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Dynamic integration of land use changes in a hydrologic assessment of a rapidly developing Indian catchment

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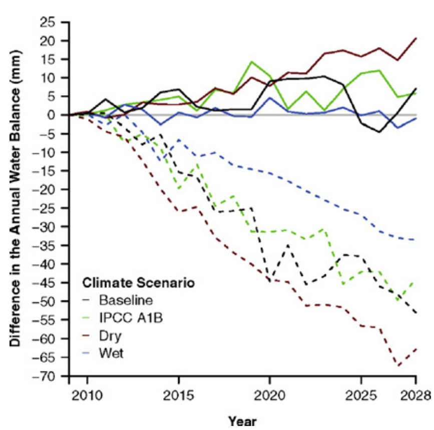
HIGHLIGHTS

- Successful integration of land use modeling and hydrologic modeling
- Projected urbanization leads to increased water yield at the beginning of monsoon.
- Extreme dry climate conditions exacerbate impacts of land use change on hydrology.

GRAPHICAL ABSTRACT



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ABSTRACT

Rapid land use and land-cover changes strongly affect water resources. Particularly in regions that experience seasonal water scarcity, land use scenario assessments provide a valuable basis for the evaluation of possible future water shortages. The objective of this study is to dynamically integrate land use model projections with a hydrologic model to analyze potential future impacts of land use change on the water resources of a rapidly developing catchment upstream of Pune, India. For the first time projections from the urban growth and land use change model SLEUTH are employed as a dynamic input to the hydrologic model SWAT. By this means, impacts of land use changes on the water balance components are assessed for the near future (2009–2028) employing four different climate conditions (baseline, IPCC A1B, dry, wet). The land use change modeling results in an increase of urban area by +23.1% at the fringes of Pune and by +12.2% in the upper catchment, whereas agricultural land (−14.0% and −0.3%, respectively) and semi-natural area (−9.1% and −11.9%, respectively) decrease between 2009 and 2028. Under baseline climate conditions, these land use changes induce seasonal changes in

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SLEUTH
SWAT
India

the water balance components. Water yield particularly increases at the onset of monsoon (up to +11.0 mm per month) due to increased impervious area, whereas evapotranspiration decreases in the dry season (up to −15.1 mm per month) as a result of the loss of irrigated agricultural area. As the projections are made for the near future (2009–2028) land use change impacts are similar under IPCC A1B climate conditions. Only if more extreme dry years occur, an exacerbation of the land use change impacts can be expected. Particularly in rapidly changing environments an implementation of both dynamic land use change and climate change seems favorable to assess seasonal and gradual changes in the water balance.

1. Introduction

Land use and land-cover change is one of the most important impacts on ecosystems worldwide (Foley et al., 2005). Changes in land use and land-cover (subsequently referred to as land use changes) have been identified as a major research focus for this century as they alter hydrologic processes such as infiltration, ground water recharge, evapotranspiration and runoff, and affect water quality (DeFries and Eshleman, 2004). Hence, land use changes are significant for a large number of ecosystem services (Bateman et al., 2013) and affect global climate (Hartmann et al., 2013). It is assumed that the impacts of land use change due to human development outweigh those of climate change with regard to human habitability (Skole et al., 1997) and water resources (Vörösmarty et al., 2000) for the next decades. Despite its importance the effects of land use change on hydrology are associated with large uncertainties (Stonestrom et al., 2009).

Particularly in countries with rapid land use changes and limited water resources, land use change has a large potential to exacerbate water scarcity. This is the case in parts of India, where rapid socio-economic development and urbanization have caused major land use change in the past and further impacts are to be expected in the future (DeFries and Pandey, 2010; Döös, 2002; Lambin et al., 2003). Recent studies illustrate that the water resources are depleted in different regions of India (Garg et al., 2012, 2013; Mishra et al., 2007; Sharma et al., 2001; Wagner et al., 2013; Wilk and Hughes, 2002). However, future projections of land use change are not employed in these studies to assess possible future impacts on water resources.

The impacts of land use change on water resources are commonly assessed with the help of hydrologic models (Gassman et al., 2007; Huisman et al., 2009). Land use change scenarios serve as an input to these models to address potential future impacts of land use change on catchment hydrology. While the utilized hydrologic models are often data-intensive and need a thorough setup of model parameters (e.g., SWAT, Arnold et al., 2012; MIKE-SHE, Refsgaard and Storm, 1995), the land use change scenarios are often based on assumed partial or complete changes (e.g., deforestation) and their representation in the hydrologic model is mostly static (e.g., López-Moreno et al., 2014; Mango et al., 2011; Wilk and Hughes, 2002). The most commonly used approach to integrate land use change in a hydrologic modeling study is the comparison of model runs for a given time frame that are based on different land use maps, e.g., Niehoff et al. (2002) used this methodology with WaSiM-ETH, Huisman et al. (2009) used it with an ensemble of ten different hydrologic models, and Im et al. (2009) applied that methodology with MIKE SHE. This so called delta approach is also commonly used in SWAT modeling studies (e.g., Bieger et al., 2015; Castillo et al., 2014; Ghaffari et al., 2010; Miller et al., 2002; Schilling et al., 2008), even though a dynamic representation of land use changes in the SWAT model is possible since 2010 (Chiang et al., 2010). The delta approach only provides a mean value of impacts and does not account for e.g., non-linear land use changes and their potentially non-linear impacts. A dynamic integration of land use changes with a hydrologic model provides a more realistic representation of the temporal development of land use changes, is likely to improve the temporal predictive ability of the model (Pai and Saraswat, 2011), and allows for a temporally explicit analysis of hydrologic impacts (Chiang et al., 2010). Castillo et al. (2014) underline that a tighter temporal integration of the dynamics of land use change and hydrology is needed to accurately represent the interactions between land use, climate, and hydrology.

Although more complex approaches to define land use change scenarios (e.g., by using land use change models; Verburg et al., 2006) are available, these are rarely dynamically integrated with hydrologic impact assessments. Land use change scenarios may be derived as a result of simple assumptions (e.g., complete or partial change of one class to another; Mango et al., 2011), or more complex approaches including models (e.g., Kim et al., 2013; Li et al., 2015; Zhang et al., 2013). Such land use change models incorporate the most important drivers of land use change (Bürgi et al., 2004) including biophysical attributes and socio-economic drivers to represent parts of the complexity of the land use system (Veldkamp and Lambin, 2001). Hence, they provide a basis to simulate land use change in a more sophisticated manner. Several land use change models have been developed (e.g., CLUE, Verburg and Overmars, 2009; LandSHIFT, Schaldach et al., 2011; SLEUTH, Clarke and Gaydos, 1998) and are used for different purposes, including empirical-statistical, stochastic, optimization, process-based, and integrated modeling approaches (Lambin et al., 2000). A thorough review of land use change models and their specific characteristics (e.g., spatial vs. non-spatial, dynamic vs. static, agent-based vs. pixel-based, global vs. regional) is provided by Verburg et al. (2006).

