

# **WATER SECURITY PERSPECTIVE TO EVALUATE ADAPTATION STRATEGIES FOR SUSTAINABLE WATER RESOURCES MANAGEMENT IN KATHMANDU VALLEY, NEPAL**

(ネパールカトマンズ盆地の持続的水資源管理に関する  
適応策の評価を目的とした水安全性の把握)



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## ABSTRACT

Water security especially in terms of potable water for drinking is a major concern in the Kathmandu Valley (KV) since long era. The rapidly increased population, urbanization, climatic, and non-climatic changes resulting in scarcity and degraded quality of water. Kathmandu Upatyaka Khanepani Limited (KUKL) is supplying only 19% and 31% of demand during dry season and wet season respectively through the springs, surface water (SW) from hills and groundwater (GW) wells. The deficit is met through the private GW pumping, traditional stone water spouts, dug wells, shallow tube wells, KUKL and private water tanker, and bottle industries. Recently in KV, 759 deep tube well are available including KUKL, hotel, industries, housing companies, and corporate offices and withdrawing about 70.9 Million Liter-a-Day (MLD) in 2009, which is in increasing with due course of time. These rate of abstraction has resulted in drawdown of 1.0 m/ year decrease in water level, which could create land subsidence problem in valley. To achieve Sustainable Development Goal (SDG) and continuous supply of water, Government of Nepal (GoN) has planned to supply additional 510 MLD water from inter basin transfer project called Melamchi Water Supply Project (MWSP).

In this background, the study of water availability in different component of hydrological cycle with different climatic and non-climatic variation has been conducted to resolve the water security problem in KV through hydro (geo) logical model formulation. This study, therefore, aims to address these knowledge gaps considering both available surface and groundwater resources, their status, their response, and how those spatial distribution of water security will affect with climate change, supply management by infrastructure development like MWSP, and groundwater management scenario.

To achieve those objective three hydrological models SWAT, BTOPMC, and HBV were formulated and water balance components were estimated. ACCESS1.0 climate data were bias corrected for representative concentration pathways (RCP) 4.5 and RCP 8.5 using Liner Scaling (LS) and Quantile Mapping (QM) techniques for near future (NF) (2011-2040), medium future (MF) (2041-2070), and far future (FF) (2071-2099). Those data were applied in SWAT model and impact of climate change on precipitation and runoff were evaluated. Due to the lack of sufficient number of rain gauge station in mountainous area of KV, high resolution satellite precipitation product PERSIANN-CCS were applied and their applicability and fresh water available from mountain were estimated. In addition to this, Groundwater (GW) model Visual MODFLOW Flex were applied to know the situation of groundwater and implication of MWSP based on deficit situation and climate change impact were evaluated. The household water security index (WSI), which is ratio of supply and demand were evaluated with development time of MWSP for different KUKL service areas (SAs). Based on those findings, sustainable surface and groundwater management option to achieve water security in KV were identified in different phase of MWSP and recommendation were proposed. The major findings of this study are as follows:

The runoff fraction (runoff/precipitation) varied from 0.55 to 0.59, and the ET component varied from 0.41 to 0.47 of the total precipitation in the three models. The yearly fluctuation in TWS varied from  $\pm 9\%$  to  $\pm 14\%$  of the total precipitation. Considering the variation in the water balance components in the three models, ET had the lowest inter-annual variation, and runoff had the greatest variation. The expected change in annual precipitation for NF, MF, and FF varies from -1.16% to 17.50% under RCP 4.5, and 2.10% to 11.02% under RCP 8.5. The maximum temperature expected to increase in hot days and minimum temperature expected to decrease in cold days. Unlike temperature, the observed as well as predicted precipitation has not followed any systematic trend and a large periodic, seasonal and spatial variation. There is not so much impact on low season runoff even though expected unpredictable high precipitation and runoff in March but predicted high flow may cause serious flood in urban area.

The high resolution satellite precipitation product PERSIANN-CCS has potential applicability in KV after bias correction, which could reproduce comparable rainfall magnitude at the station scale with comparable stream flow production at the whole catchment scale. Which shows possibility to harness additional 67 MLD and 87 MLD from mountain, which can serve additional 0.49 and 0.65 million of additional people in Kathmandu Valley during dry and wet season respectively assuming 135 liter-capita-a-day (lpcd) as demand. Water available through mountain as compared with baseline period seems to be increase in both dry and wet season. It is predicted to be increase by 61% and 40% under RCP 4.5 and 31% and 52% under RCP 8.5 during dry and wet season respectively for near future.

In year 2016, the water security situation is severe and WSI is less than 0.5 considering 135 lpcd as demand, which will expected to improve significantly after first phase of MWSP. After second phase of MWSP, the new reservoir service areas (NRAs) expected to get sufficient water with WSI > 1.0 but existing reservoir service areas (ERSAs) will be < 0.5. After second phase of MWSP and for future, the situation become different, which shows NRAs is projected to be fully satisfied whereas ERSAs area seems to be worsen. There could be in-equality in current distribution, which may lead to conflict among user. The MWSP could be the key project to combat the present and future water deficit and the re allocation of available resources is necessary for the equitable distribution of water among service areas.

Despite getting sufficient amount of utility water, there is still a possibility to abstract groundwater using the available infrastructure. A steady decline of water level by 0.69 m/year due to increased groundwater abstraction were estimated. As a result, the spatially averaged changes in hydraulic head ranged from +2.83m to +5.48m in various stages of the MWSP implementation, and -2.97m for increased pumping rates with no implementation of the MWSP. The model based study reveals not such a significant impact on groundwater system due to climate change. These findings demonstrate an improvement of groundwater

management with the implementation of the MWSP considering the proper regulations of groundwater pumping.

As a way out to achieve the equity among SAs, it is suggested to re-distribute freshwater from the reservoirs by expanding KUKL's existing distribution network. It is an appropriate time for KUKL to start preparing an inventory of community-based and other agency-supplied water infrastructures, inventory of Indigenous Water Management System (IWMS). Those infrastructures can later be integrated with KUKL system for proper management of freshwater supply system throughout the valley. It is recommended that, Kathmandu Valley Water Supply Management Board (KVWSMB) can motivate groundwater users to voluntarily reduce their pumping up-to 50 % after first phase of MWSP. After completion of MWSP, an appropriate regulation on groundwater pumping needs to be implement based on the accessibility of piped water supply and enforced with appropriate regulatory and monetary mechanisms. Hence appropriate adaptation technologies like managed aquifer recharge (MAR) using existing infrastructure like IWMS can be applied to enhance the recharge process and appropriate monitoring and regulation of groundwater withdrawal is most to protect the depleting aquifer.

This study did not considered the historical water use for water balance estimation for hydrological model. In addition, we assumed a steady-state situation in the KV aquifer system that is acceptable for evaluating change of groundwater heads. However, the decline of groundwater heads with different rates was observed at all available observation wells and the transient model will be useful to determine the response time of the groundwater system to pumping in future studies. Only ACCESS1.0 data were used for evaluating impact of climate change in water availability for both surface and groundwater. Hence more integrated robust model like SWATMOD, GSFLOW, and SHETRAN can be used by assembling more global climate data (GCMs) with historical water use and transient simulation for groundwater system can be applied in future.

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## PREFACE

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## LIST OF ABBREVIATIONS

ACCESS	Australian Community Climate and Earth-System Simulator
ADB	Asian Development Bank
BR	Bias Reduction
BTOPMC	Block-wise use of TOPMODEL
CBS	Center Bureau of Statistics
DHM	Department of Hydrology and Meteorology
DWSS	Department of Water Supply and Sanitation
DMG	Department of Mine and Geology
ET	Evapotranspiration
GCM	Global Climate Model
GDEM	Global Digital Elevation Model
GDP	Gross Domestic Product
GoN	Government of Nepal
GWRDB	Groundwater Resources Development Board
HBV	Hydrologiska Byråns Vattenbalansavdelning
ICIMOD	International Center for Integrated Mountain Development
ICRE	International Research Center for River Basin Environment
KUKL	Kathmandu Upatyaka Khanepani Limited
KV	Kathmandu Valley
KVWSMB	Kathmandu Valley Water Supply Management Board
LPCD	Liter-Per-Capita-a-Day

MDG	Millennium Development Goal
MLD	Million-Liter-a-Day
MWSP	Melamchi Water supply Project
NGD	Northern Groundwater District
NS	Nash Sutcliffe Efficiency
NWS	National Water Security Index
NWSC	Nepal Water Supply Co-operation
PBIAS	Percentage Volumetric Bias
PERSIANN CCS	Precipitation Estimation from Remotely Sensed Information using Artificial Neural Networks-Cloud Classification System
$R^2$	Co-efficient of Determination
RSA	Reservoir Service Area
SA	Service Area
SDG	Sustainable Development Goal
SGD	Southern Groundwater District
SW	Sub-Watershed
SWAT	Soil Water Assessment Tool
TWS	Total Water Storage
UN	United Nation
VDC	Village Development Committee
VMOD	Visual MODFLOW
WHO	World Health Organization
WSI	Water Security Index



## INTRODUCTION

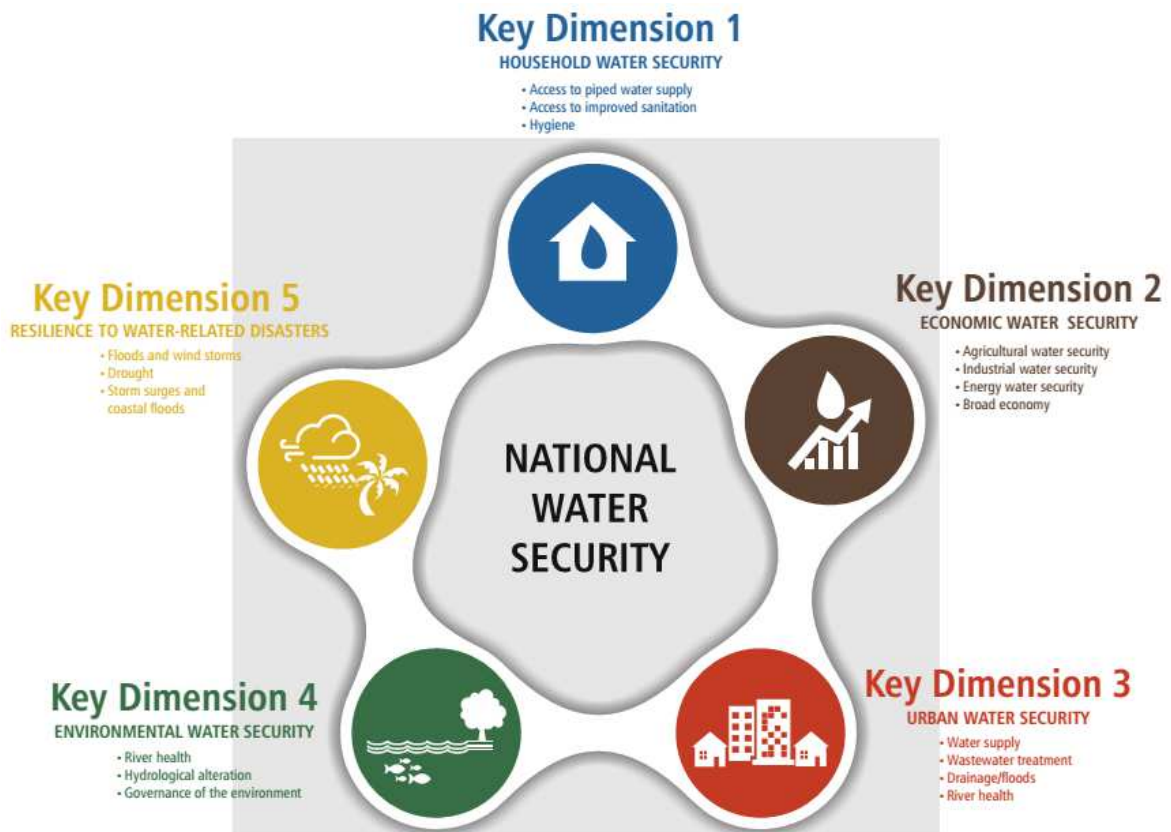
### 1.1 Background

Freshwater is a key resources for human health, prosperity and security for the well-being, poverty reduction, food security, and the preservation of ecosystems to achieve the three pillar (economic, social and environmental) of sustainable development (UN-Water, 2011; WWAP, 2015). Water is likely to become constraint on economic growth and cost of global water insecurity is estimated as \$ 500 billion annually that is likely to drag on world economy by 1% or more of gross domestic product (GDP) (Sadoff et al., 2015). The United Nations (UN) general assembly have set the global agenda to achieve universal and equitable access to safe and affordable drinking water for all by the year 2030 (ADB, 2016). To achieve and measure those targets, water security issues with indicator has become prominent in water and development communities globally in recent years. The concept of water security is complex to define and remain largely unquantified because it incorporates different dimensions such as floods, droughts, ecosystem, landslides, and human health etc. in terms of both quantity and quality i.e. ranging from bio-physical to infrastructural, institutional, political, social, and financial (UN-Water, 2013).

Water security (and its reverse - water scarcity) is more than the sustainable access to adequate quantities and acceptable quality of water for people and economic activities. It is also about the healthy aquatic ecosystem and protecting us against water related disaster in a climate of peace and political stability (ADB, 2016; Molden et al., 2016; Schultz and Uhlenbrook, 2007; UN-Water, 2014; WaterAid, 2012; White, 2012) . Security is an imbalance between supply and demand that varies with local condition (Fischer et al., 2015). Water scarcity mainly interplay between hydrological variability (availability), accessibility of available water (supply), and human need for agricultural, industrial, energy, and municipal purposes (i.e. demand) (Sadoff et al., 2015).

Climate change is severely impacting the hydrological cycle and is projected to reduce both renewable surface and groundwater resources significantly affecting both quantity and quality (IPCC, 2014; UN-Water, 2011). Under present climatic variability, most of the developing countries already in water stress due to change is quantity and quality of water both in time and space (IPCC, 2014), which is aggravated with demographic, economic, environmental, social, and technological forces (WWAP, 2015). Climate change is critical to understand the processes and hence need for an integrated, multi-sectoral and multidisciplinary response (UN-Water, 2011). Sustainable management and development of water resources will play pivotal role to make the society more resilient to adopt with climate change and water security problem, which will help to achieve the sustainable development goal (SDG) target in water sector (ADB, 2016). To achieve sustainable development, adequate quantities of water of acceptable

qualities on reliable basis for short, medium, and long terms is necessary and it becomes more complex if climate change, water security and sustainable developments comes together (Molden et al., 2016).



**Figure 1.1** Water security framework of five interdependent key dimensions adapted by (ADB, 2013)

Translating water security in numerical terms helps clarity and understand coherently the concept, and reduce ambiguity. Therefore, several indicator-based water security-related indices were developed to quantify water insecurity or the reverse (Lautze and Manthrihilake, 2012; Rijsberman, 2006). Based on available literature, the overall water security contains mainly five components such as basic needs, agricultural production, environmental flows, risk management, and independence (Lautze and Manthrihilake, 2012); and household, economic, urban, environmental, resilience to water-related disaster (ADB, 2013). Other indicators and indices used for more or less similar purpose include basic human need index (Gleick, 1998), water stress index (Falkenmark et al., 1989; Pfister et al., 2009), watershed sustainability index (Chaves and Alipaz, 2007), water supply index (McNulty et al., 2010), social water scarcity index (Ohlsson, 2000), Water demand/discharge index (Vorosmarty et al., 2000), and water poverty index (Sullivan, 2002).



Water security issues mainly broken down into as threat (flood, drought, and pollution issues) and security of supply in many uses (Young et al., 2015), hence this study focuses on the security of supply for domestic water use mainly drinking purposes. This study tries to access the household water security index adapted by ADB (2013) as discussed in **Figure 1.1**. National level analysis of water security by ADB (2016) shows that South Asia has the lowest overall water security index in 2014 among the Asia Pacific. Nepal positions itself in 43rd position among 48 Asia and Pacific countries and 4th position among 6 South Asian countries with a national water security (NWS) index of 2 out of 5. Out of five dimensions of water security considered in the ADB (2016) study, out of 20 score, Nepal got 5.3 in household, 11.3 in economic, 6.0 urban, 10.7 in environmental, and 4.0 in resilience. It reflects water insecurity in all the aspects. Hence to secure the water and enhance/sustain economic development, investment in water infrastructure and institution in developing member countries are crucial (ADB, 2016).

## 1.2 Statement of problems

Safe drinking water and basic sanitation are essential for almost all human activities for basic human wellbeing, for social and economic development. The piped water supply system started on 1891 to supply water for ruler and elite family from Sundarijal to Kathmandu Valley. Even though systematic planning started with the first five year plan 1956-1961, water security situation in Nepal is in worse condition till now. Nepal has achieved the Millennium Development Goal (MDG) target as 83.59 percent pipe coverage and 70.28 percent sanitation coverage (DWSS, 2014) but the quantity and quality of both water supply and sanitation service is very low.

Water security is a major concern in the Kathmandu Valley (KV) since long era due to rapidly increased population and urbanization resulting in scarcity and degraded quality of water (Thapa et al., 2016). Population expansion from 1.11 million in 1991 to 1.65 in 2001 (CBS, 2003) and 2.53 in 2011 (CBS, 2012), subsequent urbanization resulting in decrease in agricultural areas in the valley from 62 to 42% in between 1984 and 2000 (ICIMOD et. al 2007) are among the main drivers to make KV water insecure. The water demand of KV was estimated as 35.1 MLD (million- liters-a- day) in 1988 (Gyawali, 1988), 155 MLD in 2000 (Monech and Janakranjaan, 2006) , 320 MLD in 2000 (KUKL, 2009) , 370 MLD in 2015 (KUKL, 2015) but the supply capacity of main utility in Kathmandu Valley called Kathmandu Upatyaka Khanepani Limited (KUKL) is supply only 115 MLD during wet season and 69 MLD during dry season through the springs, surface water (SW) tapped at the hills and groundwater (GW) wells (KUKL, 2015).

