Title:

FROM THE PAST TO THE FUTURE: SPATIO-TEMPORAL DYNAMICS OF WATER-BALANCE IN A RAPIDLY URBANIZING KATHMANDU VALLEY WATERSHED OF NEPAL

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FROM THE PAST TO THE FUTURE: SPATIO-TEMPORAL DYNAMICS OF WATER-BALANCE IN A RAPIDLY URBANIZING KATHMANDU VALLEY WATERSHED OF NEPAL

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ABSTRACT

The resources of the earth are under immense pressure due to the multiple anthropogenic influences. The land resources which largely attribute to the quality as well as quantity of the water, is facing extreme stress due to the rapid urbanization resulting from population growth as well as socio-economic development. It is imperative that the response of hydrological processes to the change in landuse is properly understood for the sustainable management of water and land resources. In view of the underlying problem of unscientific landuse practice as a result of the rapid urbanization and the consequent water-stress, this study has attempted to assess the spatio-temporal dynamics of the water-balance components in Kathmandu valley watershed from the past to the future. Forecasting the future landuse scenario and applying popular semi-distributed, physically based hydrological model Soil and Water Assessment Tool (SWAT), the change in water-balance component in the past, present and future scenario was evaluated. In order to exclusively quantify the impact of landuse change, the same climatic conditions are forced for all scenarios. Projection of landuse revealed that nearly half of the total area of Kathmandu valley watershed will be covered by built-up zone by the year 2040. The increase in the built-up area is compensated mainly by agriculture areas and the forest areas which will have further implications on the multiple ecosystem services. The results and analysis clearly indicated that the rapid urbanization will significantly alter the water-balance components of the study watershed that is already reeling under the water-stress. It was also concluded that the impact of landuse change on the water availability will be felt greater at the sub-basin level than at the basin level. The findings of this study entail the urgency to regulate the landuse practice as well as formulate appropriate measures to abate the adverse impacts.

Keywords: Kathmandu Valley, Urbanization, Landuse change, Water-balance, Soil and Water Assessment Tool (SWAT), Hydrological modeling

1. INTRODUCTION

Water is an indispensable resource for human existence whose sustainability hinges on the balance among the different socio-environmental components. There is no argument over the fact that the stress on this priceless resource is being ever increasing due to the multiple climatic and anthropogenic influences. The alteration of the hydrological cycle that governs the spatio-temporal availability of water is apparent due to the human interference with the natural system. Among different components of the natural system, land resource is one of the key elements controlling the quantity and quality of water resources. Management of landuse, however, has been a major challenge across the globe. The need to accommodate the growing population, particularly in urban areas, has resulted in unplanned and unscientific landuse development which have cascading effect across multiple socio-environmental services. Population projections has estimated about 68% of the world's population to live in urban areas by 2050 (United Nations, 2018). Unsurprisingly, migration of people to urban centers is an obvious choice owing to the better economic opportunities especially in developing countries. Driven by such rapid migration and population growth, the landuse in urban areas are transforming alarmingly without due consideration of the future consequences. It is ubiquitous that the landuse landcover (LULC) changes are major driving forces attributing to environmental changes across all spatial and temporal scales (Gashaw et al., 2018). Water, a key ecosystem component, already under severe stress is further expected to aggravate due to the urbanization-triggered rapid and haphazard LULC changes. One of the most important socio-economic processes for establishing far-reaching and long-term ecological effects is land use transformation, especially the human-induced variety termed 'urbanization.' Management and protection of available water resources is a key to sustainable development of human kind. Addressing these issues requires information about the factors that drive hydrological changes and their related effects on local water resources (Aboelnour et al., 2019). Several studies have indicated that the LULC change associated with rapid urbanization impacts the ecosystem by altering the hydrological balance of a watershed (Fang et al., 2020). The urbanization process is transforming permeable land surfaces into impervious surfaces and ultimately changing regional hydrological characteristics (Zhou et al., 2013). The change in LULC can influence watershed hydrology by altering the rates of interception, infiltration, evapotranspiration, and groundwater recharge that result in changes to the timing and amounts of surface and river runoff (Baker and Miller, 2013). According to Wu et al., (2015), LULC changes due to urbanization and deforestation alters the hydrological processes and lead to change of flood frequency and annual mean discharge by impacting the evapotranspiration, soil infiltration capacity, and surface and subsurface flow regimes. Increase in impervious surface areas due to urbanization are responsible for increased runoff, reduced infiltration leading to flash floods and lower groundwater recharge (Ansari et al., 2016;Wakode et al., 2018). Hence for the long-term water-resources planning and management, it is imperative to understand the hydrological response of a watershed to LULC change. In this regard, the appropriate quantification of the change is crucial to formulate mitigation and management plans.

Hydrological modelling, in this regard, are widely adopted techniques to understand the catchment hydrological characteristics including the distribution of various water balance components at different level of a watershed. Hydrological models enable understanding and quantification of hydrological processes under the influence of characteristics describing rainfall and catchment features (Kumar et al., 2017). Also, hydrological models are used to perform scenario analysis such as the climate change impact, hydrological response of watershed to LULC change, etc. (Jothityangkoon et al., 2001).

In this study, we employed a popular semi-distributed hydrological model Soil and Water Assessment Tool (SWAT) to investigate the impact of landuse change on different hydrological components and the water availability. The future impact on water balance is also quantified after forecasting the future landuse scenario. There have been a number of researches to quantify the impact of LULC on hydrological variables using SWAT model (Kundu et al., 2017; Wagner et al., 2013; Woldesenbet et al., 2017). We chose the Kathmandu valley watershed (KVW) which is one of the rapidly urbanizing area not only in Nepal but in South Asia (Ishtiaque et al., 2017; Muzzini and Aparicio, 2013).

Several studies have been conducted previously in the KVW covering varieties of topics related to hydrology and water-resources. A study by Pandey et al. (2010) on Kathmandu valley found that due to urbanization, the groundwater extraction has exceeded the recharge rate by more than twice resulting in consistent depletion of ground water table and recommended for immediate action plans for the sustainable management of groundwater resources. Similarly, Shrestha et al., (2020) analysed the impact of climate change on groundwater resources of KVW under different climate scenarios. Their analysis predicted the decrease in groundwater recharge in future scenario of climate projection. Thapa et al., (2017) applied three different hydrological models to analyse the watershed scale seasonal variation in water-balance components. In the view of severe water deficit in the Kathmandu valley, another study by Thapa et al., (2018) analysed the role of inter-basin water transfer project in bridging the demand-supply gap and hence improving the water-security. Pokhrel (2018) applied Soil and Water Assessment Tool

(SWAT) in KVW to quantify the impact of landuse change in the watershed scale water-balance and sediment yield between 2000 and 2010 which showed that the surface runoff has increased while the groundwater discharge has decreased.

Each of the previous studies in KVW, however, didn't either consider the LULC in their analysis or didn't make an attempt to forecast future LULC and analyse the future hydrological response of LULC change. Shrestha and Acharya, (2020) analysed the impact of the landuse change on the ecosystem value services of the Kathmandu valley watershed at the basin level. A recent study by Lamichhane and Shakya (2019) analysed the integrated impact of LULC and climate change on the watershed scale water-balance. Their study however didn't analyze the spatio-temporal distribution of water balance at the sub-basin level where the effect of LULC change is more pronounced. Similarly, Lamichhane and Shakya, (2019b) studied the possible alteration in the groundwater recharge zones of KVW due to future LULC changes and revealed that the recharge areas are likely to shrink as a result of the urban expansion. This study however didn't analyse the effect of LULC change on the groundwater availability. Against this backdrop, the current study has made an effort to comprehensively quantify the effect of LULC changes not only from the present to the future but also from the past scenario. The analysis of the impact of LULC change is performed at the sub-basin level which will be more helpful for planners and policy makers in prioritizing the problematic areas for formulating the management plans. The objectives of the current study are to project the future landuse scenario based on the past trends and hence quantify the isolated impact of landuse change on the water-balance components both at the subbasin and the basin level.

2. STUDY AREA AND THE UNDERLYING PROBLEM

The study watershed also known as the Kathmandu valley watershed (KVW) constitutes of three districts viz. the capital Kathmandu, the historical Bhaktapur and Lalitpur districts within Bagmati province of Nepal. The valley forms the head water/upstream area of the Bagmati River basin which stretches to the plains of the Terai before draining to India. **Figure 1 (a-d)** depicts the location, topography, landuse and the soil types within the KVW. The Bagmati, typically a rain-fed and partially spring-fed River, drains out KVW originating on the southern slope of Shivpuri at an elevation of 2700 meter above sea level (masl) (Sharma, 1987). The KVW surrounded by the forested hills of the Mahabharat range resembles a bowl-shaped valley, covering an area of 603 km^2 at the Khokana outlet in Lalitpur district. Forest, agriculture and the built-up areas are the three major landuse types in KVW (ICIMOD, 2013) whereas the four dominant soil classes according to the classification of SOTER (Dijkshoorn and Jan Huting, 2009) are eutric cambisols, gleyic cambisols, chromic cambisols and chromic luvisols.

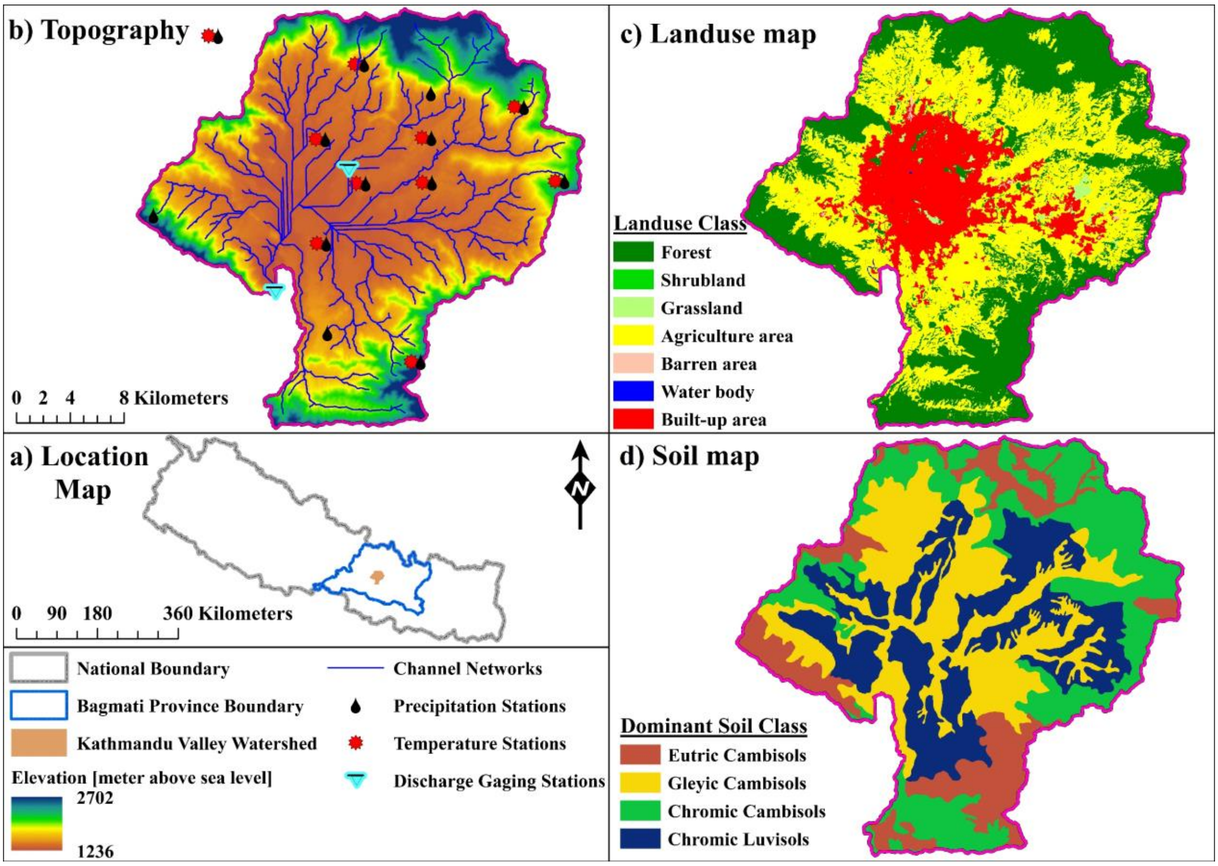


Fig. 1. a) Location b) Elevation c) Landuse and d) Soil map of the KVW

The Kathmandu valley experiences temperate to sub-tropical climate with cold winter and hot summer where the rainfall is the sole contributor to the water-flow in the basin. Based on the observed data from the Department of Hydrology and Meteorology (DHM), Nepal for the period 1990-2018, the average annual rainfall in KVW varies between 1600-1800mm of which over 80% occurs in the monsoon period that typically lasts mid-June to late September. This signifies considerable spatio-temporal variation in the rainfall pattern.