Even though the importance of a dynamic representation of land use changes has been recognized (Fohrer et al., 2005; Pai and Saraswat, 2011), a dynamic integration of spatially explicit models of land use change and hydrologic models is rarely found in the literature. Chu et al. (2010) integrated dynamic land use changes simulated by CLUE-s with a distributed hydrological model (DHSVM) for a catchment in Taiwan and found that the dynamic land use scenario is more suitable for assessing hydrologic processes. Larger interdisciplinary projects like GLOWA-Danube implemented dynamic agricultural changes in the integrated simulation system DANUBIA and applied the model to the Upper Danube catchment (Barthel et al., 2012; Lenz-Wiedemann et al., 2010). However, similar applications in developing countries such as India are widely missing, although land use change and its impacts are often more severe in these environments.

Thus, the aims of this study are (i) to dynamically integrate a land use change scenario based on the land use change model SLEUTH with the hydrologic model SWAT and (ii) to analyze the impacts of dynamic land use change on hydrology under different climate conditions in a catchment upstream of a rapidly developing Indian city.

2. Materials and methods

2.1. Study area

The city of Pune is situated in western India at the foot of the Western Ghats (18.53° N, 73.85° E). Due to various factors including its climate and the proximity to the coastal mega-city Mumbai, it has experienced rapid population growth, with growth rates above 30% per decade since 1971 (Government of India, 2011) and rapid economic growth. These changes go along with a steady spatial expansion of the city limits. The Mula and the Mutha Rivers join at the city of Pune.

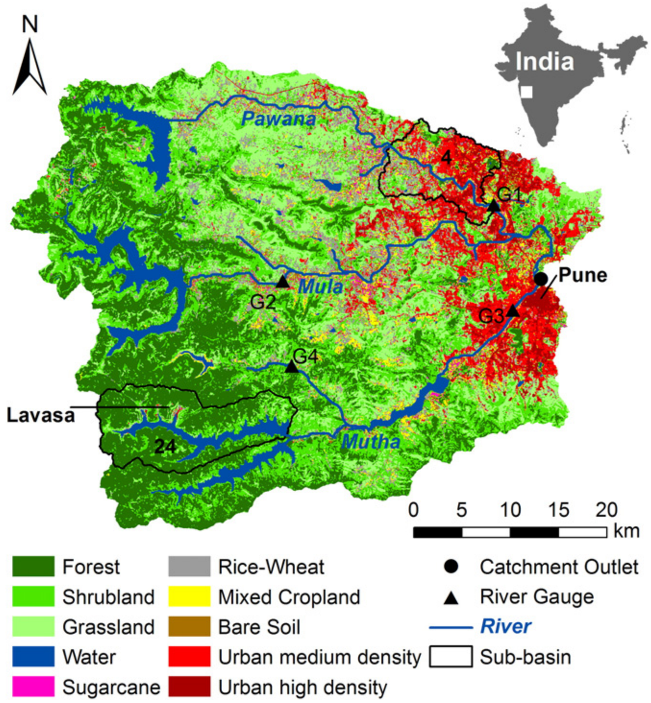

Fig. 1. The Mula and Mutha Rivers catchment depicted with a land use classification of 2009/10, the catchment outlet, the main rivers and river gauges, and the two sub-basins 4 and 24 that are analyzed in this study.

Major parts of the upstream meso-scale catchment (2036 km^2; Fig. 1) are located in the Western Ghats. The catchment is a sub-basin and source area of the Krishna River, which drains towards the east and into the Bay of Bengal. The elevation within the catchment ranges from 550 m in Pune up to 1300 m a.s.l. on the top ridges in the Western Ghats. It has a tropical wet and dry climate (Köppen–Geiger climate type Aw), which is characterized by a pronounced seasonality in rainfall that is generally limited to the summer monsoon season from June to October and a low annual temperature variation with an annual mean of 25 °C at the catchment outlet in Pune. Annual rainfall amounts decrease from approximately 3500 mm a^{-1} in the western part of the catchment to 750 mm a^{-1} in the eastern part of the catchment (Gadgil, 2002; Gunnell, 1997). According to the digital Soil Map of the World (Food and Agriculture Organization of the United Nations (FAO), 2003) major parts (92.5%) of the study area consist of a sandy clay loam (Hh11-2bc, Haplic Phaeozem) and minor parts (7.5%) are covered by a clay (Vc43-3ab, Chromic Vertisol). Two soil layers are parameterized for these soils by adapting values from regional studies (see Wagner et al. (2011) for details). Land use is dominated by semi-natural vegetation (70%), with forests mainly on the higher elevations in the west, whereas shrubland and grassland cover lower elevations (Fig. 1, Table 1). Cropland (13%) is mainly found in proximity to water sources and settlements and is dominated by small fields (<1 ha) with rainfed agriculture during the monsoon season and irrigation during the dry season (rice-wheat rotation, sugarcane, mixed cropland; Table 1). Typically two crops per year are grown, one in Kharif season (June–October) and another one in Rabi season (November–March). Urban area (10%) is predominantly found in the eastern part of the catchment, where the city of Pune and its surrounding settlements are located (Fig. 1). The newly developed city of Lavasa is being built in the south-western part of the catchment (Fig. 1). Six major reservoirs (6% of the catchment area is covered by water) are located within the study area (Fig. 1). Furthermore, water from the largest reservoir in the catchment (Mulshi) is diverted against the general drainage direction westwards over the Western Ghats escarpment. This dam serves for hydroelectric power generation for the city of Mumbai. In this study, two sub-basins are chosen for further analysis: Sub-basin 4 exemplarily shows the changes at the fringes of the city of Pune and sub-basin 24 includes the Lavasa construction site (Fig. 1).

2.2. Land use change modeling

For the entire catchment future land use changes are projected using the land use change model SLEUTH. In sub-basin 24, these projections are combined with a development plan for the new city of Lavasa. Consequently, the derived future land use scenario is a business-as-usual scenario that represents both (i) continued developments of the past and (ii) planned developments for the future.

2.2.1. SLEUTH

To project future land use change for the study area, we use the grid-based, spatially explicit urban and land use change model SLEUTH (Clarke and Gaydos, 1998). SLEUTH is an acronym of the employed input layers, 'Slope, Land use, Exclusion, Urban, Transportation and Hill shade', and is composed of two tightly coupled sub-models, the Clarke Urban Growth Model that simulates urban growth and the Land Cover Deltatron Model that simulates non-urban land use class transitions (Chaudhuri and Clarke, 2013). The SLEUTH model is especially designed to simulate land use transitions based on ongoing urban growth as the main driver of change, which is particularly the case in many regions of India. The urban sub-model is a cellular automaton that is controlled by five growth coefficients (dispersion, breed, spread, slope resistance, road gravity) derived by calibrating the model to the historic urban extent. The parameter values of these coefficients are specific to the investigated city and are therefore also referred to as 'digital DNA' of a city (Dietzel and Clarke, 2004). Four different kinds of growth behavior are implemented (spontaneous, diffusive, organic, road influenced). The modeled urban

Table 1
Setup for each land use class in the SLEUTH and the SWAT model with areal percentages at the beginning of the model run in 2009.