The deficit is met through the private GW pumping, traditional stone water spouts, dug wells, shallow tube wells, KUKL and private water tanker, and bottle industries. Recently in

KV, 759 deep tube well are available including KUKL, hotel, industries, housing companies, and corporate offices (GWRDB, 2012a). Similarly in 1999, more than 5000 privately owned small diameter shallow tube well and unknown number of dug wells were in use (Metcalf and Eddy, 2000), which are now increased significantly due to increased water deficit. Nepal Water Supply Corporation (NWSC) or current KUKL was abstracting a significant amount of groundwater since long time. The figures are reported as 2.3 MLD in 1979, 5 MLD in 1985, 18 MLD in 1986, 26 MLD in 1987, 29.2 in 1999 (Pandey et al., 2012). Considering abstraction from private sources as well, estimated total amount of groundwater abstraction had increased from 59.06 MLD in 1999 (Metcalf and Eddy, 2000) to about 70.9 MLD in 2009 (Dhakal, 2010). These rate of abstraction has resulted in drawdown of 0.72 m/year (Gautam and Prajapati, 2014), 1-4 m/year since 1984 in deep wells with greatest abstraction in North (Shrestha, 2012). Similar studies reported drawdown varies from 9 m to 68 m in late 1990s (Metcalf and Eddy, 2000) and 1m/year decrease in water level (KVWSMB, 2012), which could create land subsidence problem in valley.

In addition to those socio-economic pressure, several climatic and non-climatic parameter such as natural disaster like landslides, earthquake has posed significant water insecurity. The recent study by (Thapa et al., 2016) estimated 40% reduction in supply within KUKL service areas (SAs) due to 25<sup>th</sup> April 2015 Gorkha Earthquake. From those data, it is clear that climate change, land use change, urbanization, population growth, over exploitation of ground water, and natural disaster resulted the water security problem in Kathmandu Valley. To achieve the SDG target on water sector, government of Nepal is investing in several water-related infrastructure developments across the country. One of the mega project in water sector since 2000 is inter-basin water transfer project called Melamchi Water Supply Project (MWSP), which aims to bring water in the Kathmandu Valley (KV) from off-the-valley sources to make more water secure valley. MWSP has planned to supply 510 million-liter-a- day (MLD) of water in two phases - 170 MLD in the first phase by September 2017 and additional 340 MLD in the second phase by the year 2024 (based on the personal communication).

Still, few studies have endeavored to identify the status of water supply, demand, and deficit situation in valley for domestic use (Udmale et al., 2016) and several previous studies focused on uncertainty in hydrological modelling (Dulal et al., 2006), climate change impact (Babel et al., 2014; Dahal et al., 2016; Jha et al., 2013), hydrological modelling and impact on flooding (Manjan and Aggarwal, 2014; Sharma and Shakya, 2006), and water resources stress and vulnerability (Pandey et al., 2009) mainly in Bagmati River basin. Similarly for the hydrogeological part, most of the study focused on geological setting and formation (Binnie & Partner 1973; Binnie & Partner 1988; JICA 1990; Paudyal 2015; Yoshida & Igarashi 1984), and water quality of shallow and deep groundwater (Gurung et. al 2007; Kannel et al. 2007; Khatlwada et al. 2002; Pant 2011; Pathak et al. 2011; Shrestha et al. 2016; Shrestha et.al 2013; Tamrakar & Shakya 2013; Warner et al. 2008).

Most of the studies mainly focused with geology, water quality, and some hydrological component and suggested for the detail study to know the groundwater aquifer behavior. The previous research (Acres International, 2004; Gautam and Prajapati, 2014; GWRDB, 2012a, 2012b; KVWSMB, 2012; Pandey et al., 2012, 2011, 2010; Pandey and Kazama, 2011; Shrestha, 2012) mainly tries to describe the groundwater exploitation situation and their management, aquifer setting, groundwater development dynamics, and framework for groundwater sustainability. For sustainable management of available water resources in KV, understanding of current water resources (water balance) situation with climatic and non-climatic changes and shearing those information in index and map form is necessary. After knowing the situation, possible adaptation strategies need to be developed based on the previous findings. Hence the study of availability of water in different component of hydrological cycle with different climatic and non-climatic scenarios is crucial. However, those studies have neither deal with the spatial distribution of water security situation at service area level in terms of quantity (potable water use) considering both climatic and non-climatic factor. This study, therefore, aims to address these knowledge gaps considering both available surface and groundwater resources, their status, their response, and how those spatial distribution of water security will affect with climate change, supply management by infrastructure development like MWSP, regulation on groundwater resources, restoration of groundwater resources, and groundwater management scenario. Which is further elaborated under the proposed material and methods in **Chapter 2**.

While focusing on security of potable water for a household, it is crucial to satisfy their household water need, sanitation and improved hygiene for public health. The government of Nepal aims to provide 135 liter-capita-a-day (lpcd) of domestic water for the residence of Kathmandu Valley by the year 2025 (ADB, 2015). Whether this mega project can contribute to achieve the water security problem in KV is unclear. Therefore this study focusing to estimate the water balance components in surface as well as ground applying watershed hydrological and groundwater model and impact of MWSP and climate change on both surface as well as groundwater. In addition, this study tried to identify the sustainable management of surface, and groundwater resources to achieve SDG target and water secure KV.

### **1.3 Objectives and scope**

In this context, the objectives of this study are to evaluate household water security situation, impact of infrastructure development, climate change and suggest adaptation strategies for achieving water secure KV through sustainable management of available water resources.

### **Specific objectives**

- i. To estimate the water balance component of hydrological cycle and access the impact of climate change.
- ii. To quantify the fresh water from hill of Kathmandu Valley and access the impact of climate change.
- iii. To estimate the groundwater resources of KV applying groundwater model and access the impact of climate change.
- iv. To evaluate household water security index (WSI) on pre- and post MWSP.
- v. To suggest possible adaptation strategies through sustainable management of water resources for achieving water security in KV.

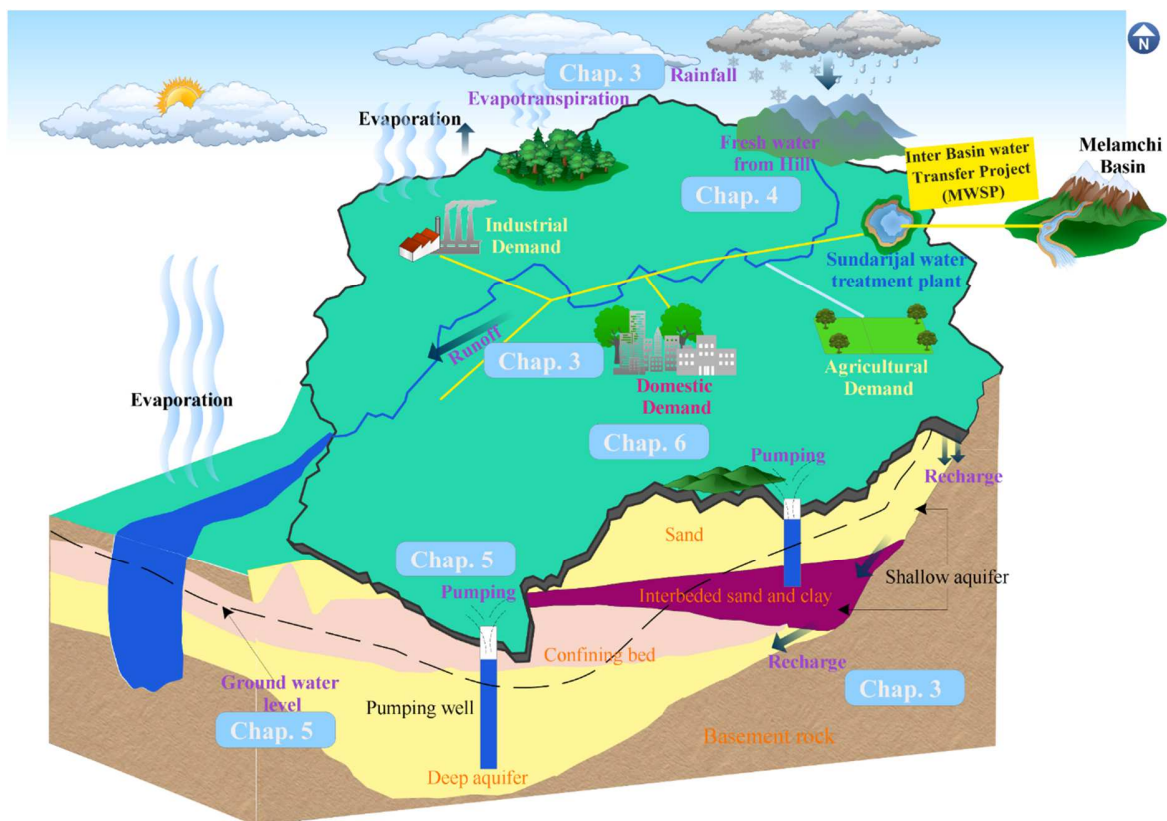
### **Scope of the study**

This study deals with (1) estimation of water balance component (runoff, evapotranspiration, and total water storage) using multi-model (SWAT, BTOPMC, and HBV) ; (2) assessment of climate change impact on water balance component applying SWAT model ; (3) evaluation of applicability of high resolution satellite precipitation product (PERSIANN-CCS) in KV; (4) quantitative assessment of fresh water available from hill for drinking purpose and evaluation of climate change impact on available resources; (5) estimation of groundwater resources by applying ground water model Visual MODFLOW Flex and evaluation of climate change impact on groundwater system; (6) evaluation of household water security index (WSI) and water supply per capita on current, pre- and post- MWSP, and future cases in KUKL service area ; and (7) proposing several adaptation strategies, policy feedback through sustainable management of both surface and groundwater (conjunctive use) for achieving the water security in Kathmandu valley.

## **1.4 Organization of the dissertation**

The conceptual diagram to understand the water management perspective in study area and organization of dissertation (structure of this study) is shown in **Figure 1.3** Structure of dissertation. The **Figure 1.2** shows the hydrological and hydrogeological setting of Kathmandu valley. In KV, KUKL is harnessing fresh water from hill to supply fresh water for drinking purpose and several shallow and deep tube wells are in operation. To meet the deficit, the government of Nepal has plan to supply 570 MLD water from inter basin water transfer project through Melamchi basin. Hence to know the status of water security, this study starts with total

water availability within basin and how those resources varies with climate change. After knowing total available water, the additional fresh water available from hill after deducting already used water and climate change impact were estimated. Similarly, the available ground water resources and its spatial variability, abstraction rate, and pumping scenarios were evaluated. The implication of MWSP on surface and groundwater were assessed. Based on the findings, surface and ground water management options were identified for sustainable management of available water resources. The brief descriptions of chapter contents are given below.



**Figure 1.2** Conceptual diagram of water management perspective in study area

**Chapter 1 - Introduction:** This chapter provides general background, statement of problems, need of research, objectives of the study and briefly describes dissertation outline.

**Chapter 2 – Material and methods:** This chapter provides the information on study area physiography, climate, socio-economic condition, hydrogeological setting, and overall methodological framework. In addition to this, the detail description of methods and data used from chapter 3 to 6.

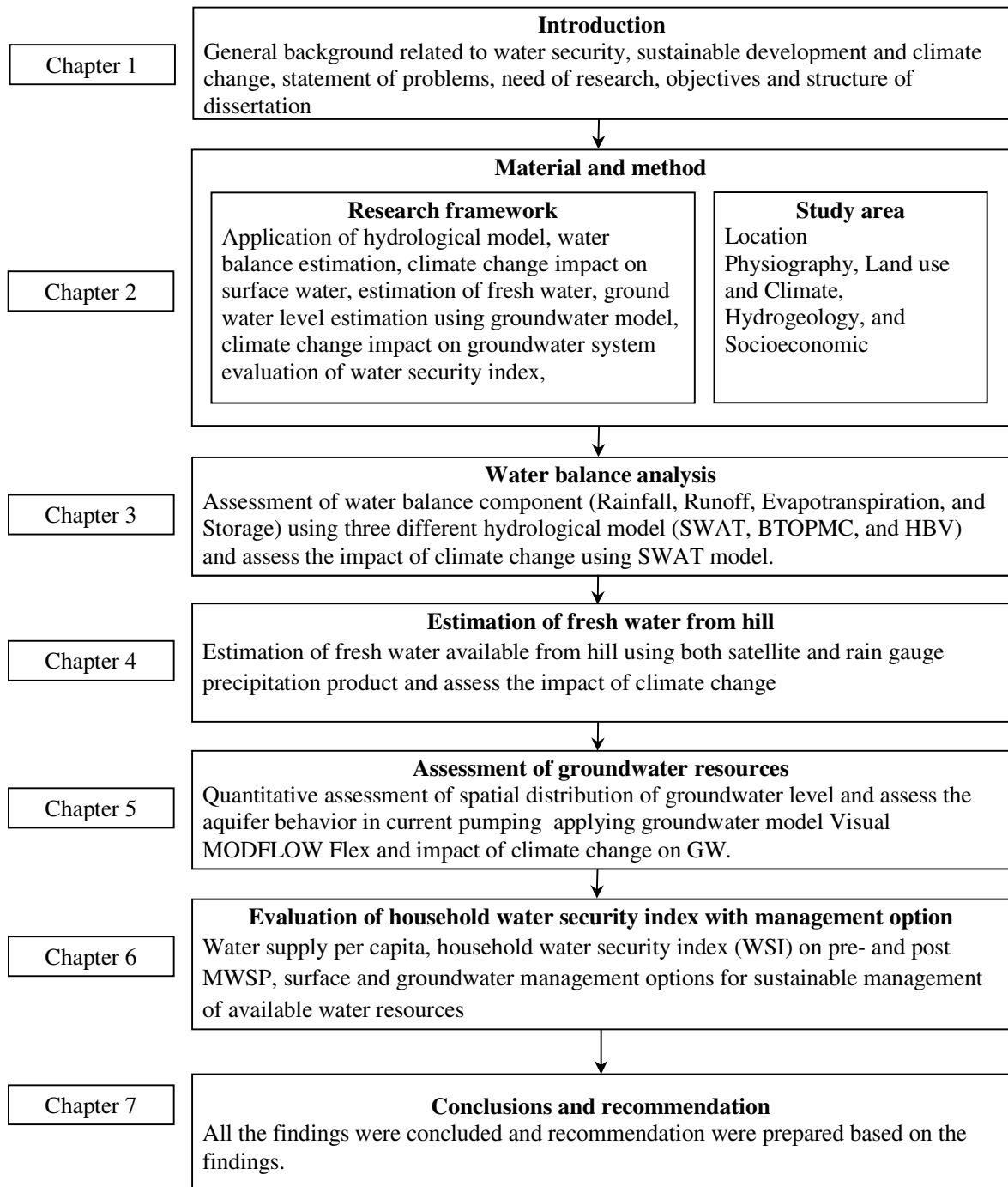
**Chapter 3 – Water balance analysis:** This chapter provides detailed description of amount of water available on different component of hydrological cycle applying three different watershed hydrological model and also discuss the impact of climate change.

**Chapter 4 – Estimation of fresh water from hill:** This chapter describes the applicability of satellite precipitation product in study area, estimate the seasonal and spatial variability of fresh water from hill and access the impact of climate change.

**Chapter 5 – Assessment of groundwater resources:** This chapter describes the application of groundwater model to estimate the ground water resources and also access the impact of climate change.

**Chapter 6 – Evaluation of household water security index (WSI) with management option:** This chapter evaluates the spatial distribution of water supply per capita and household water security index (WSI) for year 2016, first and second phase of MWSP, and year 2030. This chapter also evaluate the implication of MWSP in groundwater management and describes how the aquifer responses under different pumping scenarios based on water deficit Based on those findings, this chapter propose the adaptation strategies for sustainable management of available resources to make Kathmandu Valley water secure.

**Chapter 7 – Conclusion and recommendation:** This chapter gives the summary of the overall research with important findings, conclusions, recommendations and scope for future research work.



**Figure 1.3** Structure of dissertation





## MATERIAL AND METHODS

### 2.1 Study area and data

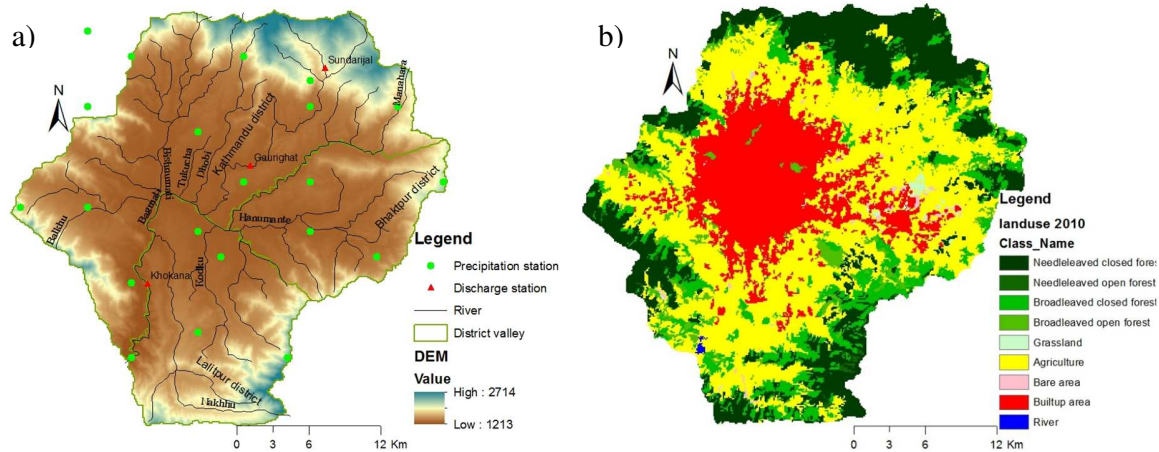
Kathmandu Valley, the capital city of Nepal was selected as study area to investigate the water security situation. To investigate the water security situation, the data on physiography, climate, hydrological and hydrogeological condition, and socio-economic were collected and analyzed, which are described in detail on following sub-section.

