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Comparing the effects of dynamic versus static representations of land use change in hydrologic impact assessments

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A B S T R A C T

Representations of land use change in hydrologic impact assessment studies mostly rely on static land use information of two points in time, even though the availability of dense time series of land use data allows for the incorporation of dynamic land use changes. We compare the hydrologic impacts of dynamic land use change assessments to those of static land use change assessments. These effects are illustrated with the help of two land use scenarios applied to a hydrologic model of a rapidly developing meso-scale (2036 km^2) catchment upstream of Pune, India. The results show that a linear dynamic land use development could be better approximated with the static approach than a non-linear development. An analysis of the impact of the frequency of land use updates indicates that the prediction of non-linear land use change impacts already improves substantially when frequent land use information every five to nine years is used.

Keywords:
Land use change
Impact assessment
Hydrologic modeling
SWAT
India

1. Introduction

Land use and land-cover change is widely recognized as one of the most important components of global environmental change (Lambin et al., 2001; Turner et al., 2007). Land use and hydrology depend on and affect each other (Foley et al., 2005; Wagner and Waske, 2016). Consequently, the assessment of land use change impacts has become a major research issue in hydrology in this century (DeFries and Eshleman, 2004; Stonestrom et al., 2009). To assess the impacts of land use change on water resources, typically hydrologic models are used (Huisman et al., 2009).

Even though land use change occurs gradually, most hydrologic modeling studies do not represent land use change as a dynamic process. Mostly, a static representation of land use is used for one model run. To analyze the impacts of land use change often a so called delta approach is applied, in which the results from two model runs for a given time frame that are based on different static land use information (e.g., two land use maps) are compared. The delta approach is used with many different hydrologic models, e.g., WaSiM-ETH (Niehoff et al., 2002), MIKE SHE (Im et al., 2009), and SWAT (Bieger et al., 2015). Moreover, the methodology is applied in many different parts of the world, e.g., in the USA (Miller et al., 2002), China (Li et al., 2009), Germany (Klöcking and Haberlandt, 2002), and Kenya (Mango et al., 2011). A dynamic integration of land use change with hydrologic models is rarely found in the literature. Few examples are dynamic integrations of six land use maps (Chiang et al., 2010) or simulated annual land use maps (Chu et al., 2010; Lamparter et al., 2016; Wagner et al., 2016) in hydrologic modeling studies. Moreover, agricultural land use changes are dynamically integrated in SWAT modeling studies by Guse et al. (2015) and Mehdi et al. (2015) as well as in the integrated simulation system DANUBIA (Barthel et al., 2012; Lenz-Wiedemann et al., 2010). As the importance of a dynamic representation of land use changes has been recognized and emphasized several times (Castillo et al., 2014; Fohrer et al., 2005; Pai and Saraswat, 2011; Wagner et al., 2016), the rare consideration of dynamic land use changes in hydrologic modeling studies may be attributed to past constraints by model capabilities as well as to a limited

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availability of frequent land use information.

Today, these constraints should not hinder the integration of dynamic land use changes. Hydrologic models are available that are capable of integrating dynamic land use changes, e.g., a dynamic integration in SWAT is possible since 2010 (Chiang et al., 2010) and Chu et al. (2010) have integrated dynamic land use changes in the distributed hydrological model DHSVM. Moreover, given the increasing availability of satellite imagery suitable for land use monitoring (e.g., the opening of the Landsat archive (Kovalskyy and Roy, 2013), start of the ESA Sentinel missions (Berger et al., 2012)) a database is available that has the potential to provide frequent land use information. In addition, well-established land use change models such as CLUE (Verburg and Overmars, 2009) and SLEUTH (Clarke and Gaydos, 1998) can provide future predictions of land use change with a good temporal resolution (e.g., annually). Hence, for studies of recent as well as possible future land use change impacts, frequent land use information is available so that land use changes can be represented dynamically.

Particularly, regions that traditionally suffer from limited data availability benefit from the described availability of frequent land use information. For example, many parts of India exhibit data limitations and dynamic land use changes, mainly due to rapid socio-economic development and urbanization (DeFries and Pandey, 2010; Lambin et al., 2003). Moreover, water resources are seasonally limited in India, so that land use changes that lead to a further shortage of water resources have more severe impacts as compared to countries where water resources are not limited. Hence, India is a country where the accurate assessment of the impacts of dynamic land use changes is particularly important.

In summary, two methodologies to assess impacts of land use changes on water resources are currently used in the literature: (i) The delta approach is a straight forward and comparatively simple static assessment, in which the output of model runs for the initial and final land use are compared. (ii) The assessment of land use change impacts with a dynamic integration of land use changes in a model run, in which the model run with the dynamic land use is compared to the model run with the initial land use. The dynamic approach can also be regarded as a sum of many delta approaches calculated for each land use update. Therefore the dynamic approach represents the changes in a more realistic way, but also involves a higher workload. It is rarely discussed, as to how large the impact of this simplification of a dynamic process to a static representation is. Regarding the involved workload when implementing dynamic changes, it would be of particular interest to assess in which situations a static and a dynamic assessment provide similar results and in which situations they differ pronouncedly. Moreover, with regard to data availability and workload, it is crucial how frequent land use data needs to be updated in a dynamic land use change impact assessment. A comparison of the hydrologic impacts derived by static and dynamic representations of land use change could shed light on these issues.