Land use	SLEUTH land use class	SWAT land use code (Neitsch et al., 2010, 2011)	Catchment	Sub-basin 4 (urban fringe)	Sub-basin 24 (Lavasa)
Forest	Forest	FRSD modified	25.2%	3.9%	58.3%
Shrubland	Shrubland	70% BERM, 30% FRSD	26.1%	8.8%	20.0%
Grassland	Grassland	BERM	18.6%	11.6%	5.6%
Mixed cropland	Mixed cropland	50% AGRR, 50% AGRL	3.8%	7.3%	0.1%
Rice–wheat	Rice–wheat	Rice (Kharif), SWHT (Rabi)	7.5%	14.2%	1.1%
Sugarcane	Sugarcane	SUGC	1.3%	3.3%	0.0%
Bare soil	–	50% BERM, 50% AGRL	1.7%	3.3%	0.0%
Water	–	WATR	5.7%	0.5%	14.1%
Urban medium density	Urban	URMD	7.0%	32.0%	0.5%
Urban high density	Urban	URHD	3.0%	15.1%	0.2%

development follows the typical S-curve growth rate with rapid development at the beginning (many pixels are available to urbanization) and decreasing urbanization at the end of the growth cycle (Silva and Clarke, 2002). The non-urban land use change sub-model (Land Cover Deltatron Model) is another cellular automaton that uses land use transition rules derived from historic land use data. It uses the concept of deltatrons, which are the artificial agents that act as "bringers of change" and track the spatial and temporal effects of land use transitions (Clarke, 2008). A deltatron tracks how much time has passed since a change has occurred, propagates change in its neighboring cells and consequently ensures spatial autocorrelation in land use transitions (see Clarke (2008) for a more detailed description of the deltatron model). SLEUTH has been used to model urban growth and land use change in over 66 applications worldwide (Chaudhuri and Clarke, 2013) and also in India (Gandhi and Suresh, 2012; KantaKumar et al., 2011; Srinivasan et al., 2013). In this study a SLEUTH model is used that is calibrated to the 38 years of historical urban extent of the study area between 1973 and 2011 (KantaKumar et al., 2011) to derive the growth coefficients (Pune's 'digital DNA') for the urban sub-model. Non-urban land use transition rules are derived by calculating transition probabilities for each class from two land use classifications of the catchment for the cropping years 1989/90 and 2009/10 (Wagner et al., 2013). The SLEUTH model run produces annual land use maps for the cropping years 2010/11 to 2028/29 at a 25 m × 25 m resolution.

2.2.2. Lavasa development plan

The planned city of Lavasa is located in the south-western part of the catchment (Fig. 1), along the Warasgaon reservoir. As SLEUTH will not represent constructions that are initiated at new locations far off recent developments (Barredo et al., 2003), the SLEUTH scenario is complemented with the development plan of the new city. Lavasa is planned in four phases, which include the construction of different parts of the planned hill city (Lavasa Corporation Limited, 2013a). The time schedule ranges from 2008 to a completion of the last phase in 2021. Planned areas of different usage (public, residential, commercial, hotel, village, etc.) are outlined in the planned city map (Lavasa Corporation Limited, 2013b). In this study, these areas are assigned to two classes: a high urban density class (public, commercial, and hotel usages) and a medium urban density class (all other uses). Subsequently, the areas are digitized and the areal changes are implemented as per the scheduled dates. The different phases are completed after 3 to 4 years. To yield an annual update, the land use changes assessed for the completion of the different phases are assumed to linearly accumulate over the previous years. This methodology strictly uses the planned developments in space (map) and time (schedule) to keep the scenario as clear as possible. No additional assumptions are used, i.e. some planned areas in phase four that are not yet assigned to a specific urban use are left unchanged and the time schedule is assumed to be accurate, although the realization of the plan is already delayed. The Lavasa land use changes take place in sub-basin 24 of the catchment area. In this sub-basin, the SLEUTH land use changes are modified by increasing urban areas according to the development of Lavasa and decreasing the other land uses (excluding water) accordingly. After the projected completion of the city at the end of 2021, the urban area in sub-basin 24 is assumed to remain constant until the end of the scenario period in 2028.

2.3. Hydrologic modeling

The Soil and Water Assessment Tool (SWAT, Arnold et al., 1998) is a widely-used (more than 2000 studies, SWAT Literature Database, 2015), open-source, semi-distributed catchment model. Land use change can be dynamically implemented in the model since version SWAT2009 (Chiang et al., 2010; Koch et al., 2012; Pai and Saraswat, 2011). Hydrologic modeling in India requires a model that is able to cope with the limited availability of environmental data. The SWAT model has originally been developed to operate in large ungauged catchments (Arnold et al., 1998) and has proven its capability to model water fluxes also in regions with limited data availability (e.g., Ndomba et al., 2008; Stehr et al., 2008). Moreover, it has been successfully applied in studies focusing on hydrologic impacts of urbanization (e.g., Chiang et al., 2010; Jeong et al., 2014). In particular, SWAT's suitability to model the hydrology in the Mula and Mutha Rivers catchment has been demonstrated in previous research (Wagner et al., 2011, 2012). Since details of the model setup and parameterization are available in these published studies, we will only present the following brief summary of data inputs and model parameterization.

The model sub-divides the catchment into sub-basins (25 in this study). Predictions are based on hydrologic response units (HRUs, here 733) that represent lumped areas with a unique land use, soil, and slope class combination within a sub-basin. The HRUs are not spatially identified within a sub-basin, which is increasing the model's computational efficiency. Runoff is calculated using the SCS curve number approach (Mockus, 1972) and potential evapotranspiration is derived using the Penman–Monteith equation (Monteith, 1965; Allen et al., 1989). In this study a particular focus is set on the water balance components evapotranspiration (ET) and water yield (WY) on the catchment and sub-basin scale. WY is defined as the net amount of water provided by the (sub-) basin that contributes to stream flow, which is the sum of surface runoff (SURQ), interflow (LATQ), and baseflow (GWQ), subtracting transmission losses (TLOSS) and pond abstractions (POND), not including inflow from upstream sub-basins (Neitsch et al., 2010):

