figures *B–F* depict the differences in flux compared to *Panel A* (legend on the *lower right* in  $\text{mm change}$ , except for the switched fluxes)

the current climate ( $-0.33 \text{ mm day}^{-1}$ ), although the size of the seepage area increased with 5.5 % (Table 2; Fig. 3e).

In the W+ scenario, water conservation measures (scenario vi) caused a 14 cm less increase (amounting to 27 cm on average) of the mean lowest water table than in the current climate (median increase of 19 cm, 1st and 99th percentiles were an increase of 122 and a decrease of 17 cm, respectively) (Fig. 2f). The mean highest water table increased with 3 cm less, amounting to 46 cm (median of 36 cm, 1st and 99th percentiles are +155 and -6 cm, respectively). The seepage flux decreased by  $0.13 \text{ mm day}^{-1}$  more than in the current climate (amounting to  $-0.53 \text{ mm day}^{-1}$ ). The size of the seepage area also decreased more than in the current climate (-2.2 %) (Table 2; Fig. 3f).

Ecology

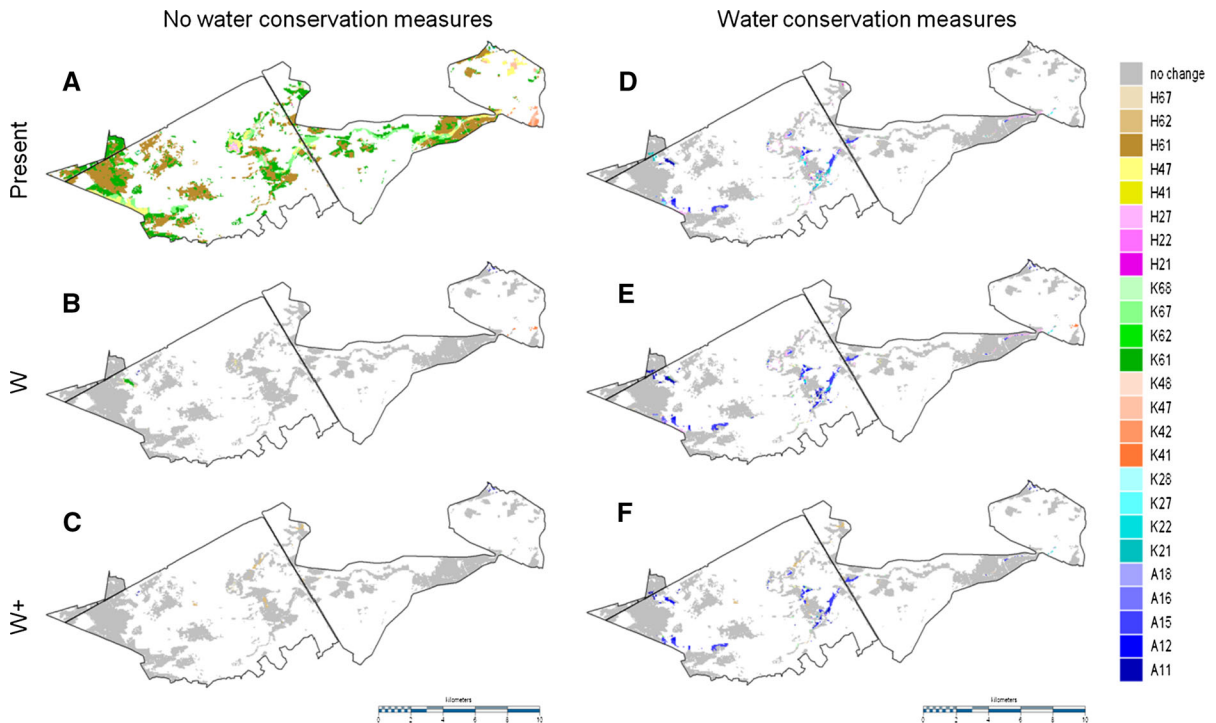
*Climate change effects on vegetation*

In the reference situation (scenario i), the PROBE model in combination with the hydrological output

predicted the correct vegetation distribution in nature areas for 64 % of the cases (Appendix 2). In the current climate, nature areas in the case study area are dominated by terrestrial herbaceous vegetation (~45 %) and forests (~55 %), with aquatic and semi-terrestrial vegetation covering less than 0.1 % (Fig. 4a).