#### 2.1.1 *Physiographic and climate*

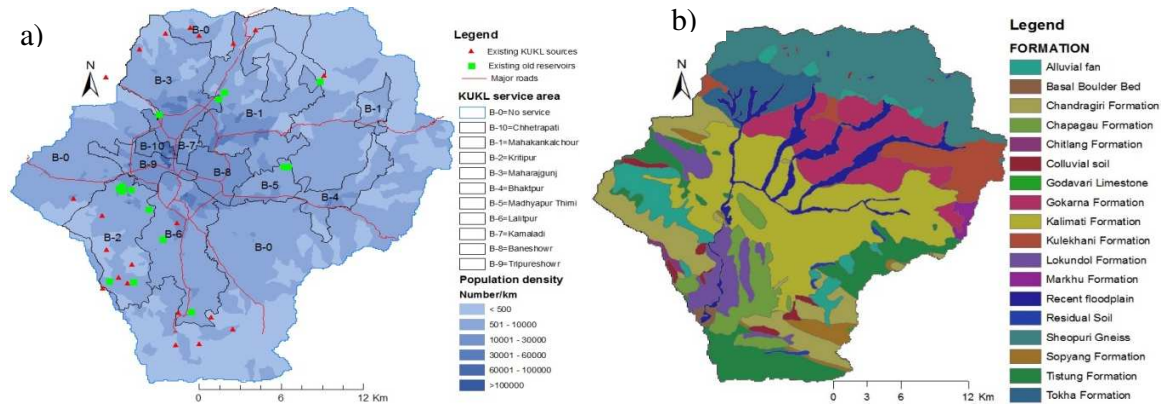
Kathmandu Valley watershed is located between 27°32'13'' and 27°49'10''N in latitude and 85°11'31'' and 85°31'38''E in longitude. The elevation of the watershed ranges from 1212 to 2722 m above mean sea level according to the 30 m ASTER global digital elevation map (GDEM), and covers an area of 664 km<sup>2</sup>. The valley is bowl-shaped and surrounded by hills (which are the origin of most of the valley's tributaries) acting as natural forts to protect the valley. The major rivers traversing the valley are the Bagmati, Bishnumati, Hanumante, Dhobi, and Manohara (**Figure 2.1 a**). The outer periphery (hilly area) of KV is covered by mixed forest, peri-urban areas are composed of a mix of agricultural and built-up land, and the central core of the valley is covered by built-up area (**Figure 2.1 b**). The surface runoff of the entire valley drains through the Bagmati River with its outlet at Katuwaldaha, located at the southern tip of the valley. The climate in the valley is characterized as warm temperate with warm days followed by cool nights and mornings. The average precipitation ranges from 1500 mm (city area) to 1800 mm (surrounding hills), the average summer temperature varies from 28°C to 30°C, the average winter temperature is around 10°C, and the average humidity is 75% according to data for 2000–2010 provided by the Nepalese Department of Hydrology and Meteorology (DHM). The rainfall is mostly monsoon-based, with 65% of the total rainfall concentrated during the monsoon months of June to August. Rainfall is highly variable and has unpredictable anomalies based on the DHM data for 2000–2010.

#### 2.1.2 *Socioeconomic*

In this study, 2011 population data from census were taken as the base year and population for future periods were projected based on the projection rate estimated by CBS (CBS, 2014). The CBS data indicated 0.25 % decrease (foot hill and hills of valley) in some VDCs to 13.05 % increase (peripheral VDCs) in between 2001-2011. The population density at VDCs level is high in central part and it decreases as we move outwards. The people residing at central part are mainly engaged in business and job, whereas peri-urban areas and hills main occupation is agriculture.



**Figure 2.1** Study area showing: a) major river with metrological and hydrological station and elevation range; b) land use map of 2010 adapted from (ICIMOD, 2013) .



**Figure 2.2** a) Population density map with current KUKL service area, major road network, b) Hydro geological map of Kathmandu Valley (source: (DMG/BGR/DOI, 1998))

### 2.1.3 Hydrogeological setting

Kathmandu Valley consists of basement rock on the bottom and the surrounding hills. It comprises of basin Fluvio-lacustrine sediments underlying the basement rocks of Precambrian to Devonian ages (Godavari, Chitlang, Chandragiri, Sopyang, Tistung, Markhu, Kulekhani and Sheopuri Gneiss) formation, Quaternary unconsolidated sediments (recent alluvial soil, residual soil, Colluvial soil, alluvial fan deposit) and Plio-Pleistocene slightly consolidated sediments (Tokha, Gokarna, Chapagaon, Kalimati, Kobagaon, Lukundol, Basal Boulder Bed ) formation as shown in **Figure 2.2 b** (DMG/BGR/DOI, 1998; Shrestha, 2012; Stocklin and Bhattarai, 1977; Yoshida and Igarashi, 1984).

The northern groundwater district (NGD) is situated on top of coarse unconsolidated deposits, and has high permeability has the most potential for groundwater abstraction, whereas the southern groundwater district (SGD) sits on top of a thick (200 m) confining unit of clay (JICA, 1990) with a deep confined aquifer composed of Pliocene sand and gravel with interbedded lignite, peat, and clay beneath the aquitard layer (Yoshida and Igarashi, 1984) (Figure 5.1). The central groundwater district (CGD) has a dual aquifer system separated by an aquitard of interbedded black clay and lignite up to 200 m thick (Yoshida and Igarashi, 1984) (Figure 5.1). The shallow unconfined aquifer of the CGD is composed of up to 50 m thick Quaternary sand, with some discontinuities, interbedded silt and clay and is underlain by thick (up to 200m) black clay accompanied by some lignite and peat with low permeability (Shrestha, 2012). The deep confined aquifer is considered a main source of groundwater for the KUKL, private companies, and industries.

#### 2.1.4 Data and source

The data used and their spatial and temporal distribution with characteristics are described detail in Table 2.1.

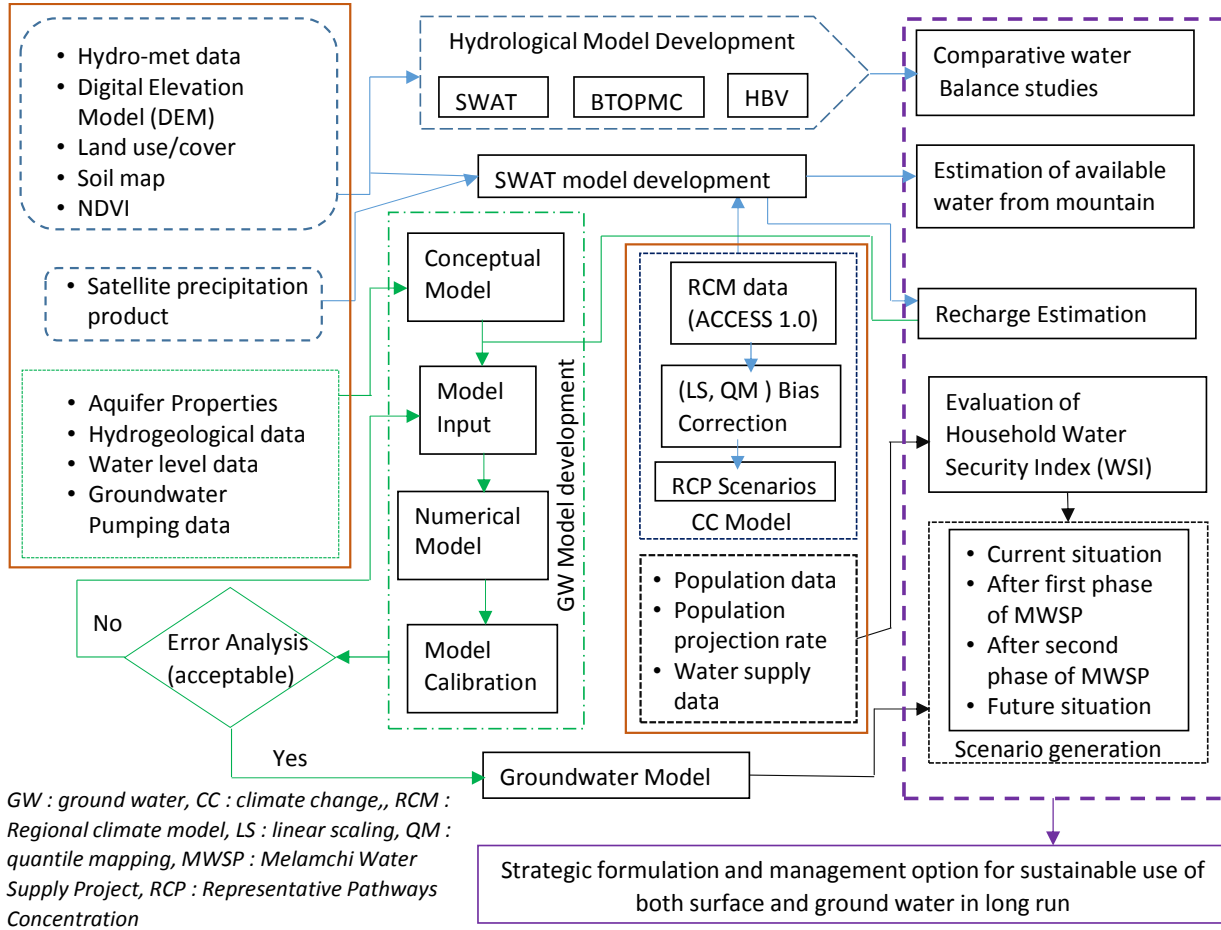
**Table 2.1** List Characteristics of data used and their extent.

Type	Description	Source	Spatial resolution	Remarks
Bio-physical data	Digital Elevation (DEM)*	USGS	30 mx 30m (~1 x 1 arc sec)	Global data
	Land use*	ICIMOD	90 m x 90 m	2010
	Soil Map*	FAO	0.25 x 0.25deg. (~25 x 25 km)	Global data
	River system Network	DOS		
	Groundwater district demarcation	JICA ,1990		Digitized
	Service area demarcation	KUKL, MWSP PID		Digitized
Hydro-Meteor. Data, ( ) : is No. of station	Precipitation (23)*, Max/Min/Mean Temperature (7)*, Solar Radiation (2)*, Wind Speed (2)*, Relative Humidity (9)*, Discharge (3)	DHM	Measured (daily)	2007-2010
Socio-economic data	Population data (ward wise)	CBS	Ward level	2001, 2011
	Population projection rate	CBS	District level	2011-2030
	Bulk distribution system network	MWSPID	Poly Line	2016
	SAs demarcation (digitized)	KVWSMB/M WSPID/KUKL	Ward level	2016
	Surface water source and reservoir location		Point location	2016
Water supply data	Service area (SA) - wise water supply		Measured (yearly) and estimated yearly	2015 and 2016
Hydro-Geological data	Environment and geological map	DMG,1998		
	Aquifer (latitude, longitude, elevation) data	Pandey and Kazama, 2011.		310 points
	Pumping well (379)	GWRDB,2009		unpublished
	Observation well (30)	GWRDB		1999-2014 (unpublished)

Note: USGS: United States of Geological Survey, ICIMOD: International Center for Integrated Mountain Development, FAO: Food and Agricultural Organization, DHM: Department of Hydrology and Meteorology, DOS: Department of Survey, CBS: Central Bureau of Statistics, GWRDB: Groundwater Resource Development Board, MWSP PID: Melamchi Water Supply Project Project Implementation Directorate, KUKL: Kathmandu Upatyaka Khanepani Limited, and JICA: Japanese International Corporation Agency. LS is linear Scaling: QM is Quantile Mapping: TWS is Total Water Storage

## 2.2 Methodological framework

The overall methodological framework for the proposed study is shown by flow chart in **Figure 2.3**.



**Figure 2.3** Methodological framework for overall study

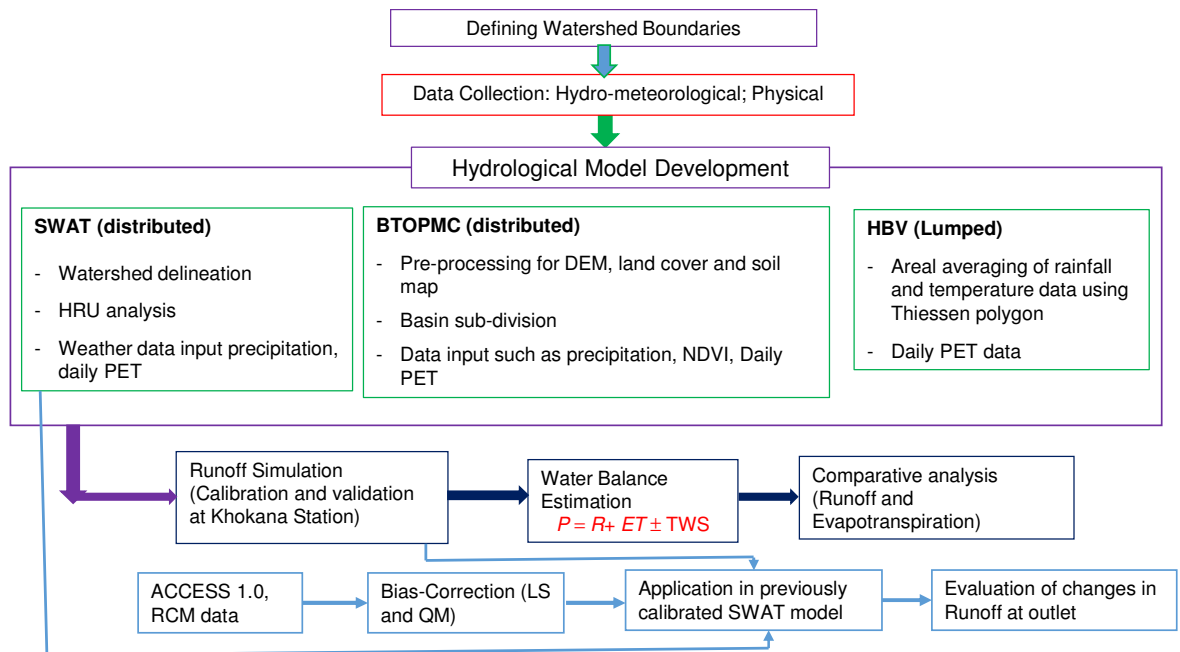
## 2.3 Assessment of water balance in hydrological cycle

Estimation of water balance techniques ranges from very simple methods, such as lumped models and field-experiments techniques, to highly complex computer based model. Those model can calculate water balance at various temporal and spatial resolution and selection depends on the objectives of the study and availability of data (Ghandhari and Alavi Moghaddam, 2011; Xu and Singh, 1998; Zhang et al., 2002). Today, numerous models with different assumptions and parameterizations are available for water balance computations, such as the NAM Module for MIKE-11 (Celleri et al., 2000), HBV (Bergström, 1992),

YHyM/BTOPMC (Takeuchi et al., 2008), SWAT (Arnold et al., 1998). These models include temporal and spatial features that make them useful as tools for water resource management, groundwater modeling, and urban and rural watershed management under different climatic conditions. Hence for this study three model SWAT, BTOPMC, and HBV model were applied to access the water balance component in Kathmandu valley. SWAT model was applied to access the climate change impact on water balance components.

### 2.3.1 Estimating water balance

A multi-model approach was applied to estimate the water balance in the KV watershed using the physical and hydro-meteorological data as listed in **Table 2.1**. The overall methodological framework adopted in this study is shown in **Figure 2.4**.



**Figure 2.4** Overall methodological framework for estimating water balance using multi-model approach (*DEM is digital elevation model, NDVI is normalized difference vegetation index, PET is potential evapotranspiration, P is Precipitation, R is runoff, ET is evapotranspiration*)

Watershed delineation was done above the outlet of Bagmati River at Katuwaldaha using 30 m ASTER GDEM. Three models, both lumped and distributed types were developed for the KV watershed to estimate water availability in the different component of hydrological cycle. The SWAT model is a distributed parameter, continuous time model that was developed to help water resource managers assess water supplies and non-point-source pollution in small to large river catchments and detail can be accessed through Arnold et al. (1998). The BTOPMC model is a physically based distributed hydrological model based on block-wise use

of TOPMODEL and the Muskingum-Cunge method that combines the advantages of both lumped and distributed models and for detail please refer [Takeuchi et al. \(2008\)](#). The HBV model is a widely used conceptual rainfall-runoff model that includes conceptual numerical descriptions of hydrological processes at the catchment scale and requires less data than other models and for detail please refer [Bergström \(1992\)](#).

The hydrological models were calibrated based on the observed runoff at Khokana station (**Figure 2.1**) located near the outlet of the KV watershed. Model parameters were adjusted manually until a reasonable statistical agreement between the observed and simulated runoff was obtained at Khokana. All of the models were run with a daily time step using the same rainfall, temperature and PET as inputs, and were individually calibrated and validated based on available observational data. Parameters were regionalized based on the soil and land-cover type in the SWAT and BTOPMC models (the parameterization was based on the discretized sub-basin, hydrological response unit, and grid size), whereas in the HBV model simulation, the parameters were regionalized for the sub-basin.

All three models were calibrated for the period 2001–2007 and validated for the period 2008–2010. Three performance indicators, the Nash-Sutcliffe efficiency (NS), percent volumetric bias (PBIAS), and coefficient of determination ( $R^2$ ), were used to evaluate the performance of the models as stated in equation 2.10–2.12. Water balance was estimated based on the principle of conservation of mass (i.e., the water entering an area must leave the area or be stored within the area) and the annual partitioning of precipitation into ET and runoff, which is controlled by the temporal distribution of water supply (precipitation) and demand (ET) and is balanced by water storage in the soil ([Milly, 1994](#); [Sokolov and Chapman, 1974](#)). The snow and ice components were not used as they were not relevant to the study area. Thus, the water balance can be expressed as:

$$R = P - ET + TWS \quad (2.1)$$

Where  $R$  is river runoff,  $P$  is precipitation,  $ET$  is evapotranspiration, and  $TWS$  is total water storage (vegetation, snow and glacier, surface detention, soil, and groundwater).

To determine the water availability in the different components of the hydrological cycle, the estimated values from the models of all of the components should be reasonably accurate. In reality, there are always discrepancies between the observed values and model predictions due to measurement errors, inadequate data capture networks, and the difficulty of representing real-life complex spatial heterogeneity in the model. However, we attempted to verify the model results with each component of the hydrological cycle such as precipitation, runoff, PET, and so forth. Observed precipitation data that had been adequately checked for continuity and consistency were used in the simulations. River runoff was estimated using the three different models and compared to observed runoff. PET values estimated from Snyder's equation 2.2 and 2.3 ([Snyder, 1992](#)) using measured pan evaporation data at Kathmandu Airport as inputs



were used with all the three models. The groundwater and surface water withdrawals for consumptive and non-consumptive uses are not considered in this study. Each water balance component in the watershed was estimated using the simple water balance equation, and the model results were analyzed and compared. The results are useful for scenario visioning and planning with stakeholders in the context of water scarcity in KV. Based on the measured precipitation data and observed PET, the percentage runoff generation (runoff fraction) and conversion of PET to ET were estimated. The runoff fraction is the percentage of total precipitation that is converted into runoff, and is calculated as the ratio of runoff to total precipitation in the study watershed.

$$ET_o = E_{pan} \cdot K_{pan} \quad (2.2)$$

$$K_{pan} = 0.482 + [0.24 \ln(F)] - (0.000376U_2) + (0.0045RH) \quad (2.3)$$

Where,  $ET_o$  is potential evapotranspiration of grass reference,  $E_{pan}$  is evaporation rate from a class “A” evaporation pan,  $K_{pan}$  is pan coefficient,  $U_2$  is mean daily wind run at 2 m height in Km/day, RH is mean daily relative humidity percentage, and F is upwind fetch of low-growing vegetation in meters.

