Assessing the hydrological effects of land-use changes on a catchment using the Markov

Chain and WetSpa models

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ABSTRACT

Predicting the effects of land use (LU) changes and hydrological processes on a rapidly urbanised catchment using the Markov Chain and WetSpa models is the main objective of this research. Hourly hydrometeorological data for 2001-2016, land use maps, a DEM and soil texture were used as inputs into the models. The simulation results verified some negative impacts of LU changes such as increases in peak discharge and flow velocity from 2001 to 2032 by 57.1% and 39.4%, respectively. Additionally, the time of concentration decreased from 6 h in 2001 to 5 h in 2016 and to 4 h in 2032. Surface runoff recorded the highest increases by 48.4% and 83.9%, respectively, in 2016 and 2032, compared to 2001. We concluded that the combination of both models is an appropriate tool for predicting the possible effects of LU changes on different hydrologic features, which are vital information for land managers.

KEYWORDS: catchment response; human impact; interactive relations; Markov Chain; WetSpa.

1 INTRODUCTION

Deforestation, agriculture development, and urban growth are recognised as major land use and land cover (LULC) changes worldwide, especially in developing countries (Bahremand *et al.* 2007, Kharazmi *et al.* 2018, Hazbavi *et al.* 2019). LULC changes strongly affect the hydrological processes (Chen and Yu 2015, Wang *et al.* 2015, Cerdà *et al.* 2019). Impervious surfaces in urban areas limit the infiltration of water into the soils resulting in increased surface runoff, and having a reduction in surface roughness shortens the overland flow detention time (Bosmans *et al.* 2017,

Hazbavi 2018). This can drastically affect water quality and storage (Kavian et al., 2018, Vargas-Pineda et al., 2020) and vegetation status or soil properties (Jafarian & Kavian, 2013).

For decades, different hydrological models, ranging from physical to empirical types (e.g., such as Soil and Water Assessment Tool (SWAT), Water Erosion Prediction Project (WEPP), and Runoff Routing Model (RORB) have been used to estimate runoff (Memarian *et al.* 2014, Khoi and Suetsugi 2014, Chen and Yu 2015, Tan *et al.* 2015). Additionally, some models like Water and Energy Transfer between Soil, Plant and Atmosphere (WetSpa) can combine the hydrological processes with land use (LU) change detection techniques (Bahremand *et al.* 2006, 2007, Albhaisi *et al.* 2013, Wang and Chen 2019).

The high potential of WetSpa in predicting spatial hydrological components of different conditions have been well documented (Bahremand *et al.* 2006, 2007, Tavakoli and De Smedt 2013, Karimi *et al.* 2016). Major advantages of the WetSpa model include the use of a GIS (Geographic Information System) platform, based on physically-based processes, incorporating distributed hydrological modelling and requiring a few parameters for calibration (Hosseini and Ashraf 2015, Abdollahi *et al.* 2018).

Integration of the effect of spatiotemporal land cover changes on the ecosystem with hydrological modelling has received much attention recently. The importance of vegetation processes in catchment hydrologic systems is well documented too (e.g., (Kavian et al., 2017, Wang et al., 2013; Minea *et al.*, 2019, Saint-Laurent *et al.*, 2019). In this regard, the Markov Chain model has been widely used to predict future land cover changes (Keshtkar and Voigt 2016, Hamad *et al.* 2018, Gebremedhin 2019). This model is recognised as the most widely used for LU predictions in different regions due to its dynamic considerations in LULC in terms of both spatial

and temporal scales (Gebremedhin 2019), as well as being precise and dependable (Hamad *et al.* 2018).

In the scientific literature, there are many investigations that assess LU change effects on hydrological regimes. For example, Nejadhashemi *et al.* (2011) studied the LU change effects on hydrologic responses in the agricultural regions of Michigan and Wisconsin, USA. In Saudi Arabia, Mahmoud and Alazba (2015) assessed the spatial changes of surface runoff as a result of LU change in the Al-Baha region. They used the Soil Conservation Service Curve Number (SCS-CN) method combined with Markov Chain analysis. Zhang *et al.* (2016) also investigated the hydrological impacts of LU change and climate variability during two periods of 1995-2014 and 2015-2024 in China. In this study, LU models of Markov Chain and Dyna-CLUE were combined with the SWAT model. Hamad *et al.* (2018) predicted the LULC changes for 2023 under two scenarios of “Iraq under siege” and “Iraq after siege”. They used LU maps of 1993, 1998, 2003, 2008 and 2017 for the Cellular Automata (CA)-Markov Chain model.