$$WY = SURQ + LATQ + GWQ - TLOSS - POND. \quad (1)$$

The following spatially distributed data sets are available to this study and are used to set up the baseline SWAT model that represents the current land use conditions: (i) a 30 m resolution digital elevation model (DEM) that has been derived from ASTER satellite data, (ii) the 1:5,000,000 scale digital Soil Map of the World (Food and Agriculture Organization of the United Nations (FAO), 2003) with soil parameters that are in part replaced by parameters taken from a regional modeling study (Immerzeel et al., 2008), and (iii) a 24 m resolution multi-temporal land use classification for the cropping year 2009/10 (Fig. 1, Wagner et al., 2013) that is complemented with regionally specific cropping schedules. Mixed cropland is split up in two general SWAT crop classes cultivated in each season, rice and wheat are implemented as a crop rotation for rainy and dry season, respectively, whereas sugarcane is cultivated year-round (Table 1). An irrigation scheme based on plant water demand is used for these crops (Wagner et al., 2011). Shrubland is implemented as a combination of 70% grassland and 30% forest, and the forest growth module is adapted to the monsoon climate by shifting the dormancy period to the dry season (Wagner et al., 2011). The bare soil class is equally split between the mixed cropland and grassland class. Two urban land use classes with different percentages of impervious surfaces (60% for high density, 38% for medium density) are employed (Table 1). Daily weather data (temperatures, rainfall, humidity, solar radiation, wind speed) are available as point measurements for a weather station of the Indian Meteorological Department in Pune (ID 430630) and additional rainfall measurements from 15 rain gauges in the region are used. All measurements are gap-filled and quality-tested (Wagner et al., 2011). Temperature values are adjusted to the 25 sub-basins based on adiabatic temperature gradients. Similarly, relative humidity is calculated for each sub-basin using adjusted temperatures and the specific humidity in Pune. Rainfall data are interpolated using a regression kriging approach (Wagner et al., 2012) that incorporates satellite-based rainfall patterns measured by the Tropical Rainfall Measuring Mission (TRMM). A management scheme for the six major dams in the catchment has been developed that allows for water storage during rainy season and water release during dry season (Wagner et al., 2011, 2012). Model parameters have either been estimated from readily available GIS databases, or have been chosen from the literature for the given site conditions, or default parameters from the SWAT database have been selected. This parameterization procedure has been successfully applied in this catchment (Wagner et al., 2012) and other studies, where SWAT input parameters are estimated without calibration from readily available GIS databases (e.g., Fontaine et al., 2002; Srinivasan et al., 2010; Zhang et al., 2008).

The land use update functionality in SWAT provides the opportunity to update land use percentages per sub-basin on a daily basis. The changes are technically realized by changing the fractions of the respective HRUs. A prerequisite of this methodology is that every land use is available in each sub-basin, as no new HRUs can be added during the model run. For this reason, six pixels of the land use map are modified in those sub-basins that did not contain every land use class, to guarantee that every land use class is present in each sub-basin. The change of the land use distribution as derived from the land use scenario is implemented by changing the fraction of the HRUs in the respective sub-basin: First, a change factor for each land use class is calculated from the ratio of the land use percentages in the scenario and the original 2009/10 classification in each sub-basin. Second, each HRU fraction of the respective land use in the sub-basin is multiplied with this change factor, so that HRUs are consistently changed in proportion to their original size. Third, to prevent an implicit change of the original soil and slope class distributions, the fractions of the changed HRUs are modified within the constraint that the original soil and slope class distributions and the changed land use distribution are preserved within each sub-basin. This optimization of HRU fractions is possible, as there is usually more than one HRU per land use class. In our study, the optimized values deviate less than 0.42% from the original slope distribution, less than 0.08% from the original soil distribution, and less than 0.001% from the updated land use distribution in each sub-basin and time step.

The integration of dynamic land use change in SWAT requires the specific land use fractions in each sub-basin for every update time. Hence, all annual land use projections provided by SLEUTH on a 25 m × 25 m grid are used to calculate the percentage of each land use in every sub-basin. Then these percentages are modified according to the model setup for the vegetation land use classes (splitting rules for the mixed cropland class and the shrubland class, Table 1). Furthermore, the urban land use class is split up into high and medium density areas. As SLEUTH does not provide different urban density classes (Table 1), the sub-basin specific proportion of urban medium and urban high density as derived from the 2009/10 land use classification is preserved in the future scenario. The annual SLEUTH land use scenario projections correspond to the cropping year (June to May), so that the HRU fractions are updated on 1 June in each year of the scenario period between 2010 and 2028 with the respective land use for the cropping years 2010/11 to 2028/29. The annual increase of urban area in sub-basin 24 that is derived from the development plan of Lavasa is updated on 1 January during the development phase between 1 January 2009 and 1 January 2022 (completion). By this means, the grid-based SLEUTH projections are transferred to sub-basin specific land use updates, are combined with the development plan for Lavasa, and are dynamically integrated with the SWAT scenario model run.

2.4. Land use and climate change scenarios

In a first step the effects of one business-as-usual land use change scenario (based on SLEUTH and the Lavasa development plan) on hydrology are analyzed using a baseline climate for the scenario period (2009 to 2028). For this baseline climate we use the measured weather data from 1989 to 2008. In a second step the impacts of the developed land use scenario are analyzed for different climate conditions to assess the effect of dynamic land use changes under possible future climates. Therefore, three additional climate scenarios are used in combination with the business-as-usual land use scenario (Table 2). The first is based on the IPCC scenario A1B (Nakićenović et al., 2000). For the IPCC climate conditions we use regional climate model data (COSMO-CLM driven by ECHAM5/MPIOM) that have been downscaled in a previous study (Wagner et al., 2015). The data show a long-term trend for the 21st century of 0.29 °C and 0.25 °C per decade in maximum and minimum temperatures, respectively. However, the used near-term scenario period (2009–2028) does not differ strongly from the baseline period 1989–2008 (mean temperature deviation +0.24 °C, mean catchment rainfall deviation +21 mm; Table 2). The majority of temperature and rainfall values are well within the range of observed values of the baseline (only one annual rainfall sum deviates more than one standard deviation from the mean annual rainfall). As these differences for the evaluated near-term scenario period (2009–2028) are rather small and as one climate realization is rather limited with regard to representing a range of possible future climate realizations, we use two more extreme, synthetic climate scenarios that provide an insight into the theoretic impacts of land use changes under extreme climate conditions. These scenarios are based on the combination of 20 years of dry and wet conditions using the driest (2000: 1617 mm) and the wettest year (2005: 3895 mm) of the baseline period, respectively. With these scenarios we are aiming at deriving the theoretical range of climate influences. In comparison to the baseline and IPCC climate conditions these scenarios do not have an inter-annual climate variation. Therefore, the analysis of their hydrologic impacts reveals the single effect of the land use changes (in dry and wet years).

2.5. Model validation and assessment of changes

To test the performance of the SLEUTH model, land use of 2009/10 is projected and compared to the remote sensing based classification of 2009/10. In the validation model run the same urban model parameters as in the scenario model runs are used (taken from KantaKumar et al., 2011), whereas non-urban land use transition rules are derived from the change between the land use classifications 1989/90 and 2000/01, so that the model setup is independent from the 2009/10 classification

Table 2
Rainfall and temperature characteristics of the applied climate scenarios.

	Climate scenario			
	Baseline (1989–2008)	IPCC A1B (2009–2028)	Dry (repetition of driest year 2000)	Wet (repetition of wettest year 2005)
Mean and (standard deviation) of annual catchment rainfall (mm)	2420 (660)	2441 (398)	1617 (−)	3895 (−)
Range (min.–max.) of monthly catchment rainfall (mm)	0–1631	0–1438	0–569	0–1452
Mean and (standard deviation) of mean annual min. and max. temperature in Pune (°C)	17.8 (0.40) 31.6 (0.39)	18.1 (0.30) 31.8 (0.35)	17.3 (−) 31.8 (−)	17.5 (−) 31.6 (−)
Range (min.–max.) of mean monthly min. and max. temperature in Pune (°C)	8.1–24.3 26.5–38.7	9.3–23.6 26.6–38.6	8.1–22.9 27.9–38.6	10.2–23.3 27.2–37.9

that is used for validation. Additionally, the relative operating characteristic (ROC), which is commonly used for land use model evaluation, is calculated to compare predicted urban growth with actual growth (Pontius and Schneider, 2001; Wu et al., 2009).