Therefore, we analyze dynamic and static assessments of land use change impacts on water resources in a catchment upstream of a rapidly developing Indian city. The aims of this study are (i) to compare the results of static versus dynamic assessments of land use change impacts for linear and non-linear courses of land use change, and (ii) to evaluate the importance of frequent land use information for hydrologic impact assessment.

2. Materials and methods

2.1. Study area

The Mula and Mutha Rivers catchment upstream of the city of Pune, India, experiences land use changes as a consequence of the socio-economic development and rapid population growth of Pune. The catchment is a source area of the Krishna River, which drains towards the east and into the Bay of Bengal. Major parts of the meso-scale catchment (2036 km^2) are located in the Western Ghats (Fig. 1). Its elevation 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, which is characterized by a pronounced seasonality in rainfall that is generally limited to the summer monsoon. Annual rainfall amounts decrease from approximately 3500 mm yr^{-1} in the western part of the catchment to 750 mm yr^{-1} in the eastern part of the catchment (Gadgil, 2002; Gunnell, 1997). Soils are dominated by sandy clay loams (Food and Agriculture Organization of the United Nations (FAO), 2003).

A land use classification from the year 2009/10 (Fig. 1, Wagner et al., 2013) shows that land use is dominated by forest (25%), shrubland (26%), and grassland (19%), which cover most parts of the more remote, upper catchment. Urban area (10%) is predominantly found in the lower part of the catchment, where the city of Pune and its surrounding settlements are located (Fig. 1). In addition, the newly developed city of Lavasa is being built in the south-western part of the catchment (Fig. 1). Different densities of urban settlements can be differentiated (Fig. 1), which are modeled with different percentages of impervious surfaces (60% for high density and 38% for medium density). Cropland (13%) is mainly found in proximity to water sources (6% of the catchment area is covered by water) and settlements. Typically two crops per year are grown, one rainfed crop in Kharif season (June–October) and an irrigated crop in Rabi season (November–March). A typical crop rotation is to grow rice during Kharif and wheat during Rabi season (rice-wheat rotation 7.5%, Fig. 1). Sugarcane (1,3%) is a perennial plant. The mixed cropland class (3.8%) includes all other agricultural land use types that have been combined due to their diversity and small-scale patchiness (Wagner et al., 2013). It is modeled using the general cropland classes AGRR and AGRL in SWAT (Neitsch et al., 2010) in both cropping seasons. Six major reservoirs are located

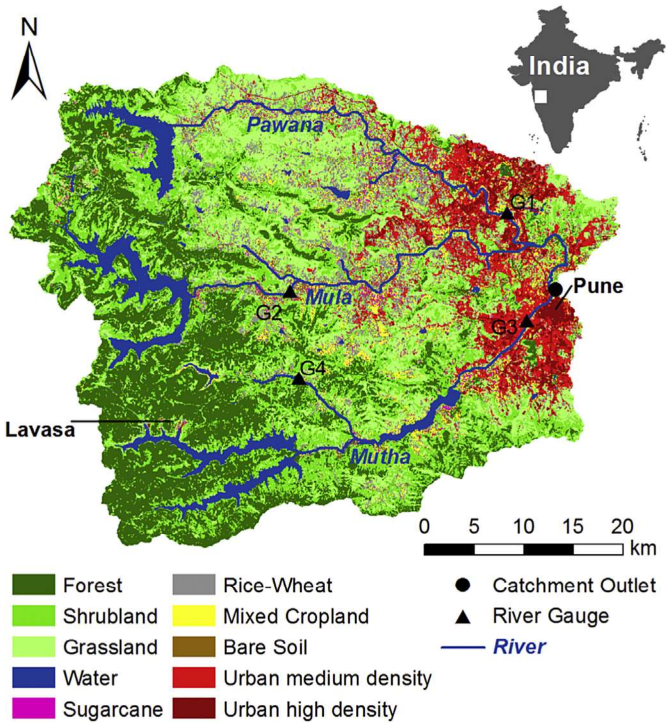

Fig. 1. The Mula and Mutha Rivers catchment depicted with a land use classification of 2009/10. Rice-Wheat refers to a crop rotation for the two cropping seasons per year.

within the study area (Fig. 1, Wagner et al., 2013).

2.2. Land use change scenarios

Two land use change scenarios are employed, which allow for an analysis of static versus dynamic assessments of land use change for different courses of land use change. One of the scenarios shows a linear development (linear scenario, Fig. 2A) and the other a non-linear development (non-linear scenario, Fig. 2B). Both scenarios cover the period from 2009 to 2028 represented by annual land use maps for the cropping years 2009/10 to 2028/29. During the 20 year scenario period urban area (+7.9% of the catchment area) increases and semi-natural area (forest, shrubland and grassland: −4.3%) and cropland (−3.6%) decrease in both scenarios. On the sub-basin level these changes were more pronounced, e.g., +23.1% increase of urban area in sub-basin 4 at the urban fringe of Pune. Two major developments are represented by the scenarios: (i) urban growth at the fringes of the city of Pune and (ii) a new construction site in the Western Ghats (Lavasa, Fig. 1). The linear scenario is available from Wagner et al. (2016). For this scenario general developments from the period 1989/90–2009/10 have been projected to the period 2010/11–2028/29 using the urban growth and land use change model SLEUTH (Clarke and Gaydos, 1998; KantaKumar et al., 2011). To incorporate the new city Lavasa the SLEUTH projections are complemented with an increase of urban area as derived from the Lavasa development plan in sub-basin 24 (Wagner et al., 2016). Consequently, the scenario represents both (i) continued developments of the past and (ii) planned developments for the future. Further details on the linear land use scenario are available in a previous publication (Wagner et al., 2016).