This type of research is generally not common in rapidly developing countries like Iran that are experiencing drastic urbanisation processes. In Iran, Mohammady *et al.* (2018) modelled the hydrological effects of LU change of the Baghsalian catchment in the Golestan Province. The LU changes in terms of conversion of forest and rangeland to agriculture and urban settlement in this catchment increased surface and sub-surface runoff. Recently, Gebremedhin (2019) evaluated the spatiotemporal variation of LULC change in northern Ethiopia. They concluded that conducting such a study could help to formulate sound policies and strategies concerning sustainable development. With the ever-changing climate, it is imperative that more research is conducted on the topic in developing countries (van der Bank & Karsten, 2020, Gondhalekar & Ramsauer, 2016).

Understanding the present and future LULC changes, and their impacts on the hydrological processes, could be vital for natural environment conservation in rapidly developing countries, especially at the catchment scale (e.g., Visessri and McIntyre 2016, Marhaento *et al.* 2018), thus preventing irreparable land degradation over the short to medium term (Memarian *et al.* 2014). Therefore, the present research is formulated for the Ziarat Catchment, Golestan Province, northern Iran. The specific objectives of this study are to a) assess the LU changes during the 2001-2016 period; b) predict the future LU changes during 2001-2032 using a Markov Chain method; and c) assess the changes in hydrological processes caused by LU changes using the WetSpa model. In different parts of the Ziarat Catchment, the rapid urbanisation has resulted in unusual LU changes that have influenced the water resources to a large degree. In this study, the main novelty is the combination of a predictive model such as the Markov Chain method and the WetSpa model to investigate LU changes for the first time for a rapidly urbanising area in a developing country. Using the results of this study, water managers and policymakers could be more capable of making proper decisions to mitigate flood-related problems including biodiversity losses and pollutant transport.

2 MATERIALS AND METHODS

2.1 STUDY AREA

The Ziarat Catchment (9580 ha) is situated within the mountainous area of the southern part of Golestan Province, Iran (Figure 1). It lies between longitudes of 54° 20' 13" and 54° 35' 55" E and latitudes of 36° 35' 58" and 36° 47' 11" N. The elevation of the study catchment varies between 491 and 3,027 m. It has steep hillslopes with an average slope of about 41.4%, suggesting

significant erosive power of generated runoff and its capability to transport sediments and debris downstream. Although the catchment receives some snow in winter, its hydrology is primarily driven by rainfall which contributes about 30% of the domestic water supply of Gorgan City.

<<Figure 1>>

The climate of the region is warm and temperate, falling under class Csa of the Köppen-Geiger method (Peel *et al.* 2007). It experiences an average annual, monthly maximum (March) and monthly minimum (August) precipitations of 550, 90 and 18 mm, respectively. For the temperature, the average is 17.8°C, with the maximum occurring in July (28°C) and minimum in January (8°C). The highly erodible formation of Shemshak and Gorgan Schists form approximately 36% of the catchment. Different erosion facies consisting of falls, debris, and streamside erosion manifest in this catchment (Kornejady *et al.* 2017). The catchment has diverse LULC including forests, rangelands, farmlands, and urban areas. In recent years, this catchment has been subjected to environmental risks because of tourist facilities and settlement developments. This is particularly the case for the village of Ziarat, with about 2000 inhabitants, which is an important tourist destination in Golestan Province (Zamani *et al.* 2012). Because of the rapid conversion of forest lands and farms to residential areas (Figure 2), it is hypothesised that runoff volume and flood peak will increase with negative consequences on social, economic and financial fronts.

<<Figure 2>>

2.2. Data collection and processing

Figure 3 shows a flowchart explaining the methodological procedure. In the ensuing sections, the different parts of the modelling process are explained in detail.

<<Figure 3>>

The hydrometeorological data were obtained from the Meteorological Organization of Golestan Province (<http://portal.golestanmet.ir/>) and the Golestan Regional Water Authority (<http://www.gsrw.ir/?l=EN>) and the stations are presented in Table 1. The data consists of 16 years (2001-2016) of hourly precipitation data from two stations (Abgir, ID: 12-212 and Naharkhoran, ID: 12-024), hourly temperature and evapotranspiration from the Abgir Station (ID: 12-215), and hourly discharge data from Naharkhoran Station (12-043).