The SWAT model performance is evaluated by comparing modeled and measured daily discharge data at four river gauges (G1 to G4, see Fig. 1) during rainy seasons between 2001 and 2007. For this validation the baseline model with the static land use representation of 2009/10 and the described parameterization is used. Since a more detailed validation of streamflow dynamics is available in Wagner et al. (2012) only percentage bias and Nash-Sutcliffe efficiency (Nash and Sutcliffe, 1970) are shown here. The classification of the quality of these indicators follows Moriasi et al. (2007).

Hydrologic changes are derived for each climate condition (Table 2) separately by comparing the model outputs of the dynamic land use scenario model run to the static land use baseline model output using the same weather data in both runs. The nonparametric Wilcoxon–Mann–Whitney test is used to test if the annual (or monthly) water balance components resulting from the static land use model run on the one hand and from the dynamic land use model run on the other hand are from the same population.

3. Results

3.1. Model validation

On the catchment scale, the performance of the SLEUTH model is reasonable (Fig. 2) with a slight overestimation of urban area by +1.5% of the catchment area, an underestimation of agricultural areas by −2.1% (−2.3% rice, −0.6% sugarcane, +0.7% mixed cropland), and a deviation by +2.7% for semi-natural areas (+13.5% grassland, −6.4% shrubland, −4.4% forest). The larger deviation in the semi-natural classes can be attributed to the confusion between these classes, which are a continuum and have been hard to distinguish in the land use classifications (Wagner et al., 2013). The slight increase of water area by 0.3% of the catchment area is not predicted as water area remains constant during the SLEUTH model run. In the classified images, 1.7% of the catchment area account for the class bare soil, which is not simulated by SLEUTH. On the sub-basin scale, the mean absolute deviation is smaller than 5% for the aggregated classes with 2.4% in urban, 3.3% in agricultural (2.9% rice, 1.0% sugarcane, 1.5% mixed cropland), 4.7% in semi-natural (14.1% grassland, 8.4% shrubland, 4.8% forest), and 0.6% in water areas. The reasonable performance for modeling urban growth is also supported by an ROC value of 80%, which is within the range for a reliable precision (70–90%, Wu et al., 2009) and obviously better than a random prediction (50%).

The SWAT model validation based on the available daily rainy season discharge data results in Nash-Sutcliffe efficiencies of 0.68 and 0.67, and a percentage bias of +4% and +24% at the river gauges G1 and G4 (Fig. 1), respectively. According to comparative values given in Moriasi et al. (2007), the performance can be classified as good (G1) to satisfactory (G4). Model performance in the highly managed sub-catchments G2 and G3 depends strongly on dam management, which is assumed constant during rainy season and does therefore not account for more complex dam operations.

3.2. Future land use change

The hybrid land use scenario that combines the business-as-usual projections from SLEUTH with the Lavasa development plan results in increasing urban area (from 10% to 18%) and decreasing semi-natural area and cropland between 2009 and 2028 (Table 3). Due to the exclusion of water areas in the SLEUTH modeling, water areas remain unchanged. On the sub-basin scale, the changes are more pronounced. In sub-basin 4 at the urban fringe of Pune modeled urban areas increase from 47.1% to 70.2%, while agricultural areas (26.5% to 12.5%) and semi-natural areas (26.0% to 16.9%) decrease. In sub-basin 24 that includes the Lavasa construction site land use change is also dominated by an increase of urban area (0.7% to 12.9%), but losses are mainly found in semi-natural land (from 83.9% to 72.0%) due to a major decrease of forests (Table 3).

3.3. Hydrologic impacts of dynamic land use change

Comparing model outputs of the baseline climate and land use to model outputs of baseline climate and dynamic land use results in relatively small (<10 mm), not significant changes in the annual water balance components on the catchment scale. These small differences are mainly due to large unchanged areas in the upper catchment and compensating effects on the large scale. Thus, the following analysis is focused on the sub-basin scale, i.e. sub-basin 4 (urban fringe) and 24 (Lavasa), where impacts on the water balance components are more pronounced.

In sub-basin 4 land use changes induce a continuous decrease in annual evapotranspiration (ET) up to a maximum of −53 mm (−7.0%) in 2028 (Fig. 3). On average annual water yield (WY) increases with a maximum increase of +10 mm (+4.5%) in 2023, but also years with smaller differences can be observed (Fig. 3). In both cases no statistically significant differences between the annual values of all 20 years can be found, which also results from the fact that differences are small in the first years. In sub-basin 24 the impacts on the annual scale are comparatively smaller. In most years

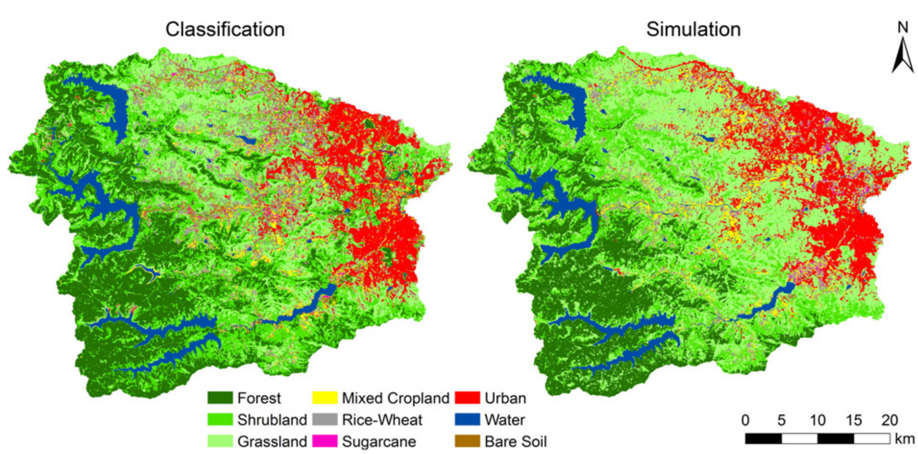

Fig. 2. Comparison of the SLEUTH simulation and the land use classification for 2009/10.

Table 3
Land use changes during the scenario run between 2009 and 2028 given as percentage of the catchment/sub-basin area.

Land use	Catchment	Sub-basin 4 (urban fringe)	Sub-basin 24 (Lavasa)
Forest	−0.3%	−0.8%	−8.3%
Shrubland	−2.6%	−2.9%	−3.4%
Grassland	−1.4%	−5.4%	−0.3%
Cropland	−3.6%	−14.0%	−0.3%
Water	0.0%	0.0%	0.0%
Urban medium density	+6.0%	+15.6%	+9.7%
Urban high density	+1.9%	+7.5%	+2.5%

a slight decrease in ET (−5 mm maximum in 2027) and an increase of WY (+3 mm maximum in 2025) can be observed (Fig. 3). These small impacts result from opposed seasonal impacts that average out on the annual scale, so that the analysis is carried out on a finer temporal resolution in the following section.