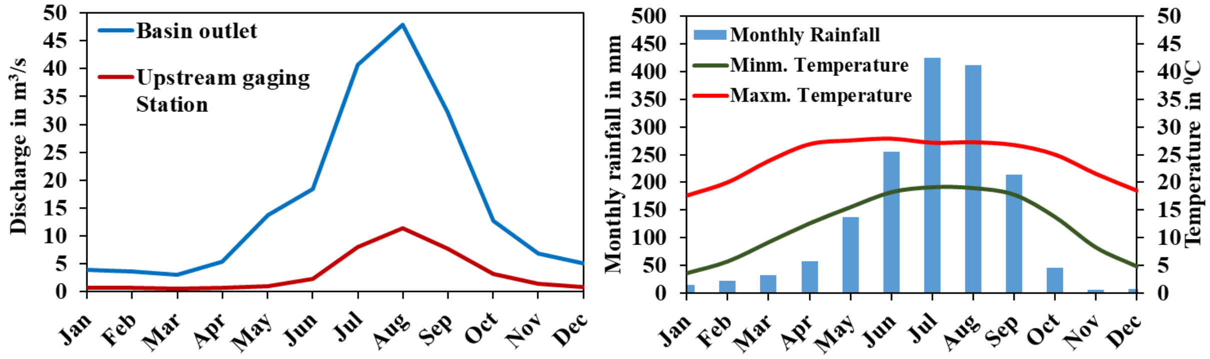


Figure 2. Inter-annual variation of a) streamflow and b) Rainfall and Temperature

The monthly variation of rainfall and the mean monthly minimum and maximum temperatures are presented in Figure 2 (a). As illustrated in Figure 2(b), the long-term mean monthly discharge at the outlet (Khokana Station) of KVW varies between 3m^3/s to 48m^3/s where March and August experience minimum and maximum discharge respectively. The pattern is similar at the upstream gaging station (Gaurighat, Catchment area=68 Sq. km) where the minimum discharge of 0.5 m^3/s occurs in March and the maximum monthly discharge (11 m^3/s) occurs in August. There is a high variation between the dry and the monsoon period average flow in the basin. Due to this variation, there is significant water-deficit during the dry period.

One of the fastest growing cities of South Asia, Kathmandu valley has witnessed a rapid upsurge in the population in the last few decades. The period 1990-2010 marked a rapid urbanization in the history of Kathmandu valley during which the valley inhabitants increased over two folds from about 1.1 million to 2.5 million (CBS, 2012). Migration of the people from other districts for administrative, economic, educational and medical purposes being a driving factor behind this rise. Studies and the population projections have claimed this trend to continue in the future. Unplanned urbanization and development ensued due to the proliferation of population has adversely impacted socio-environmental services. Among several sectors, the unscientific conversion of landuse pattern overtops others with cascading effect on multiple sectors. The land acts as a recharge medium as well as storage beneath the ground and any shift in the landuse dynamics is certain to alter the quality and quantity of water availability. As it will be discussed later, the haphazard conversion of forest and agriculture areas into settlements has put further stress on already deteriorating water-resources of the KWV with dire consequences.

The people of the valley are facing acute shortage of water-supply for daily consumption. With growing population, the daily household water demand has grown to nearly 400 million litre per day (MLD). But, Kathmandu Upatyaka Khanepani Limited (KUKL), a government entity managing Kathmandu's water supply, is able to fulfil just about 120 MLD in wet season while a meagre 73 MLD in dry season (Bhusal, 2019). To meet this deficit, people are forced to rely on the private tanker industry. The unregulated and unscientific extraction of groundwater by the tanker industries have led to the severe depletion of groundwater table. Furthermore, due to the rapid extension of residential areas, the groundwater recharge zones have shrunk. On the other hand, the encroachment of the floodplain and drainage area due to the construction of buildings and roads have risen the risks of inundation during monsoon as evident from regular flooding in various parts of the KVW in the recent years. If the current trend continues, the situation will get bad to worse. Sustainable water management approach could be the solution to the water-crisis in Kathmandu valley.

3. MATERIALS AND METHODS

3.1 Hydro-meteorological and geographical data

Hydro-meteorological time series as an input forcing to the hydrological model used in this study includes mean daily discharge, daily rainfall, mean daily maximum and minimum temperatures, relative humidity, solar radiation and the wind speed. Except solar radiation and wind speed, all the above-mentioned dataset was obtained from the Department of Hydrology and meteorology (DHM), Government of Nepal which is the mandate organization for hydro-meteorological measurements in Nepal. The spatial distribution of the different stations covering the study area is indicated in **Figure 1 (b).** A 30m*30m resolution ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer) digital elevation model (DEM) was used for catchment delineation and the extraction of various catchment attributes like stream networks, slope, etc. A soil map that defines the physical properties of soil layers was acquired from the Soil and Terrain (SOTER) database of Food and Agriculture Organization (FAO). Raster layers of the land-use and land cover were obtained from the International Center for Integrated Mountain Development (ICIMOD, http res.icimod.org) for both the period of 1990 and 2010. The details on different datasets used in the current study are presented in **Table 3.1**.

Table 1 Details on the data used for the study

Input data	No. of stations	Resolution	Time Period	Source
Climate				
Rainfall	13	Daily	1990-2000	DHM, Nepal
Temperature	10	Daily	1990-2000	DHM, Nepal
Relative Humidity	5	Daily	1990-2000	DHM, Nepal
Solar Radiation	1	Daily	1990-2000	CFSR-NCEP
Wind Speed	1	Daily	1990-2000	CFSR-NCEP
Hydrology				
Discharge	2	Daily	1990-2000	DHM, Nepal
Geographical				
DEM		30m		ASTER
Soil		1:1000000		SOTER-FAO
Landuse		30m	1990 & 2010	ICIMOD-Nepal

3.2 Landuse change Prediction

The projection of future landuse was performed using Land Change Modeler (LCM) tool within Terrset software package (https://clarklabs.org/terrset/land-change-modeler/). The prediction of future landuse in LCM is based on the historical landuse change between time 1 and 2. Landuse prediction in LCM is an empirically driven process which moves stepwise from 1) Change analysis 2) Transitional potential modeling and finally 3) the change prediction (Eastman, 2016). LCM employs a multiperceptron neural network built on the Markov chain modelling method with cellular automata (CA) (Sinha and Eldho, 2018). The CA-Markov model is one of the commonly used models among many LULC modelling tools and techniques, which models both spatial and temporal changes. CA-Markov model combines cellular automata and Markov chain to predict the LULCC trends and characteristics over time. Moreover, the CA-Markov model is one of the planning supports tools for analysis of temporal changes and spatial distribution of LULC (Hamad et al., 2018). There have been a number of analysis on past landuse change and future landuse prediction using the LCM tools, for example (Hamad et al., 2018; Anand et al., 2018; Sinha and Eldho, 2018), etc.

Landuse maps of two different time period is first given as the input for the model. In change analysis step, the assessment of actual change between time 1 and time 2 is performed. The quantitative assessment of different LULC categories, net change of each LULC class and the contributors to the net change experienced by each LULC category are calculated. The changes in the landuse are the transition from one landuse class to another landuse class. If the study area contains high number of landuse classes, the combination of transitional potential could be very large.

3.3 SWAT model set-up, Sensitivity Analysis, Calibration and Validation

Soil and water assessment tool (SWAT) (Arnold et al., 1998) employed in this study is a physically based, continuous time-scale semi-distributed model capable of simulating different physical processes pertaining to the movement of water, sediment, nutrient, crop growth, etc. within a watershed (Neitsch et al., 2011). SWAT model requires information on the climate, hydrology, soil, topography and land use. It allows the impact assessment of management practices and climate on water resources, sediment, and agricultural related processes at watersheds and larger river basins with varying soils, land use, and management conditions over long periods of time (Abbaspour *et al.*, 2007; Winchell *et al.*, 2013). SWAT accounts for the spatial heterogeneity by partitioning of a watershed into different sub-basins and sub-basins further discretized into Hydrological Response Units (HRUs) which are aggregated land areas within a sub-basin comprising unique landuse, soil, slope and management conditions (Neitsch et al., 2011). The study watershed as depicted in Fig. 2 was divided into 16 subbasins and further into 148 HRUs. Land phase of the hydrologic cycle which controls the amount of water, sediment, nutrient and pesticide loadings to the main channel is solved by SWAT model using the following water balance equation:

$$SW_t = SW_0 + \sum_{i=1}^{t} (R_{day} - Q_{surf} - E_a - w_{seep} - Q_{gw})$$

Where, SW_t is the soil water content at the end of the day, SW_0 is the initial amount of soil water content, t is the current time in days, R_{day} gives the amount of rainfall in i^{th} day, Q_{surf} indicates the amount of surface runoff on day i, E_a gives the amount of evapotranspiration, w_{seep} gives amount of percolation on day i and Q_{gw} is the amount of return flow on day i. All the components are in mm.

The runoff from the daily rainfall was computed based on the modified Soil Conservation Service (SCS) curve number method whereas the Potential evapotranspiration (PET) was estimated using the Penman-Monteith method.