<<Table 1>>

In Figure 4 are presented the maps of the digital elevation model (DEM) and soil texture used as inputs to the WetSpa model. The 30-m grid size DEM of the Ziarat Catchment was derived from the 1:50,000 topography map of Iran while the 30-m grid size soil texture map was collected from the Forests, Ranges and Watershed Management Organization of Iran. There are three soil texture categories, namely sandy loam (SL), silty loam (SL) and clay loam (CL) in the study catchment.

<<Figure 4>>

The LU maps of 2001 and 2016 were based on the Landsat Satellite images (30-m spatial resolution) retrieved from USGS Landsat ETM/TM satellites (<http://glovis.usgs.gov/>) and initially they were interpreted visually. Then, the pre-processing requirements including atmospheric and radiometric corrections were carried out. This was followed by the application of the maximum likelihood classification (MLC) to generate the final LU maps of 2001 and 2016 (Karan and Samadder 2016). The ArcGIS 10.3 Software (ESRI, USA) was used as the primary environment to prepare all the maps. However, the prepared maps in ArcGIS were imported into ArcView

Software for further processing as required by the WetSpa model. Note that the WetSpa model is supported and implemented entirely within the ArcView environment (Liu and De Smedt 2004).

2.3. Land-use change assessment

Transition probabilities required by the Markov Chain landscape prediction model (Weng 2002, Keshtkar and Voigt 2016) were derived from the 2001 to 2016 time series of the LU maps. According to Tang *et al.* (2007), all LU spatial transition models could be explained by the following matrix equation:

$$V_{t+1} = V_t \times P \quad (1)$$

where V_{t+1} and V_t are vectors consisting of fractions of each LU type at times of $t+1$ and t , respectively. The square matrix P is the transition probability $P(i,j)$ from landscape i to j during the study period. Here, the $P(i,j)$ in k steps is calculated as (Anderson and Goodman, 1957; Tang *et al.*, 2007):

$$P_{i,j} = \sum_{k=1}^k \frac{P_m(i,j)}{kn_m} \quad (2)$$

$$P_m(i,j) = \frac{N(i,j)}{\sum_{j=1}^n n_{ij}} \quad (3)$$

where $N(i,j)$ is the observed data (i.e., vectors of each LU type) during the transition, n_{ij} is the number of years between time steps i and j , and n_m is the total number of years (Tang *et al.* 2007).

It was assumed that the LU change is stochastic. It is also supposed that the transition probability matrix (P) stays constant in consecutive periods (Chakraborty *et al.* 1995). The spatial transition probabilities, when more than one step is needed, are obtained from the elements of P_{ij} . The primary limitations of Markov Chain transition probability-based models for LULC change

analysis include i) the assumption of spatial independence of transitions; and ii) the difficulty of ascribing causality within the model, i.e., the transition probabilities are often derived empirically from multi-temporal maps with no description of the process (Baker, 1989). Another limitation of this model is the division method of small regions, in which cells with the same land-use class transit to other land use classes according to the same transition probability (Yang et al., 2014). Also, the main limitation of the Markov Cellular Automata model is that it assumes that the factors of change in the past remain the same in the future (Yagoub et al., 2014).

For the current research, three scenarios of 2001, 2016 and 2032 were evaluated. Hypothetically, the Markov Chain model assumes that the transition possibility is spatially independent (Brown *et al.* 2000). Due to the effect of neighbouring cells, the forthcoming tendency of a specific pixel would not be a simple function of its present status which is disregarded in the stand-alone Markov Chain model (Tang *et al.*, 2007).

In this paper, the Markov Chain model was applied based on the classified LU map of 2001 to estimate the future LU change (i.e., 2032). To validate the model, we first estimated the LU map of 2016 using the LU maps of 2001 and 2016 as inputs to the Markov Chain model. Then, the obtained results were compared with the LU map of 2016 which was extracted from Landsat image analysis. The LU maps which were generated by Landsat image analysis (i.e., 2001 and 2016) and that predicted by the Markov Chain model (i.e., 2032) were applied as inputs into the WetSpa model. Three indices of overall, user and producer accuracies, as well as the Kappa statistic, were finally derived for validation of the results of the LU classes of 2001 and 2016 (Zakerinejad and Maerker 2015). For the accuracy assessment, we used the information obtained from the field observations and photo-interpretations using Google earth images.