On a monthly time scale more distinct differences in ET and WY are resulting from the continuous land use changes (Fig. 4). Minor impacts in the first years increase to maximum impacts in the last few years in both sub-basins. Fig. 4 shows that the different land use changes in the two sub-basins lead to a different monthly pattern of hydrologic impacts. While WY increases in both sub-basins at the beginning of the monsoon season, the magnitude of the increase and the impacts on ET differ. In sub-basin 4 the impact on ET is more pronounced. Evapotranspiration increases in the post-monsoon period (Oct–Nov) and decreases in the rest of the dry season (Dec–May). Water yield increases by up to +7.6 mm and ET decreases by up to −15.1 mm with maximum differences in June 2027 and February 2028, respectively (Fig. 4). However, only the changes of ET in the dry season months February ($p < 0.01$) and March ($p < 0.001$) are significant. The monthly pattern in sub-basin 24 differs from the pattern in sub-basin 4 (Fig. 4). Compared to sub-basin 4, an even more pronounced peak increase of WY at the beginning of the monsoon season can be observed in sub-basin 24 (up to +11.0 mm in June 2025, Fig. 4). But these changes are small in comparison to the mean WY of the model run without land use change of about 390 mm and

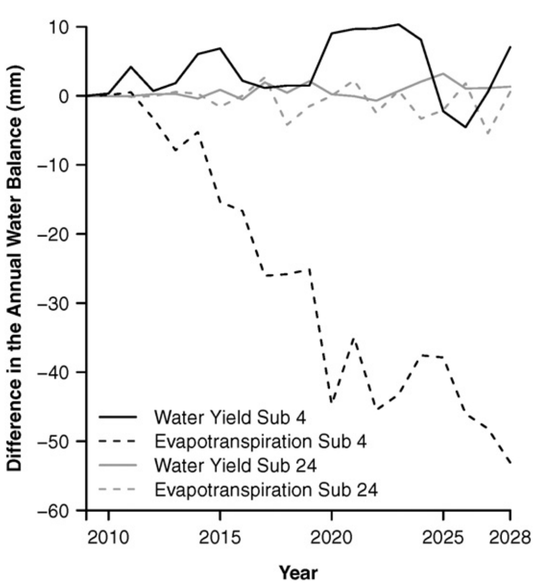

Fig. 3. Annual impacts of land use changes in sub-basin 4 and sub-basin 24 on water yield (solid line) and evapotranspiration (dashed line) for baseline climate conditions, derived by calculating the difference between annually aggregated outputs from model runs with dynamic and static land use representation.

are not significant. However, the decrease of ET is most pronounced in December ($p = 0.081$) with a maximum −5.8 mm in 2024. Moreover, with an increase of the magnitude of land use changes the seasonal pattern becomes more pronounced towards the end of the scenario period (Fig. 4).

3.4. Hydrologic impacts of dynamic land use change under different climate conditions

The analysis of the impacts of the dynamic land use change scenario under the four different climate conditions is exemplarily shown for sub-basin 4, where both WY and ET are affected by land use changes. In all climate conditions the dynamic land use change scenario leads to a decrease in evapotranspiration (changes between −33 mm and −63 mm in 2028) and in most years to slight increases in water yield (changes between −1 mm and +21 mm in 2028) on the annual time scale (Fig. 5A). The decrease in ET is only significant in the dry scenario ($p < 0.05$), whereas the changes in WY are not significant. The largest decrease of ET (−67 mm in 2027) and increase of WY (+21 mm in 2028) are found under dry climate conditions, whereas the smallest differences are observable in wet climate conditions (absolute changes in WY < 5 mm and absolute changes in ET < 33 mm in all years). Annual WY and ET of the baseline repetition and the IPCC A1B scenario are mostly in-between the two more extreme dry and wet scenarios. However, both baseline and IPCC A1B scenario show more variability in the reaction to land use changes. These inter-annual variations in WY and ET are mainly due to inter-annual climate variations, as the extreme dry and wet scenarios show a more continuous and less variable response to land use changes. The two extreme climate conditions (dry and wet) use the looped weather data of one year and hence inter-annual climate variations are excluded (Fig. 5A).

On the monthly scale, the averaged monthly patterns (Fig. 5B) show that the seasonal patterns of the land use change induced differences are stable and preserved under IPCC A1B climate change conditions as well as in case of extremely wet years. The peak WY difference in June (+2.3 mm) and the lower ET in the second part of the dry season are also preserved in extremely dry years (between −4.5 mm and −7.7 mm from November to March). However, in dry conditions WY also increases in all rainy season months (between +1.2 mm and +2.3 mm from June to September) and the post-monsoon increase of ET is less pronounced (+0.8 mm) and limited to October. Similar to the baseline climate, the decreases in ET are only significant ($p < 0.01$) in February and March. In relative terms the impact on the seasonal courses of the water balance components are more pronounced with regard to the significant decrease of ET in the dry season (between −19.8% and −25.2% in March), whereas the increase of water yield at the beginning of the monsoon is less pronounced (between +1.8% and +9.3% in June) and not significant in all scenarios.

4. Discussion

4.1. Future land use scenario

The applied land use change scenario is based on the observed trends of the past and includes additional planned land use changes. The main driver of land use change in the study area is urbanization. As compared to the previous, observed development between 1989 and 2008 (Wagner et al., 2013), the scenario shows faster urbanization in the catchment area (past: +5%, scenario: +7.9% of the catchment area). This non-linear development is possibly due to the S-curve growth as implemented in SLEUTH as well as due to the new construction of Lavasa. Although the magnitude of urban growth might have been slightly overestimated as indicated by the validation of the SLEUTH model, the result is generally reasonable as it corresponds well with the rapid socio-economic development of the region. A major difference to the developments of the past is the decrease of agricultural area in the scenario, whereas agricultural area has increased in

