Modelling effects of land use/cover changes under limited data

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ABSTRACT

Watershed models are valuable tools used in the study of impacts of land use/cover (LULC) changes on hydrology. We use the Soil and Water Assessment Tool (SWAT) to study the impacts of LULC changes in a coastal Alabama watershed, where flow data did not exist at the onset of the study. We set up and calibrated the model in the neighbouring Magnolia River watershed. Relevant model parameters were then transferred to the Wolf Bay watershed. Impacts of LULC changes on hydrology are studied in the Wolf Bay watershed by running the model with the default parameters, transferred model parameters (from the Magnolia River watershed), and calibrated parameters at the Wolf Bay watershed with limited data that became available later during the study. The relative changes in flow duration curves (FDCs) due to differing LULC showed a similar pattern with each parameter set: There is a clear threshold of around 1% probability of exceedance where the relative change is at its maximum. The relative change in flow due to LULC change drops drastically with increasing probability of exceedance of beyond 2% until it reaches a plateau at p = 20%. Hence, small to medium range flows are less sensitive to the parameter set. Further, the impact of LULC change on flow gradually decreases with the size of the storm for very large events (probability of exceedance <1%).

KEY WORDS watershed hydrology; modelling; land use change; regionalization

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INTRODUCTION

Quantifying the impacts of land use and land cover (LULC) changes on the hydrologic processes and water balance of river basin has been an area of interest to hydrologists in recent years. Little is known so far if there is a well-defined quantitative relationship between the LULC properties and the runoff generation mechanisms. The assessment of future LULC changes with respect to their hydrological impacts is still an unsolved problem (Fohrer, 2002). Several methods were developed to study the implications of LULC changes on hydrologic processes, such as the paired catchments approach, time series analysis (statistical method), and hydrological modelling (Li et al., 2009). Among these approaches, hydrological modelling has been widely applied in many different places in the world as it requires fewer resources and provides more flexibility.

Fohrer et al. (2001) assessed the hydrologic response to LULC changes in four meso-scale watersheds in Germany with different LULC distributions. The model performance for changing LULC was then tested in an artificial watershed with one crop at a time and one underlying soil type to eliminate the complex interactions of natural watersheds. Simulation results showed that LULC changes on the annual water balance was moderate. Surface runoff was most susceptible to LULC change at both the artificial and the natural catchments. Hundecha and Bardoosy (2004) simulated the effect of LULC changes on the runoff generation of the Rhine River basin through parameter regionalization of the Hydrologiska Byrån Vattenbalansavdelning (HBV) model. The results suggested that increased urbanization leads to an increase in the smaller peak runoffs stemming from summer storms. Increase in the larger peaks resulting from winter rainfall was negligible. A considerable reduction of both the peak runoff and the total runoff volumes resulted from intensified afforestation. Savary et al. (2009) assessed the effects of historical LULC change on runoff and low flow using the Gestion Intégrée des Bassins versants à l’aide d’un Système Informatisé (GIBSI) model in the Chaudiere River watershed, Canada. Simulations showed strong correlations between LULC changes and stream discharge at the outlet of the watershed, especially for the summer and fall seasons. Simulated annual and seasonal low flows were also strongly correlated to agricultural and forested land. Guo et al. (2008) studied the combined effects of climate and LULC change on hydrological processes in the Poyan Lake basin, China, using the Soil and Water Assessment Tool (SWAT). They found that while the climate effect is dominant in altering annual streamflow, LULC change may have a moderate impact. Both the climate effect and LULC change strongly influence seasonal streamflow and alter the annual hydrograph of the basin. Ma et al. (2009) also considered climate change impacts on hydrological responses in a different watershed in southwestern China using SWAT. In contrast to the results obtained by Guo et al. (2008), they found...
that climate had a more profound effect on seasonal variations in streamflow with LULC change having a moderate impact. On the other hand, they observed a much stronger influence by LULC change on mean annual streamflow. Their simulation results also showed that the impact of climate change on surface water, baseflow, and streamflow was offset by the impact of LULC changes.

As mentioned above, LULC impacts on hydrologic responses have been thoroughly studied through modelling. However, models are mathematical simplifications of natural processes, with inevitable errors and deficits. Therefore, the reliability of hydrologic models should be evaluated by the fitness between measured flow data and model simulations. In this regard, the observed data are quite valuable. Hydrologists often need to adjust model variables in order to attain close to optimal parameter values by minimizing the error between model simulations and observed data. However, observed data are sometimes insufficient or not available at all, in which case one can run the model without calibration by estimating parameter values from the literature or rely on regionalization approaches.