2.4. The WetSpa model

The WetSpa model was initially developed by Wang *et al.* (1996) in the context of water and energy transfer between soil, plants and the atmosphere. This spatially distributed physically based model has been adapted for flood prediction (De Smedt *et al.* 2000, Liu *et al.* 2003, 2004, Liu and De Smedt 2005). A combination of empirical as well as physical relations was employed to characterise the hydrological regimes in the WetSpa model. The hydrological processes of precipitation, evapotranspiration, depression storage, interception, infiltration, percolation, water balance and flow components of surface runoff, interflow, and groundwater flow were considered in the model. A combination of a segregated water balance for the vegetated, bare-soil, and the impermeable portion of each raster cell, and open water is considered as the total water balance for each cell (Zeinivand 2015, Karimi *et al.* 2016). The model simulates the spatial pattern of hydrological components at the catchment scale and predicts peak discharges and hydrographs for the stream network.

A moisture-related modified rational method with potential runoff coefficient was applied for excess rainfall calculation (Liu and De Smedt 2004, Bahremand *et al.* 2006, Albhaisi *et al.* 2013). These calculations were done according to land cover, soil type, slope, the magnitude of rainfall, and the antecedent soil moisture as documented in previous research (Liu and De Smedt 2004, Bahremand *et al.* 2006, Albhaisi *et al.* 2013).

The interflow and percolation are assumed to be gravity-driven in the model (Famiglietti and Wood 1994). The percolation out of the root zone is associated with the hydraulic conductivity at effective saturation (Eagleson 1978). It is assumed that the interflow occurs in the root zone after percolation when the field capacity is less than the soil moisture. A kinematic wave approximation and Darcy's law were applied to estimate the amount of interflow produced from

each cell as a function of the hydraulic conductivity, slope angle, the root depth, and the moisture content (Liu and De Smedt 2004).

The WetSpa model is made of a simple structure so that evapotranspiration, excess runoff, interflow, percolation and infiltration are calculated pointwise (Liu and De Smedt 2005). The routing of channel flow and excess runoff is carried out using the diffusive wave approximation of the St. Venant equation given as (Bahremand *et al.* 2006):

$$\frac{\partial Q}{\partial t} = d \frac{\partial^2 Q}{\partial x^2} - c \frac{\partial Q}{\partial x} \quad (4)$$

where Q [L^3T^{-1}] is the discharge at time t [T], x [L] is the distance along the flow direction, d [L^2T^{-1}] is the dispersion coefficient and c [LT^{-1}] is the location-dependent kinematic wave celerity. Parameters c and d could be predicted as $c = (5/3)v$ and $d = (vH)/(2S_0)$. The necessary prerequisites were also fulfilled before applying this equation as recommended by Henderson (1966). Here, v [LT^{-1}] and H [L] are respectively the flow velocity and hydraulic radius (or flow depth average). H [L] is defined as (Molnar and Ramírez 1998):

$$H = a_p (A_i)^{b_p} \quad (5)$$

where A_i [L^2] is the upstream drainage area of the cell. The constant network parameter of a_p [-] and the geometry scaling exponent of b_p [-] could also be calculated based on the catchment characteristics, both depending on the discharge frequency (Liu *et al.* 2003). The spatial distribution of the soil, LU and topographic properties within the study area were modelled on a small GIS-derived sub-catchment scale (Liu and De Smedt 2004, 2005).

Some other limitations of the WetSpa model are (Liu and De Smedt 2004): i) the defined LU category groupings can be ambiguous with some uses potentially aligning with several identifiable categories or even not aligning with any category; ii) different extensions of the software or input data with different resolution can generate different results; iii) 30x30 m of resolution cannot

distinguish some elements such as roads, bridges or houses; and iv) the spatial distribution of the groundwater table, as well as its variation during the simulation periods, cannot be predicted.