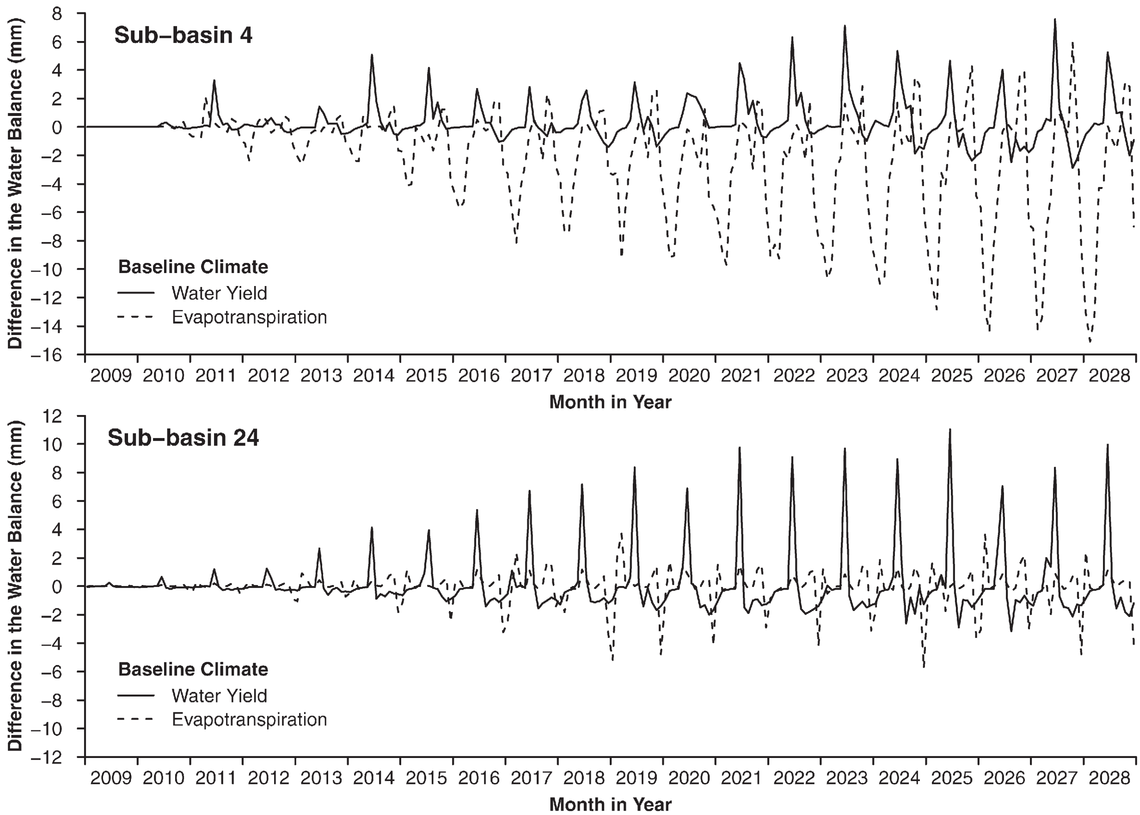

Fig. 4. Hydrologic impacts of continuous land use changes in sub-basins 4 and 24 on the monthly time scale for baseline climate conditions, derived by calculating the difference between outputs from model runs with dynamic and static land use representation.

the past (by −3.6% and +3.8% of the catchment area, respectively). The future decrease seems reasonable if agricultural areas at the fringes of Pune are converted to urban areas. Semi-natural areas decrease in a less pronounced way in comparison to the past (past: −9.1%, scenario: −4.3% of the catchment area), as the pressure from the expanding agricultural areas ceases in the scenario. A possible overestimation of agricultural loss is also indicated in the validation of the SLEUTH model. Other alternatives for the future development of agriculture in the study area would be a relocation of agricultural areas or an intensification of management practices on the remaining agricultural fields. However, to model agricultural intensification with SLEUTH, it would have been necessary to have more detailed land use information to separate agricultural classes of different management intensities. This information has not been available to this study. To model relocation of agriculture with SLEUTH, similar land use change probabilities (e.g., from grassland to agriculture) would have been needed to be observed in the past, which is also not the case. It seems likely that some agriculture is relocated, but a complete compensation of the agricultural losses within the catchment is less probable due to the rapid rate of urbanization. The projected loss of agricultural land is also in agreement with the general loss of agricultural land in developing countries, calculated by Döös (2002). Hence, within the constraints of the SLEUTH model the scenario provides one possible and justifiable projection of future land use development in the study area.

The sub-basin analysis shows that the land use class that is converted to urban area differs across the catchment area. Whereas primarily agricultural area is converted at the fringes of the city (e.g., sub-basin 4), semi-natural areas are converted to urban areas in the developed areas of the Western Ghats (sub-basin 24; Table 3). The assumptions made for the implementation of the Lavasa development plan in the land use scenario are on the one hand conservative regarding its spatial implementation (areas with no specific urban use in the last phase remained unchanged) and on the other hand strict regarding the temporal implementation of the development schedule. However, the Lavasa development plan is under public discussion and the progress of the project is already not in accordance with the schedule. Therefore, the employed scenario implementation provides an overview of the potential impacts of the project.

4.2. Impacts on the water balance

In this study, impacts on the water balance are analyzed on different temporal scales and under different climate conditions for the entire catchment and two sub-basins. The impacts are relatively small on the catchment scale. This is a commonly known effect, as different effects can balance each other (Fohrer et al., 2001) and sometimes changes are too small to be observable on the catchment scale (Ashagrie et al., 2006). In our study, large parts of the upper Mula and Mutha Rivers catchment have experienced relatively little land use changes. At the same time, these areas receive the greatest amounts of rainfall and hence have a disproportionately high impact on the catchment's water balance.

The focus on two sub-basins indicates more pronounced and different effects on the sub-basin level (Fig. 4) resulting from the different land use changes in the two sub-basins. Seasonal changes in response to land use change have been identified in several studies (e.g., Costa et al., 2003; Guo et al., 2008; Koch et al., 2012). Kim et al. (2013) have found that urban growth leads to increased stream flow in wet periods and decreased streamflow in dry periods in a small catchment in South Korea. The analysis on a monthly time scale in our study reveals seasonal impacts as well. This is in accordance with previous findings for past developments in the catchment that indicate an increase of ET in the dry season as a consequence of an increase of irrigation agriculture and an increase of water yield in the rainy season as a consequence of urbanization (Wagner et al., 2013). While the effect of urbanization is the same in our future assessment, the decrease of agriculture in the

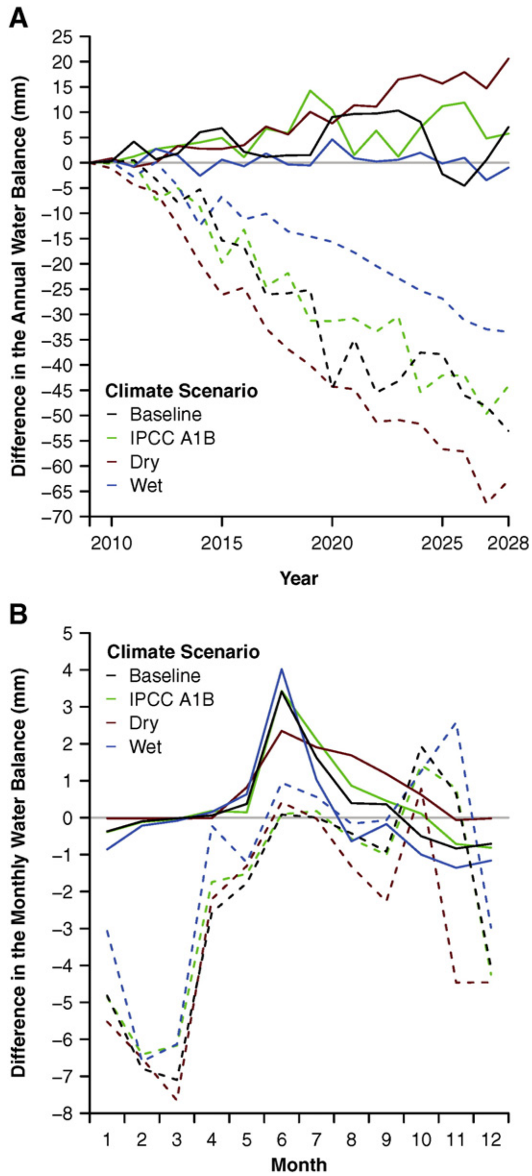

Fig. 5. Annual (A) and monthly (B) impacts of land use changes in sub-basin 4 on water yield (solid line) and evapotranspiration (dashed line) under different climate conditions, derived by calculating the difference between annually (A) and monthly (B) aggregated outputs from model runs with dynamic and static land use representation.