SWAT-Calibration and Uncertainty Analysis Program (SWAT-CUP), a stand-alone tool was employed to perform the sensitivity analysis, the calibration and validation of SWAT model. Sensitivity analysis is a procedure of recognizing the most significant parameters for calibration and validation purpose ((Moriasi et al., 2007). Its objective is to evaluate the sensitivity of the model output to the changes in input parameter values particularly when the model consists of large number of parameters. Model calibration

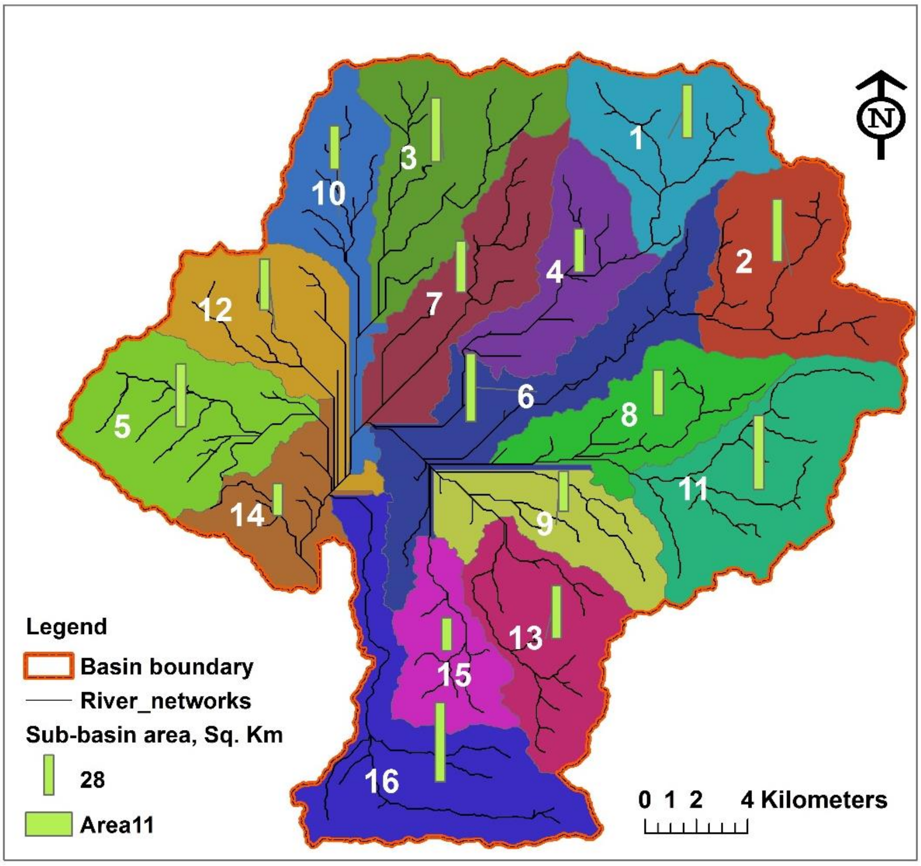


Fig. 3. Subbasin delineation of the study watershed.

consists of the overall procedures performed to achieve the best possible agreement between the simulated and the observed values. The agreement between the observed and the predicted variables are measured statistically based on some goodness-of-fit indicators known as objective functions. In essence, model calibration is a procedure of modifying the model parameters, within their recommended ranges, with an objective of attaining the best possible values of the objective functions. Model validation is performed to assure that the calibrated model properly assesses all the variables and conditions which can affect model results, and demonstrate the ability to predict observations for periods separate from the calibration effort. In this study, the popularly used Nash-Sutcliffe Efficiency (*NSE*) was selected for the model calibration purpose (McCuen et al., 2006). However, additional three objective functions were also assessed for the performance evaluation of the model. Coefficient of Determination (R^2), PBIAS (Gupta *et al.*, 1999; Moriasi et al., 2007) and the Kling-Gupta Efficiency (KGE) (Gupta et al., 2009) were also assessed. Krause *et al*. (2005) reported that R^2 and NSE are the most widely used statistics for both calibration and validation.

The model calibration and validation were executed for the daily discharges but the results were evaluated for the monthly values as well. Two discharge gauging sites, one located at sub-basin 4 and the other at the basin outlet, were chosen for calibration and validation purposes. A five-year period [1992-1996] was selected for the calibration while the validation was done for the period 1997-2000. A warm up period of two years [1990-1991] was used for both the sites during the calibration. Warm up period was aimed at stabilizing initial conditions of soil water (Cibin et al., 2010; Kim et al., 2018).

4. Sensitivity Analysis, Calibration and Validation of SWAT model

The selection of input parameters for this study were based on the previous studies on this watershed (Pokhrel, 2018). The most sensitive parameters are represented by groundwater process, evaporation and surface runoff. It is found that for the study area; SURLAG.bsn, SOL_Z.gw, GW_delay, EPCO.hru, SOL_AWC.sol and REVAPMN.gw were among the most sensitive parameters.

The calibration-validation was performed using two gaging stations simultaneously, one at sub-basin 4 (Gaurighat Station) and the other at the outlet of the basin (Khokana Station). The use of multiple sites helps to preserve the spatial heterogeneity of the catchment during parameter calibration. The calibration and validation are basically performed for daily discharge. However, the daily calibrated model was also run for the monthly time step and the performance were evaluated. The comparison of observed and simulated discharge at the two gaging stations as illustrated in **Fig. 4 (a-d)** shows that the model has quite well reproduced the actual condition. However, in some instances, peak flows are underestimated while the low flows are accurately mimicked. For both the stations, the observed and simulated mean monthly flows showed closer resemblance than the daily case for both low as well as peak flows. Similarly, **Fig. 5** depict the scatterplot of observed versus simulated discharge where it can be seen that the flows are in good agreement with each other for both the stations. The comparison of the flow duration curve (FDC) for the calibration and validation period are shown in **Fig.6**. Although FDC is a subjective approach of model evaluation, it gives an important information about the occurrence of flows which are vital in the design and allocation of water-resources projects (Karki, 2012). The overall occurrence of flows was precisely simulated for basin outlet while the low flows were slightly underestimated at subbasin-4.

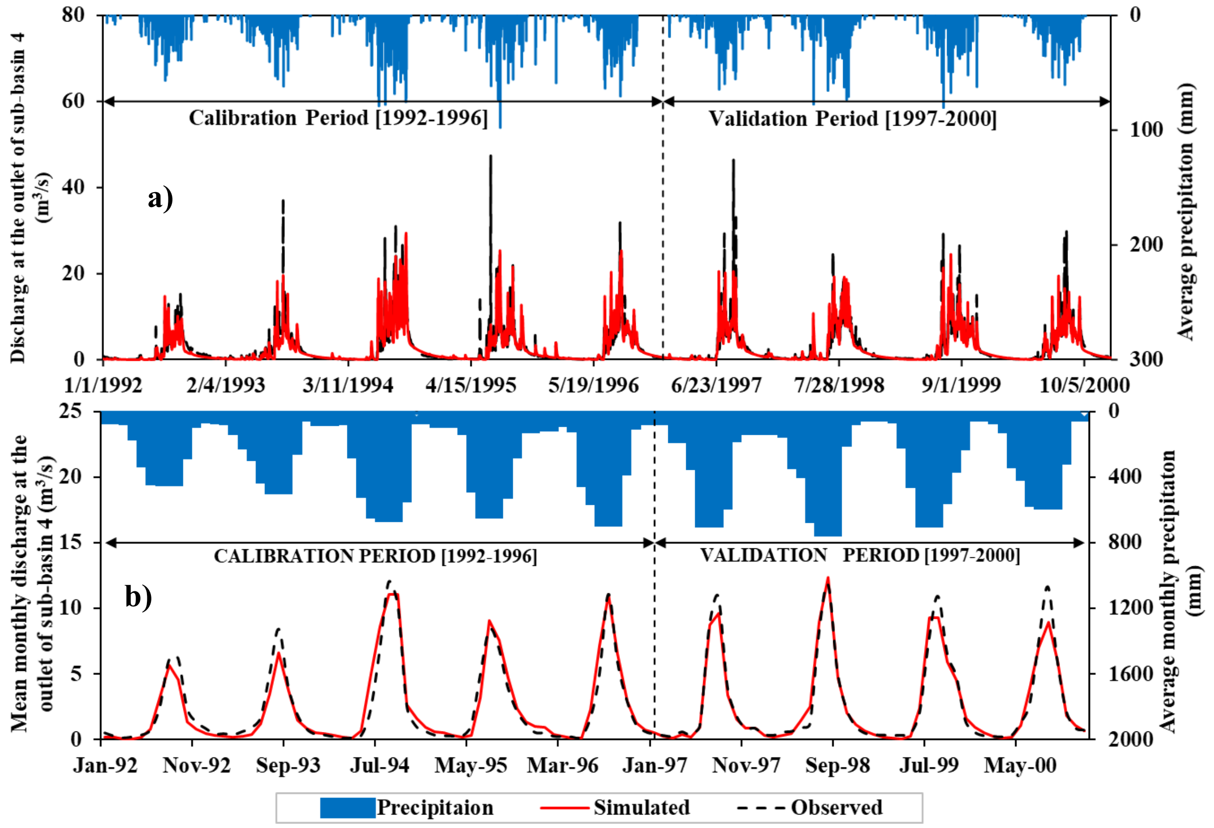


Fig.4. Comparison of observed and simulated discharge at sub-basin 4 **a)** daily **b)** monthly

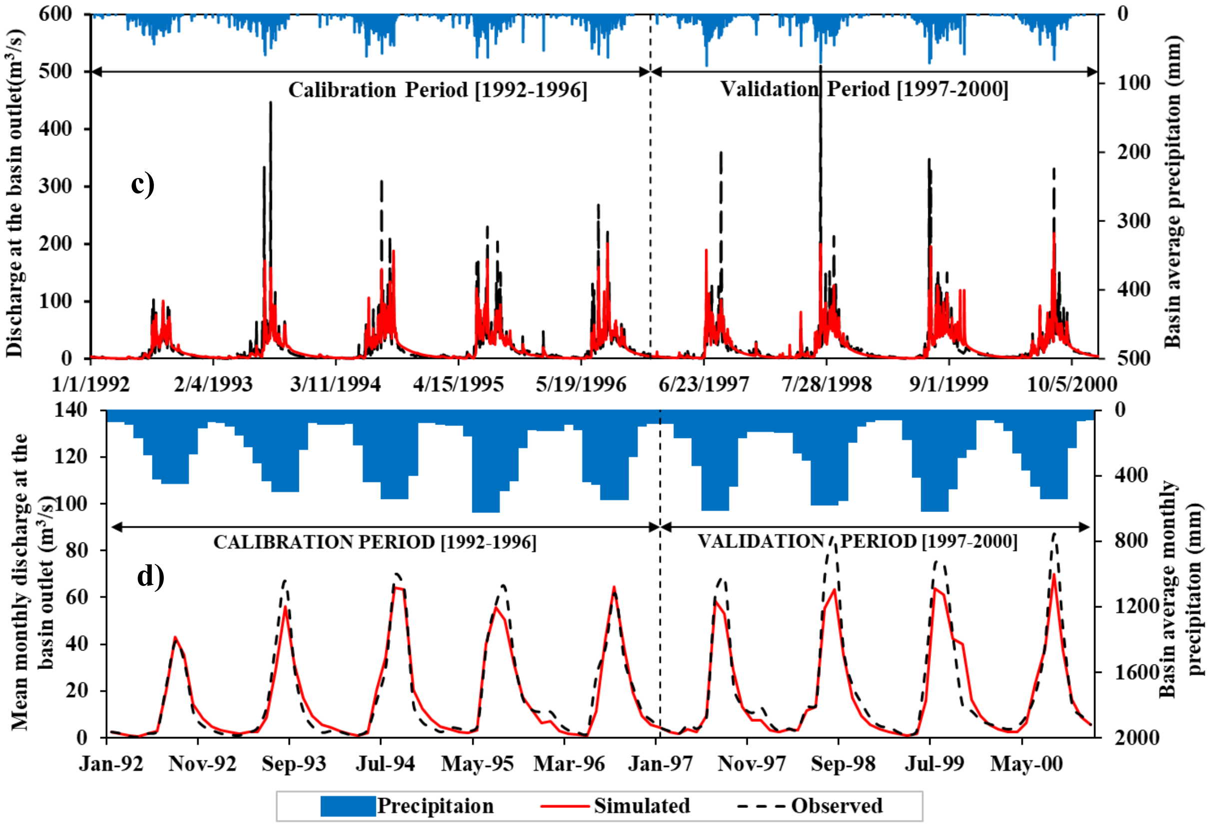


Fig.4. Comparison of observed and simulated discharge at the basin outlet **c)** daily **d)** monthly