2.5. Gridded model data input

A 30-m grid size DEM was used to extract the hydrologic and topographic features. For this research, two support area thresholds of 100 and 1000 cells were used to define the stream network and the 72 sub-catchments, respectively. A minimum slope threshold value of 0.01% was considered to deal with the flat areas or zero inclination in the area (Liu and De Smedt 2004; Bahremand *et al.* 2007).

The exceedance probability of 0.5 with a two-year return period of flow depth was used to produce the hydraulic radius grid. Correspondingly, the average hydraulic radius of 0.005 and 1.5 (m) resulted in the upland cells and main river outlet, respectively. In the next step, the reclassification of grid layers of soil hydraulic conductivity, residual moisture, plant-wilting point, porosity, pore size distribution index, and field capacity was done based on the grid of the soil texture layer by means of an attribute lookup table (Liu and De Smedt 2004, Bahremand *et al.* 2007). According to the WetSpa requirements, the grid of LU was also used as a basis for reclassification of layers of interception storage capacity, root depth, and Manning's roughness coefficient. More information about the pedotransfer functions used and the look-up tables is available in Rawls *et al.* (1983), Rowe (1983), Cosby *et al.* (1984) and Liu and De Smedt (2004). The Manning's coefficients of the lowest and the highest stream order grids of 0.055 and 0.025 $\text{sm}^{-1/3}$ were used as the basis for linear interpolation of the Manning's coefficient for the channels (Liu *et al.* 2004, Bahremand *et al.* 2007). The combination of LU, DEM and soil texture were used

to generate the maps as suggested by Liu and De Smedt (2004). The coefficient of potential runoff for the whole study catchment was set as 0.54.

The appropriate grids of precipitation, temperature and potential evapotranspiration (PET) were determined with the help of geographical coordinates of the study stations and catchment boundary. The Thiessen polygon extension of the ArcView Spatial Analyst was applied to generate the precipitation map. Additionally, temperature and PET maps were depicted. To this end, the hourly values of temperature were generated by computing a sine curve from daily minimum and maximum (Liu and De Smedt 2004). The daily to hourly disaggregation of evaporation data were also done using a sine curve (Liu and De Smedt 2004). Finally, the flow velocity, mean travel time to the basin outlet and the standard deviation grids were determined according to the flow routing approach as explained above (Eqs. 4 and 5). These data enabled the calculation of the instantaneous unit hydrograph (IUH) of each grid cell and the catchment outlet (Albhaisi *et al.* 2013). The coefficient of groundwater flow recession was fitted according to the base flow of the observed hydrograph. In addition, the recession part was adjusted using an interflow scaling factor (Bahremand *et al.* 2007).

From the total study period from 2001 to 2016, two periods of 2001-2010 and 2011-2016 were considered for WetSpa model calibration and validation, respectively, using hourly hydrometeorological data. Manual calibration and parameter ESTimator (PEST) Software were used to set the optimal parameters (Karimi *et al.* 2016, Bahremand 2016). The 11 calibrated parameters are given in Table 2.

<<Table 2>>

For this research, the hourly hydrometeorological data (i.e., precipitation, temperature and evapotranspiration) of the 2001-2010 and 2011-2016 periods were used, respectively, for the

calibration and validation steps of the WetSpa model. Both steps were carried out based only on the LU map of 2001. Then, the simulations of the calibrated WetSpa model were conducted using the hourly hydrometeorological data of the 2001-2016 period for the three LU maps of 2001, 2016 and 2032. The soil texture and DEM remained unchanged for the calibration, validation and simulation steps.

2.6. Model evaluation

Qualitative and quantitative assessments were used to evaluate the performance of the WetSpa model in two steps of calibration and validation. In addition to the comparison of graphical results of measured and predicted hydrographs, statistical analysis was also considered (Karimi *et al.* 2016). The Nash-Sutcliffe Efficiency (NSE) performance statistic was used to evaluate WetSpa simulations. NSE, a dimensionless coefficient with values ranging between $-\infty$ and 1 (perfect match), is expressed mathematically as (Nash and Sutcliffe 1970):

$$NSE = 1 - \frac{\sum_{i=1}^n (Q_{si} - Q_{oi})^2}{\sum_{i=1}^n (Q_{oi} - \overline{Q_o})^2} \quad (6)$$

where Q_{si} and Q_{oi} are the simulated and measured flow components at time step i , respectively. In Eq (6), $\overline{Q_o}$ and n represents the average of the measured flows and the number of time steps over the simulated period, respectively.