### 2.3.2 Future climate projection

In this study, the climate data using a fully coupled earth system model - The Australian Community Climate and Earth-System Simulator (ACCESS) was used. ACCESS output is available in map form as gridded data products. The ACCESS coupled model has two version namely ‘ACCESS1.0’ and ‘ACCESS1.3’. ACCESS1.0 considered as basic version having spatial resolution of approximately 25 km was used in this study. ACCESS 1.0, regional climate model (RCM) was developed using six forcing global climate models (GCMs). ACCESS1.0 daily climatic data (precipitation and temperature) were downloaded and bias correction was done using linear scaling (LS) and quantile mapping (QM) techniques. Both bias correction were done using 2001-2010 as a base period data. After bias correction, precipitation and temperature data up to year 2099 were read as input in hydrological model SWAT for evaluating the impact of climate change under representative concentration pathways (RCP) 4.5 (medium growth) and 8.5 (high growth) scenarios.

Every Global Climate Model (GCM) demonstrated some biases with observed data in the projected output, which need to be corrected before applying in hydrological model. In this study two bias correction methods were applied to evaluate the systematic errors.

In linear scaling method, future time series is obtained by scaling daily observed precipitation and temperature (Mpelasoka and Chiew, 2009). These are shown in the equation below. The correction for temperature is additive and multiplicative for the precipitation.

$$P_{cor,m,d} = P_{raw,m,d} * \left( \frac{\overline{P_{obs,m}}}{\overline{P_{raw,m}}} \right) \quad (2.4)$$

$$T_{cor,m,d} = T_{raw,m,d} + (\bar{T}_{obs,m} - \bar{T}_{raw,m}) \quad (2.5)$$

Where, subscripts obs, cor, raw, m and d refers to observed, corrected, raw, month and day respectively.

$$P_{t,i} = \text{ecdf}_{\text{day},i}^{\text{mod,calc}}(X_{t,i}) \quad (2.6)$$

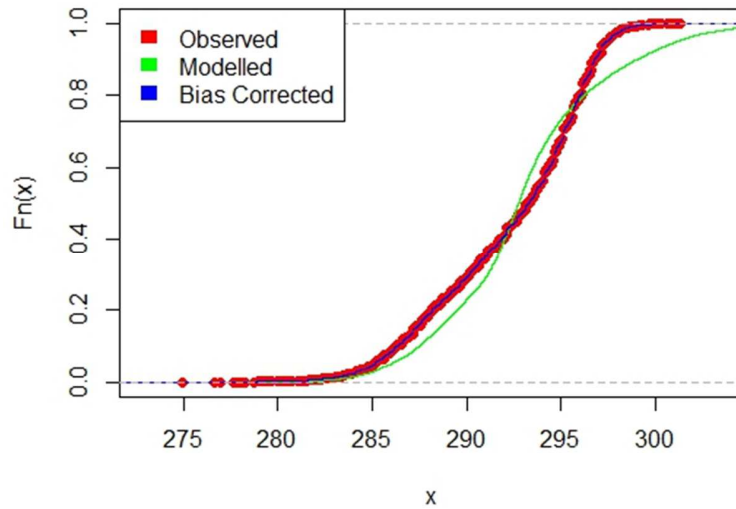
$$CF_{t,i} = \text{ecdf}_{\text{day},i}^{\text{obs,calc}^{-1}}(P_{t,i}) - \text{ecdf}_{\text{day},i}^{\text{mod,calc}^{-1}}(P_{t,i}) \quad (2.7)$$

$$Y_{t,i}^{\text{cor}} = X_{t,i}^{\text{raw}} + CF_{t,i} \quad (2.8)$$

In quantile mapping method both dry and wet days are included so as to estimate empirical cumulative density functions (ecdf) (Jakob Themeßl et al., 2011; Themeßl et al., 2012).  $P_{t,i}$  is cumulative probability at point i and day t, which is calculated using equation 2.6. The correction term  $CF_{t,i}$  is calculated as the difference of inverse ecdf ( $\text{ecdf}^{-1}$ ) of the observation ( $\text{ecdf}_{\text{day},i}^{\text{obs,calc}^{-1}}$ ) and model ( $\text{ecdf}_{\text{day},i}^{\text{mod,calc}^{-1}}$ ) for the corresponding day in a year (day) of the calibration period (calc) for inverse ecdf ( $\text{ecdf}^{-1}$ ) at probability P as in equation 2.7. The correction term  $CF_{t,i}$  is added to the raw model value  $X_{t,i}^{\text{raw}}$  to get  $Y_{t,i}^{\text{cor}}$  for both precipitation and temperature as in equation 2.8. Where,  $Y_{t,i}^{\text{cor}}$  is correction function for both precipitation and temperature for time 't' on grid 'i'.

Climate Models contain substantial biases in frequency of rainfall, intensity and total amount of rainfall (Ines and Hansen, 2006) and used various methods for calibrating both intensity and frequency distribution of rainfall to be used for the maize yield simulation. In this method the simulated precipitation from the climate model for the future period is corrected on the basis of the point wise developed daily ecdf as shown in **Figure 2.5**.





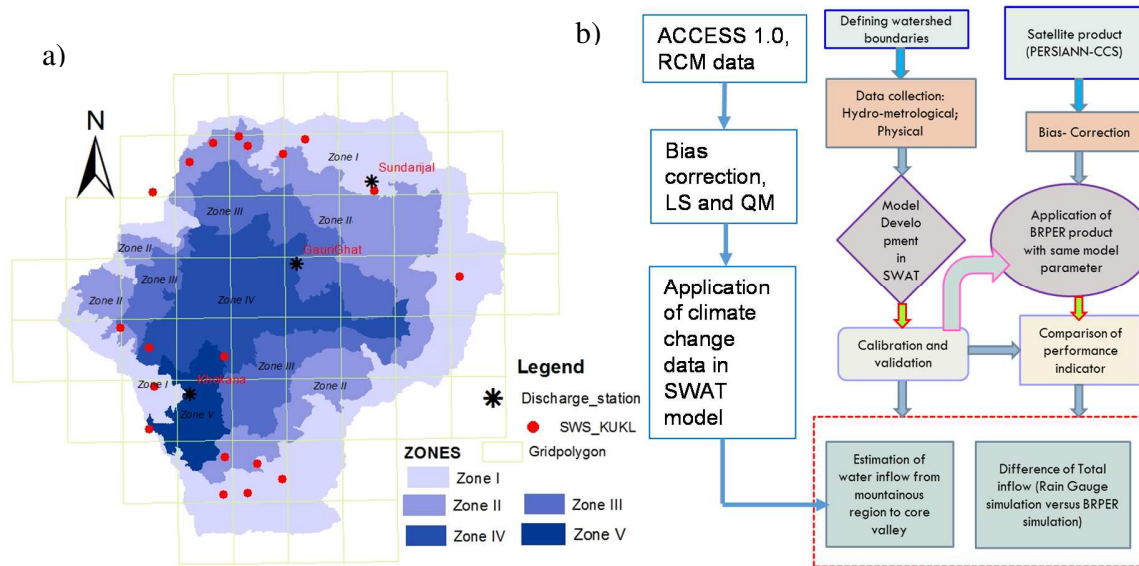
**Figure 2.5** Quantile mapping Methodology

### 2.3.3 Assessment of climate change impact on water balance components

All the climatic and water balance parameters (precipitation, temperature, and runoff) were analyzed for the year 2001-2010 as base period, 2011-2040 as near future (NF), 2041-2070 as medium future (MF), and 2071-2099 as far future (FF) under both RCPs. The seasonal and yearly change in all the parameter based on the base period were analyzed to assess the impact of climate change.

## 2.4 Estimation of fresh water from hill

In Kathmandu Valley, river water quality is not good as it flows down to valley through hill. KV is categorized as zone I (natural conservation zone) having water quality in good condition, Zone II (rural zone) is moderately polluted, zone III (peri-urban area) which is emerging towards urbanization, are critically polluted, zone IV (urban zone) where urbanization has reached in extreme point and extremely polluted, and zone V (Downstream zone) is southern part of KV dominated by agriculture and river ecosystem is extremely polluted (NTNC, 2008) as shown in **Figure 2.6 a**. KUKL is tapping surface water from those conservation zone and supplying to valley's population. Hence the status of fresh water available in hill need to be estimate. SWAT hydrological model was applied using both rain gauge and satellite precipitation data to estimate the spatial distribution of available water from hill. The overall methodological framework applied to estimate fresh water from hill is presented in **Figure 2.6 b**.



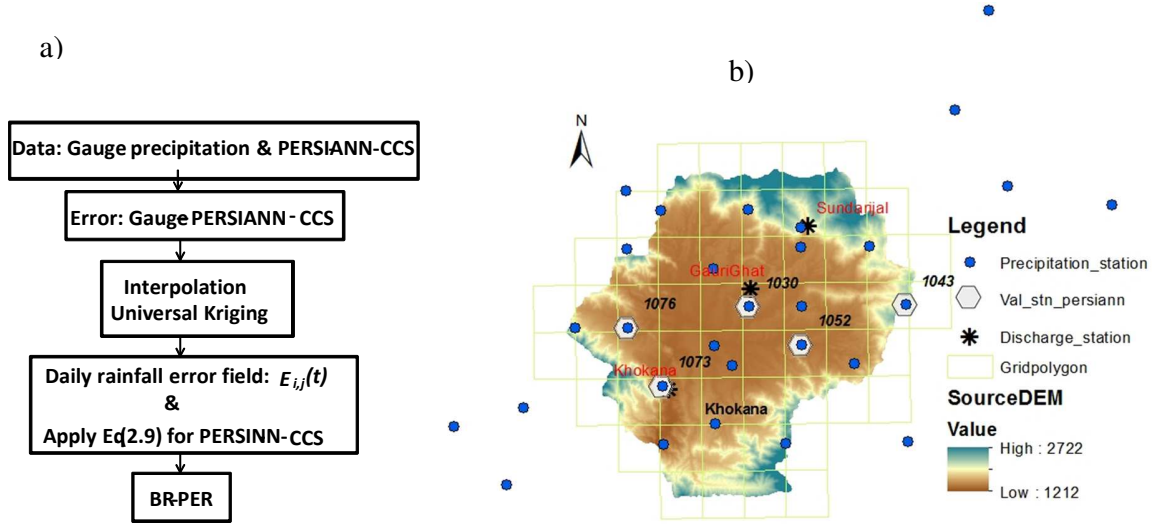
**Figure 2.6** a) Zonation of Kathmandu valley as per the water quality criteria (source NTNC, 2008); b) Overall Methodological framework for estimating fresh water from hill

#### 2.4.1 Application of satellite precipitation product

Zone I is the main sources of surface water for municipal potable water use, and lacking of hydro metrological observation stations in this zone is one of the most challenges for scientific understanding of hydrological regime and processes for short term and long term water resources project planning, development and management. In that circumstances, satellite-derived precipitation estimates is promising data source to improve the precipitation pattern information in data sparse mountainous region of KV. Because of very high spatial resolution ( $0.04^\circ \times 0.04^\circ$ ), Precipitation Estimation from Remotely Sensed Information using Artificial Neural Networks- Cloud Classification System (PERSIANN-CCS) was utilized in this study from <http://chrs.web.uci.edu/>.

#### 2.4.2 Bias-correction and validation of satellite precipitation product

However, these PERSIANN-CCS significantly underestimates the heavy rainfall and hence need to be merged with the rain gauge data using bias correction method. In this study, the bias reduction method proposed by Bui and Ishidaira (2015) was used to enhance the quantitative accuracy of PERSIANN-CCS product. Because the Bias Reduction (BR) satellite gauge merging method showed good rainfall estimations leading to excellent stream flow simulation in several river basins located in different climate. It was applied to blend the high resolution remote sensing product PERSIANN-CCS and the rain gauge data. **Figure. 2.7 a** presents the steps for retrieving the satellite-gauge merging precipitation used in this paper.



**Figure 2.7** a) Summary of bias reduction approach; b) Study area showing major tributaries along with precipitation and discharge measurement locations, grid box represents pixel of PERSIANN-CCS

At the first stage, the point differences between the rain gauge and the PERSIANN-CCS were computed with the assumption that the satellite precipitation value at each rain gauge has the same values as the PERSIANN-CCS pixel containing the rain gauge. After that, Universal Kriging was employed to obtain the daily error field corresponding with the grid of the remote sensing data. Finally, the daily satellite-gauge merging precipitation (BR-PER),  $BR-PER^{ij}(t)$  is calculated as the summation of the remote sensing precipitation  $PER^{ij}(t)$  and the daily interpolated rainfall error  $E^{ij}(t)$  as following:

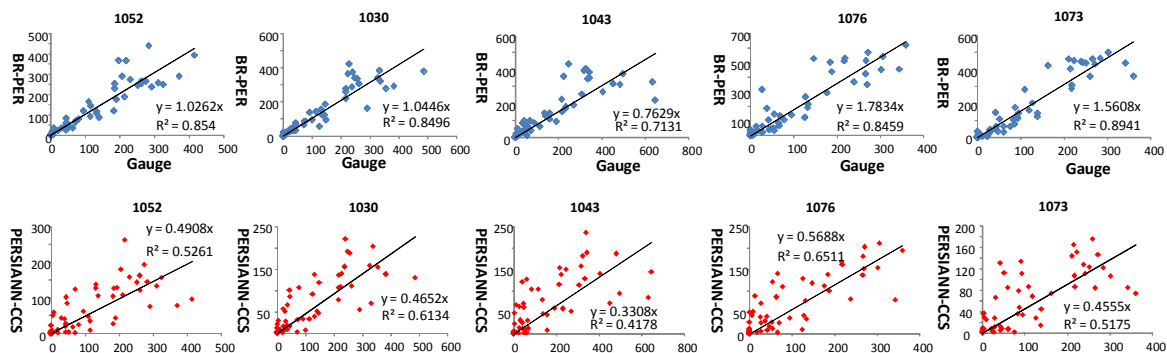
$$BR-PER^{ij}(t) = PER^{ij}(t) + E^{ij}(t) \quad (2.9)$$

Where,  $i$  and  $j$  are locations (longitude and latitude of the rainfall pixel centre)

The performance of satellite-gauge merging method was evaluated before applied as the input for hydrological model in KV. In this study, BR-PER values at five (Figure 2.7 b) out of 29 rain gauges randomly selected were validated against ground-based rain gauge observations from the DHM for the period of 2006-2010. At the first stage, 5 out of 29 available rain gauges were combined with PERSIANN-CCS rainfall estimates to obtain the BR-PER data set. The values of this BR-PER data containing the five validated rain gauges are compared with the corresponding rain gauge value. After the performance of bias reduction satellite gauge merging approach is confirmed in KV, the whole number 29 rain gauge stations were merged with the PERSIANN-CCS to produce input for SWAT model.

It can be seen from **Figure 2.8** that PERSIANN-CCS significantly underestimates the precipitation and moderate relationship with the observed rainfall, showing the gradient values always less than 0.6 and the  $R^2$  values ranging from 0.42 to 0.65. After combining the local rain gauges with PERSIANN-CCS, the relationship between BR-PER and the observed rainfall showed significant improvement compared with the original satellite precipitation product with the  $R^2$  ranging from 0.71 to approximately 0.89.

Especially, at the stations number 1052 and 1030, BR-PER data exhibited excellent fitness with the rain gauge data, the slopes of the fit line are around 1.03 and 1.04 respectively. However, BR-PER at station number 1043 slightly underestimates rainfall with the slope around 0.76; while at station number 1076 and 1073, BR-PER shows moderate rainfall overestimations. These results can be explained by the fact that the quality of satellite-gauge merging precipitation data depends upon the utilized rain gauges. The number of rain gauges used to interpolate the pixels containing stations 1043, 1076, 1073 is very sparser than the cases of stations 1030, 1052 when five validated rain gauges are eliminated from the merging process between local rain gauges and PERSIANN-CCS. In addition to the superior ability to capture the rainfall spatial distribution of BR-PER than the few rain gauge in the mountainous area in KV, the excellent fits at the station number 1030, 1052 and moderate matches (due to rain gauge eliminations for validation process) at the remaining three stations between BR-PER and PERSIANN-CCS indicate the high potential uses of BR-PER for stream-flow simulation in KV.



**Figure 2.8** Scatter plot between rain gauge vs BR-PER (blue dots) and rain gauge vs PERSIANN-CCS (red dots) at 5 validated rain gauge

### 2.4.3 Hydrological model selection and development

Three hydrological model were used to understand the water balance at whole watershed level. All three model shows satisfactory performance but for the estimation of spatial distribution of available fresh water from hill, even though only SWAT model was applied. SWAT, which is distributed, physically based hydrological model with ArcGIS interface for

pre and post processing, was used in this study for discharge simulation. Watershed boundaries for the KV were defined utilizing DEM using watershed delineation techniques in ARCSWAT.

#### 2.4.4 Calibration and validation of hydrological model

Hydro metrological and physical data (as listed on **Table 2.1**) were used for the hydrological simulation and calibrated (2007-2008) and validated (2009-2010) at Khokana (station No 550.05) near the outlet. Three performance indicator Nash Sutcliffe (NS), Percentage Biasness (PBIAS), and correlation coefficient ( $R^2$ ) as stated in equations (2.10), (2.11), and (2.12) were used to evaluate stream flow simulation in Kathmandu valley near the outlet of the basin of station Khokana (550.05).

$$NS = 1 - \frac{\sum_{i=1}^n (Y_i^{obs} - Y_i^{sim})^2}{\sum_{i=1}^n (Y_i^{obs} - \overline{Y^{obs}})^2} \quad (2.10)$$

$$PBIAS = 100 \times \frac{\sum_{i=1}^n (Y_{obs} - Y_{sim})_i}{\sum_{i=1}^n Y_i^{obs}} \quad (2.11)$$

$$R^2 = \left[ \frac{\sum_{i=1}^n (y_i^{obs} - \overline{Y^{obs}})(y_i^{sim} - \overline{Y^{sim}})}{\sqrt{\sum_{i=1}^n (y_i^{obs} - \overline{Y^{obs}})^2} \sqrt{\sum_{i=1}^n (y_i^{sim} - \overline{Y^{sim}})^2}} \right]^2 \quad (2.12)$$

Where:  $n$  is the total number of observations,  $Y_i^{obs}$  and  $Y_i^{sim}$  are the value of observed and simulated variables at the  $i^{th}$  time-step respectively,  $\overline{Y^{obs}}$  and  $\overline{Y^{sim}}$  are the average of the observed and simulated values.