The non-linear scenario (Fig. 2B) has been derived by compressing the temporal development of the linear scenario. It covers the same time period as the linear scenario (2009–2028), but reaches the final land use distribution already in 2018 (Fig. 2). Moreover, it is characterized by a rapidly increasing urbanization rate that reaches its peak by 2014. The non-linear scenario is clearly hypothetical, but it serves the study purpose for which a scenario with a non-linear development is needed. Also, it can be regarded as an extreme type of urban growth, following the typical S-curve growth rate with a decreasing urbanization at the end of the growth cycle (Silva and Clarke, 2002). A high level of comparability to the linear scenario is retained as only the timing of the land use updates is changed (consecutively leaving out 1, 2, 4, 2, and 1 years of intermediate states of land use change), but no other part of the model implementation is changed for the non-linear scenario.

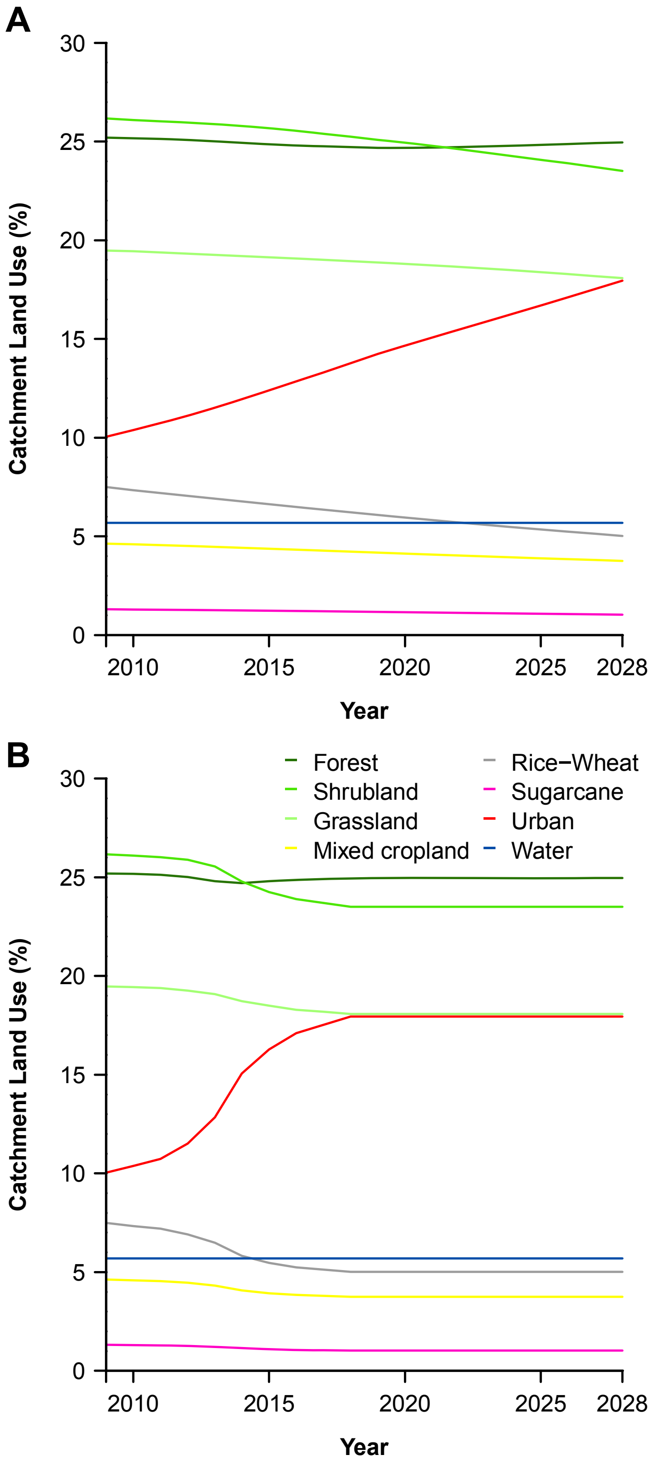

Fig. 2. Course of the catchment's land use percentages in the two employed land use scenarios: A) linear scenario and B) non-linear scenario.

2.3. Hydrologic model

The Soil and Water Assessment Tool (SWAT, Arnold et al., 1998) is a widely-used, open-source, semi-distributed catchment model. Model predictions are based on hydrologic response units (HRUs) representing lumped areas with a unique land use, soil, and slope class combination within a sub-basin. We use the SCS curve number approach (Mockus, 1972) for rainfall excess calculation and the Penman–Monteith equation (Monteith, 1965; Allen et al., 1989) to derive potential evapotranspiration. Most importantly, land use change can be dynamically implemented in the model since version SWAT2009 (Chiang et al., 2010). It can be realized on a daily basis with an update of land use percentages in the sub-basins. Technically, these land use changes are implemented by changing the fractions of the respective HRUs.