The Kling-Gupta Efficiency (KGE) was also calculated to minimise the calibration problems of the un-normalised mean square error component in NSE (Gupta *et al.* 2009).

$$KGE = 1 - \sqrt{(r - 1)^2 + (\alpha - 1)^2 + (\beta - 1)^2} \quad (7)$$

where α is the ratio of the standard deviation of Q_o to that of Q_s , β is the ratio of the average of Q_o to that of Q_s , and r is the Pearson correlation coefficient. Based on the obtained LU change maps, model parameters were re-calculated, and the model was run to deliver the corresponding flows.

3 RESULTS

3.1 Land use change assessment

The LU classification of 2001 and 2016 conducted using the maximum likelihood classification (MLC) method within ENVI 4.8 Software is presented in Figure 5. The accuracy of each LU map using the producer, user and overall accuracies, and the Kappa coefficient, are summarised in Table 3. The accuracy of the Kappa statistic obtained is substantial (>0.77) as stated by Landis and Koch (1977).

<<Figure 5>>

<<Table 3>>

The validation step for the output of the Markov Chain Model was carried out by comparing the 2016 modelled output with the classified LU (Landsat images analysis) obtained for the same year, and overall spatial accuracy of 83% was obtained. The predicted LU change in 2032 which was projected using the Markov Chain Model is depicted in Figure 6. The changes in the total area from one LU type to another from 2016 to 2032 are summarised in the transition matrix in Table 4.

<<Figure 6>>

<<Table 4>>

The area and percentage change in each LU class from 2001 to 2016 and from 2001 to 2032 are compared in Table 5. As seen in Table 5, the LU for 2001 was classified into four different classes as urban (53 ha), forest (7562 ha), agriculture (594 ha) and rangeland (1371 ha). Forest occupied the highest percentage of the total area in 2001. However, by 2016 the urban area had increased from 53 to 932 ha while forest and rangeland areas had decreased (with percentage changes of 11.5% and 0.5%, respectively), with the forest area remaining the dominant LU.

It is predicted that there would be an increase in urban area from 2001 to 2032. The percentage of change from 2001 to 2016 is very high for the settlements (1658.5%) and the projected change from 2001 to 2032 is also very much elevated (4692.5%). Rangeland, agriculture, and forest areas would decrease in 2032 by 22.1%, 56.7% and 33.3%, respectively, compared to 2001.

<<Table 5>>

3.2 Hourly streamflow simulation

The simulation results by application of LU change maps are compared to the observed hydrographs in Figure 7. Table 6 shows the comparison of changes in the simulated flow components to each LU change in the Ziarat Catchment.

<<Figure 7>>

<<Table 6>>

The calibrated base temperature and degree-day coefficients, respectively, was 1°C^{-1} . The calibrated groundwater flow recession coefficient was $0.0025 (\text{d}^{-1})$ which gives a good estimation for all base flows. The model performance was also satisfactory because the NSE was 0.72 for the validation step and the modified NSE for high and low flows were, respectively, 0.81 and 0.82. The model outputs also showed that 15.9%, 83.5% and 83.7 % of the precipitation was intercepted by plant canopy, infiltration and evapotranspiration, respectively. Additionally, 19.3% became runoff, of which 17.5% recharged the groundwater reservoir, while 1.5% and 0.4% contributed to interflow, and a direct flow, respectively.

The model evaluation criteria of NSE of 0.68 and 0.72 was obtained for the direct discharges at calibration and validation steps, respectively. Additionally, the KGE of 0.73 and 0.79 were calculated for the calibration and validation periods.

3.3. Land-use change impacts on hydrological parameters and flow components

Table 7 presents the results of the impact of LU changes on the hydrological parameters and flow components. As mentioned previously, after calibration and validation of the WetSpa model, the base inputs of this model were applied using the data from 2001 to 2016 for all three LU maps of 2001, 2016 and 2032. The average meteorological data were similarly considered for detection of changes in the hydrological parameters and the flow components under the effects of the three LU maps in the study time steps. The results indicate that urbanisation produced the highest change in peak discharge by 26.9% and 57.1% in 2016 and 2032, respectively, compared with 2001 values. The runoff coefficient value was projected to increase during the future, which caused an increase in surface runoff and peak discharge. With increasing runoff coefficient and velocity, and decreasing roughness, the time of concentration also decreased by 4.4% and 29.7% in 2016 and 2032, respectively. The flow velocity also experienced a modification influenced by the LU changes, which generated an increase in runoff coefficient and a decrease in roughness.