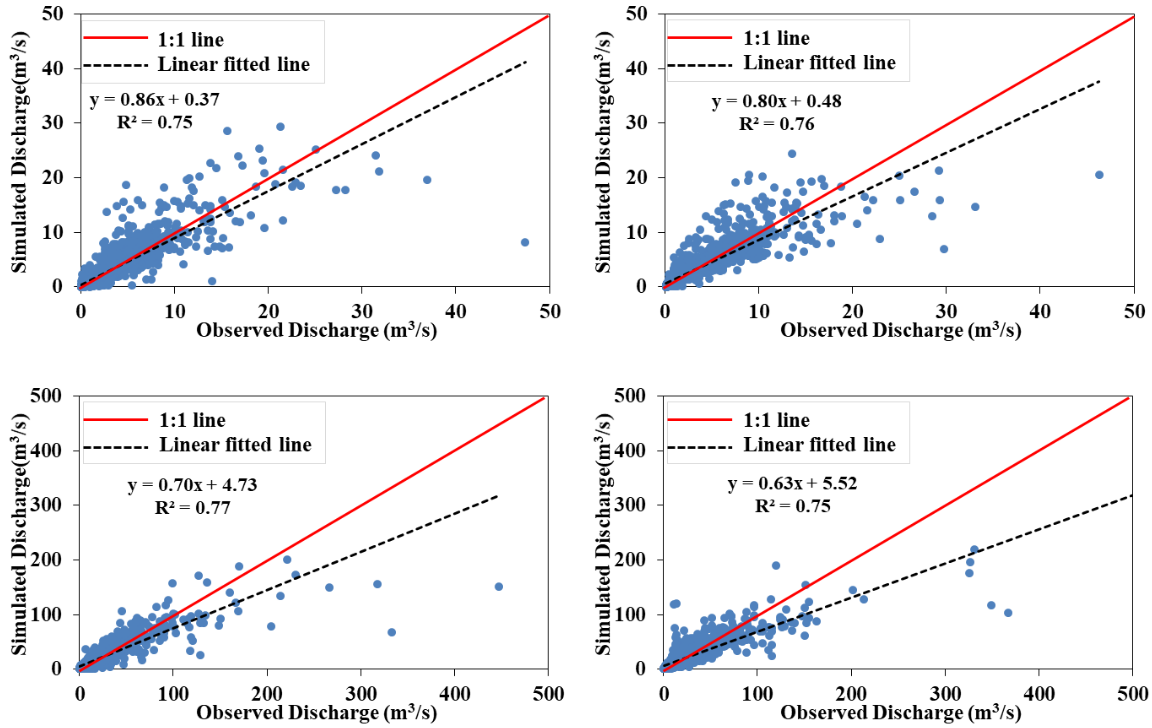


Fig. 5. Scatterplot of observed vs simulated discharge for subbasin 4 (a) Calibration and b) Validation and for basin outlet (c) Calibration (d) Validation

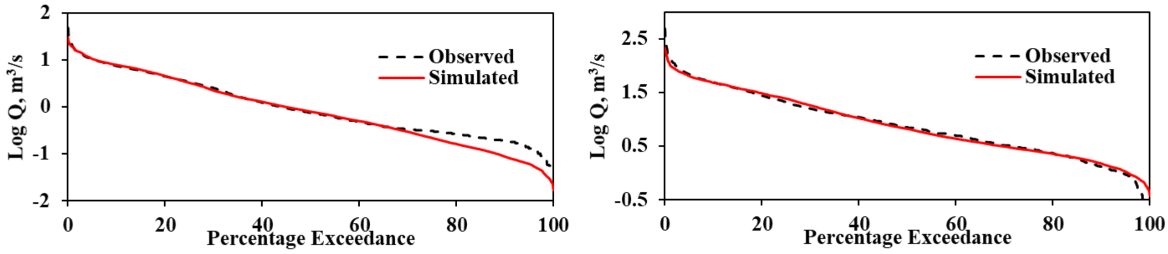
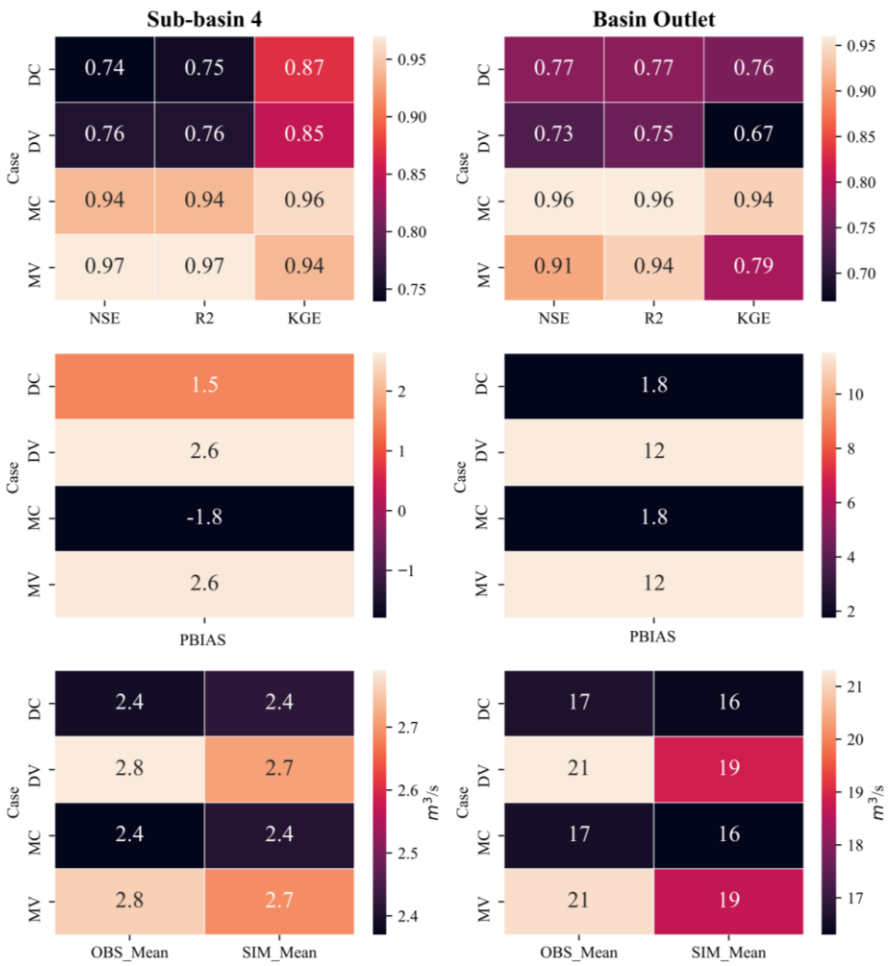


Fig. 6. Comparison of observed and simulated flow duration curve during the simulation period for a) subbasin 4 and b) basin outlet

Different model performance indices which portray the accuracy of the predicted results are presented in **Fig.7**. Each performance indices obtained for both the gaging stations are well above the satisfactory range as described in Moriasi et al., (2007). The performance indicators showed further improvement for monthly time-step. Also, the comparison between the observed and the simulated mean discharge were found to be matched closely.



DC: Daily calibration, DV: Daily Validation

MC: Monthly calibration, MV: Monthly Validation

Fig. 7. Performance evaluation of SWAT model based on different objective functions [Right column represents basin outlet while left column represents Sub-basin 4]

5. RESULTS AND DISCUSSIONS

5.1 Landuse change prediction

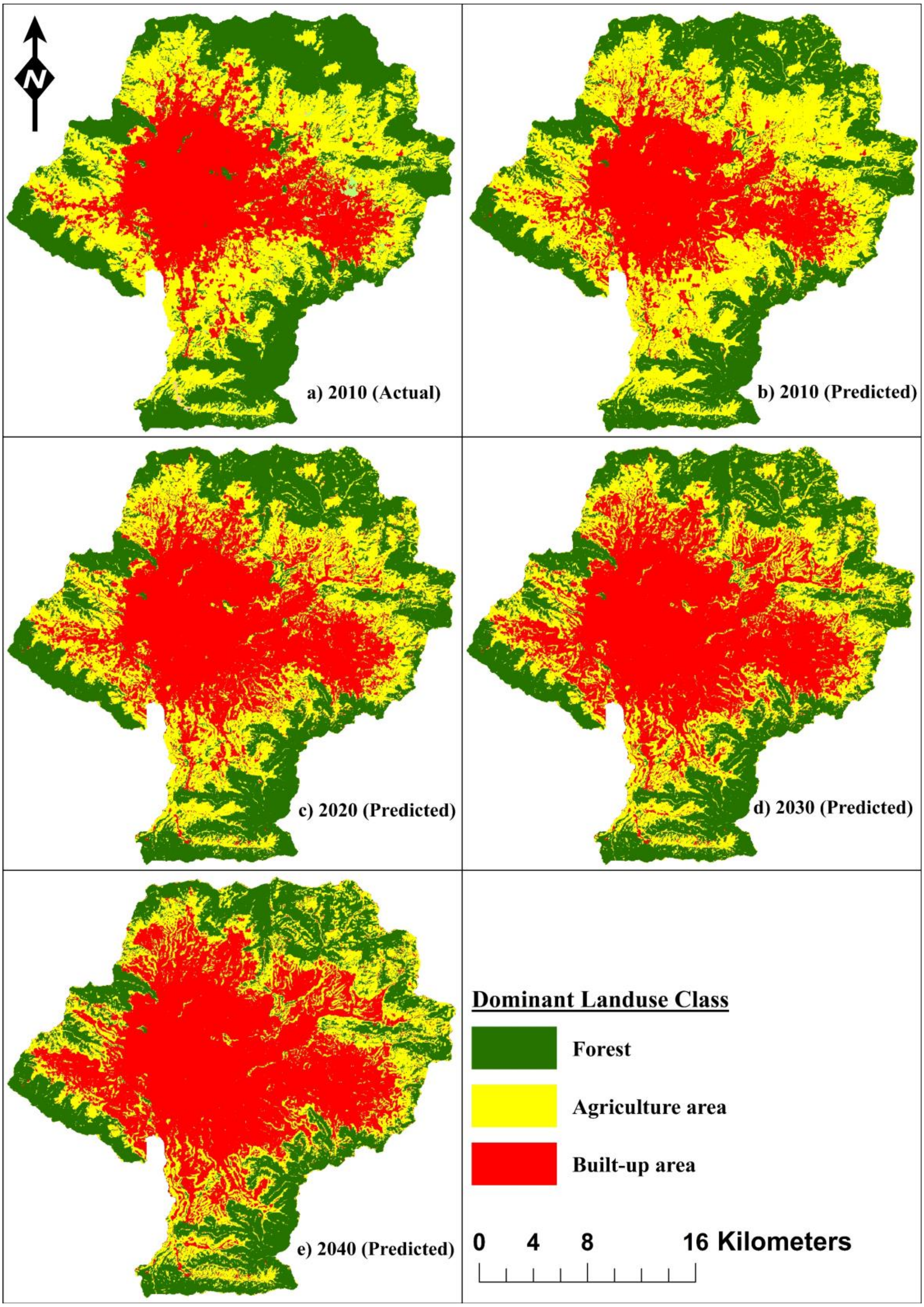


Fig. 8. Predicted landuse map of KVW for different years

The available landuse map of 1990 and 2000 were used to calibrate the model and hence forecast the landuse for the year 2010. The available landuse map of 2010 and the predicted map of 2010 as illustrated in **Fig.8**, **a** and **b** respectively were compared to confirm the accuracy of the predicted results. The comparison of actual and predicted landuse of 2010 in **Fig.8** demonstrate that the spatial distribution of different landuse is predicted quite well. Finally, the future landuse map of 2020, 2030 and 2040 were projected. Based on the trend of the past decades, the forest and the agricultural areas are expected to decrease while the built-up areas indicate rising pattern. The quantification of the landuse for different years are summarized in **Fig.9**. From 1990 to 2010, the forest cover and agriculture areas decreased by about 25 Sq. km and 45 Sq. km respectively. This decreased area has been transformed to built-up areas which increased by approximately 70 Sq. km. This period marks a rapid urbanization period in the history of the Kathmandu valley. The population of the Kathmandu during this period nearly increased by 2.5 times from about 1.1 million to 2.5 million. It can be seen in Figure 5.8 that the forest areas in 2040 will reduce to approximately 175 Sq. km from 216 Sq. km in 2010. Similarly, the agriculture areas will decrease by about 60 Sq. km to 155 Sq. km in between 2010-2040. The forest and agriculture areas combined contributed to more than 80% of the total catchment in 1990. However, it is expected that this will reduce to about 55% of the total catchment area. In the same period, the percentage of built-up areas will increase from 17% to nearly half of the total catchment area. This change in the landuse can have a profound effect on the overall water-balance scenario of the basin.