The term regionalization has its roots in the process of regime classification and watershed grouping. It has later been extended in the rainfall–runoff modelling context to refer to the transfer of parameters from neighbouring gauged watersheds (also called donor watersheds) to an ungauged watershed. Nowadays, the concept of regionalization applies to all methods aimed at estimating model parameter values on any ungauged watershed in a definable region of consistent hydrological response. Several methods are available in the literature for the transferring of model parameters. Regionalization based on regression is the most popular method, which attempts to link parameter values to climate and watershed physical characteristics, such as annual rainfall, temperature, area, slope, and LULC in a gauged watershed (Yokoo et al., 2001; Kim and Kaluarachchi, 2008). Another commonly used approach is regionalization based on physical similarity. Generally, information is transferred between neighbouring watersheds, not necessarily geographically connected but rather in terms of observable watershed descriptions (Oudin et al., 2008). Parameters are transferred from one or many donor watersheds, whose physical descriptors are similar to the ungauged one, based on a synthetic rank that reflects the similarity of all physical descriptors between donors and target. The third kind of regionalization is based on spatial proximity. It uses the parameter values calibrated in nearby watersheds, which have sufficiently long data for calibration. The rationale of this method is that the physical and climatic characteristics are relatively homogeneous within a small region, thus the neighbours should have similar hydrology.

Over the past few decades, several researchers have attempted to identify the best regionalization approach appropriate for different hydrological models. For example, Oudin et al. (2008) applied two lumped rainfall–runoff models to daily data over a large set of 913 French watersheds. Their research indicated that the spatial proximity approach provided the best solution and the regression approach was the least satisfactory in France, where a dense network of gauge stations is available. Merz and Bloschl (2004) investigated the water balance dynamics of 308 watersheds in Austria using the HBV model. They compared regionalization methods for estimating model parameters in ungauged watersheds. The performance of their method, which was based on multiple regressions with watershed attributes, was significantly poorer than that of the other two. They found that spatial proximity was a better surrogate of unknown controls on runoff dynamics than watershed attributes. Reichl et al. (2009) compared the Nash–Sutcliffe efficiency and monthly relative volume error of the SimHyd lumped conceptual rainfall–runoff model by averaging, spatial proximity, local calibration, and simple regression approaches in 184 Australian watersheds. Averaging method, which selects a number of candidate models from available gauged watersheds and weighs them based on likelihood, can be considered as the improvement of regionalization by physical similarity. They showed that the averaging method, while inferior to local calibration, is superior to methods based on regression and spatial proximity.

This article focuses on estimating the impacts of LULC changes on hydrological responses in a coastal Alabama watershed. In particular, using the SWAT model, it investigates how limited hydrological data affect our understanding of LULC change impacts on hydrology. To address this issue, LULC maps corresponding to two different periods (1992 and 2005) are used. Model parameters are obtained from a nearby watershed through regionalization based on spatial proximity. Model efficiency is compared through use of time series of flow and flow duration curves (FDCs) when transferred parameters and default ones are utilized. The effects of parameter transfer on modelling the impacts of LULC changes on low, medium, and high flows are discussed.

METHODOLOGY

Study area

Wolf Bay is located on the Gulf of Mexico in Baldwin County, Alabama, nestled between Pensacola Bay in the east and Mobile Bay in the west, with a watershed covering about 126 km². It is a sub-estuary of Perdido Bay with a connection to the Intracoastal Waterway and includes various freshwater, nutrient, and sediment inputs from several sub-watersheds through Wolf, Sandy, Miflin, and Hammock creeks (Figure 1).

The watershed is primarily rural, but several municipalities exist, including Foley, Elberta, Gulf Shores, and Orange Beach. Baldwin County’s beaches, bays, and rivers promote an expanding tourism industry, which exerts substantial influence on water extraction for human use. Baldwin County experienced a 43% increase in population from 1990 to 2000. As a result of population
growth, there is an increased demand for commercial, residential, and infrastructure development, thus bringing growth management issues to the forefront for local elected officials. One of the more visible changes in the landscape of Baldwin County is the rapid transformation of agricultural and forested lands to residential development. These developmental pressures are threatening the natural resources that make Baldwin County, a popular place to live in or visit (Stallman et al., 2005). As a result, detecting the impact of potential LULC changes is urgent and necessary, because it provides policy makers with some valuable suggestions that strike a balance between development and the protection of natural resources.