#### 2.4.5 Estimation of fresh water from hill

The sub-watersheds on mountainous region where fresh water is available were identified and inflow were assessed. Water available for potable water use for dry and wet season were estimating assuming the minimum and average flow of December to May for dry season and minimum and average flow of June to October for wet season assuming 10% release as environmental flow (MoWR, 2001) and diverting 20% as the agricultural demand (WECS, 2008). While estimating the average wet season water availability, the peak season flow for month July and August were discarded in this section.

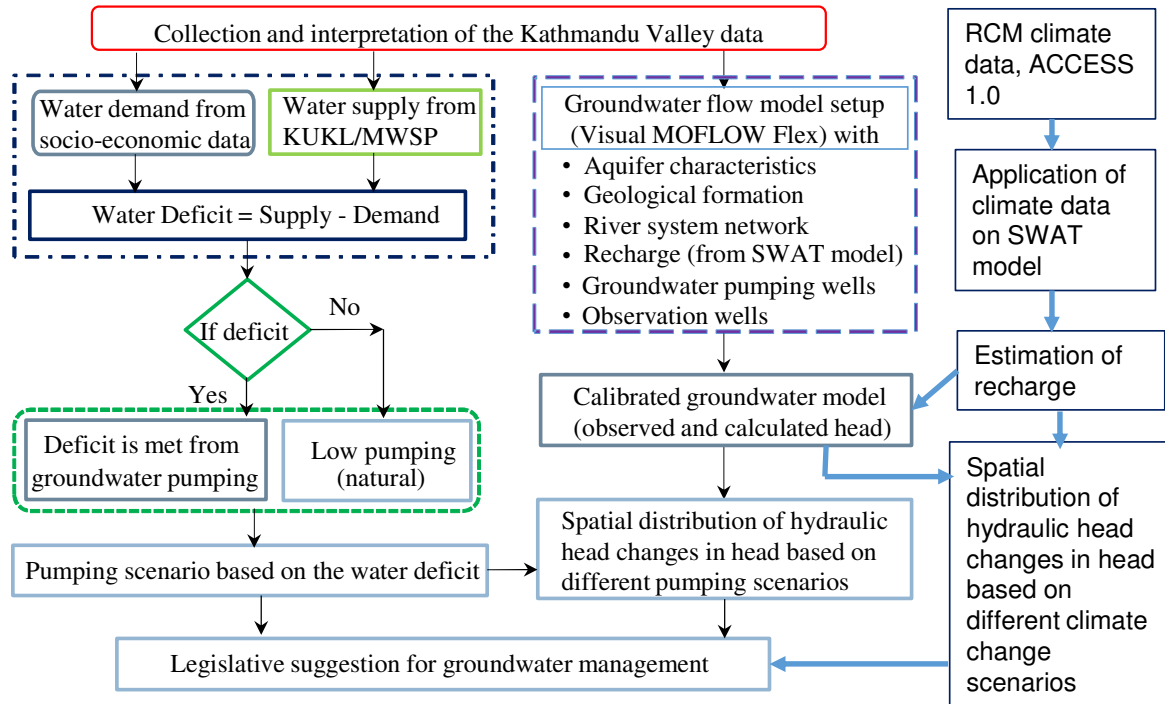
#### 2.4.6 *Impact of climate change on water availability from hill*

The water availability on each sub-watersheds were quantified and seasonal change of flow were also assessed for three case near future, medium future, and far future with respect to base period 2001-2010.

### 2.5 Estimation of groundwater level

In Kathmandu Valley, Groundwater is considered as a safe and reliable source of water, which has resulted in steady increase in groundwater pumping from valley's aquifer (Pandey et al., 2010) resulting decline in groundwater level. The decline may have been exacerbated by the reduction of groundwater recharge due to a rapid urbanization with impermeable surfaces in the valley (Cresswell et al., 2001). Therefore, the current practices of groundwater use are unsustainable and could lead to irreversible groundwater quality deterioration and land subsidence in the valley. To achieve sustainable water resources management, the Government of Nepal has planned to increase valley's water supply by implementing an inter-basin water transfer project known as Melamchi Water Supply Project (MWSP). The MWSP focuses on developing a bulk distribution network through improvement of the distribution network located mostly in the central groundwater district, and will be operated by the KUKL to supply water to valley's existing user as well as to future users in the new service area in the Kathmandu Valley. The MWSP implementation will provide an additional 510 MLD of water supply from the Melamchi River as the off-the-valley source in two phases: 170 MLD by September 2016 (delayed by a year due to unforeseen circumstances such as the 2015 Gorkha Earthquake) and 340 MLD by 2023 (personal communication with procurement officer of MWSP). Despite this planned surface water supply, the existing groundwater use in the valley is unlikely to be completely abandoned after the successful completion of the MWSP. This may be due to high investments in groundwater supply infrastructure and the high pricing of KUKL water. Therefore, there is a need to investigate the impacts of various groundwater pumping scenarios on the valley's groundwater system with pre- and post-MWSP situation to evaluate appropriate water resources management actions. In addition to this, there is need to access the impact of climate change in groundwater system in Kathmandu Valley. The detail methodological framework for estimating groundwater level is presented in **Figure 2.9**.

SWAT model has been selected for estimating the recharge component, which has given as boundary condition for groundwater model. SWAT model is distributed model, which can provide recharge at sub-basin and HRU level. Average recharge for year 2001-2010 were estimated and provided as boundary condition for groundwater model. All the three model have similar performance, even though due to simplicity of data interpretation, recharge component at sub-basin level, SWAT model has been selected for this study.



**Figure 2.9** Methodological framework for evaluating groundwater environment in Kathmandu Valley (KUKL is the Kathmandu Upatyaka Khanepani Limited, MWSP is the Melamchi Water Supply Project, RCM is Regional Climate Model)

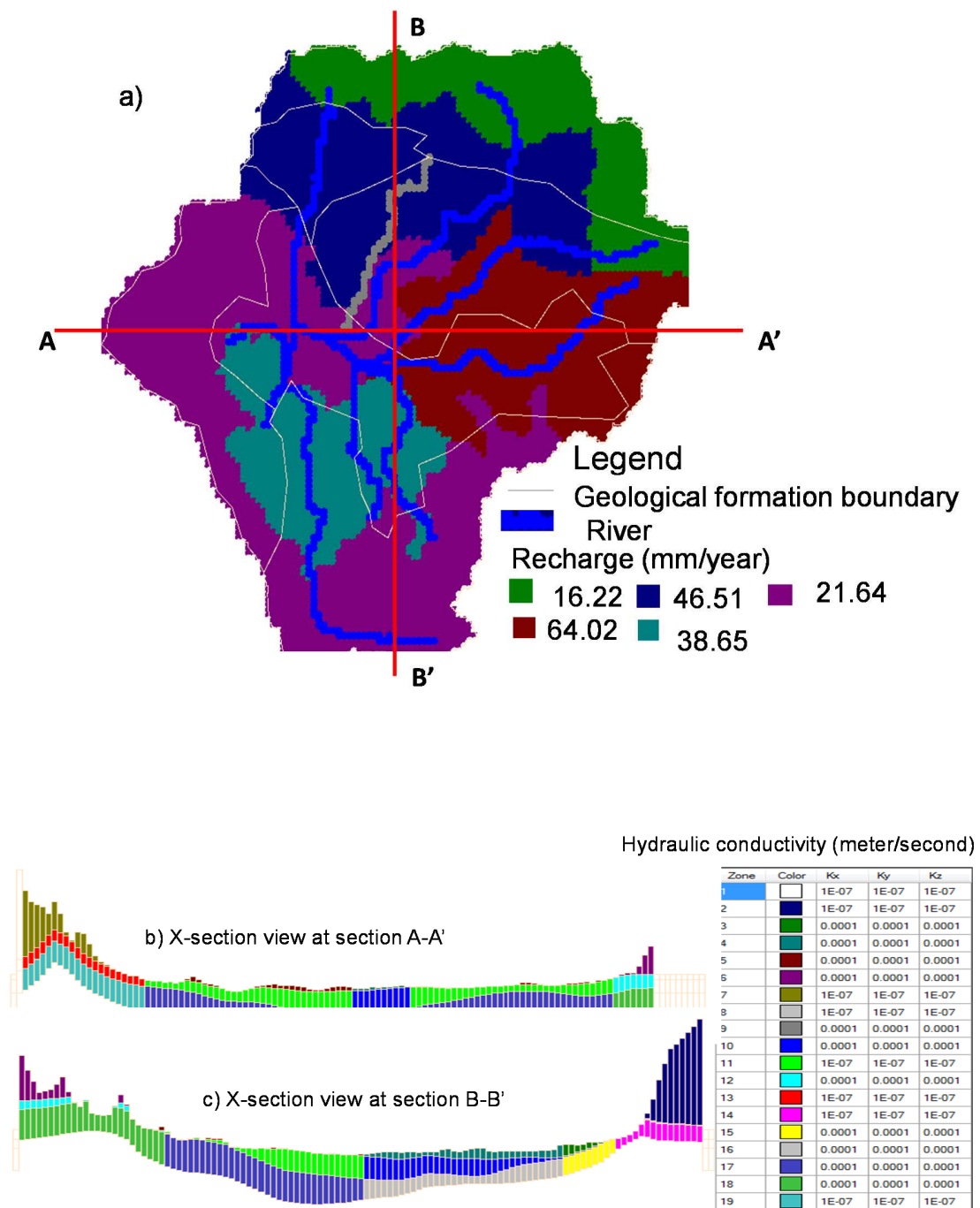
### 2.5.1 Groundwater model development

A finite-difference groundwater flow model of the KV watershed was setup in the Visual MODFLOW (VMOD) Flex with a uniform grid size of 120 m (**Figure 2.10**). The VMOD model has three layers implemented with data obtained from Pandey and Kazama (2011) to represent the shallow and deep aquifers separated by the aquitard. The spatially distributed geological formations were reclassified into six VMOD property zones in Layer 1 (one zone having same hydraulic and storage properties values) as shown in **Figure 2.10 a** and implemented at each of three layers resulting in 18 zones as shown in **Figure 2.10 b & c** (zone 1 is inactive zone shown in the cross-sections). Hydraulic conductivity values were assigned at each zone based on available information following aquifer material properties and modified during the model calibration. In **Figure 2.10**, nine perennial rivers were implemented in Layer 1 as river boundary conditions and one intermittent surface water feature was implemented as drain. These were assigned as segments using river bed conductance, river water and bed bottom elevations at the start and end of each segment. From the Ground Water Resources Development Board (GWRDB), 19 groundwater observation wells with observed data on January 2003 were used for the model calibration and 379 pumping wells with available



information such as latitude, longitude, screen depth and abstraction rates were implemented in the VMOD model using well package (**Figure 5.1**). For the numerical simulation, MODFLOW 2005 run numerical engine were used and rewetting option was active. The manual model calibration was conducted by trial-and-error to obtain an acceptable difference between observed and simulated heads. The water balance was evaluated using the VMOD zone budget assigned following the 18 aquifer property zones in the VMOD model of the KV.





**Figure 2.10** Groundwater flow model setup in the Visual MODFLOW Flex for Kathmandu Valley a) top-view of aquifer recharge zones with river and drain networks and boundary of reclassified geologic formation utilized for property zones Cross-sections with hydraulic conductivity zone values are shown in b) A-A' and c) B-B'

### 2.5.2 *Climate change scenarios*

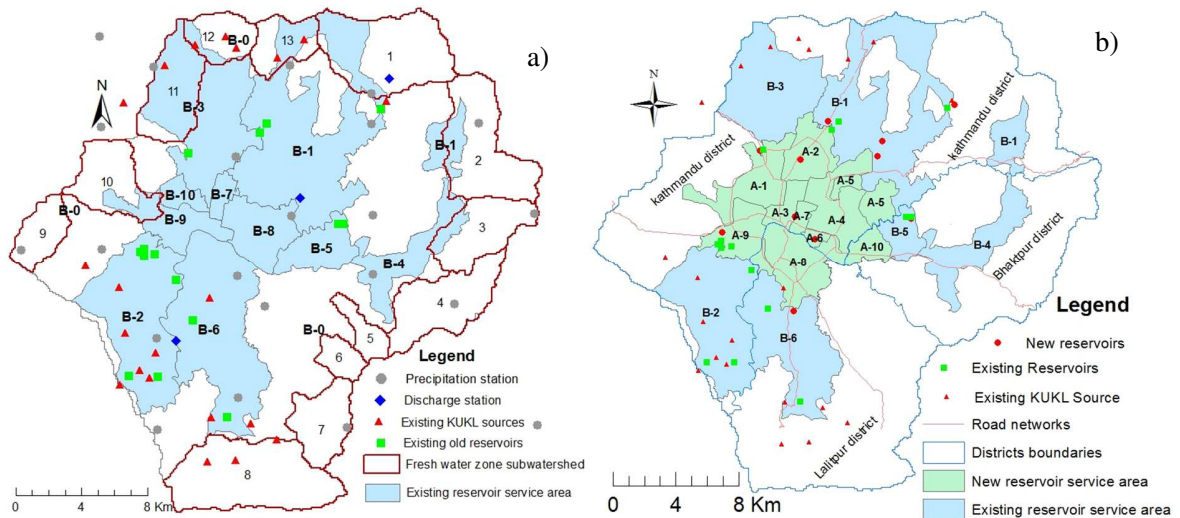
After calibrating the model with current rate of pumping, the ground water model was considered as base scenario (BS). Recharge from SWAT were quantified for the near future, medium future and far future under RCP 4.5 and 8.5 scenarios using both liner scaling and quantile mapping bias correction techniques. The recharge obtained from both bias correction techniques were averaged to prepare average recharge on RCP 4.5 and 8.5 scenarios for NF, MF, and FF. Those recharge values were applied on groundwater model and changes in head with BS were assessed to evaluate the impact of climate change.

### 2.5.3 *Climate change scenarios*

After calibrating the model with current rate of pumping, the ground water model was considered as base scenario (BS). Recharge from SWAT were quantified for the near future, medium future and far future under RCP 4.5 and 8.5 scenarios using both liner scaling and quantile mapping bias correction techniques. The recharge obtained from both bias correction techniques were averaged to prepare average recharge on RCP 4.5 and 8.5 scenarios for NF, MF, and FF. Those recharge values were applied on groundwater model and changes in head with BS were assessed to evaluate the impact of climate change.

## 2.6 **Evaluation of household water security index (WSI)**

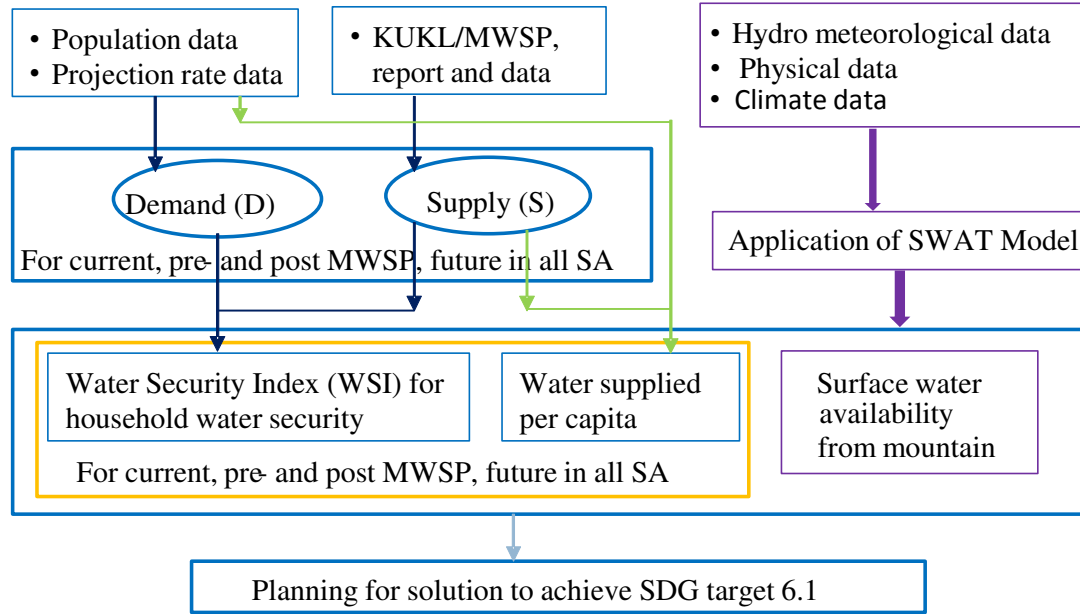
While focusing on security of potable water for a household, it is crucial to satisfy their household water need, sanitation and improved hygiene for public health. Various international organizations like the World Bank (WB) and World Health Organization (WHO) have recommended 50 lpcd as the basic water requirements for drinking, sanitation and hygiene, cooking, and bathing (Gleick, 1998; WHO, 2010). Higher estimate of water requirement was proposed by different organization and researcher for the economic use of water for domestic and industrial needs such as 274 lpcd (Falkenmark, 1986; Shuval, 1992), and 135 lpcd (BIS, 1993; Chenoweth, 2008). The government of Nepal aims to provide 135 lpcd of domestic water for the residence of Kathmandu Valley by the year 2025 (ADB, 2015).