Related to the flow components are surface runoff, interflow, and groundwater, which also experience important changes (Table 7). As observed in Table 7, the surface runoff amount increased with increasing urban areas. The surface runoff, interflow, and groundwater of 2001 were the lowest at 3.10, 16.00 and 305.90 mm, respectively, but gradually increased and reached the highest levels in the predicted model in 2032. There were gradual increases in groundwater levels and interflow amounts due to the LU changes.

<<Table 7>>

4 DISCUSSION

The interaction and process of rainfall-runoff have been highly influenced by LU type and changes (Bahremand *et al.* 2006, Albhaisi *et al.* 2013, Guadie *et al.*, 2020). The WetSpa model was calibrated to simulate hourly hydrographs of the Ziarat Catchment under different LU maps (2001, 2016, and 2032). The changes in the mean flow travel time and the standard deviation caused a change in the IUH of each cell and the total catchment. The simulated peak discharge for the 2001 LU was 3.01 m³/s and was 3.82 m³/s for the current (2016) LU, which means that the peak discharge has increased by 26.9%, and for the future 2032 LU this would be 57.1%. Additionally, the effects of LU change on flow components of surface, interflow and groundwater runoffs were also evaluated quantitatively from the model results. It was found that LU change from 2001 to 2032 resulted in increased surface and total runoffs by 83.9% and 6.3%, respectively.

Increased discharge due to the growth of urbanisation has been reported by other researchers and, due to the climate change expectations, this dynamic would be even worse, further complicating land management plans (Higashino and Stefan, 2014, Miller and Hutchins, 2017). For example, Bahremand *et al.* (2007), simulating flows in the Margecany–Hornad Catchment, Slovakia, observed a decrease in peak discharge by 12% that was caused by a 50% increase in forest areas. Albhaisi *et al.* (2013) also found a systematic groundwater recharge increase due to clearing of the non-native hillslope vegetation for the Upper Berg Catchment, South Africa. Niu and Sivakumar (2014) reported increasing and decreasing flows, respectively, due to deforestation and afforestation for the East River catchment in South China.

Our results confirmed that the forest and agricultural areas decreased. Undeniably, the vegetation cover, in the form of natural plants or agricultural fields, is one of the most important sources of water to the atmosphere (Právělie *et al.* 2019) and it deaccelerates runoff generation

and river incisions (Bertalan *et al.* 2019). The detection of a strong relationship between an increase in the water yield with a decrease in evapotranspiration also agrees with studies conducted under different environmental circumstances, but all are highly affected by human activities (e.g., Wagner *et al.* 2013). A clear example that highlighted the impact of the LU changes caused by substituting the vegetation with urban areas was reported in the Jinjiang Catchment of China (Lin *et al.* 2015).

The expansion of urban areas and traffic is considered a key factor driving the decrease of the vegetation areas in numerous catchments in mountainous areas (Rose and Peters 2001; Salesa and Cerdà, 2019). For example, Hosseini *et al.* (2012) showed a progressive increase in surface runoff (7.3%) and a decrease in the lateral flows (11.3%). For our study, the groundwater is gradually increased, but that may be due to the low value of evapotranspiration that was also very small during the study periods. Solutions and alternatives must be developed, but undoubtedly, they cannot be proposed without considering the opinion of stakeholders, inhabitants and policymakers (Crossland *et al.*, 2018, Petrakis *et al.*, 2020, Rodrigo-Comino *et al.*, in press)

5. CONCLUSIONS

A land use (LU) change assessment on hydrological processes was done for the Ziarat Catchment in northern Iran. The LU changes during 2001 to 2016, including forest (-11.5%), agricultural (-2.2%) and grassland (-0.5%) reductions as well as an urban land increase (+16.6%), caused significant changes in peak discharge (+26.9%), time of concentration (+4.4%), flow velocity (+24.6%), total runoff (+2.6%), surface runoff (+48.4%), interflow runoff (+2.5%) and groundwater runoff (+2.2%). Scenario-based analysis of future LU changes to 2032 also showed that the hydrology pattern of the Ziarat Catchment would be significantly affected. For the period

2001-2032, the peak discharge, time of concentration, flow velocity, total runoff, surface runoff, interflow runoff, and groundwater runoff were projected to increase by 57%, 29%, 39%, 6%, 84%, 5% and 6%, respectively. Because of the high capability of the Markov Chain and WetSpa models in LU change and impact analysis, it is highly recommended to use these results for future allocation of available water resources and effective management of the studied catchment.