scenario projection leads to a decrease of ET in the dry season. At the annual scale general trends are discernible, but seasonal differences are masked (Fig. 5). Water yield increases at the beginning of the rainy season by up to +7.6 mm (+6%) in sub-basin 4 and +11.0 mm (+1%) in sub-basin 24 (Fig. 4). An increase of peak discharge due to urbanization has been found in other studies of land use change impacts (e.g., Du et al., 2012; Ott and Uhlenbrook, 2004; Tavakoli et al., 2014). The limitation of the increase to the beginning of the monsoon season in our study is due to the fact that the soils are dry and can take up larger amounts of water at the onset of monsoon. Impervious urban areas that increased during the study period seal the soils and consequently cause differences in runoff. In the later monsoon months the soil water content of pervious areas is higher and the capacity to take up rainwater is smaller, resulting in a fast runoff response to rainfall. Consequently, this response is similar to the fast runoff resulting from impervious areas. Thus, soil sealing has less impact on runoff in the later monsoon months. Also, the increase in WY at the beginning of the rainy season is more pronounced in the Lavasa area (sub-basin 24) as compared to the fringes of Pune (sub-basin 4). This difference is mainly due to the higher amounts of rainfall in the Western Ghats (average rainfall sum in June of 692 mm in sub-basin 24 as compared to 236 mm in sub-basin 4).

Changes in evapotranspiration show a clear seasonality (Fig. 5B). ET mainly decreases in the dry season months. This is a consequence of the decrease in agriculture (sub-basin 4) and forests (sub-basin 24). However, the impact on ET during dry season is not as pronounced in sub-basin 24 (up to −5.8 mm per month) as in sub-basin 4 (up to −15.1 mm per month), due to the fact that less (irrigation-intensive) agriculture is present and affected in this sub-basin. While a decrease of ET usually goes along with an increase in WY, this is not the case in sub-basin 4, because ET mainly relies on external irrigation water, which is taken from the rivers. The slight increase of ET in October and November can be attributed to low ET from agricultural fields at this time of the year (1.6 mm mean ET per day for mixed cropland in October), when the Kharif crop is harvested and the Rabi crop is sown. Urban areas that replace cropland have a higher ET at this time of the year (3.5 mm mean ET per day in October), originating from the unsealed, vegetated urban areas.

In those sub-basins where urban area increases at the expense of agriculture the observed seasonal changes lead to an increase of water that is lost from the sub-basin in the rainy season (increase in WY), while less water is used by agriculture in the dry season (decrease in ET). In comparison to past developments, when an expansion of agricultural area has led to an increased water demand (Wagner et al., 2013), the future projections show that the conversion of cropland to urban area has a balancing effect on the annual water balance, assuming no change in agricultural water demand due to intensifying agricultural practices or changing crop types. The increased runoff at the beginning of the rainy season that can be observed in both sub-basins leads to a supply of more water (cumulative increase of WY in June: +68 mm in sub-basin 4, +119 mm in sub-basin 24) to downstream water users at less favorable times, as water availability is already sufficient in the rainy season.

Hydrologic impacts of land use change are different under different climate conditions (Quilbé et al., 2008). The course of the seasonal impacts of land use change on the water balance components at the urban fringe of Pune is stable under different climate conditions (Fig. 5B). But the impacts are more pronounced under dry conditions (max. change in ET −67 mm, max. change in WY +21 mm) than under wet conditions (max. change in ET −33 mm, max. change in WY +5 mm; Fig. 5A). Hence, in a possible future climate with more extreme dry years or droughts induced by climate change, land use changes may have a larger impact on water balance components as compared to the present climate. However, a model run with IPCC A1B climate change input data for the period 2009–2028 indicates that land use change has similar effects (Fig. 5), as the actual differences to the current climate are relatively small in this near future projection. Thus, an exacerbation of land use change impacts on hydrology is more likely, if more extremely dry years occur. In the long-term climate projection up to 2079 extremely dry years are not projected to be significantly increasing as compared to the current climate (Wagner et al., 2015). On this basis, it can be concluded that the land use change scenario in this study would result in similar impacts under current and possible future climates.

Although the importance of a dynamic representation of land use changes in hydrologic modeling studies is recognized (Fohrer et al., 2005), land use changes are rarely implemented dynamically in hydrologic models (Chiang et al., 2010; Chu et al., 2010; Pai and Saraswat, 2011). Our results indicate a successful integration of dynamic land use changes into the hydrologic model SWAT. With an increase of the magnitude of land use changes the magnitude of the hydrologic impacts increases as well (Figs. 4, 5A). Therefore, the dynamic representation of land use changes allows for a temporally explicit analysis of land use change impacts, underlining similar findings by Chiang et al. (2010). Moreover, for a static representation of land use change Huisman et al.

(2009) have shown that the predictions of SWAT are in agreement with nine other hydrologic models with regard to the direction of the impact on streamflow. Additionally, the importance of a dynamic representation of land use changes has also been shown for another hydrologic model (Chu et al., 2010). Therefore, it is likely that our findings are independent of the hydrologic model employed.

5. Conclusion

This study demonstrates the importance of a dynamic integration of land use change in hydrologic models. Integrating the projections of a land use model with a hydrologic model has the advantage of explicitly assessing the temporal dynamics of water fluxes. Seasonal impacts are revealed that are otherwise masked on broader temporal scales, like the increase of water yield by up to +11 mm at the beginning of the monsoon season in this study. Most prominent is the continuous decrease of evapotranspiration (−53 mm (−7.0%) in 2028), which results from the loss of irrigation agriculture and can mainly be attributed to less evapotranspiration (up to −15.1 mm per month) in the dry season. The incorporation of climate change scenarios shows that the hydrologic impacts of dynamic land use changes would be similar under possible future climates. Only if more extreme dry years occur, an exacerbation of the impacts of land use changes can be expected.

Notably, the SLEUTH land use projections indicate that the past trend of increasing agricultural area turns in the scenario period, mainly because of the urban growth at the fringes of the city of Pune (+23.1%), where agricultural area is lost (−14%). The integration of development plans for the new city Lavasa in the Western Ghats has been proven suitable to quantify future land use changes in the respective subbasin. The new city (+12.2% urban area) is constructed at the expense of forests (−8.3%) and shrubland (−3.4%), leading to the increase of water yield at the beginning of the monsoon season.

For the first time SLEUTH modeling results have been dynamically integrated with the SWAT model. Both models show a reasonable performance in the study area. Moreover, the steady increase of the impacts on the water balance components with the increase of land use changes indicates a successful implementation of dynamic land use changes with the hydrologic model. As the SWAT and the SLEUTH model are popular in their respective disciplines and are used in many different regions, there is a high potential for transferring the applied methodology to other areas worldwide.

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