Our study is particularly relevant for regions of strong and rapid land use changes. These regions often exhibit limited data availability. We have chosen the SWAT model, as it has proven its applicability in data scarce regions (e.g. Ndomba et al., 2008; Stehr et al., 2008). SWAT's suitability to model hydrology in general (Wagner et al., 2011, 2012) and dynamic land use changes in particular (Wagner et al., 2016) in the Mula and Mutha Rivers catchment has been demonstrated. Moreover, Wagner and Waske (2016) show that simulated patterns of hydrologic variables are reasonably modeled by SWAT as they can explain land use changes in the area. We use the model setup of Wagner et al. (2016) that is based on an ASTER digital elevation model, the digital Soil Map of the World (FAO, 2003), and the multi-temporal land use classification for the cropping year 2009/10 shown in Fig. 1 (Wagner et al., 2013) that is complemented with regionally specific cropping schedules and irrigation schemes (Wagner et al., 2011). Daily weather data for the years 1988–2008 including spatially interpolated rainfall data (Wagner et al., 2012) are used. Moreover, a generalized management scheme for the six major dams in the catchment allows for water storage during rainy season and water release during dry season (Wagner et al., 2011, 2012). This setup results in a model representation of the study area with 25 sub-basins and 733 HRUs. Water fluxes are simulated at a daily time step. Further details on model input data and model setup are available in Wagner et al. (2016).

The applied model parameterization (Wagner et al., 2016) has been evaluated with the available daily discharge data at four river gauges during rainy seasons between 2001 and 2007. The model shows a good to satisfactory performance (Moriasi et al., 2007) indicated by Nash-Sutcliffe efficiencies (Nash and Sutcliffe, 1970) for daily river discharge of 0.68 and 0.67, and a percentage bias of +4% and +24% at the river gauges G1 and G4 (Fig. 1), respectively, which are the gauges where measured discharge is less affected by the management of upstream dams.

2.4. Land use change impact assessment

In this study, we employ SWAT model runs from 2009 to 2028 with different representations of land use change. The land use representation in the model runs is either static (one land use map) or dynamic (land use updates). The two land use scenarios provide annual data on land use changes that serve as an input for the dynamic model runs. The land use changes are dynamically integrated in SWAT by changing the fraction of the HRUs in the respective sub-basin in accordance to the change of the land use distribution in the scenarios (Wagner et al., 2016). Overall, seven model runs are performed to compare the results of different land use change impact assessment methods for linear and non-linear courses of land use change (Table 1). All other model inputs including the weather input, which is a repetition of the measured weather between 1989 and 2008, remain the same. In addition to the model runs with annual land use updates (LU1S1, LU1S2), coarser dynamic representations of land use changes with a land use update every third (i.e. in 2010, 2013, 2016, etc.), fifth, and ninth year are tested for the non-linear scenario (LU3S2, LU5S2, LU9S2). Another model run with a static land use representation using the land use of the final simulation year 2028/29 (LU28) has been carried out for the commonly used delta approach, in which two static land use setups are used for different model runs. Hydrologic impacts are assessed by comparing the model outputs of the dynamic model runs to the static baseline model outputs (LU09). For the delta approach, the model is run with the most extreme change (here: land use of 2028/29; LU28) and is compared to a model run without land use change (here: land use of 2009/10; LU09).

Table 1
Performed model runs with different land use representations.

Land use representation	Land use scenario	Model run abbreviation
Static (2009/2010)	–	LU09
Static (2028/2029)	–	LU28
Dynamic (time step 1 yr)	linear	LU1S1
Dynamic (time step 1 yr)	non-linear	LU1S2
Dynamic (time step 3 yrs)	non-linear	LU3S2
Dynamic (time step 5 yrs)	non-linear	LU5S2
Dynamic (time step 9 yrs)	non-linear	LU9S2

$$Delta\ Change\ V = (V(LU28) - V(LU09))/2, \quad (1)$$

where *V(LU28)* and *V(LU09)* are the cumulative values of a water balance component *V* for the model runs LU28 and LU09, respectively. To derive the cumulative change between 2009/10 and 2028/29 from the delta approach, changes in the water balance components are divided by 2 (formula 1). Otherwise, the delta approach would yield an overestimation of impacts in every year. Assuming a linear change, after dividing the changes by 2, impacts are only overestimated during the first half of the period and underestimate during the second half. Ideally, these over- and underestimations cancel out, so that the cumulative change during the period is approximated. For the dynamic assessments with an annual land use update (LU1S1, LU1S2; Table 1) the cumulative change is derived as the difference to the baseline model outputs (LU09), which can be expressed as:

$$Dynamic\ Change\ V = \sum_{i=2009}^{2028} [V(LUi) - V(LU09)], \quad (2)$$

where *i* represents the land use update time (e.g. year 2012). *V(LUi)* and $V(LU09)$ are the cumulative values of a water balance component *V* for the model runs LU_i and LU09 for the same time period of one year between the current (i) and the next ($i+1$) land use update. Therefore, the assessment of land use change impacts with a dynamic integration of land use changes in a model run can also be regarded as the sum of many delta approaches.

In the coarse dynamic land use model runs (LU3S2, LU5S2, LU9S2), the land use update is performed before its actual date at the beginning of the period that it represents, i.e., if land use information is available every three years, the land use information of 2012 is representative for the period 2011 to 2013, so that the update can be performed in 2011. This implementation leads to an overestimation of impacts before and an underestimation of impacts after the respective date, so that it represents a refinement of the delta approach. We applied this optimized setup for all three model runs with land use updates every 3rd, 5th, and 9th year, respectively.

We focus on the changes in the water balance components evapotranspiration (ET) and water yield (WY). 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).