There is only one flow monitoring station in the watershed on the Wolf Creek operated by the US Geological Survey (USGS). However, at the commencement of this study, no flow data was available. USGS essentially monitors the flow stages and converts them to discharge through stage-discharge curves only when they have enough flow measurements that cover range of flows. Magnolia River watershed, which is adjacent to the Wolf Bay watershed in the northeast (Figure 1), has 10 years of continuous flow and climate data. Using the regionalization based on spatial proximity, we can set up a model in the Magnolia River watershed, calibrate it, and transfer the model parameters to Wolf Bay watershed. Besides their spatial proximity, Wolf Bay and Magnolia River watersheds also have a number of similar physical characteristics (Table I). Although it was still partly provisional, almost 2 years of flow data (5 December 2007 to 30 September 2009) later became available from the USGS gauge on Wolf Bay Creek, which provided us an opportunity to assess the feasibility of parameter transfer from the Magnolia River watershed to the Wolf Bay watershed.

Watershed model
SWAT is one of the most commonly used watershed models for assessing the impact of management practices and land disturbances on watershed responses. It has a solid track record of applications (Kalin and Hantush, 2006). SWAT has been widely used around the world, such as at the Cottonwood River near new Ulm, Minnesota (Hanratty and Stefan, 1998); southern Alberta, Canada (Chanasyk et al., 2003); and Jeker river basin, Belgium (El-Nasr et al., 2005) to assess the various

<table>
<thead>
<tr>
<th>Physical characters</th>
<th>Wolf Bay</th>
<th>Magnolia</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum elevation (m)</td>
<td>0.0</td>
<td>6.0</td>
</tr>
<tr>
<td>Maximum elevation (m)</td>
<td>34.0</td>
<td>36.0</td>
</tr>
<tr>
<td>Mean elevation (m)</td>
<td>16.6</td>
<td>25.3</td>
</tr>
<tr>
<td>Area (km²)</td>
<td>130.0</td>
<td>44.8</td>
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<tr>
<td>Rural area 2005 (%)</td>
<td>72.8</td>
<td>73.6</td>
</tr>
<tr>
<td>Urban area 2005 (%)</td>
<td>27.2</td>
<td>26.4</td>
</tr>
<tr>
<td>Soil clay (%)</td>
<td>8.6</td>
<td>12.3</td>
</tr>
<tr>
<td>Soil silt (%)</td>
<td>18.4</td>
<td>24.2</td>
</tr>
<tr>
<td>Soil sand (%)</td>
<td>73.0</td>
<td>63.4</td>
</tr>
<tr>
<td>Mean slope</td>
<td>1.9</td>
<td>1.4</td>
</tr>
</tbody>
</table>
impacts of agricultural practices and land use activities on water quantity and quality. SWAT is also suitable for coastal and flat areas, which have more complicated geo-hydrologic conditions (Wu and Xu, 2006). ArcSWAT, version 2.3.4, which runs on ArcGIS® was used for preparing the input data and processing the output files.

SWAT is a distributed, process-based watershed model, but with a significant number of empirical relationships. The physical backbone of the model facilitates the interpretation of model parameters, whereas the empirical simplifications keep data requirements low compared to physically based models (Hevnemans et al., 2004). SWAT divides a watershed into several sub-watersheds based upon drainage areas of the tributaries. Each sub-watershed is split into multiple hydrological response units (HRUs) based on LULC and soil types. Each HRU is assumed to be spatially uniform in LULC, soil, topography, and climate. Major hydrologic processes that can be simulated by SWAT include evapotranspiration (ET), surface runoff, infiltration, percolation, shallow aquifer and deep aquifer flow, and channel routing (Arnold et al., 1998). Details and the theoretical background of the SWAT is beyond the scope of this article and can be found in Neitsch et al. (2005).

In addition to streamflow, SWAT can also provide baseflow and surface runoff estimates as model outputs. Therefore, we used a baseflow filter to split the observed streamflow into baseflow and surface components to better calibrate the model. The algorithm presented by Arnold et al. (1995) is employed for this purpose. In this algorithm, a digital filter, which is borrowed from signal processing, is successively applied to streamflow. Filtering surface runoff (high-frequency signals) from baseflow (low-frequency signals) is analogous to the filtering of high-frequency signals in signal analysis and processing. The filter can be passed over the streamflow three times. At each pass, a slower component of streamflow (less baseflow as a percentage of total streamflow) is obtained.