Based on the projection, nearly 50% of the total area of the KVW will be covered by built-up areas by 2040 which is more than 250% of the baseline period of 1990.

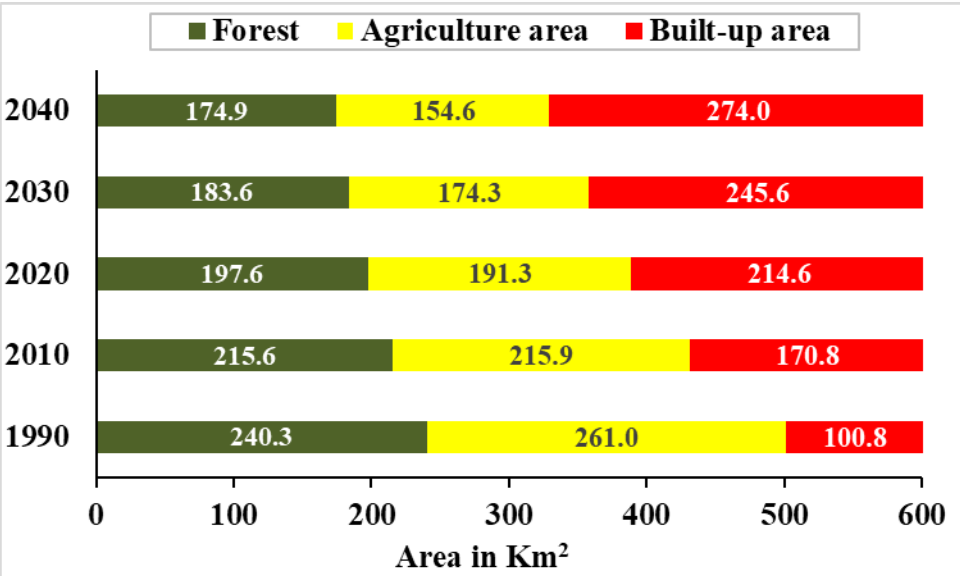


Fig. 9. Change in dominant landuse classes in KVW from 1990 to 2040

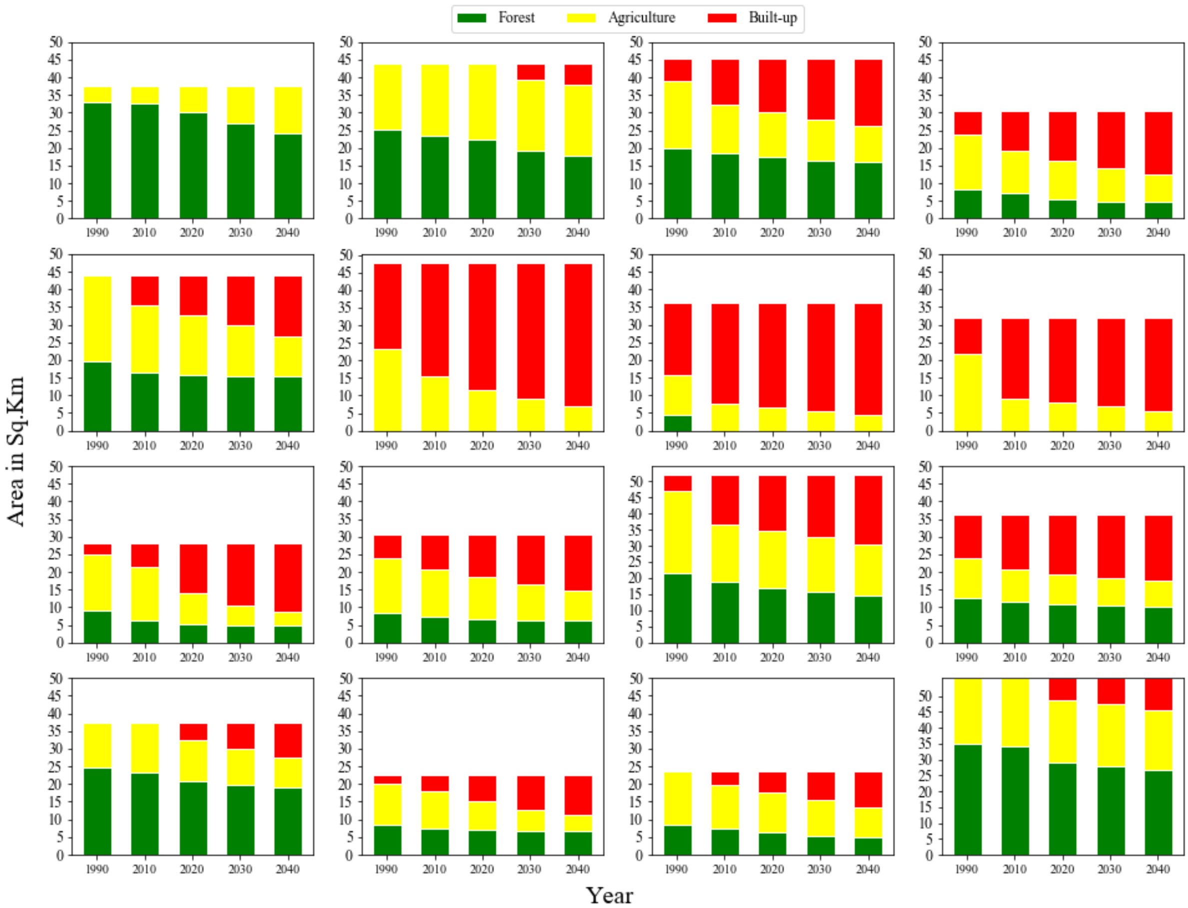


Fig. 10. Change in the landuse in different sub-basins within KVW

5.2 Analysis of water-balance

5.2.1 Water-balance under the past landuse of 1990 (the baseline scenario)

The validated model was run for the period 1990-2000 (1990-91: two years warm-up period) under the landuse of 1990 and the climate data of the same period. This case is considered as the baseline scenario in this study. Based on the simulated results, different water-balance components were quantified both at the sub-basin as well as basin level. **Fig. 11** illustrate the spatial distribution of different water-balance components at the sub-basin level of KVW. In **Fig. 11(a)**, the two labels (top and bottom) inside the map represent the sub-basin number and the mean annual precipitation (in mm) respectively. The spatial distribution of mean annual precipitation in different subbasins as shown in **Fig. 11(a)** indicate the considerable variability within the KVW. The difference between the least rainfall receiving subbasin to the most rainfall receiving subbasins is more than double of the least value. During the simulation period, the mean annual precipitation ranged from below 1200mm to above 2500mm and is generally higher for north-eastern (upper) and lesser for south-western (lower) subbasins. In the **Fig.11(b-**

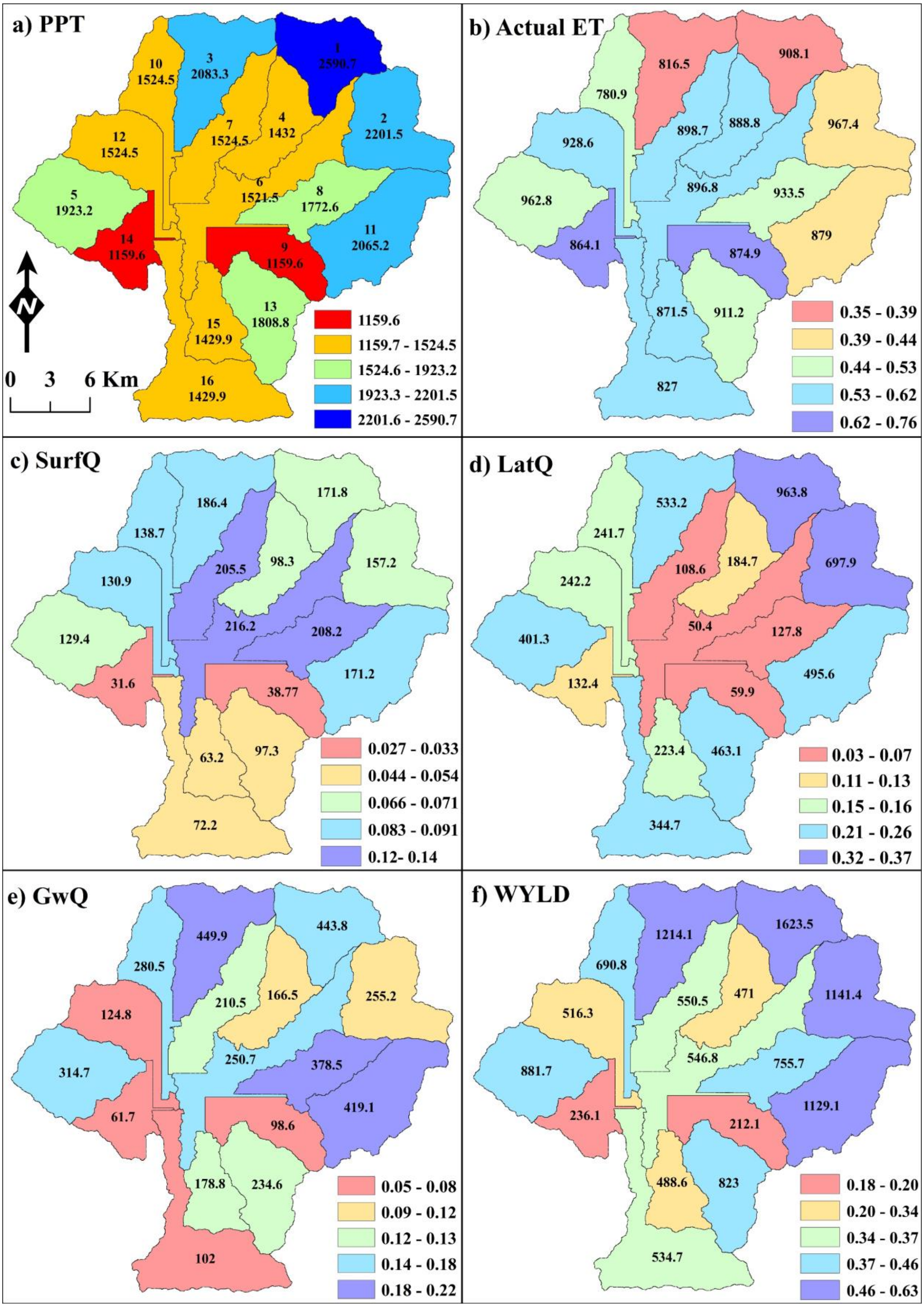


Fig. 11. Spatial distribution of different water-balance components at the subbasin level under 1990 landuse conditions (baseline scenario)

f), the value labelled in the map represent the actual values while the values of the colour-bar indicate the values normalized by annual rainfall of the respective subbasins. These color-bar therefore depicts different water balance components as a fraction of the mean annual precipitation of the corresponding sub-basins.