To evaluate the different land use representations against each other, we use the model runs LU1S1 and LU1S2, which have the highest temporal resolution of dynamic land use change (update on an annual basis) as reference. The underlying assumption is that the finest temporal representation of land use changes yields the most accurate hydrologic results. This is evident when expressing the dynamic assessment as a sum of delta approaches (formula 2). First, we evaluate the delta approach (formula 1) against the dynamic approach (formula 2) for the linear (LU1S1) and non-linear (LU1S2) land use scenario. Second, we compare coarser dynamic assessments of land use change impacts (LU3S2, LU5S2, LU9S2) to the respective dynamic representation of the non-linear scenario (LU1S2).

3. Results

3.1. Comparison to the delta approach

Most pronounced differences are found when comparing the dynamic land use representation to the commonly used delta approach. Fig. 3 shows the cumulative impacts over the 20 year period for the delta approach and for the dynamic assessment with the linear land use change scenario and with the non-linear land use change scenario. Generally, all assessments indicate an increase of water yield (WY) and a decrease of evapotranspiration (ET) when compared to a model run without land use changes (LU09), which is a result of the increase of urban areas (Fig. 2) in most sub-basins. The changes in WY and ET are not equal as irrigation water taken from rivers and reservoirs influences the water balance. In some rare cases (e.g. sub-basin 6) decrease of irrigation agriculture and increase of urban areas thus lead to a decrease of both, WY and ET. The sub-basin pattern resulting from the dynamic assessment of the linear scenario and the delta approach are very similar, whereas the pattern of the dynamic assessment of the non-linear scenario shows stronger impacts in some sub-basins (e.g. 4, 5, 12). The hydrologic impacts are most pronounced at the urban fringe (sub-basin 4, Fig. 3). In this sub-basin, the linear dynamic land use scenario results in a total increase of 42 mm in WY and a decrease of −498 mm in ET between 2009 and 2028, whereas the impacts of the non-linear dynamic land use scenario are larger with an 89 mm increase in WY and a −737 mm decrease in ET. The cumulative ET results for the 20 year period from the delta approach (−507 mm) provide a good estimate of changes in ET (1.8% deviation), when compared to the linear dynamic representation (−498 mm). However, changes in WY are not represented equally well in this sub-basin by the delta approach, as they overestimated the results of the linear dynamic representation by 19.6% (51 mm compared to 42 mm). The results from the delta approach differed even more from the non-linear scenario impacts, which are underestimated by 31.1% (ET) and 43.2% (WY) in sub-basin 4.

This comparison is carried out for all sub-basins to assess how well the linear and the non-linear scenario can be approximated using the delta approach. Fig. 4 shows the percent difference of the results from the delta approach as compared to the two dynamic representations for all sub-basins. Focusing on the linear land use change scenario, the figure indicates that the delta approach provides reasonable approximations for water yield (WY) in a total number of 3 sub-basins and for evapotranspiration (ET) in a total number of 5 sub-basins, indicated by an absolute deviation below 5%. One sub-basin shows an absolute deviation below 5% in both water balance components and in another one the deviation is below 10% for both, WY and ET. Impacts on WY and ET both are overestimated by more than 5% in a total number of 13 sub-basins, and underestimated by more than 5% in a total number of 9 (WY) and 7 (ET) sub-basins, respectively. However, it has to be noted that large percentage differences are often due to small hydrologic impacts. Therefore, sub-basins with small absolute impacts below 5 mm in the dynamic assessments (as shown in Fig. 3) are depicted in white in Fig. 4. These sub-basins are mostly located in the western parts of the catchment that experience only minor land use changes. The approximation of the non-linear scenario results by the delta approach is worse. Only in sub-basin 16 the deviation in ET is below 5% and below 10% in WY. In all other sub-basins the deviation is above 10%, of which the majority are underestimations (WY: 21 sub-basins, ET: 23 sub-basins) and only in a few sub-basins impacts are overestimated (WY: 3, ET: 1). Large differences (>70%) only occur in WY in sub-basin 22 and can also be attributed to small