Model performance evaluation

The statistical measures of mass balance error (MBE), coefficient of determination ($R^2$), and the Nash and Sutcliffe (1970) efficiency ($E_{NS}$) are used as indicators of model performance

$$E_{NS} = 1 - \frac{\sum_{i=1}^{N}(O_{sim,i} - O_{obs,i})^2}{\sum_{i=1}^{N}(O_{obs,i} - \bar{O}_{obs})^2}$$

where $O_{sim,i}$ and $O_{obs,i}$ are simulated and observed flows at $i$th observation, respectively, $N$ is the number of observations. Similarly, $\bar{O}_{sim}$ and $\bar{O}_{obs}$ are average of simulated and observed flows over the simulation period. $R^2$ describes the proportion of the total variances in the observed data that can be explained by the model and ranges from 0 to 1. $E_{NS}$ is a measure of how well the plot of observed versus predicted values fit the 1:1 line, and can theoretically vary from $-\infty$ to 1, with 1 denoting a perfect model with respect to data agreement. Although $R^2$ and MBE values have been used often in the past to quantitatively compare model results with data, $E_{NS}$ is a better representative measure for model goodness of fit (ASCE, 1993; Legates and McCabe, 1999).

Modelling LULC changes

LULC changes affect various components of the hydrologic cycle, either directly or indirectly. The infiltration and ET processes are the two vital components of the hydrologic cycle directly affected by LULC changes. SWAT uses Soil Conservation Service (SCS) curve number method to simulate infiltration process. Each soil/LULC combinations are assigned specific curve numbers, with higher values representing higher surface runoff and less infiltration. Urbanization within a watershed increases the area of impervious surfaces (high curve number), which decreases infiltration and increases runoff. As a result, the amount of surface runoff generated from a specific rain event increases. Reduced infiltration results in less groundwater recharge, which decreases baseflow contribution to streamflow, eventually causing reduction in low flows. If change in ET is relatively small, then urbanization, in essence, redistributes baseflow and runoff components of the streamflow.

SWAT calculates ET from potential ET (PET). One key component in PET calculation is the net radiation, which is a function of the plant albedo (reflectivity). Thus, change in LULC should change net radiation and eventually PET. In SWAT, changing LULC has little or no effect on PET depending on the choice of the PET calculation method (Penman–Monteith, Priestley–Taylor, and Hargreaves). In calculating the actual ET, SWAT evaporates intercepted water in the canopy first. If water intercepted in the canopy cannot fulfill the PET demand (which is usually the case), SWAT then calculates transpiration from plants. Transpiration is a function of PET, leaf area index (LAI), and soil water content. LAI changes with land cover and plant growing seasons. Higher LAI means more transpiration. Calculation of transpiration and water uptake are described in detail in Neitsch et al. (2005).

Two LULC maps representing the years 1992 and 2005 have been employed to investigate the impacts of
LULC changes on hydrologic responses in Wolf Bay watershed. The 1992 National Land Cover Data (NLCD) is a raster data set with a 30-m resolution. The second LULC map circa 2005 is a vector dataset attained by the trend analysis focused on LULC changes of urban and built-up areas, utilities, and transportation from 2001 to 2005 based on colour infrared imagery of 2001 and 2005. As these two maps had different LULC classifications, we reclassified them according to the SWAT classification to make it consistent with the model’s database.

RESULTS AND DISCUSSION

Calibration and validation in the Magnolia River watershed

The SWAT model was first set up in the Magnolia River watershed, then calibrated and validated with a split data set approach. The period from 1 October 1999 to 30 September 2004 of the daily flow data from USGS gauge #02378300 was used for calibration and the period from 1 October 2004 to 30 September 2009 was used for validation. Model validation is defined as the process of demonstrating whether the model is capable of making accurate predictions for periods outside a calibration period. Usually, calibration of a model is based on 3–5 years of data (Sorooshian et al. 1983; Xia et al. 2004), and validation on another period of similar length (Ma et al., 2009; Tu, 2009). Table II shows the calibrated model parameters along with their default values. Model simulations actually started from 1 October 1989 with the measured precipitation data as input. This corresponds to a warm-up period of 10 years. The idea behind using such a long warm-up period was to minimize the effect of initial unknown conditions such as antecedent moisture and initial groundwater table height (Kalin and Hantush, 2006).

Model parameters were calibrated first at monthly, then at daily timescales for flow. Figure 2a shows the observed and simulated monthly flows during the calibration and validation periods. Monthly streamflow values match well with the observed ones. Model performance statistics are shown in Table III. Note that only MBE is shown for baseflow as suggested by Santhi et al. (2001). It is difficult to estimate the spatial and temporal distribution of the groundwater table. Quantifying the impact of a deep aquifer system on baseflow response is also challenging (Lee et al., 2005). Therefore, it is hard to capture the temporal dynamics of baseflow simulations. Overall, the performance of the SWAT model at monthly timescales is good during both the calibration and validation periods.