According to **Fig.11(b)**, the actual ET, in general, was found to be higher for forest and agriculture dominated subbasins like 1, 2, 5, 8,12, 13, etc. The annual rainfall values in these subbasins are also relatively higher. However, the fraction of the rainfall lost as ET was higher for subbasins like 4, 6, 7, 9, 12, 14, 15, 16, etc. Most of such subbasins are built-up area dominated. The surface run-off is mainly influenced by the impervious cover of the landuse i.e., built-up area as well as the amount of precipitation. In relation to this, the surface runoff component (SurfQ), as expected, was observed to be higher for built-up areas dominated subbasins like 6, 7 and 8 as depicted in **Fig.11(c)**. The higher values of surface run-off component in other subbasins like 1, 2, 3 and 11 is attributed to the greater rainfall and steeper slopes in these subbasins. Also, the fraction of precipitation transformed to surface run-off is greater in built-up areas dominated subbasins 6 and 7. Similarly, the lateral flow (LatQ) is generally smaller for these subbasins whereas its contribution is higher in forest and agriculture dominated subbasins as shown in **Fig.11(d).** The groundwater component is also mainly controlled by the land cover type and the amount of annual precipitation. It was observed that the highest groundwater discharge occurred in forest and agriculture dominated sub-basins like 1, 3, 5, 8, 10 and 11. Similarly, the least groundwater discharge was observed in sub-basin 9, 12, 14 and 16. However, the distribution of lateral Q showed that it was least in sub-basin 6, 9 including 4, 7, 8 and 14. The distribution of average annual water yield for each sub-basin is illustrated in **Fig.11(f).** Water yield is generally higher in subbasins with higher precipitation as well as forest dominated sub-basins like 1-3, 5, 8, 11 and 13. The water yield of different subbasins varied between 212mm to 1623mm with an average value of 784mm for the KVW. 8 out of 16 subbasins of KVW were found to have below-average water-yield. Also, it can be deduced that the subbasins surrounding the KVW results in greater water yield than those located at the valley floor.

The intra-annual (monthly) variation of different water-balance components including the water-yield has been illustrated in **Fig.12** which signifies a high temporal variation in the water-balance components. Water yield is below 50mm from October to April and increases between May to September as contributed by the precipitation in these months. The relative contribution of surface run-off, lateral Q and the groundwater Q to the total water yield for each subbasins has been demonstrated in **Fig.13**. The contribution of surface run-off to total water yield is higher for subbasins 6, 7 and 8 whereas the contribution of GwQ and LatQ is higher for other subbasins. The contribution of surface runoff to the water yield varied between 0.11 in subbasin 1 to 0.4 in subbasin 6. Similarly, the contribution of lateral Q to the water yield varied between 0.09 in subbasin 6 to 0.64 in subbasin 16. On the other hand, the contribution of groundwater Q to the water yield varied between 0.19 in subbasin 16 to 0.50 in subbasin 8.

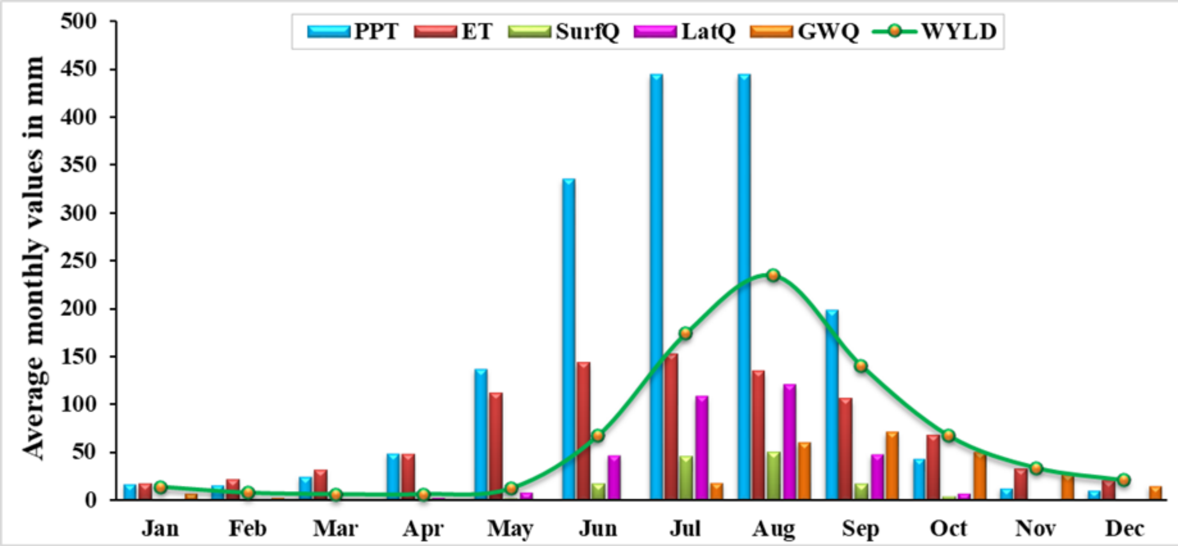


Fig. 12. Intra-annual variation of different water-balance components in KVW

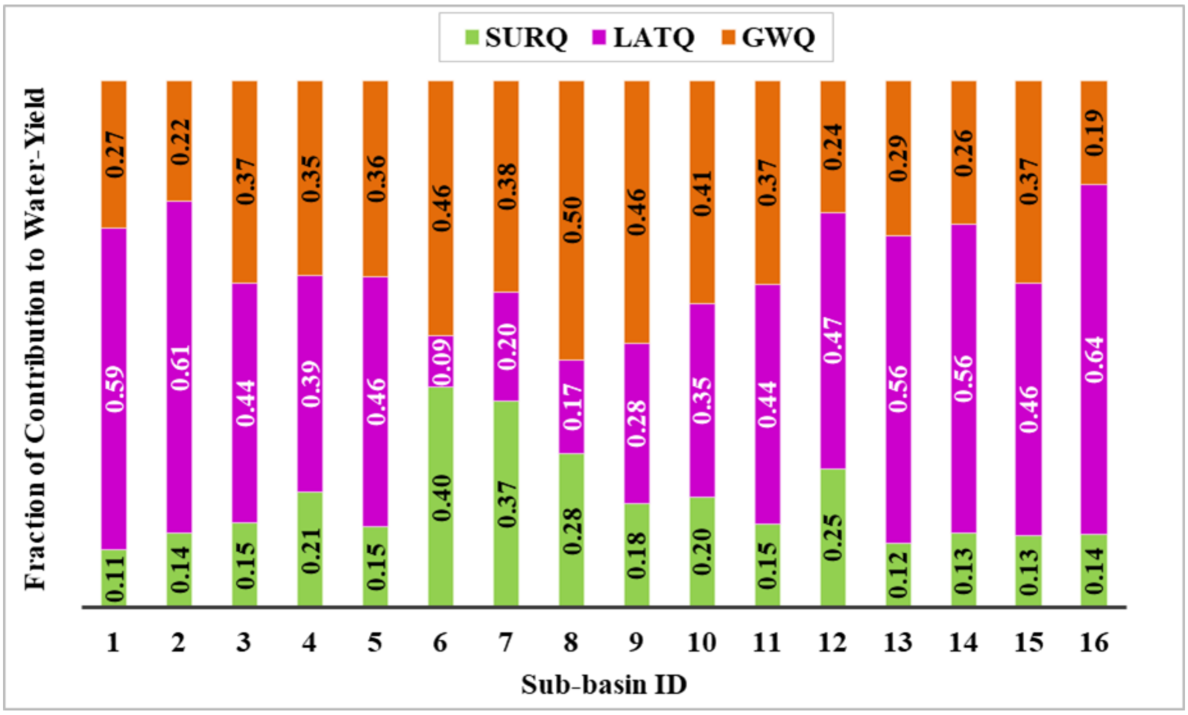


Fig. 13. Fraction of contribution of water-balance components to water yield in each subbasin in the KVW.

5.2.2 Water-balance change analysis under the present and future landuse at the basin level

The impact of landuse change on different components of water-balance is discussed herein. The average annual water-yield at the basin outlet for the baseline period was 784mm. However, there was no change in the water-yield at the basin outlet for future landuse because the input climate data were the same in all periods. But the impact of landuse was mainly observed in the change in the relative contribution of each components of the water-yield. **Fig.14** illustrates the actual change (+ve or -ve) in different water-balance components relative to the baseline scenario of 1990 landuse at the basin level. Positive values indicate the increase while the negative values suggest the decrease. Surface runoff is expected to increase in the future scenario of 2040 by nearly 100mm of which almost 50% (48mm) increased between 1990 and 2010. On the other hand, the lateral Q and groundwater Q showed decreasing trend with future landuse change. Lateral Q decreased by 33mm whereas groundwater Q showed a fall of 59mm between 1990 and 2040. The increase in the urban areas will shrink the recharge zones which will affect the quantity of water entering the aquifer in the sub-surface layer.

The percentage contribution of each component to the total water yield at the basin level is shown in **Fig. 15**. The effect of landuse change was more intense on the surface run-off, followed by groundwater and lateral Q. The contribution of surface runoff increased from 18% in 1990 to 30% in 2040. Meanwhile, groundwater contribution to the water yield was 37% in 1990 but it is expected to reduce to 29% in 2040. Similarly, the contribution of lateral Q will reduce by nearly 4% from 45 to 41% between 1990 and 2040. The intra-annual variability in the water-balance for different time period at the basin level is illustrated in **Fig. 16.**

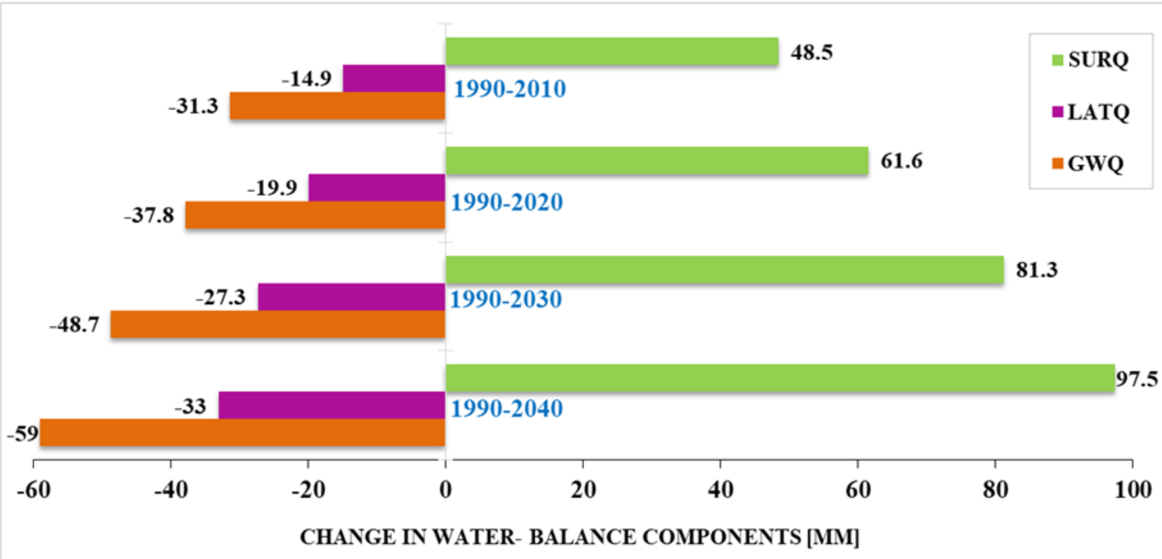


Fig. 14. Projected change in water-balance components with reference to baseline scenario.