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Disclosure statement

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Figure Captions

Figure 1. Location of the study area in Iran (a) and Golestan Province (b), and digital elevation model of the Ziarat Catchment (c).

Figure 2. Urban areas of the Ziarat Catchment.

Figure 3. Flowchart describing the methodology used in this study.

679 Figure 4. Digital elevation model (a) and soil texture (b) maps of the Ziarat Catchment.

680

681 Figure 5. Land use maps of the Ziarat Catchment for 2001 and 2016.

682

683 Figure 6. Land use map of the Ziarat Catchment for 2032.

684

685 Figure 7. Graphical comparison between observed and calculated hourly flow data for March
686 2010 from the calibration period.

687

Table 1. Hydrometeorological station characteristics

ID	Station	Type of hourly data	Height	Longitude	Latitude
12-212	Abgir	Precipitation	950	54° 28' 23.68"	36° 42' 1.23"
12-024	Naharkhoran	Precipitation	500	52° 43' 48.32"	36° 29' 41.58"
12-043	Naharkhoran	Discharge Temperature and	330	54° 27' 60.00"	36° 44' 0.01"
12-215	Abgir	Evapotranspiration	950	54° 28' 50.53"	36° 42' 38.89"

Table 2. Evaluation results of land use classification.

Year	Land use class (km ²)	Producer accuracy	User accuracy	Overall accuracy (%)	Kappa coefficient
2001	Forest	96.83	98.95	89.4	0.77
	Urban	72.57	32.07		
	Agriculture	74.59	45.98		
	Grassland	96.53	96.53		
2016	Forest	94.57	95.96	89.4	0.81
	Urban	73.65	67.55		
	Agriculture	67.82	72.71		
	Grassland	9.72	88.87		

Table 3. Transition probability for converting land use classes into another.

Land use class	Urban	Agriculture	Forest	Grassland
Forest	0.30	0.00	0.68	0.02
Agriculture	0.88	0.10	0.00	0.02
Urban	0.59	0.07	0.01	0.32
Grassland	0.08	0.20	0.24	0.48

Table 4. Total area and percentage of change of each land use class among different years.

Land use	ha		%	2001 to 2032	
	2001	2016	2001 to 2016	ha	%
Forest	7562	6689	- 11.54	5046	- 33.27
Urban	53	932	+ 1658.49	2540	+ 4692.45
Agriculture	594	581	- 2.18	931	- 56.73
Range land	1371	1378	- 0.50	1068	- 22.10

Table 5. Introduction of land use change maps.

Land use map	Introduction
1	2001 (Past condition)
2	2016 (Current condition)
3	2032 (Future condition)

Table 6. Comparison of changes in simulated hydrological parameters parallel to the land use changes in the Ziarat Catchment.

Hydrological parameters	2001	2016	% of change (2001-2016)	2032	% of change (2001-2032)
Peak discharge (m^3/s)	3.01	3.82	+26.91	4.73	+57.11
Flow time (h)	6.09	5.82	+4.43	4.28	-29.72
Flow velocity (m/s^2)	0.07	0.09	+24.63	2.79	+39.43

Table 7. Comparison of changes in simulated flow components to each land use change in the Ziarat Catchment

Flow components	2001	2016	% of change (2001-2016)	2032	% of change (2001-2032)
Total runoff (R)	325.00	333.4	+ 2.58	345.50	+6.30
Surface runoff (SR)	3.10	4.60	+ 48.38	5.70	+83.87
Interflow runoff (IR)	16.00	16.40	+ 2.50	16.80	+5.00
Groundwater runoff (GR)	305.90	312.50	+ 2.15	322.90	+5.55

Figure 1. Location of the study area in Iran (a) and Golestan Province (b), and digital elevation model of the Ziarat Catchment (c).

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