Daily simulations of total streamflow are not as good as monthly simulations, but the $E_{NS}$ of the calibration period is still acceptable. Owing to the temporal scale effect discussed in the previous paragraph, we only focus on total streamflow at daily timescale. According to Moriasi et al. (2007), $E_{NS}$ values above 0.5 with low MBE are considered satisfactory. To gain more insight, we also compared FDCs of observed and simulated flows in the Magnolia River watershed from 1999 to 2009 (Figure 2b). Observed and simulated flows have good

<table>
<thead>
<tr>
<th>Curve number</th>
<th>Soil AWC (available water capacity)</th>
<th>ESCO (soil evaporation compensation coefficient)</th>
<th>Surlag (Surface lag coefficient)</th>
<th>Revapmn (Threshold water level in shallow aquifer for revap (mm))</th>
<th>Alpha_BF (baseflow recession constant)</th>
<th>Manning’s $n$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Default</td>
<td>Varies$^a$</td>
<td>0.95</td>
<td>4</td>
<td>10</td>
<td>0.048</td>
<td>0.014</td>
</tr>
<tr>
<td>Calibrated</td>
<td>+3</td>
<td>−0.01</td>
<td>1</td>
<td>500</td>
<td>0.015</td>
<td>0.114</td>
</tr>
</tbody>
</table>

$^a$Varies by soil type and LULC.

$^b$Varies by soil type.

Figure 2. Simulated streamflow compared with observed data from 1999 to 2009 in the Magnolia River watershed (a) monthly time series and (b) daily flow duration curve.
agreement for flows having probability of exceedance >0.2%. The model underestimates flow as much as 50% for probability of exceedance <0.2%, which is not uncommon in modelling (Wang and Melesse, 2005; Larose et al., 2007; Baffaut and Benson, 2009).

Note that the SWAT is not an event-based model. Although it works reasonably well for long-term simulations, it has limitations in extreme events. It cannot capture the dynamics at sub-daily scale. For example, from 31 March 2005 to 6 April 2005, there were a series of several very strong storms. The total amount of rainfall in this 1 week period was 440 mm, which is about one-fourth of the average annual precipitation. The model failed to reflect these huge events properly. The MBE of streamflow in this period was −53%. The most improper simulation happened on 1 April 2005. Observed daily average flow was 197 m$^3$ s$^{-1}$ (the largest ever recorded), yet SWAT estimated only 35 m$^3$ s$^{-1}$ of flow. Such extreme events can significantly alter the performance statistics. For instance, if we ignore the event on 1 April 2005, the $E_{NS}$ for monthly simulation improves from 0.65 to 0.74 (Table III). Other than the potential deficiencies of the model in dealing with such significant events, there are two other possible reasons for this. USGS measures stage not discharge; discharge is estimated from stage–discharge relationships (i.e. regression equations) which are known to have problems outside their range. Thus, observed flow during such an extreme event, which is actually estimated from stage, could have serious errors. Spatial variation in precipitation and the rain gauges not being able to capture these accurately is another source of error. Our precipitation data source is a rain gauge located at the watershed outlet. On 1 April 2000, the USGS gauge at Magnolia River recorded a storm event where average daily flow was 6 m$^3$ s$^{-1}$, up from 0.6 m$^3$ s$^{-1}$ from the day before. However, no flow is generated by SWAT because the rain gauge did not record any trace of rainfall. The most likely scenario is that it only rained at the upstream portion of the watershed and this went undetected by the rain gauge.

We tried different climate data sources to improve model performance. However, current rainfall data offered by the USGS station proved to be the best data source. Two other alternatives to the USGS gauge was an NOAA rain gauge and an NEXRAD radar. The USGS rain gauge is at the watershed outlet. The NOAA rain gauge is about 16 km away from the Magnolia River watershed outlet and well outside its boundaries. Further, it records daily rainfall from 6:00 am to 6:00 pm and thus does not represent a calendar day. This may cause problems in daily flow simulations if there is an overnight rain event. The NOAA rain gauge also had extended periods of missing data (e.g. the whole months of November 2002, December 2002, and September 2009 were missing). As in the case of the USGS rain gauge data, we observed inconsistencies during heavy rainfall events in the NOAA data. Summer rains in Alabama are dominantly localized pop-up thunderstorms. Capturing these storms requires a very dense network of rain gauges. Radar data seems to be a good alternative but that has its own problems too. We obtained NEXRAD radar data for the Magnolia River watershed for the period 2002–2008 and tried to calibrate the model. Even NEXRAD data did not capture rainfall accurately and we had poorer model performance. The annual average precipitation from 2002 to 2008 based on the NOAA rain gauge, NEXRAD, and the USGS rain gauge were 1794, 1520, and 1315 mm, respectively, which shows the discrepancies between these three rainfall data sets and the degree of spatial variation in this area.