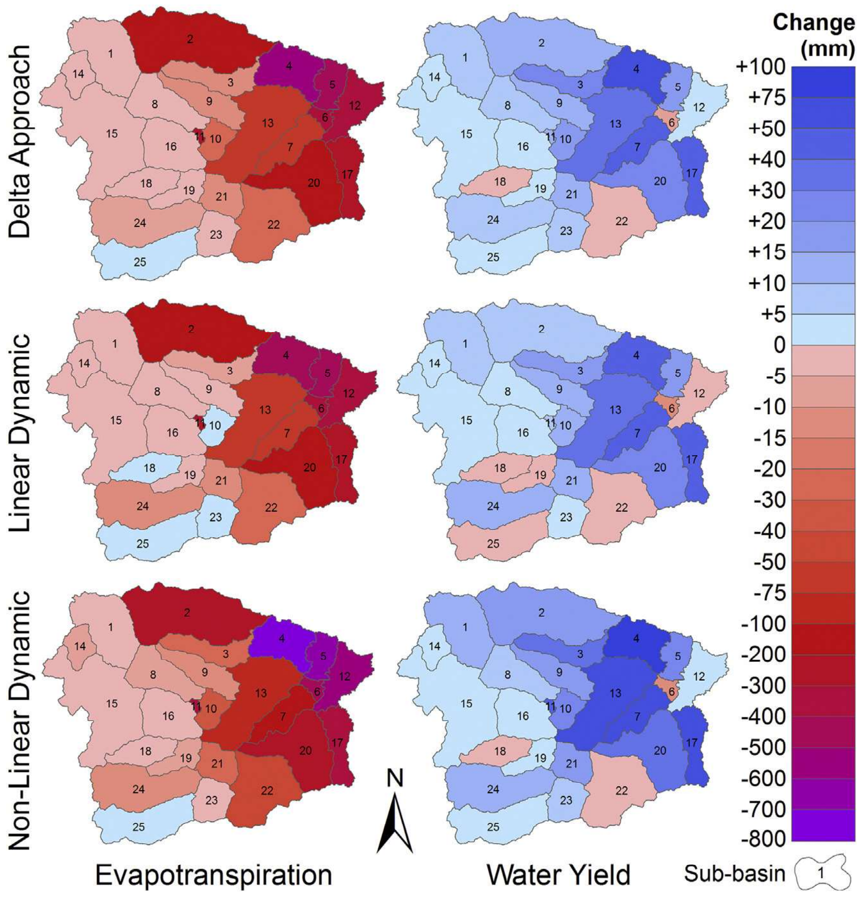

Fig. 3. Cumulative impacts on the water balance components resulting from different land use change impact assessments.

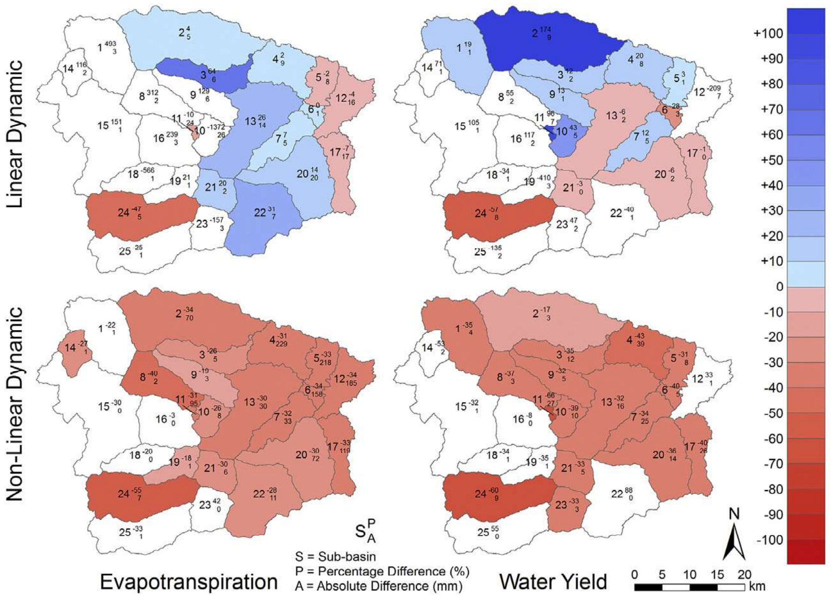

Fig. 4. Over- and underestimation of evapotranspiration and water yield on the sub-basin level resulting from the delta approach. Sub-basins with small absolute hydrologic impacts below 5 mm in the dynamic assessments are depicted in white.

absolute differences (<1 mm) there.

3.2. *Coarser representations of land use change*

The delta approach uses only two land use maps and is the coarsest possible representation of land use change in an assessment of hydrologic impacts. The previous assessment indicated that the delta approach is more suitable to approximate the linear scenario, whereas it deviates stronger from the non-linear scenario (Figs. 3 and 4). This result is also supported by goodness of fit indicators like the mean absolute error (MAE), the root mean square error (RMSE) and the Nash-Sutcliffe efficiency (NSE, Nash and Sutcliffe, 1970) that can be used to calculate how well WY and ET resulting from the dynamic assessments are approximated by the delta approach in all sub-basins. While ET and WY of the linear scenario can be approximate with a RMSE of 10.6 mm and 4.0 mm, and a NSE of 0.995 and 0.931, respectively, the approximation of the non-linear scenario by the delta approach is much worse with a RMSE of 88.3 mm and 13.5 mm and a NSE 0.844 and 0.722 for ET and WY respectively (Table 2). It is expected that results are closer to the dynamic land use representations, if more land use maps are used. Therefore, we approximate the non-linear land use scenario by using three different land use update frequencies with land use updates every 3rd, 5th, and 9th year.

Fig. 5 shows that the frequent updates approximate the dynamic non-linear land use change impacts much better than the delta approach. The results from the 3 and 5 year update model runs are mostly on the same level as the results from the dynamic (annual) land use change model run, whereas the deviation of the model run with a 9 year update frequency is a bit larger. Table 2 supports these results, as for ET the RMSE and NSE of the approximation by LU3S2 (5.6 mm, 0.999) and LU5S2 (5.5 mm, 0.999) are on the same level and better than those of LU9S2 (25.0 mm, 0.988). However, for WY LU9S2 (RMSE: 5.1 mm, NSE: 0.960) slightly outperforms LU5S2 (RMSE: 6.9 mm, NSE: 0.927), but the mean absolute error is the same (MAE: 2.6). In general, this assessment supports the expectation that a higher frequency of land use updates would yield hydrologic impacts that are closer to those impacts of dynamic real world changes (e.g. on an annual time scale). In this study, the delta approach represents an update frequency of 20 years. The good approximation by the 9 year update model run shows that doubling the update frequency already improves the estimation substantially.