In the W scenario (scenario ii), hardly any changes in most likely vegetation type were predicted by the model (Figs. 4b, 5) with the biggest increase being only 0.4 % [from 34.1 to 34.5 % for herbaceous vegetation on dry, oligotrophic acid soils (K61)]. Woods and shrubs on dry, mesotrophic soils (H67), increased in cover from 1.1 to 1.4 %. These minor increases predominantly occurred at the expense of herbaceous communities on dry, oligotrophic, neutral soils (K62, decreasing from 0.5 to 0.1 %) and forests on dry, oligotrophic, neutral soils (H62, decreasing from 0.7 to 0.4 %) respectively.

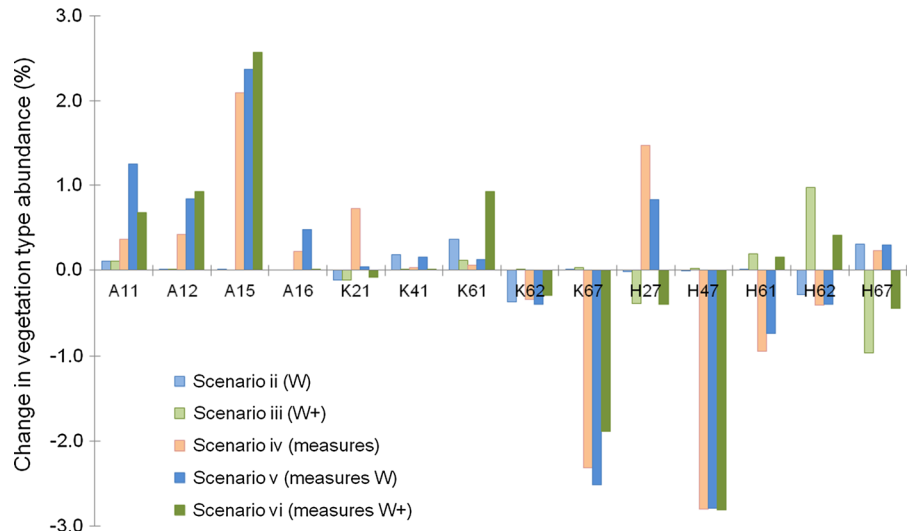
In the W+ scenario (scenario iii; Fig. 4c) also relatively minor changes were predicted. The biggest changes were predicted for the forest types, up to 1 % compared to a maximum change of 0.1 % in the



**Fig. 4** Effects of climate change and the water conservation measures on the stability of vegetation patterns in the nature areas. From *top to bottom* are the present climate, the W and the W+ climate. *Left* figures are without water conservation measures, the *right* ones include the water conservation

measures. The present vegetation patterns are shown in *Panel A*. Vegetation types K61 and H61 are by far the most dominant vegetation types in the case study area. *Panels B–F* depict the changes in vegetation types, compared to *panel A*. For an explanation of the legend see [Table 1](#)

**Fig. 5** Changes in vegetation types due to climate change and water conservation measures compared to the vegetation distribution in the current climate without water conservation measures. Changes are in percentages, the vegetation types are on the *x*-axis. Only the most abundant ones are included. Especially for the woods and shrubs vegetation it is clear that climate change overrules the water conservation effects in the W+ scenario (scenario vi)



herbaceous communities. The highest increase was observed for forests on dry, oligotrophic, neutral soil (H62, increasing from 0.7 to 1.6 %) at the expense of forests on dry, mesotrophic soil (H67, decreasing from

1.1 to 0.1 %), which is the exact opposite pattern of that observed for the W scenario (Fig. 5). For herbaceous communities, the vegetation on dry, oligotrophic, acid soil increased most (K61, increasing

from 34.1 to 34.3 %) and vegetation on wet, oligotrophic, acid soil showed the biggest decrease (K21, from 0.1 to 0 %); they disappeared entirely from the nature areas in the catchment.

#### *Water conservation effects on vegetation in the current climate*

As expected, water conservation measures in the current climate (scenario iv) resulted in a substantial increase in semi-terrestrial vegetation (increase from 0.01 to 3.1 %). Particularly vegetation of mesotrophic neutral wetlands (A15) benefited from water conservation measures (from 0 to 2.1 %) (Fig. 4d). Woods and shrubs declined more (−2.2 %) than herbaceous vegetation (−0.9 %). For woods and shrubs, the wet mesotrophic community increased in abundance (H27, increase from 0.5 to 1.9 %), while the moist mesotrophic community decreased (H47, decrease from 7.4 to 4.6 %). The same pattern was observed for the herbaceous communities, where the wet, oligotrophic, acid vegetation types increased (K21, increase from 0.1 to 0.8 %), and dry mesotrophic herbaceous vegetation types decreased (K67, decrease from 8.5 to 6.2 %).