Transferability of model parameters from the Magnolia River to the Wolf Bay watershed

In the Section on Calibration and Validation in the Magnolia River Watershed, SWAT was manually calibrated for flow in the Magnolia River watershed with the calibrated parameters shown in Table II. The next step was to transfer these parameters systematically to the Wolf Bay watershed. Table IV shows the daily model performances with the default and transferred parameter sets. Although SWAT performed better with the transferred parameters, $E_{NS}$ is negative and MBE is above 50%. Default parameters resulted in a much lower $E_{NS}$ value (compare −2.07 to −0.21). Although, to some extent, we expected low performance with the default parameters, having such low performance with the transferred parameters was surprising as the watersheds have similar physical and morphological characteristics and are adjacent to each other. Note that in spite of low $E_{NS}$, $R^2$ is high. High $R^2$ with a low $E_{NS}$ means simulated values have the same trend with observed values in time, but at a disproportionate rate. In other words, the model systematically over/underpredicts the observed data. In this case, it is an overprediction.

Sometimes, when models are run outside their calibration/validation periods, changing LULC may result in poor model performance. The model was set up using the LULC map of 2005, but the simulation period was extended to 2009. If LULC changed significantly from 2005 to 2009, then the model performance should have deteriorated over time. However, LULC did not change.
much in that period. We also ran SWAT with the LULC map of 2008 and compared the daily simulation results to the ones obtained with the 2005 LULC. No significant difference was detected between the two daily simulation results.

On the basis of the above findings, it is seen that parameter transfer improves the predictable capabilities of the SWAT model in the study area, but not necessarily at the desired level. However, we calibrated and validated the model over a long time period (5 + 5 years) and tested the model with transferred parameters over a short period (~2 years). Whether the model performed well at the donor watershed during the testing period October 2007–September 2009 is not clear. Note that although the validation period included this period, the length of the validation period (5 years) along with higher flows during the first year (2005) could potentially hinder the model performance in the testing period. If the model cannot accurately predict flow in this specific period at the donor watershed, then the problem is beyond parameter transferability. Indeed, model performance in the Magnolia River watershed during this testing period is not good at all. $R^2$, $E_{NS}$, and MBE for daily streamflow are 0.45, −0.21, and 0.48, respectively, quite similar to what we attained in the Wolf Bay watershed with the transferred parameters. Exchanging the roles of donor and target watersheds, that is, calibrating the SWAT model at the Wolf Bay watershed and transferring the calibrated model parameters to the Magnolia River watershed, resulted in a different story. Daily model performance statistics for the period October 2007–September 2009 was $R^2 = 0.63$, $E_{NS} = 0.62$, and MBE = −2.5% at the calibration and $R^2 = 0.54$, $E_{NS} = 0.51$, and MBE = 12.0% at the test watersheds. This is a substantial improvement over the previously reported values based on calibration at the Magnolia River watershed. Therefore, transferring parameters from neighbouring watersheds indeed improves the predictive power of the model.

<table>
<thead>
<tr>
<th>Year</th>
<th>Default parameters</th>
<th>Transferred parameters</th>
<th>Calibrated parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>2000 (dry)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2005 (wet)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table IV. Model performance at daily timescale in the Wolf Bay watershed.

Table V. K–S test for daily and monthly simulated streamflows generated with different parameter sets.