Service Area (SA) No	Service area name served by existing reservoirs	Service Area (SA) No	Service area name served by existing reservoirs	Service Area (SA) No	Service area name served by new reservoirs	Service Area (SA) No	Service area name served by new reservoirs
B-1	Mahankalchour	B-6	Lalitpur	A-1	Balaju North	A-6	Minbhavan East
B-2	Kritipur	B-7	Kamaladi	A-2	Bansbari North*	A-7	Anamnagar East
B-3	Maharajgunj	B-8	Baneshowr	A-3	Panipokhari East	A-8	Khumaltar North
B-4	Bhaktapur	B-9	Tripureshowr	A-4	Mahankalchour North	A-9	Kritipur North
B-5	Madhyapur Thimi	B-10	Chhetrapati	A-5	Arubari North	A-10	Tigeni North

**Figure 2.11** Study area showing a) Conservation zone for freshwater, KUKL's existing sources and service areas, and hydro meteorological stations; b) Planned water supply service areas after Melamchi Water Supply Project (MWSP). *New reservoir service area will get water from MWSP and Existing reservoir will get water from existing network*

To achieve the sustainable development goal (SDG) target on water sector, the Government of Nepal (GoN) is investing in several water-related infrastructure development across the country. The development of infrastructure and institution is overcoming urban water insecurity in large cities (Padowski et al., 2016). One of the mega project in water sector since the year 2000 is inter-basin water transfer project called MWSP, which aims to bring water in the Kathmandu Valley from off-the-valley sources. Whether this mega project can contribute to achieve the SDG target in Nepal is still unclear. Hence in this study, water security situation in the KV over the time with implementation of MWSP were assessed, the detail methodological framework is presented in **Figure 2.12**.



**Figure 2.12** Methodological framework for evaluating household water security index (WSI) (KUKL: Kathmandu Upatyaka Khanepani Limited, MWSP: Melamchi Water Supply Project, SAs: Service Areas)

### 2.6.1 Estimation of water demand and supply

The existing and planned water supply data for each SAs were taken from the KUKL/MWSP reports. Water demand is the potable water demand for each service area considering per capita demand as 135 lpcd (for basic as well as economic growth) and 50 lpcd (for basic human water requirement). Population for 2016 (current), 2018 (after 1<sup>st</sup> phase of MWSP), 2024 (after 2<sup>nd</sup> phase of MWSP), and 2030 (future, i.e., post-MWSP or SDG target year) were estimated for each SAs based on the population projection rate published by (CBS, 2014) using 2011 population (CBS, 2012) as the base data. The population projection rate was only available at district level. Hence to make it more relevant with wards and village development committees (VDCs) level, the incremental rate of population from 2001 (CBS, 2003) and 2011 (CBS, 2012) census data were calculated. Those rates based on the growth between 2001 and 2011 is known as old growth rate and converted it into new growth rate at ward or VDCs level using Eq. 2.13 below.

The new growth rate at ward or VDC level (NGR) is estimated as

$$NGR_i = \frac{NGR_j}{OGR_j} OGR_i \quad (2.13)$$

Where, NGR is new growth rate, OGR is old growth rate subscript  $i$  represents ward level for municipalities and VDCs and  $j$  is corresponding district (Kathmandu, Lalitpur, and Bhaktapur).  $OGR_i$  and  $OGR_j$  are calculated as the growth rate calculated from the population census data of year 2001 and 2011.  $NGR_j$  is obtained from projected growth rate for corresponding district.

The ward and VDC level annual population beyond 2011 was projected based on exponential growth formula as follows as estimated by (Udmale et al., 2016):

$$P_t = P_0 * e^{rt} \quad (2.14)$$

Where,  $P_t$  is Population at time  $t$ ,  $P_0$  is Population at time  $t_0$ ,  $r$  is New growth rate (NGR) calculated from Eq. (1) it can,  $t$  is Time in year (number of periods).

After knowing the population for each SAs for different time period (year 2016, 2018, 2024, and 2030), water demand is calculated as,

Demand (D),

For basic human water requirement = Population \* 50 lpcd

For economic growth = Population \* 135 lpcd

Supply (S) were taken from the KUKL report for current year 2016 and for rest of the year those data were taken from Melamchi Water Supply Project Implementation Directorate (MWSPID), and Kathmandu Valley Water Supply Management Board (KVWSMB).

### 2.6.2 Analysis of water deficit

Water deficit is a balance between demand and supply. In each service area, water deficit was calculated based on the estimated demand and supply. If demand is not fulfilled by KUKL supply, then there is water deficit situation.

$$\text{Deficit} = \text{Demand (D)} - \text{Supply (S)} \quad (2.15)$$

### 2.6.3 Analysis of household water security index (WSI)

Water supply per capita is calculated as the ratio of total water supplied to the total population in each SA for the corresponding year. Similarly, the household water security index (WSI) is calculated only considering the quantity aspect for both criteria (135 lpcd and 50 lpcd) assuming KUKL will provide good quality of water as:

$$\text{WSI} = (\text{Amount of water supply, S}) / (\text{Potable water demand, D}) \quad (2.16)$$

#### 2.6.4 Pumping scenarios

Five different groundwater pumping scenarios were formulated based on the water deficit situation for the KUKL service areas considering the MWSP timelines. As per the estimated completion of the MWSP, water deficit situations were calculated for 2018 (after the completion of first phase), 2023 (after the completion of second phase) and 2030 (post-MWSP as well as the target year of sustainable development goal (SDG)). Note that we used a steady-state groundwater flow model in this study, although the five scenarios were generated for different time periods. Transient response of the groundwater system to a major change in pumping rates is an important factor, but not considered in the present analysis. The effects of pumping scenarios were simulated using the calibrated groundwater model in both new and existing (old) reservoir service area (RSAs) (**Figure 2.11**) to compare simulated hydraulic head distributions under the five scenarios. Those scenarios were formulated based on the water availability, demand, and deficit in different service areas, which are summarized for new and old RSAs and simulation results were analyzed for each groundwater district to propose regulatory interventions for the sustainable management of groundwater resources in the valley. A brief narrative of the baseline and five scenarios is given below and summarized in **Table 2.2**:

- *Current rate of pumping (BS)*

In 2016 (current situation), all the KUKL service areas provide water with rates ranging from 27 to 66 lpcd, which is less than the basic human requirement of 50 lpcd in some areas (**Figure 6.2 a**). The existing water deficit of domestic and industrial water use is matched by groundwater abstractions from privately owned wells with current pumping rates. This scenario is the baseline case for pumping and these pumping rates are used to generate other scenarios with different percentage of pumping.

- *Pumping decreased by 50% of current rate (S1)*

All the KUKL service areas get more water than 2016 after the first phase of MWSP in 2018. The new RSA receive water supply at rates ranging from 70 to 130 lpcd and existing RSA – from 56 to 157 lpcd (**Figure 6.2 b**). In this scenario, we assume the 50% reduction in pumping for both new and existing RSA as the future water demand is partly fulfilled.

- *Pumping at 10% of the baseline rate in new RSA and 125 % in existing RSA (S2)*

The new RSA receives a sufficient amount of water after the second phase of MWSP in 2023, but the situation in existing RSA becomes worse than the baseline (**Figure 6.3 a**). Hence, this scenario considers pumping in the new RSA at 10% of the baseline and 125% of the

baseline in the existing RSAs. The 10% rate is considered “natural” because, even after getting sufficient water from utility, people may use groundwater for some domestic use (may be not possible to fully stop pumping).

- *Pumping at 10% of the baseline rate in new RSA and 150 % in existing RSA (S3)*

For the target year 2030 for the sustainable development goal, the new RSA has sufficient water supply with 10% pumping as in the previous scenario, but the situation in the existing RSA is much worse than the year 2023 (**Figure 6.3 b**). Hence, this scenario considers an increased pumping by 150% in the existing RSA.

- *Pumping at 10% of the baseline (or optimistic scenario) (S4)*

This scenario considers natural state in the entire watershed. The proper water redistribution in the KULK service areas satisfies the water deficit due to the inequality of water distribution. If the water is redistributed properly, there is no water deficit in the KUKL service areas and 10% pumping is assumed in both RSAs in this scenario.

- *Pumping 150% of baseline, (or pessimistic scenario) (S5)*

This scenario considers a delay in the MWSP implementation due to various reasons and considers an increased groundwater abstraction by 150 % of the baseline scenario.

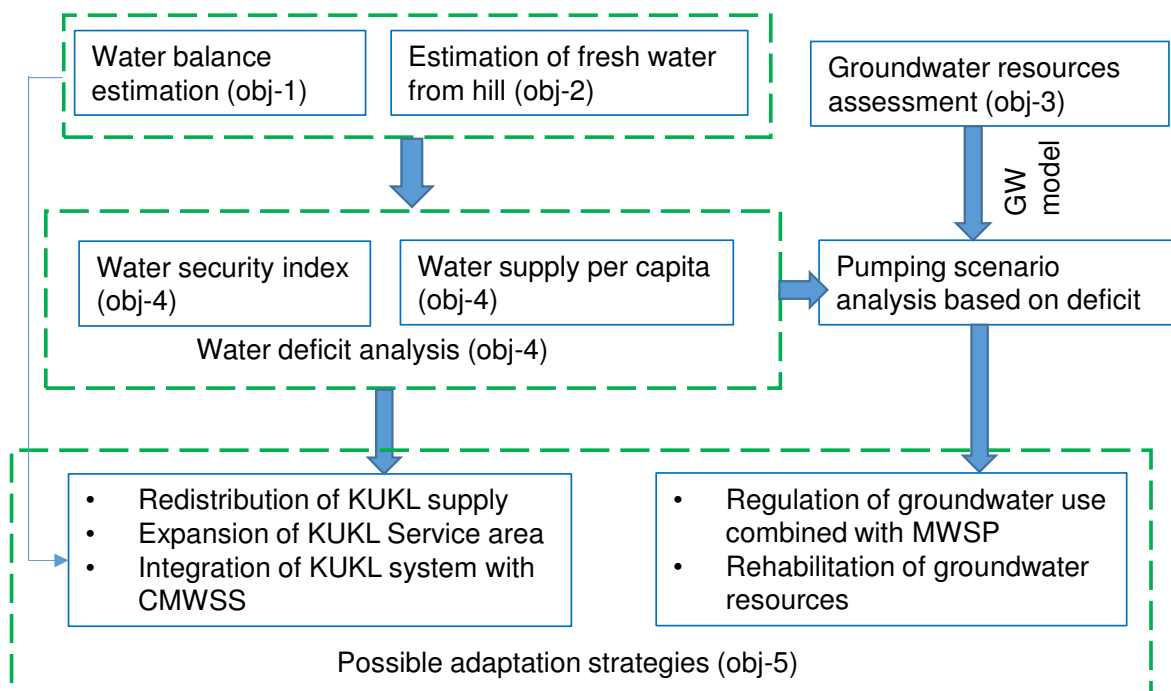
**Table 2.2** Groundwater pumping scenarios selected based on the potable water supply, demand, and deficit in the new and old (existing) reservoirs service areas.

Reservoir service area/ Pumping scenario	Baseline scenario (Current situation) <b>(BS)</b>	After 1 <sup>st</sup> phase of MWSP, <b>(S1)</b>	After 2 <sup>nd</sup> phase of MWSP, <b>(S2)</b>	Future (SDG target year), <b>(S3)</b>	Optimistic scenario, <b>(S4)</b>	Pessimistic scenario, <b>(S5)</b>
New	Estimated pumping rate of 2016 (A)	50% of A)	10% of A)	10% of A)	10% of A)	150% of A)
Old (existing)			125% of A)	150% of A)		

## 2.7 Identification of possible adaptation strategies

From the methodology adopted in previous section, water balance situation, additional fresh water available from mountain that can be used for drinking purpose, impact of possible changes like population, infrastructure development, and climate change on demand, supply, and both surface and groundwater resources were estimated. After knowing the situation of holistic water balance and potable water availability using objective 1 and 2, water security situation were reported. To resolve the water security situation, MWSP is in progress but what will be the condition is not well understood. Hence the supply and demand situation were

accessed in the timeline of MWSP implementation. Water security situation in different phase of MWSP implementation were accessed using objective 4. In addition to this groundwater resources were estimated applying groundwater model and result on objective 3 were obtained. Based on the finding of objective 1-4, possible adaptation strategies were proposed for sustainable management of available both surface and groundwater resources. That adaptation strategies could be redistribution of available resources, integration and expansion of KUKL system with community managed water supply schemes (CMWSS), rehabilitation of traditional infrastructure, and regulation on groundwater resources. The methodological framework adopted for adaptation strategies is outlined in **Figure 2.13**.



**Figure 2.13** Methodological framework for evaluating the possible adaptation strategies (GW: Groundwater, obj: objective)

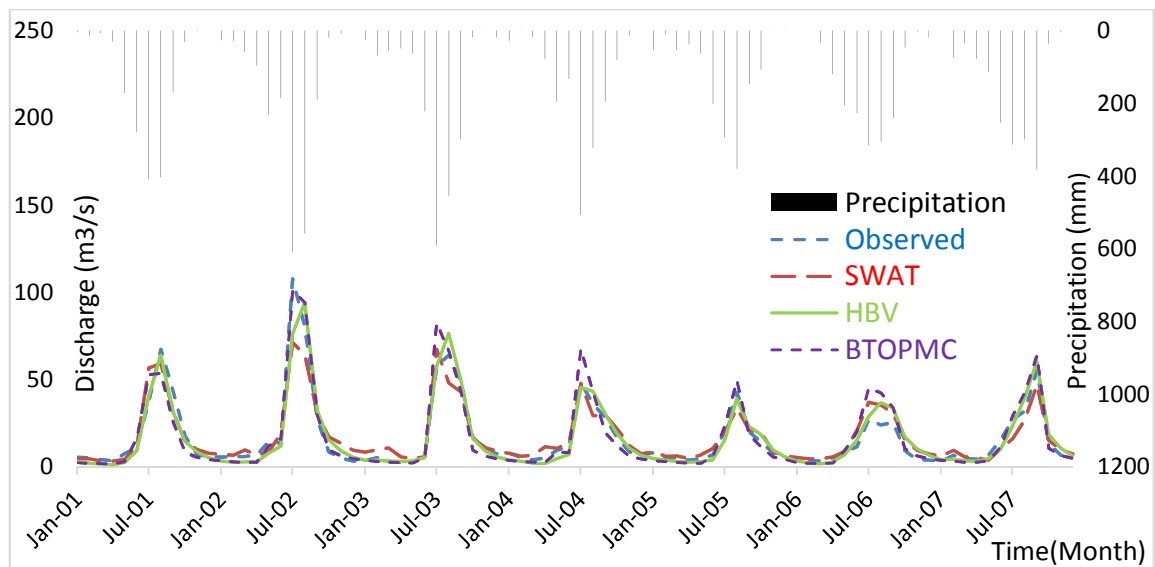


## WATER BALANCE ANALYSIS

### 3.1 Model calibration and validation

All three models were calibrated and validated at the outlet of the basin, capturing flows generated at almost all the parts of the valley and reflecting the results of all of the flow processes and their interactions occurring in the entire valley. Monthly simulated runoff values were compared to observed runoff values from the three models, and performance indicators were calculated and summarized.

Plots of the runoff simulated by the three hydrological models with the observed runoff at the outlet (i.e., Khokana station) for the entire calibration period (2001–2007) are shown in **Figure 3.1**. All three models adequately simulated the general trends in runoff fluctuations in the KV watershed and responded well to rainfall events (**Figures 3.1 and 3.2**). All three models simulated average monthly runoff during the lean season better than the peak season flows. In addition, NSE values were 0.88, 0.92, and 0.89, and PBIAS values were -0.04, 0.02, and 0.0 in the SWAT, HBV, and BTOPMC models, respectively (**Table 3.1**). No generally agreed absolute thresholds exist for the performance indicators; however, based on published studies, hydrological simulation of monthly values with NSE above 0.65 can be considered satisfactory ([Moriassi et al., 2007](#)). Values of performance indicators and the reasonably well-correlated plots of simulated versus observed monthly runoff in this study suggest satisfactory performance of all the three hydrological models for the purpose of water resource assessment and water balance analysis.



**Figure 3.1** Plot of simulated (by three models) and observed monthly runoff at Khokana (Station ID: 550.05) during calibration period (2001-2007)

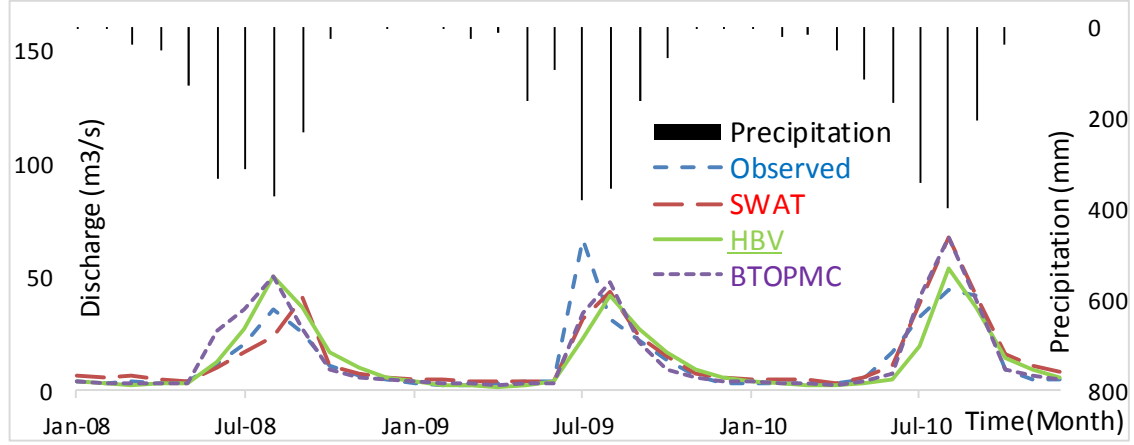
The simulated mean monthly runoff was 16.91 m<sup>3</sup>/s in the SWAT model, 15.02 m<sup>3</sup>/s in the HBV model, and 15.56 m<sup>3</sup>/s in the BTOPMC model during the calibration period. The difference in mean runoff during the calibration period was 0.61 m<sup>3</sup>/s, 1.28 m<sup>3</sup>/s, and 0.73 m<sup>3</sup>/s in SWAT, HBV, and BTOPMC models, respectively. Predictive analysis showed that the runoff was underestimated by the HBV and BTOPMC models, and overestimated by SWAT during the calibration period. Although comparison of the performance indicators and statistical analyses with the observed runoff suggested reasonably good simulation of monthly flow by all the three models. The focus during calibration was mainly on storm fitting for lean season flow and performance for the entire period of calibration. Because of the reason, there are differences in estimation on yearly basis, such as underestimation of general trend of peak flow in wet year (e.g., 2002) and overestimation in dry year (e.g., 2006). As the performance were evaluated for average conditions, the model results are useful for the purpose of water resources assessment and not for flood-related studies.