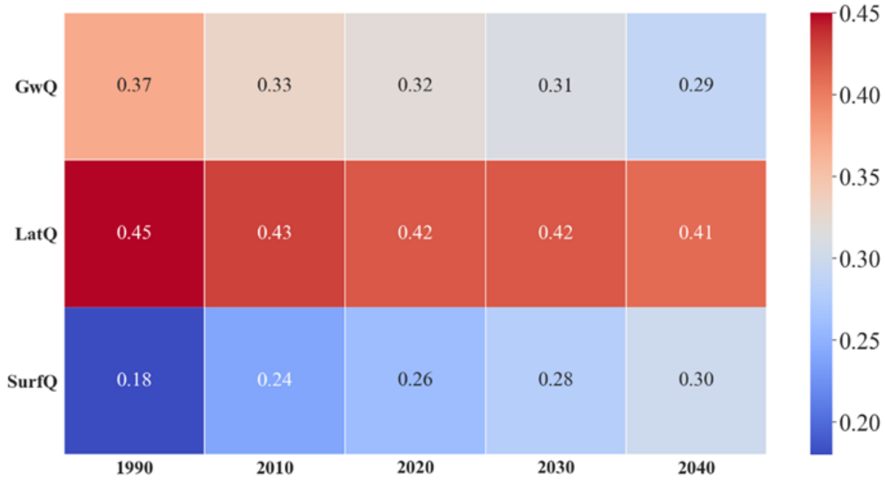


Fig. 15. Comparison of relative contribution of water-balance components for different decades

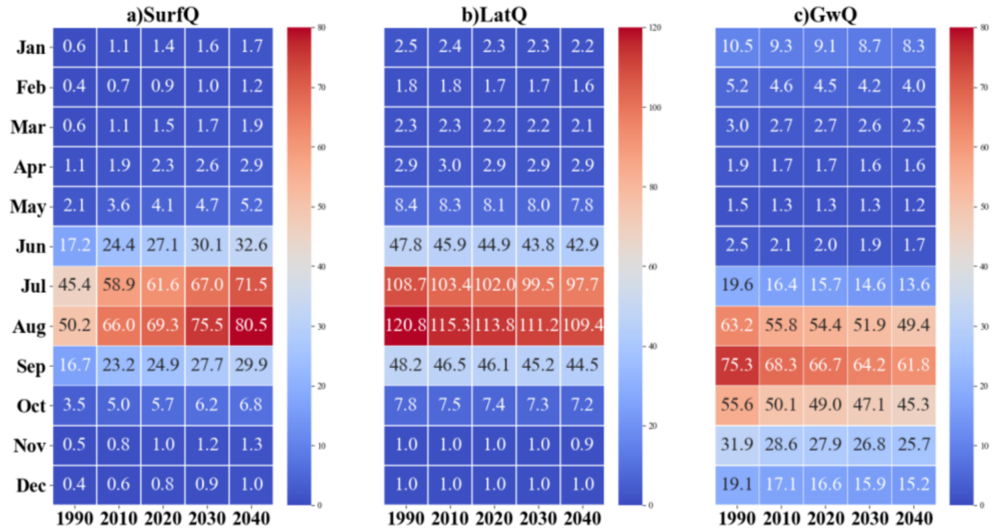


Fig. 16. Intra-annual variation of a) SurfQ b) LatQ and c) GwQ in different period.

With the continuous increase, the minimum-maximum range of surface Q annually is projected to get further wider in the future. The maximum surface Q and lateral Q will occur in August while the groundwater Q is predicted to peak in September. Similarly, groundwater Q shows decreasing trend with time as depicted in **Fig.16c**.

5.2.3 Water-balance change analysis under the present and future landuse at the basin level

It is recognized that the effect of landuse change on the water-balance is more pronounced at the subbasin scale. It is therefore crucial to identify the potential areas impacted by landuse change for prioritizing water-management plans. The overall effect of landuse on different water-balance component may be nullified by each other at the basin scale. So, the actual picture of the changes within the basin may not be understood clearly. Hence, to better understand the actual effect on water-balance and water availability, the analysis should be performed at the sub-basin level. In this section, the change in the water-balance component corresponding to the change in different landuse types in each sub-basin is quantified and analyzed.

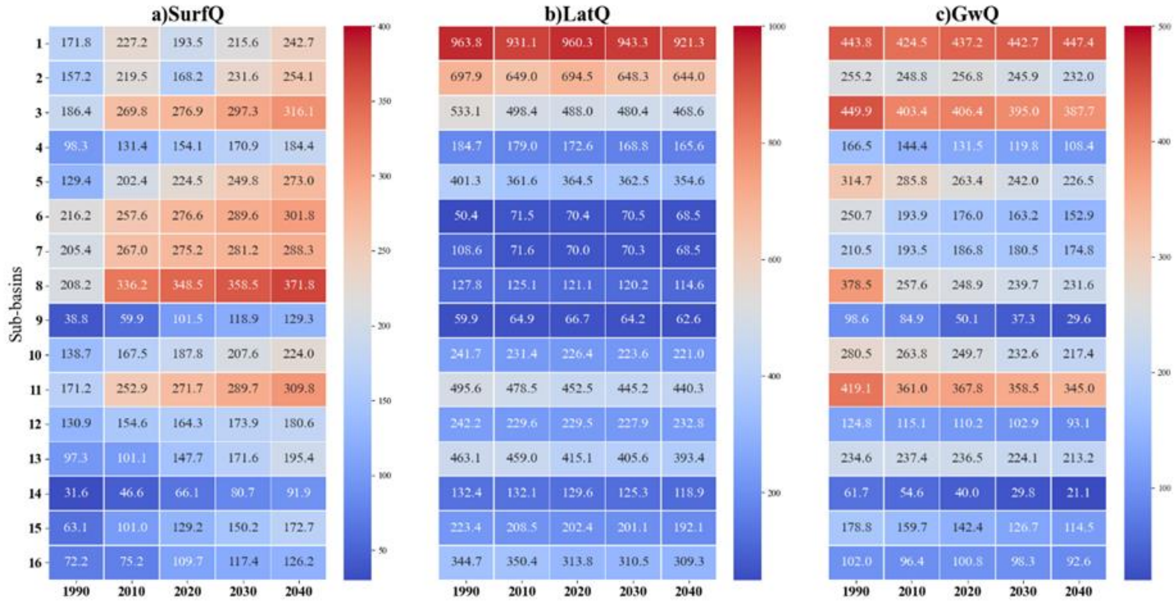


Fig. 17. Subbasin wise variation of a) SurfQ b) LatQ and c) GwQ for different period.

Fig.17 portray the subbasin wise annual water-balance components surface runoff, lateral Q and the groundwater Q at different time period. The surface runoff in **Fig. 17(a)** shows consistent increase from the past to the future scenario. The increase in surface runoff is higher for those subbasins which are yet to be urbanized in comparison to those which are already highly urbanized. For instance, the surface runoff increased by nearly two folds in subbasin 4 (from 98 to 184mm), subbasin 5 (from 129mm to 273mm), also 13, 14 and 15 while in subbasin 6, it increased from 216mm to 301mm and in subbasin 7, it increased from 205mm to 288mm. The change in landuse and the urbanization level of these subbasins can be seen in **Fig. 10**. This shows that the future impact of urbanization will be felt greater in subbasins that are least urbanized at present. The increase in surface runoff will likely increase the flash floods and inundation extent in the future. Similarly, the groundwater component showed a consistent decline from past to the future scenario as depicted in **Fig. 17(c)**. The decline is relatively greater in smaller subbasins like 9, 10, 11, 15, etc. Subbasin 1 is exception which is due to the fact that the landuse projection shows no built-up areas in the future too. The only transition is from forest to the agricultural areas due to which a slight increase in groundwater component is observed in subbasin 1. The sub-basin wise variation in lateral Q component as demonstrated in **Fig. 17(b)**, in general, resembled the groundwater Q pattern. However, the change in the lateral Q was relatively smaller in comparison to the groundwater Q.

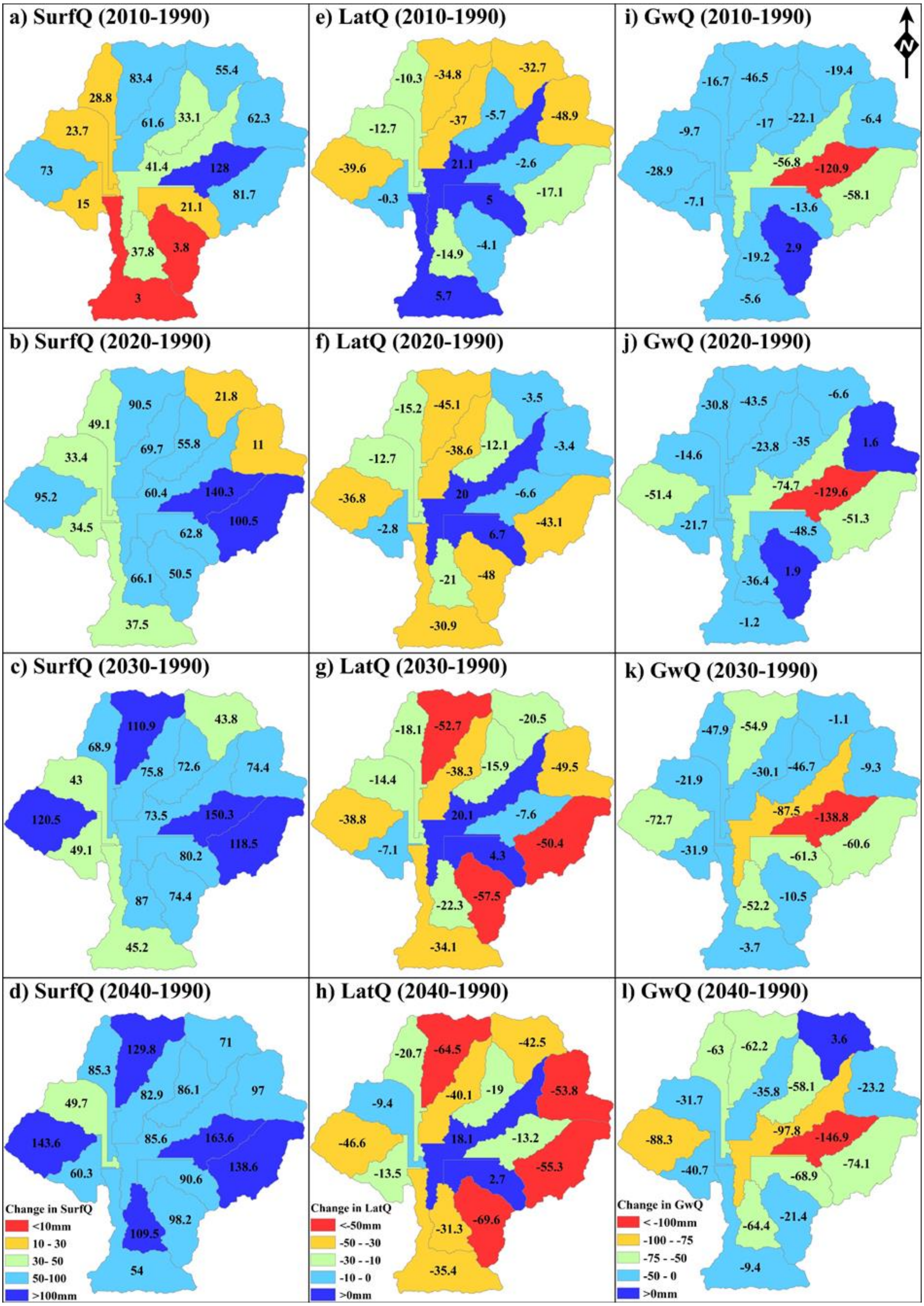


Fig. 18. Subbasin wise change in a) SurfQ b) LatQ and c) GwQ for different decade.