<table>
<thead>
<tr>
<th>Year</th>
<th>Kolmogorov–Smirnov test</th>
<th>Daily average rainfall (mm)</th>
<th>Maximum daily rainfall (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>KSa daily</td>
<td>p-daily</td>
<td>KSa monthly</td>
</tr>
<tr>
<td>2000 (dry)</td>
<td>11.42</td>
<td>&lt;0.0001</td>
<td>0.82</td>
</tr>
<tr>
<td>2005 (wet)</td>
<td>2.92</td>
<td>&lt;0.0001</td>
<td>0.61</td>
</tr>
</tbody>
</table>

Effect of parameter transfer on hydrologic responses

In the Section on Transferability of Model Parameters from Magnolia River to Wolf Bay Watershed, we demonstrated that the transferred parameters increase model reliability as opposed to using model default parameters. Here, we explore the implications of this on hydrological responses. Monthly flow simulation results using default and transferred parameters are shown in Figure 3. Visually, there are no significant differences. The two-sample Kolmogorov–Smirnov (K–S) test, which is sensitive to differences in both location and shape of the empirical cumulative distribution functions of the two samples, is employed to compare the two streamflow time series. The K–S test indicated no significant differences ($p = 0.482$) in simulation results of monthly flow due to use of two separate parameter sets. However, at the daily timescale there are striking differences. As shown in Table V, two specific years, 2000 and 2005 are selected to represent dry and wet conditions, respectively. The K–S test is employed to check if there are any significant changes in the time series obtained by the two parameter sets, both at daily and monthly timescales. Again, no significant differences exist at monthly timescale, neither in dry nor in wet years ($p = 0.518$ and 0.848, respectively). However, if the simulation scale is changed to daily step, significant differences appear in both years ($p < 0.0001$ in both).

FDCs for these two years and the whole 10-year period were also compared (Figure 4a–c). Differences are evident at high and low flows, regardless of dry or wet years. Note that simulations with default parameters always resulted in higher flows at low exceedance.
probabilities (<1%). Being in a wet or dry year did not change the fact that if default parameters are used in predicting high flows, we will end up overpredicting the flow. Similarly, the default parameter set consistently generated lower flows than the transferred parameter set during both dry and wet years, when the probability of exceedance was >3%. Similar results were obtained when the FDC for the whole period was considered. Default parameters always resulted in higher flows at low probability of exceedance and lower flows at high probability of exceedance.

Impact of LULC change on hydrologic responses

Table VI shows the LULC distributions in 1992 and 2005. Percentage forest cover has been reduced by 9% from 1992 to 2005. On the contrary, total urban land has increased by almost 20%. Pasture has been lost to agricultural fields such as sod farming, and low-density residential areas. Same climate data and a parameter set (the one calibrated in the Magnolia River watershed) were utilized as model inputs to run SWAT with both the 1992 and 2005 LULC maps. Simulation results for flow for each year are summarized in Table VII. For each year, we tabulated annual maximum, minimum, and mean daily flow values obtained with the LULC of 1992 and 2005. The relative change in mean annual flow due to LULC change indicates little variation and on average is about 2%. Although change in LULC did not have a significant impact on streamflow, it affected the partitioning of streamflow to baseflow and surface runoff as evidenced by changes in annual maximum and minimum flows. In every single year, annual minimum flow was predicted to decrease due to LULC change with a range from -16.8 to -36.9%, and an average of -29.7%. Annual maximum flow appears to be most sensitive to LULC changes. It is estimated to increase by 40.6–115.3% with an average of 58.0%. Similar results are found in other studies (Rose and Peters, 2001; Kauffman et al., 2009). Figure 5 shows the variation in average monthly streamflows before and after LULC changes. Flow was predicted to increase as much as 12% during the summer months of June through September, which is the growth season with the highest ET rates.

Note that most of the increase in urban land was in the form of low-density residential areas (Table VI), which are only partially covered by impervious land. SWAT assumes that parts of urban areas not covered by impervious surfaces are bermudagrass. On the basis of the SWAT database, maximum LAI for forest is 5, while for bermudagrass it is 4. Thus, forest to grass conversion does not cause significant change in ET. Over the whole simulation period, SWAT predicted about 20% less ET from grassland compared to forested land. Estimated annual average ET over the whole watershed based on the 1992 and 2005 LULC were 457 and 435 mm, respectively (~5% reduction). Low-density residential and high-density residential areas have on average 12 and 60% imperviousness, respectively, according to the USDA SCS classification. Thus, the total increase in percentage of impervious areas from 1992 to 2005 is only 2.95%. As LULC from 1992 to 2005 did not change uniformly over the whole watershed, it is not reasonable to attempt to explain the alterations in flow and ET purely by changes in forest cover and urban LULC. Note that from 1992 to 2005, pasture had also decreased by 28.3% and agricultural land increased by 15.5%. Therefore, there is a compound effect of all these mixed LULC changes.