Table 2
Approximation of dynamically assessed sub-basin water balance changes by the delta approach and coarser land use representations as indicated by mean absolute error (MAE), root mean square error (RMSE), and Nash-Sutcliffe efficiency (NSE).

Evapotranspiration	MAE (mm)	RMSE (mm)	NSE
LU1S1 approximated by Delta[a]	7.6	10.6	0.995
LU1S2 approximated by Delta	50.3	88.3	0.844
LU1S2 approximated by LU3S2	2.7	5.6	0.999
LU1S2 approximated by LU5S2	3.0	5.5	0.999
LU1S2 approximated by LU9S2	13.5	25.0	0.988
Water Yield			
LU1S1 approximated by Delta	3.0	4.0	0.931
LU1S2 approximated by Delta	8.9	13.5	0.722
LU1S2 approximated by LU3S2	2.1	4.5	0.969
LU1S2 approximated by LU5S2	2.6	6.9	0.927
LU1S2 approximated by LU9S2	2.6	5.1	0.960

[a] Delta is defined as the impacts of (LU28 − LU09)/2.

4. Discussion

Some previous studies have integrated dynamic land use changes in SWAT and found that these have a substantial impact on hydrology (Chiang et al., 2010; Pai and Saraswat, 2011; Wagner et al., 2016). However, none of these studies has compared these impacts to the impacts of coarser land use representations or to the delta approach, which is still the common method in hydrologic impact studies focusing on land use change. This approach only allows for the analysis of aggregated values, as only two land use maps are used and two model runs with different land use maps are performed and compared to evaluate the impacts on the water balance. The sub-basin analysis indicates that the delta approach results in moderate to strong over- and underestimation of impacts in nearly all sub-basins. As the example of sub-basin 4 that experiences most pronounced land use changes shows, the cumulative

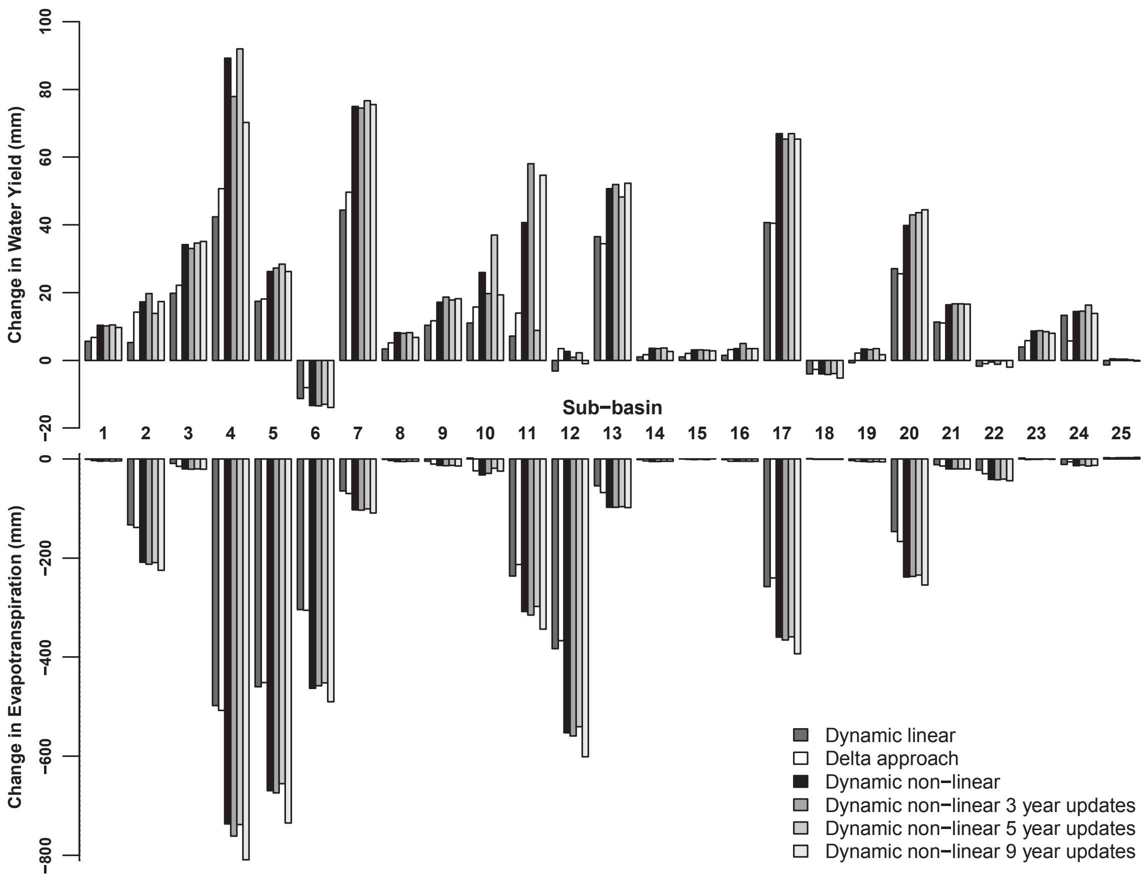

Fig. 5. Comparison of sub-basin impacts on the water balance components resulting from different land use change impact assessments.

change in ET is relatively close to the cumulative result from the linear dynamic scenario, while the cumulative change in WY is not well approximated by the delta approach (overestimation by 19.6%). Nevertheless, the delta approach provides a relatively good approximation of the impacts of the linear land use change scenario (Table 2, Fig. 3). In contrast, the delta approach is not suitable if the non-linear land use change scenario is employed. Hence, it can be concluded that the delta approach might provide reasonable results in cases where land use changes develop linearly, but that it might not be suitable in cases in which land use changes develop in a non-linear way.