**Table 3.1** Statistical analysis of observed and simulated runoff at Khokana (Station ID: 550.05)

S.N.	Items	Calibration Period (2001-2007)				Validation Period (2008-2010)			
		Observed	SWAT	HBV	BTOPMC	Observed	SWAT	HBV	BTOPMC
1	Mean monthly runoff (m <sup>3</sup> /s)	16.30	16.91	15.02	15.56	12.52	13.90	12.76	13.76
2	Minimum monthly runoff (m <sup>3</sup> /s)	2.39	3.27	1.19	1.61	1.50	2.94	1.43	2.20
3	Maximum monthly runoff (m <sup>3</sup> /s)	107.76	71.35	93.85	101.18	66.01	67.37	53.63	66.92
4	Standard deviation of runoff	19.65	16.16	18.43	20.96	15.23	15.13	14.66	17.24
5	Coefficient of determination (R <sup>2</sup> )		0.89	0.92	0.92		0.72	0.65	0.75
6	Nash Sutcliffe Efficiency (NSE)		0.88	0.92	0.89		0.69	0.63	0.67
7	% PBIAS		-0.04	0.02	0.00		-0.11	-0.02	-0.10

The calibrated parameters were used with all the three models to simulate runoff for the validation period of 2008–2010. Performance of the models during the validation are shown in **Figure 3.2** and **Table 3.1**. The annual precipitation is less than the average precipitation over the basin for all the three years considered for validation. For year 2008 and 2010, all the three models overestimated the peak flow, as in calibration, for dry year but for year 2009 it is not following the general pattern. The reason behind could be variation in precipitation pattern in the year 2009 compared to other years considered in validation. To be more precise, precipitation in June 2009 was very low compared to the same months in other years. As a result, all three models underestimated peak flow during June 2009 (**Figure 3.2**). However, overall performance to simulate average hydrological conditions seems reasonably well during validation as well with the NSE values of 0.69, 0.63, and 0.67; the PBAIS of -0.11, -0.02, and -0.10; and R<sup>2</sup> of 0.72, 0.65, and 0.75 for SWAT, HBV, and BTOPMC models, respectively. The simulated mean discharges were 13.90, 12.76, and 13.76 m<sup>3</sup>/s (as shown in **Table 3.1**),

respectively, for the validation period. The differences in mean runoff during the validation period are 1.38 m<sup>3</sup>/s for SWAT, 0.24 m<sup>3</sup>/s for HBV, and 1.24 m<sup>3</sup>/s for BTOPMC model.



**Figure 3.2** Plot of simulated (by three models) and observed monthly runoff at Khokana (Station ID: 550.05) during validation period (2008-2010)

### 3.2 Comparison of water balance component

After evaluating the performance of each model at outlet of watershed based on runoff, water balance component runoff, evapotranspiration, and total water storage as stated in eq. (2.1) were assessed and described as bellows.

#### 3.2.1 Runoff

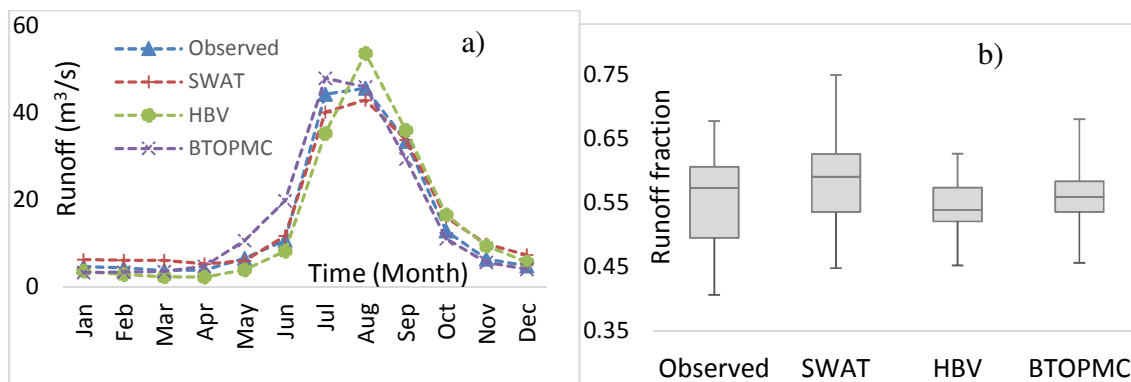
The monthly averaged runoff volumes produced by the three models are listed in **Table 3.2**. The absolute difference between the long-term average (2001–2010) for the observed and simulated runoff was higher during August, September, October, and November for the SWAT model; during June, July, August, October, and November for the HBV model; and during May, June, July, and September for the BTOPMC model. These results show the differences in the seasonal fluctuation for each model from the range of values of runoff for each month. The difference in runoff from the long-term average was small from December to April in all three models, indicating that the dry season values were well-reproduced by the models relative to the observed values. The main focus of this study was water resource assessment rather than flood forecasting, and in this context, all three models provided reasonable values for the water balance components.

In addition to mean monthly flows, we also investigated whether the variabilities in the observed time series were reproduced well by the models. The values of significance for the differences among mean monthly discharges and the box plot of the runoff coefficient for 2001–2010 shown in **Figures 3.3 a & b** indicate that the SWAT model overestimated the total

runoff component with a large range of variation, whereas BTOPMC model overestimated total runoff with a small range of variation and HBV model underestimated the total runoff values with a small range of variation compared to the observed values. The peak flow of runoff estimated by the HBV model was slightly to the right with higher values than the other two models and the observed values. The receding limbs of runoff generated by the SWAT and HBV models overestimated the observed values and they were shifted to the right, whereas the values produced by the BTOPMC model closely matched the observed values. However, the simulated rising limbs from the SWAT and HBV models closely matched the observed values, whereas they were overestimated and shifted towards the left in the BTOPMC model. The mean monthly runoff plots and annual variation in the runoff fraction (2001-2010) showed that all models provided reasonable fits and close correlations relative to observational data

**Table 3.2** Differences between mean monthly observed and simulated runoff at Khokana (550.05) from 2001-2010 (m<sup>3</sup>/s)

Item (m <sup>3</sup> /s)/month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Observed	4.70	4.36	3.81	3.88	6.58	10.74	44.36	45.75	33.58	12.87	6.46	4.86
SWAT	6.30	6.13	6.15	5.30	6.03	11.73	40.23	43.02	33.82	16.04	9.88	7.40
HBV	3.63	2.84	2.33	2.28	3.94	8.25	35.37	53.75	36.08	16.62	9.49	5.70
BTOPMC	3.29	3.45	3.60	4.81	10.65	19.85	48.05	46.03	29.49	11.13	5.63	4.06

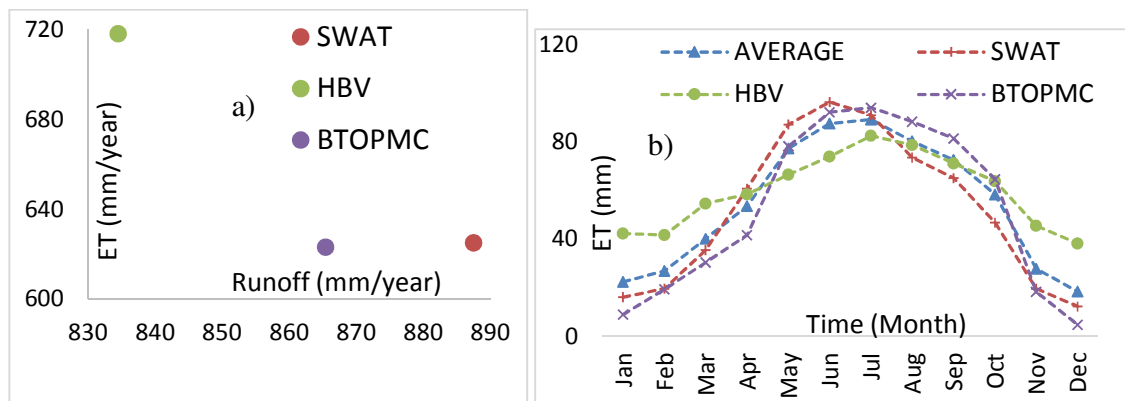


**Figure 3.3** a) Multi-model mean monthly runoff in comparison with observed runoff values, b) Box plots illustrating the smallest annual runoff fraction (runoff/precipitation), lower quartiles, medians, upper quartiles, and the largest runoff fraction values for observed and participated model from year 2001-2010

### 3.2.2 Evapotranspiration

Although all three models used the same observed precipitation data and PET as inputs, and the same indicators (NS, PBIAS, and R<sup>2</sup>) to evaluate their performance, they used different methods to calculate ET based on the model characteristics. PET for 2001–2010 was estimated from a pan evaporation equation (Snyder, 1992) using measured pan evaporation data from Kathmandu Airport station located in the central part of the watershed.

The average monthly seasonal fluctuation in ET estimated by the SWAT and BTOPMC models showed similar trends, whereas the values estimated by the HBV model were different (**Figure 3.4 b**). The ET estimated by the HBV model for October to March was higher than that produced by the other two models, and in the other months, the ET estimated by the HBV model was smaller than that for the other two models. In general, the average annual ET estimated by the HBV model was higher than that estimated by the other two models. The average ET estimated by the SWAT model was 625 mm/y, and the value estimated by the BTOPMC model was 623 mm/y, but the value estimated by the HBV model was 718 mm/y. The seasonal fluctuation in ET was greater in the SWAT model in April, and greater in the BTOPMC model in August, September, and October; in the other months, there was close agreement between the BTOPMC and SWAT models but not with the HBV model. The average ET used in **Figure 3.4 b** is the average of ET calculated by all three model.

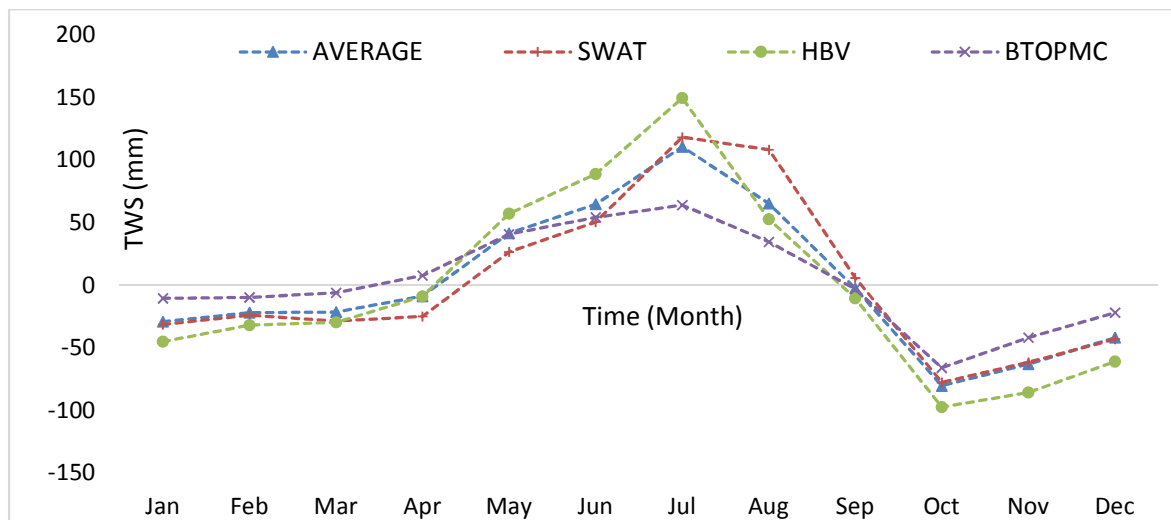


**Figure 3.4** a) mean model predicted runoff and (ET) evapotranspiration values in mm/year b) Mean monthly ET (Evapotranspiration) in mm for the 10 years simulation period (2001-2010)

### 3.2.3 Total water storage

The average TWS component was balanced in all three models, and showed inter-annual variation; i.e., it was positive in some years, and negative in others (**Table 3.3**). Predictive analysis showed that the estimated TWS component varied from +209 to -108 mm/y in the SWAT model, +62 to -146 mm/y in the HBV model, and +135 to -90 mm/y in the BTOPMC model. The minimum and maximum estimated TWS component varied between  $\pm 10\%$  and  $\pm 14\%$  of the total annual precipitation. The average TWS component for the period 2000–2010 was 5 mm/y in the SWAT model, -35 mm/y in the HBV model, and 29 mm/y in the BTOPMC model, which was 0.34%, 2.3%, and 1.9% of the average annual precipitation. Predictive analysis of all three models showed that the average TWS component was well reproduced over the long term. Precipitation, the only source of water for recharge and storage in the study area, is concentrated from mid-May to mid-September in the KV. **Figure 3.5** shows the seasonal fluctuation in the TWS component, which was negative in January–March and

October–December, and positive in June–August in all three models. The TWS estimated by the BTOPMC model for April was positive; it was negative for the other two models. Similarly, for September, the TWS estimated by the SWAT model was positive. The average TWS value in **Figure 3.5** is the average of values calculated by all three model. The analyses of the mean monthly average water balance components indicate that, from October through March, streams are supplemented by groundwater, and for the rest of the year, groundwater is recharged by the precipitation falling in the watershed. In all three models, the month with the most negative water storage was October followed by November and December. The month with the most positive water storage was July followed by August and June. These analyses reveal greater water storage in the rainy season, and less storage in the driest season. Therefore, when planning any water resource development project, developers and decision-makers should take into account the temporal and seasonal fluctuations in all of the water balance components to plan for sustainable use of water.



**Figure 3.5** Monthly average total water storage (TWS) component by three models and average values in Kathmandu Valley watershed for 2001-2010

### 3.2.4 Annual water balance

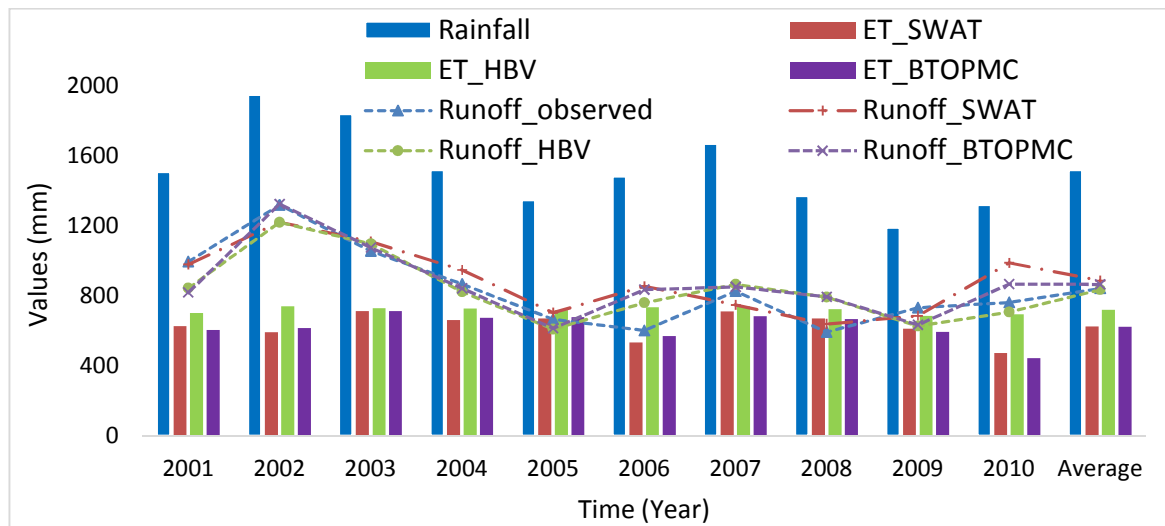
Annual precipitation in the KV fluctuated between 1188 and 1947 mm from 2001 to 2010, and the fluctuation displayed no statistically significant trend (**Figure 3.6**). The simulated runoffs from the three models were similar for each year and comparable with the observed data (**Table 3.3** and **Figure 3.6**). Because the calibration process was primarily based on storm fitting rather than annual runoff fitting, the overall annual runoff was overestimated by the SWAT and BTOPMC models, and underestimated by the HBV model. The annual runoff was overestimated by all three models in 2006, and underestimated in 2009. The annual runoff fraction for the simulation period varied from 0.41 to 0.68 in observation data and 0.45 to 0.75 in the SWAT model, 0.45 to 0.63 in the HBV model, and 0.46 to 0.68 in the BTOPMC model,

reflecting temporal variation in the runoff components in different years and their ranges. The average annual runoff in the watershed was 887 mm for the SWAT model, 834 mm for the HBV model, and 865 mm for the BTOPMC model, which is 59%, 55%, and 57% of annual precipitation, respectively

**Table 3.3** Components of annual water balance in the Kathmandu Valley watershed for 2001-2010

Year	Precipitation (P), mm/y	Runoff (R), in mm/y				Evapotranspiration (ET) in mm/y			TWS in mm/y			PET (Observed), mm/y
		Observed	SWAT	HBV	BTO PMC	SWAT	HBV	BTO PMC	SWAT	HBV	BTO PMC	
2001	1508	996	980	844	818	626	701	604	-98	-38	85	918
2002	1947	1320	1221	1220	1325	591	739	614	135	-13	8	741
2003	1839	1056	1110	1097	1075	711	728	711	17	13	52	983
2004	1518	868	947	823	841	660	726	674	-90	-31	2	835
2005	1345	666	702	609	614	670	717	677	-27	20	54	845
2006	1479	601	855	761	835	532	733	570	93	-14	75	707
2007	1667	827	748	866	850	710	739	682	209	62	135	895
2008	1369	592	638	792	794	669	724	665	62	-146	-90	895
2009	1188	731	686	626	634	610	684	593	-108	-122	-38	892
2010	1318	762	988	707	866	472	694	443	-142	-82	9	669
Average	1518	842	887	834	865	625	718	623	5	-35	29	853

Potential Evapotranspiration (PET) observed means the estimated PET by Snyder's equation using pan evaporation observed data

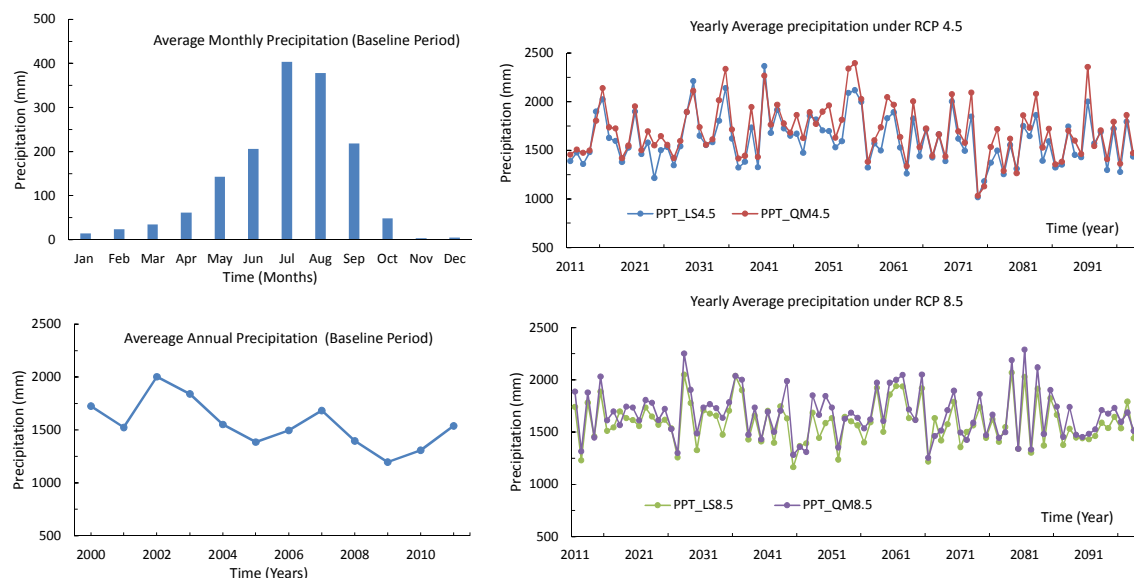


**Figure 3.6** Temporal variation of water balance component by three model in Kathmandu valley watershed for 2001-2010 (values in mm)

The PET calculated from Snyder's equation varied from 38% to 75% during the simulation period, and the average value was 56% of the total precipitation. The average estimated ET in the watershed ranged from 472 to 711 mm/y for the SWAT model, 684 to 739 mm/y for the HBV model, and 443 to 711 mm/y for the BTOPMC model. The average ET estimated by the SWAT, HBV, and BTOPMC models was 41%, 47%, and 41% of the annual precipitation respectively, which was 0.75, 0.87, and 0.75 times the observed PET. The highest ET was given by the HBV model, followed by the SWAT and BTOPMC models. The differences among the models might be due to the different methods used by each model to estimate the ET from the same observational data. The HBV model gave higher values of ET for each year, which might be due to the temperature anomaly correction factor used for estimating ET from PET.