Impact of parameter transfer on modelling LULC change

Figure 6a–c shows the FDCs of daily flow simulations in the Wolf Bay watershed (a) dry year 2000, (b) wet year 2005, and (c) whole period 1999–2009.
To get a better insight into the effect of parameterization on the differences in FDCs due to LULC changes, relative difference in FDC, i.e., \( \frac{\text{FDC of 2005 LULC} - \text{FDC of 1992 LULC}}{\text{FDC of 1992 LULC}} \), are depicted in Figure 7. The trends are similar in all three. Moving from left to right, i.e. from low to high probability of exceedance, the relative differences in flow due to LULC change (from 1992 to 2005 conditions) increase up to around 1% and stay at that level up to 2%. Thus, LULC change has the largest impact on flows with 1% exceedance probability. As flow gets larger (probability of exceedance <1%) the impact of LULC change is gradually reduced. Beyond 2%, all three parameter sets exhibit a sharp drop and reach a plateau again. With the default and transferred parameter sets, the relative change in flow becomes negative around 7–10% exceedance probabilities and stays negative beyond that point, mostly in the −15 to −20% range. On the contrary, with the calibrated parameter set, relative change in flow becomes negative around 20% exceedance probability and stays negative until 60% exceedance probability. Except for a short duration, the relative change in flow during this period is around 2%. Beyond 60% exceedance probability, all the parameter sets show increase in relative change.

In short, Figure 7 reveals very interesting facts. First, the choice of the parameter set in simulating LULC changes does not seem to play a big role in relative changes of flow (it does for absolute flows). Although there are differences in the FDCs, trends are mostly consistent and the differences between them are not major. Secondly, LULC change influences most of the flow in quite a steady and moderate manner. Flows with 1–2% probability of exceedance appear to be most sensitive to LULC changes.

**SUMMARY AND CONCLUSIONS**

In this article, we explored how transferring model parameters from a neighbour (donor) watershed to a target watershed affects modelling LULC changes. The
regionalization based on spatial proximity method was employed to transfer the model parameters from the donor Magnolia River watershed to the target Wolf Bay watershed. For this purpose, the SWAT model was first set up and calibrated in the Magnolia River watershed, which has 10 years of continuous measured flow data. Calibrated model parameters were then transferred to the Wolf Bay watershed, which, at the start of the study, had no flow data. Model performances were compared by using two different parameter sets: the SWAT default parameters and the transferred parameters.

About 22 months of measured flow data in the Wolf Bay watershed, which later became available, was used for that purpose. The transferred parameter set resulted in a slightly better model performance than the default parameter set, but not at the desired level (both had negative $E_{NS}$). The low model performance was due to the fact that when data related to a long period are used in model calibration, the emphasis is on the whole period and the model performance may not be up to the desired level in some sub-sections of the entire time period. Hence, extensions of parameter transfer from donor watersheds through long-term calibration to target watersheds for short-term predictions requires extra caution, and, most likely, vice versa.

FDCs are effective tools in visualizing the whole flow range. We created FDCs to get a better insight into the impacts of both LULC change and parameter transferring. Simulations with default parameters always resulted in higher flows at low probability of exceedance (<1%). On the contrary, the default parameter set consistently generated lower flows than the transferred parameter set when probability of exceedance was >3%, regardless of a dry or wet year. Similar results were obtained when the FDC for the whole period was considered. Default parameters always resulted in higher flows at low probability of exceedance, and lower flows at high probability of exceedance.

Two LULC maps from 1992 and 2005 were utilized to assess the effect of parameter transfer on modelling LULC changes. The 2005 LULC had about 20% more urban classified land than the 1992 LULC. However, the estimated change in impervious cover from 1992 to 2005 was only 2.95%. Average streamflow was only slightly affected by LULC changes. Maximum and minimum annual streamflows were found to be very sensitive to LULC changes. Annual minimum streamflow decreased moderately and annual maximum streamflow increased substantially due to LULC change. Again FDCs were developed from model-generated daily flows based on...
the 1992 and 2005 LULC maps. This was done for each of the three parameter sets: default, transferred, and Wolf Bay calibrated. The relative changes in FDCs due to differing LULC showed a similar pattern with each parameter set: Relative change is highest around 1% exceedance probability and drops drastically with increasing exceedance probability until it reaches a plateau. The impact of LULC change diminishes gradually as the storm gets bigger and beyond 1% probability of exceedance.

This study clearly showed the benefits of using data from nearby watersheds to improve the model performance under limited data conditions in the study watershed. The analysis carried out in this study further suggests that the choice of the parameter set, whether it is default model parameters or transferred from a donor watershed, has a marginal effect on modelling the impacts of different LULC scenarios on streamflow.

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REFERENCES