#### *Climate change and water conservation effects on vegetation*

The effects of water conservation measures in the W scenario (scenario v) on vegetation distribution clearly dominate over the impacts of climate change and, as a result, the predicted changes in vegetation distribution are very similar to those in the current climate (Fig. 4e). The semi-terrestrial vegetation increased even further in the W scenario, from 3.1 % (without climate change) to 5 %. Especially oligotrophic, acid vegetation increased (A11, from 0.4 to 1.3 %), followed by the neutral (A12, from 0.4 to 0.9 %) and mesotrophic (A15, from 2.1 to 2.4 %) semi-terrestrial communities. Herbaceous vegetation declined more strongly than woods and shrubs (−1.3 and −0.5 % respectively) compared to the current climate with water conservation measures (Fig. 5).

Interestingly, in the W+ scenario that includes water conservation measures (scenario vi), most of the changes in semi-terrestrial vegetation seen for the W scenario were maintained although the total increase in semi-terrestrial communities was less (from 3.1 to

4.2 %) (Fig. 4f). The mesotrophic, neutral semi-terrestrial community increased (A15, from 2.1 to 2.6 %), while the alkaline communities decreased (A16, from 0.2 to 0.01 %). Woods and shrubs declined more than herbaceous communities (−0.9 and −0.2 % respectively) (Fig. 5).

## Discussion

### Integrated spatially explicit analysis of hydrology-vegetation interactions

Up to now, most studies that model climate adaptation measures focus on hydrological consequences only (Candela et al. 2009; Georgakakos et al. 2012; Sekhar et al. 2013) without taking the ecological consequences into account. This was also shown in an extensive review by Orellana et al. (2012) who reported that numerous hydrological models that simulate water conditions in a catchment in various ways, do not simulate responses in vegetation patterns. In addition, hydrological studies tend to mainly focus on water quantity (Candela et al. 2009; Georgakakos et al. 2012; Sekhar et al. 2013) and not on the presence or absence of seepage. Studies that do incorporate seepage do not take the next step to modelling vegetation patterning (Batelaan et al. 2003). Species distribution models, used for exploring climate change effects, characteristically use simplified quantitative hydrological data (Guisan and Thuiller 2005). Also here seepage impacts are often overlooked. Previous studies that integrated hydrology and vegetation modelling focus on water quantity alone and vegetation is modelled as a single species in terms of biomass only (Broilma et al. 2010a, b) or as species types (Loheide and Gorelick 2007). Thus, our study is one of the very first to integrate these two model types at a higher level of detail than has been done so far for evaluation of climate and water conservation scenarios.

Within our integrated approach, the simultaneous impacts of water quantity and seepage on vegetation patterns were assessed by applying generic rules reflecting the impacts of both abiotic drivers on vegetation functioning. The generic rules applied in our vegetation model have been derived by linking proximate abiotic drivers, e.g. oxygen and drought stress and P mineralization rate as defined in the

current study, to vegetation characteristics as identified in a national database. The use of proximate abiotic drivers is considered of critical importance for climate change impact studies given that environmental conditions correlating to vegetation characteristics and other environmental conditions may be uncoupled in a future climate (Douma et al. 2012b; Witte et al. 2012). As a consequence, estimates of climate change impacts on vegetation may be biased. The use of proximate abiotic drivers avoids such biases (Bartholomeus et al. 2012) and the use of national databases avoids locally optimized relations that may be valid in the current climate only.

Based on the above-mentioned considerations, we conclude that our approach is a sound way to improve the accuracy of predicting impacts of climate change and hydrological measures on catchment-wide vegetation patterns.

#### Application of our integrated approach to the Tungaloyse beek case study

Our integrated hydrology-vegetation approach enabled us to assess hydrological and ecological consequences of climate change and water conservation measures and their interactions. The W and W+ scenarios had contrasting impacts on groundwater water levels and seepage. The increased precipitation in the W scenario led to an increase of the groundwater level and of the seepage area and flux. For the W+ scenario, with its reduced summer precipitation, groundwater tables dropped, as did the seepage area and flux. Although the magnitude of these changes was not always beyond the accuracy threshold level of our model, the changes do indicate the different responses of the groundwater system to the different scenarios. The changes in hydrological characteristics were however too subtle in the W scenario to cause any major changes in vegetation distribution. The vegetation changes in the W+ scenario were bigger than in the W scenario, especially for the forest communities where the forest types on oligotrophic soils increased, and the mesotrophic soil types decreased. These changes are related to the lowering of the groundwater table.