The spatial distribution of the actual change (increasing: +ve or decreasing: -ve) in surfQ, latQ and gwQ relative to the baseline scenario is illustrated in **Fig. 18 (a-l).** We found that the amount of changes was greater during the period 1990-2010. It is because the major landuse change also occurred during this period. Among all the subbasins, the surface runoff component in **Fig. 18 (a-d)** is projected to increase between 54mm to164mm in 2040 relative to the baseline scenario of 1990. On the other hand, the lateral Q and the groundwater Q component is likely to decrease in majority of the subbasins. The lateral Q is expected to decrease between the range of 10mm to 70mm while the groundwater Q will decline by 10mm to 147mm annually.

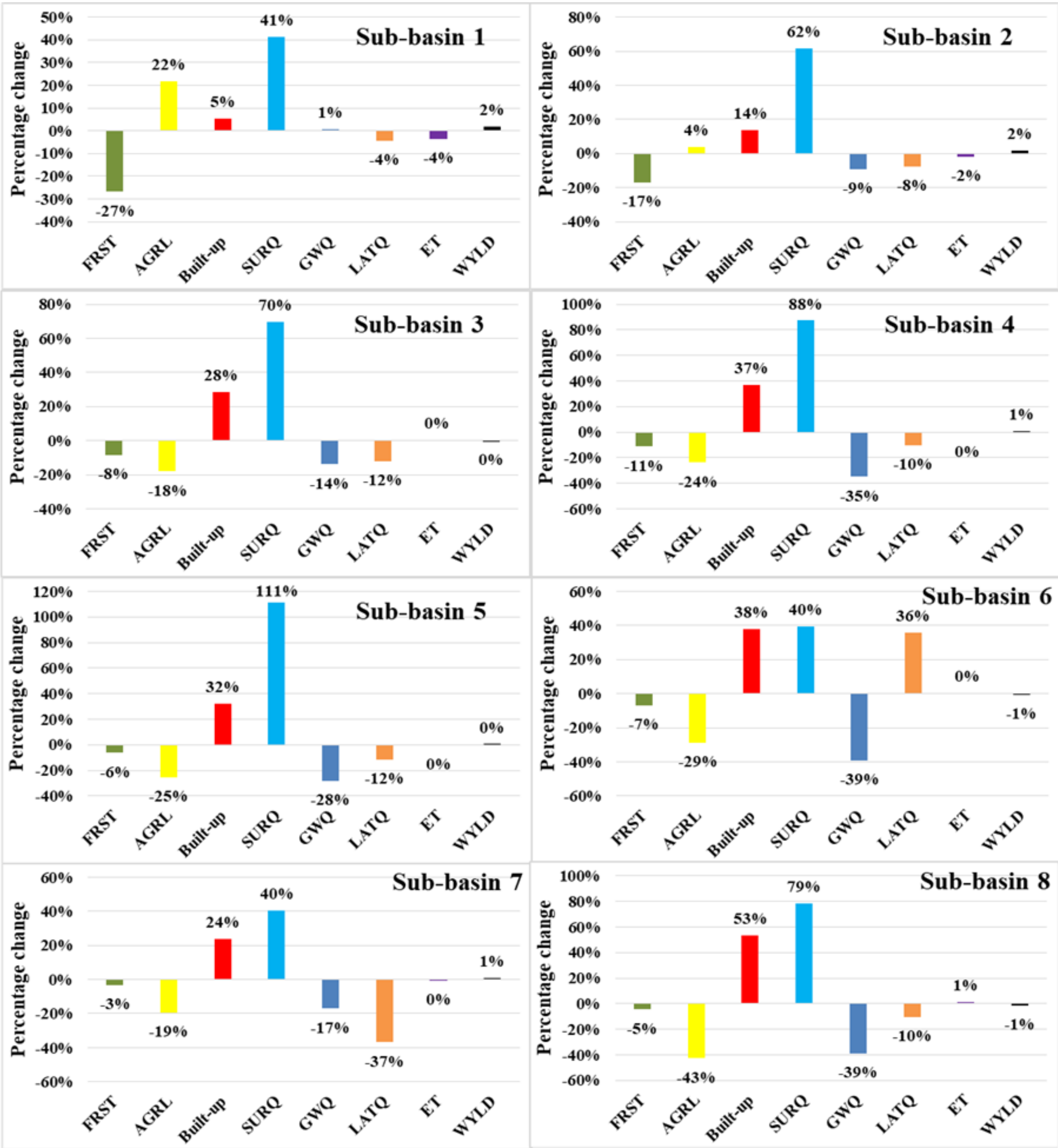


Fig. 19. Projected change in the landuse and different water-balance components for 2040 with reference to the baseline scenario for subbasin 1-8 (-ve: decrease and +ve: increase)

In order to further understand the relation between the landuse change and the corresponding change in water balance component for each sub-basin, the percentage change in landuse types and water-balance components are plotted in **Fig. 19** and **Fig. 20** for each sub-basins. The percentage increase in built-up areas ranged from little over 5% to more than 50% while the increase in surface run-off ranged from about 40% to over 200%. Generally, the percentage increase in surface run-off was higher for those sub-basins where the built-up area increased. However, the relation was not linear. For example, surface runoff increased by 234% in sub-basin 9 **(Fig.20)** in which the built-up area had increased by 57%. But in sub-basin 8 in **Fig.19**, the percentage change in surface-runoff was only 79% where the built-up area had increased by 53%. This suggest that each hydrological process in a sub-basin is affected by different other processes. Therefore, it will not always be reasonable to find the one is to one relation.

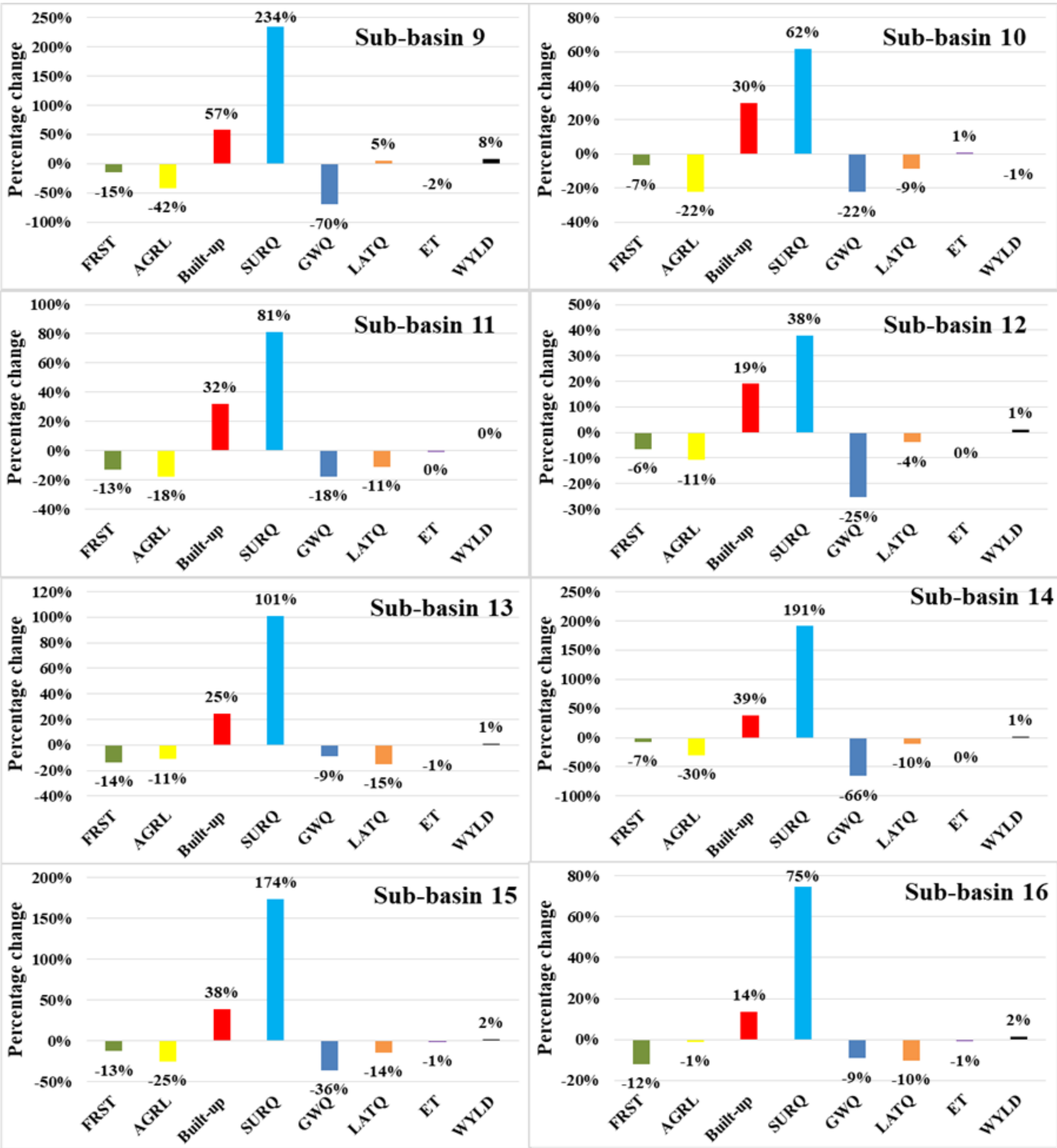


Fig. 20. Projected change in the landuse and different water-balance components for 2040 with

reference to the baseline scenario for subbasin 9-16 (-ve indicate decrease and +ve indicate increase)

Similarly, the decline in groundwater discharge varied from 9% to 70%. The groundwater discharge depends on the pervious cover of the land. Conversion from forest and agriculture to the built-up areas will increase the impervious cover and hence reduces the permeability of the surface. Consequently, the groundwater discharge will decrease. The maximum decline in the groundwater discharge also occurred in sub-basin 9 corresponding to a maximum increase of built-up areas. However, as with the surface run-off, the relation is not linear between the percentage increase of the surface runoff and the built-up areas.

6. CONCLUSIONS

The current study evaluated the water-balance dynamics of the most rapidly urbanizing KVW of Nepal under the past, present and the future landuse scenario. The isolated impact of landuse change was assessed keeping the same climatic conditions for all scenarios. The results and analysis clearly indicated that the rapid urbanization will significantly alter the water-balance components of the study watershed that is already reeling under the water-stress. Projection of landuse revealed that near-about 50% of the total area of KVW will be covered by built-up zone by the year 2040. The increase in the built-up area is compensated mainly by agriculture areas and the forest areas which will have further implications on the multiple ecosystem services. Surface runoff is expected to increase in the future scenario of 2040 by nearly 100mm of which almost 50% (48mm) was found to increase between 1990 and 2010. This will likely have a tremendous impact on the flooding intensity and the extent of inundation within the basin. Another important component, the groundwater discharge which form a basis of daily water consumption in the study watershed is also predicted to decline and that too, without considering the water extraction from the tanker industries. The decline was relatively greater in smaller subbasins. The study also revealed that the response of the subbasins to the landuse change is not necessarily the same for each subbasins rather it depends on the initial landuse distribution of the subbasin. The response was sharper for those subbasins which are yet to be urbanized in comparison to those which are already highly urbanized. The quantification of the changes of different water-balance components revealed that the impact of urbanization on water-balance will be felt greater at the subbasin level. The spatio-temporal distribution of the projected changes in the landuse and the consequent water-balance components at the subbasin level is believed to provide useful information to the policy makers and the related stakeholders to prioritize and formulate the suitable interventions, both soft and hard, to subdue the adverse impact.

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