Whereas it seems preferable to include land use changes on an annual time step, one may argue that a coarser time step for integration of land use changes might also be sufficient when analyzing aggregated impacts on the water balance over time. Our analysis with land use updates every 3rd, 5th, and 9th year shows that these are superior to the delta approach, which could be regarded as a land use update every 20th year. Moreover, as expected, the more frequent land use updates mostly yield predictions that are closer to the dynamic (annual) land use scenario impacts. However, the differences between the accuracy of the 3 and 5 year updates are small and even the 9 year updates yield relatively good results. It has to be noted that the coarser updates that are implemented before the actual change, so that over- and underestimation could balance out, maybe regarded as a series of delta approaches. For all tested frequencies the results are relatively close to those of the model run with annual land use updates, even though the land use changes developed in a non-linear way. Hence, coarser land use representations may also be suitable for land use change impact assessment if annual data is not available. From the given results one may conclude that land use updates every 5 years are sufficient in most cases, as they have been in the case of our non-linear land use changes. In other cases, less frequent updates, e.g. 10 or 20 years or a delta approach spanning these time periods may be sufficient. Nevertheless, it has to be taken into account that the results may deviate from the real impacts, e.g. WY in sub-basin 4 has been overestimated by 19.6%.

These findings shed light on the importance of land use change monitoring, which is usually based on satellite data. Land use maps or classifications may not be available for every year due to constraints of data (e.g., availability of cloud-free images for methods based on multispectral satellite data), time, or money. Our results show that the integration of data available every five to nine years would already mean an improvement of the prediction accuracy of land use change impacts as compared to coarser temporal resolutions or the delta approach. Particularly in rapidly developing regions such as in many parts of India, continuous monitoring of land use changes is important to achieve most accurate results in impact studies. Given the availability of new satellite data e.g., from the Sentinel missions and the opening of the Landsat archive, a regular monitoring of land use changes since 1984 (launch of Landsat 5) every five to nine years seems perfectly doable for the most parts of the world. Hence, land use change impacts can be assessed with a reasonable accuracy, even if annual data is not available.

Moreover, with regard to future hydrologic impact assessments the outputs from land use change models should be implemented at a high frequency. The use of dynamic weather data simulated by complex climate models in climate change impact studies (e.g., Arnell, 1999; Mauser and Bach, 2009; Wagner et al., 2015) should be complemented by a dynamic representation of land use changes, particularly when combined impacts of land use and climate change are studied. However to date, static land use representations prevail in these cases (e.g., Kim et al., 2013; van Roosmalen et al., 2009; Wang et al., 2014) and only rarely land use and climate changes are both represented dynamically (e.g., Mehdi et al., 2015). Based on the study result we recommend to include land use changes in climate change impact studies at least on a decadal basis. In summary, our findings are in agreement with and substantiate the conclusion by Castillo et al. (2014) who underline that a tight temporal integration of the dynamics of land use change and hydrology is needed to accurately represent the interactions between land use, climate, and hydrology.

5. Conclusions

This study compares the cumulative hydrologic impacts of dynamic land use representations to those of static land use representations. We have used a scenario based approach and compare the derived impacts to a dynamic model implementation of annual land use changes, which serves as a benchmark in this study. We have found that the static delta approach could provide reasonable results for linear land use changes, but underestimates the hydrologic impacts, if land use change followed a non-linear course. It seems preferable to include land use information on an annual time step, as even for a linear development of land use change we have found pronounced deviations in some sub-basins. However, if annual land use information is not available, our assessment has shown that the integration of land use changes every five to nine years means a pronounced improvement of prediction accuracy as compared to the use of static land use information. Although the research carried out is academic, it nevertheless brings out the importance of the dynamic approach when land use changes are developing rapidly and non-linear, as in regions that experience fast socio-economic development. Given the fact that the course of the applied non-linear scenario is an extreme case, one may conclude that the integration of land use data every five years, should be suitable for other less extreme cases. However, other researchers should carefully examine the course of the changes in their catchments and compare this to the shown cases, before taking a decision on the required land use update frequency. Although the implementation of dynamic land use changes goes along with a considerably higher workload as compared to land use change impact assessments with static land use representations, it is worthwhile to include dynamic land use information to improve the accuracy of the assessed hydrologic changes. Also in other hydrologic impact studies like climate change impact studies, it is important to implement realistic, dynamic representations of land use change. Moreover, our results point towards the necessity of continuous land use change monitoring especially in rapidly developing regions, being a prerequisite for the accurate assessment of hydrologic impacts of such developments.

6. Software and data availability

We use the freely available open source hydrologic model SWAT (Arnold et al., 1998; available from http://swat.tamu.edu/) to assess the effects of different land use representations on the model output (Wagner et al., 2016). All calculations and analyses are carried out in R (R Core Team, 2016), which is available from https://www.r-project.org/. R and SWAT run on Microsoft Windows and linux computers with no special hardware requirements. Please contact the corresponding author for any further information at pwagner@hydrology.uni-kiel.de.

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