Water conservation measures directly affected the vegetation composition with a strong increase in semi-terrestrial vegetation, as may be expected because of the high increases in groundwater levels. All terrestrial

vegetation types representing a wetter regime increased at the cost of moist and dry vegetation types.

Also the changes in the presence or absence and the amount of seepage, played an important role. Although the average seepage flux decreased, the total seepage area did not always decrease. This led to contrasting changes in vegetation types. For example acid, semi-terrestrial vegetation increased with water conservation measures in the W scenario (less seepage), although the neutral and alkaline communities also increased (increase seepage area). Furthermore, areas that endured a water table rise and a switch from seepage to infiltration flux, triggered a different vegetation change than sites that became wetter, but sustained their seepage flux. The results of our study thus stress the importance of combining an integrated hydrology-vegetation modelling approach that includes both water quantity and seepage flux impacts on vegetation performance.

#### On the importance of customized climate adaptation measures

From our results, it is clear that water conservation measures can be a very powerful tool to mitigate the negative effects of climate change on regional hydrology. Even the decrease in mean lowest water table in the W+ scenario is reduced or even reversed by the water conservation measures. In the W scenario, the implemented water conservation measures increase the water tables even further. This shows that climate adaptation measures can be an effective tool to counteract any potential negative effects of climate change. However, it also implies that the measures need to be adjusted to the most likely scenario, since the area over which the measures are effective differ greatly between the climate scenarios (Fig. 2). Furthermore, these adaptation measures may yield positive results in one climate scenario (the W+ scenario) but may result in negative impacts, such as flooding, in another scenario (the W scenario). Also changes in seepage flux depended on the climate scenario, since the size of the seepage area increased in the W scenario, but decreased in the W+ scenario, although seepage fluxes decreased in both scenarios. It is therefore essential to identify the most suitable area to implement the water conservation measures. In this case, the water table rise increases water availability but decreases the seepage flux. To ensure sufficient

water and seepage availability, a different set of water conservation measures should be implemented. For example, measures that stimulate groundwater recharge at the higher areas can increase the seepage in lower areas and thereby maintain the seepage locations. It thus seems of critical importance to account for the combination of local conditions, projected climate change and the impacts of water conservation measures when designing where to implement the adaptation measures without damaging other areas of the catchment. The approach presented here offers a useful tool to achieve this.

These complex interactions also become clear when evaluating the impacts on vegetation distribution under climate change, which is particularly apparent in the W+ scenario. Forests and shrubs of dry, acid conditions increase where climate change effects prevail (further away from the stream), while mesotrophic forests decrease. Closer to the stream, semi-terrestrial oligotrophic to mesotrophic herbaceous vegetation increases at the cost of dry oligotrophic to mesotrophic herbaceous vegetation (here water conservation effects dominate). This again points to the importance of integrated approaches as applied in this study.

Furthermore, our approach also allows for cost-benefit analyses for each individual measure. This will help developing the most beneficial water conservation scenario, in terms of water and seepage availability, vegetation development and financial costs.

#### Habitat quality and future directions

In this study, we focused on modelling the effects of climate change and adaptation measures on the probability of vegetation occurrence. The vegetation types can be used as indicators of habitat quality. In addition to sufficient habitat size and habitat connectivity (Tilman et al. 1994; Soomers et al. 2013) habitat quality is a vital constraint determining the quality of ecological networks. Hence, if habitats are severely deteriorated, then what does it add to the ecological network, if undesired species are increasing in cover? Incorporating habitat quality therefore adds to completing the picture. Our hydrological results showed that when water conservation measures were implemented, the water quantity around the stream increased and seepage fluxes changed. Based on the water quantity and seepage maps we can make accurate predictions of

where additional ecological corridors will be most successful. Combined with our vegetation model, we can test the suitability of these new corridors, i.e. the habitat quality, in a future climate. For future applications of our approach, the impacts of habitat connectivity on the dispersal of plant species (Ozinga et al. 2009) may additionally be taken into account. Our approach so far assumes that this dispersal is not limiting, but this may be explicitly tested allowing for a full integration of our approach with habitat connectivity models (Van Bodegom et al. 2014).

#### Conclusion

From our results it is evident that an integrated model approach increases our understanding of the effects of water adaptation measures in a future climate on vegetation occurrence. This approach is very useful when searching for water conservation measures that yield positive results in multiple climate scenarios, i.e. the no-regret options. Furthermore, since multiple vegetation classifications can be modelled, the integrated models can be used in a range of ecosystems and are not limited to solely stream catchments. We propose that this integrated model approach is a useful tool that helps to implement the right management in nature areas to ensure the quality and robustness of the ecological network in the future.

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