### 3.3 Climate change projection for precipitation and temperature

A wide range of uncertainties prevail in projecting the future climate in Nepal due to the limitation of GCMs to capture complex topographical induced climatic variation (Kripalani et al., 2007; Shrestha et al., 2000). Hence bias correction approach for both precipitation and temperature were done applying LS and QM methods, which are presented in below **Figure 3.7, 3.8, 3.9, and 3.10**. The observed temperature trend shows the systematic increasing trend whereas the observed precipitation has not follow any systematic trend and a large seasonal and spatial variation has existed as per the record from 2001 to 2010 (**Figure 3.7 a & b and 3.8 a & b**).



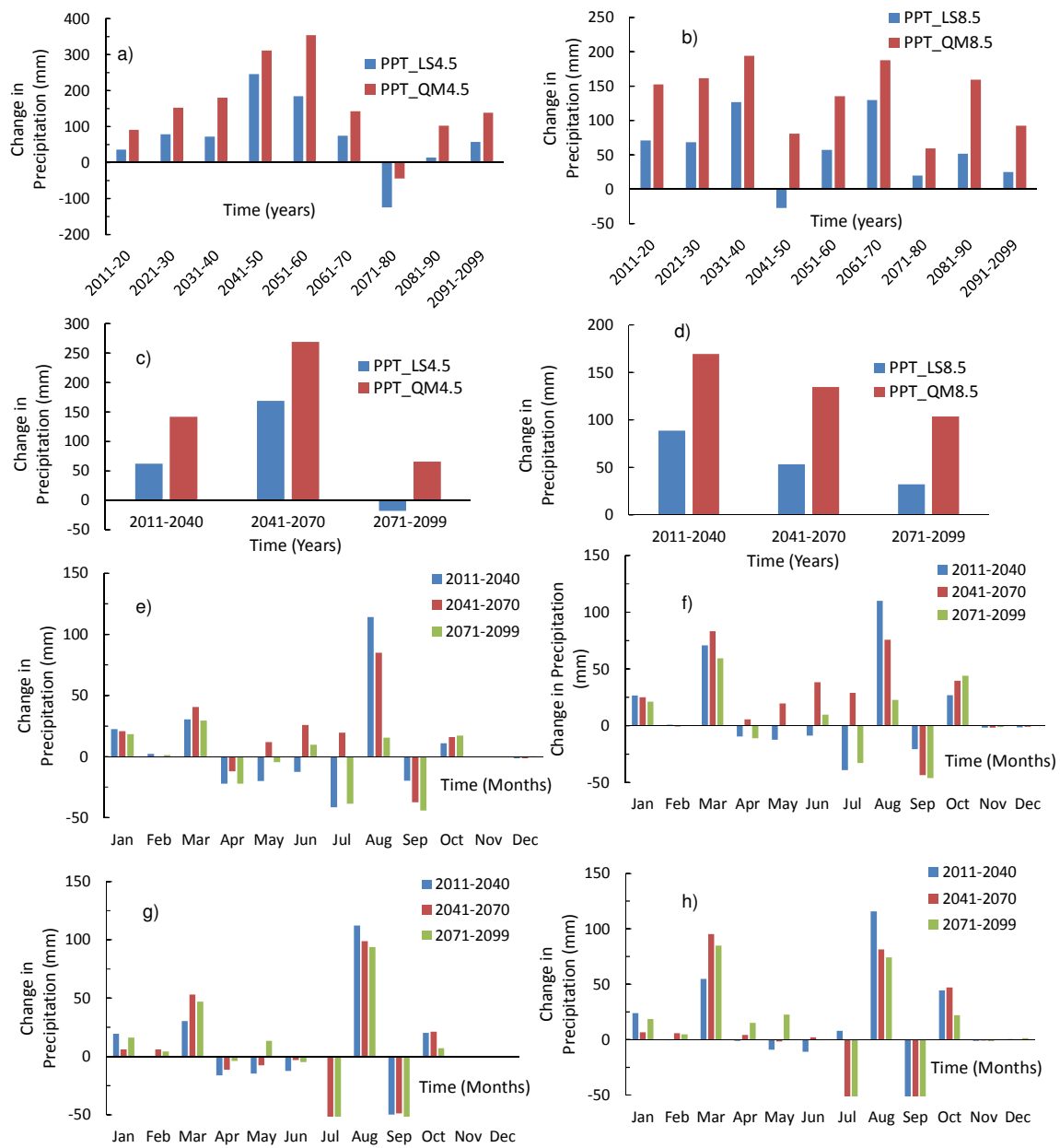
**Figure 3.7** Precipitation a) Average monthly precipitation for year 2001-2010. b) Average annual precipitation for year 2001-2010. c) Average projected annual precipitation under RCP 4.5. d) Average projected annual precipitation under RCP 8.5. LS is linear scaling, QM is quantile mapping.



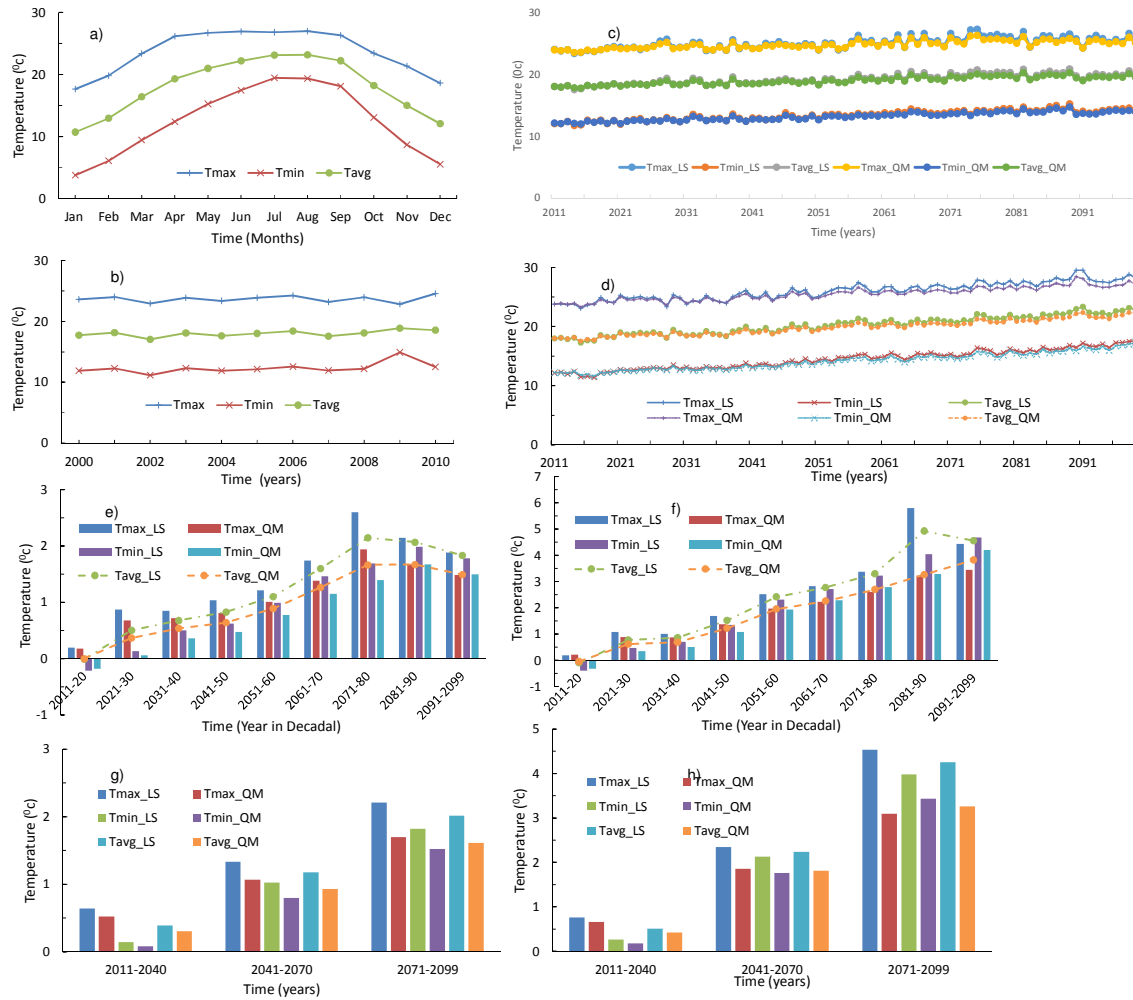
The average annual precipitation is greater than 1500 mm however most of the rain fell during the four months of the season (June -September) causing the water scarcity in rest of the month. The average annual precipitation has not followed any systematic trend, with periodic and inter-annual fluctuation for all the four cases (RCP4.5: linear scaling and quantile mapping bias correction; RCP8.5: linear scaling and quantile mapping bias correction). The expected positive change in precipitation is higher for 2041-50 and 2051-60 under RCP 4.5 and 2031-40 and 2061-70 under RCP 8.5 for both bias correction approach. Similarly the expected negative change in precipitation seems only in 2071-80 under RCP 4.5 for both bias correction, whereas exist only in 2041-50 under RCP 8.5 for linear bias correction approach.

The change in average annual precipitation is positive for all the cases except FF, RCP 4.5, and LS. The change in precipitation is higher for MF under RCP 4.5 and for NF under RCP 8.5 as shown in **Figure 3.8 c, d**. The month receiving the higher amount of rainfall (i.e. in August) are expected to increase, which may lead severe flooding events for all the cases. The seasonal pattern of change in pattern shows negative change in month of September, positive change in January, February, March, and October for all the cases (**Figure 3.8 e, f, g, h**).

For the annual average prediction for both temperature and precipitation, there is no any significant difference noted for both RCP 4.5 and 8.5. The decadal prediction for precipitation is slightly higher by QM bias correction method than the LS bias correction method for both RCPs, whereas the predication for temperature is slightly higher for LS than QM for both RCPs. Similarly for NF, MF, and FF, the prediction by QM is higher than the LS for both RCPs. For FF under RCP 4.5, the change in precipitation by LS is negative whereas positive by QM. For monthly prediction, QM and LS predicted almost similar for all the months except March. In March, QM predicted higher positive changes in precipitation than LS. The prediction for temperature is almost opposite than the precipitation. For decadal, NF, MF, and FF temperature prediction, LS predicted higher values than QM. The monthly temperature prediction under RCP 8.5, the maximum temperature by LS is almost 1.5 times for each month than predicted by LS. Even though, there is not such a significant difference for the annual average prediction by LS and QM bias correction. Hence for evaluating the water availability, the average values of QM and LS under same RCP were taken after this section.



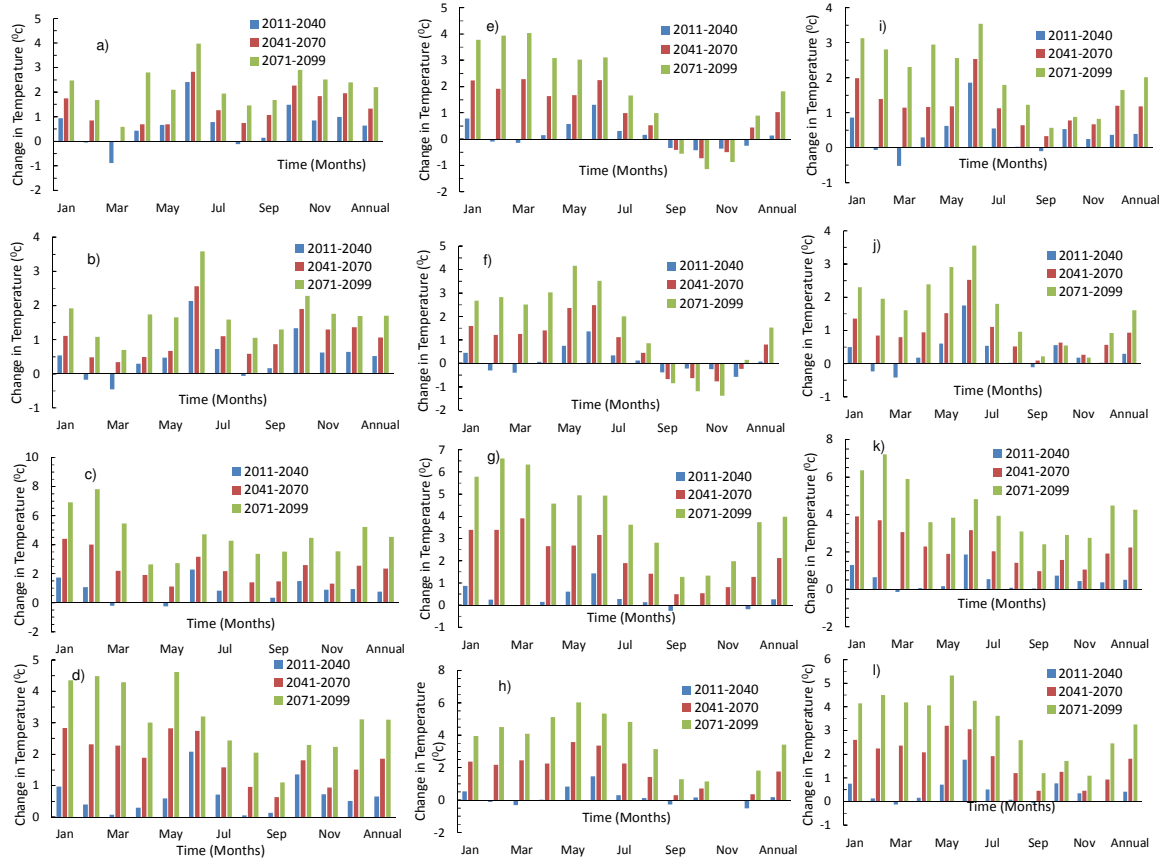
**Figure 3.8** Decadal average annual change in precipitation, a) under RCP4.5. b) under RCP 8.5 , Average change in precipitation for 2011-2040 (near future), 2041-2070 (medium future), 2071-2099 (far future) c) under RCP 4.5. d) under RCP 8.5 , Average monthly change in precipitation, e) under RCP 4.5. LS, f) under RCP 4.5 QM, g) under RCP 8.5 LS, h) under RCP 8.5 QM, LS is linear scaling, QM is quantile mapping.



**Figure 3.9** a) Average monthly observed temperature (2001-2010), b) average annual observed temperature (2001-2010), Expected Average annual temperature c) under RCP 4.5 d) RCP 8.5, Average change in decadal temperature with baseline e) under RCP 4.5, f) under RCP 8.5, Average change in temperature for 2011-2040 (near future), 2041-2070 (medium future), 2071-2099 (far future) with respect to base line period f) under RCP 4.5, g) under RCP 8.5

The average observed annual maximum, minimum, and average temperature has systematic increasing trend as shown in **Figure 3.9 a, b**. The temperature is expected to increase with due course of time for all the cases (**Figure 3.9 c, d**). The decadal average increase in temperature is expected to be higher in 2071-80 under RCP 4.5 and in 2081-90 under RCP 8.5 (**Figure 3.9 e, f**). The maximum temperature is expected to increase by 0.64 and 0.52 degree Celsius ( $^{\circ}\text{C}$ ) in NF, 1.33 and 1.07  $^{\circ}\text{C}$  in MF, 2.21 and 1.70  $^{\circ}\text{C}$  in FF for LS and QM respectively under RCP 4.5. The minimum temperature is expected to increase by 0.14 and 0.08  $^{\circ}\text{C}$  in NF, 1.02 and 0.80  $^{\circ}\text{C}$  in MF, 1.82 and 1.52  $^{\circ}\text{C}$  in FF for LS and QM respectively under RCP 4.5. Similarly the average temperature is expected to increase by 0.39 and 0.30  $^{\circ}\text{C}$

in NF, 1.18 and 0.93 °C in MF, 2.01 and 1.61 °C in FF for LS and QM respectively under RCP 4.5. Under RCP 8.5, these values are in increasing trend and maximum, minimum, and average temperature is expected to increase by 4.54 °C, 3.98 °C, and 4.26 in NF, MF, and FF respectively (Figure 3.9 g, h).

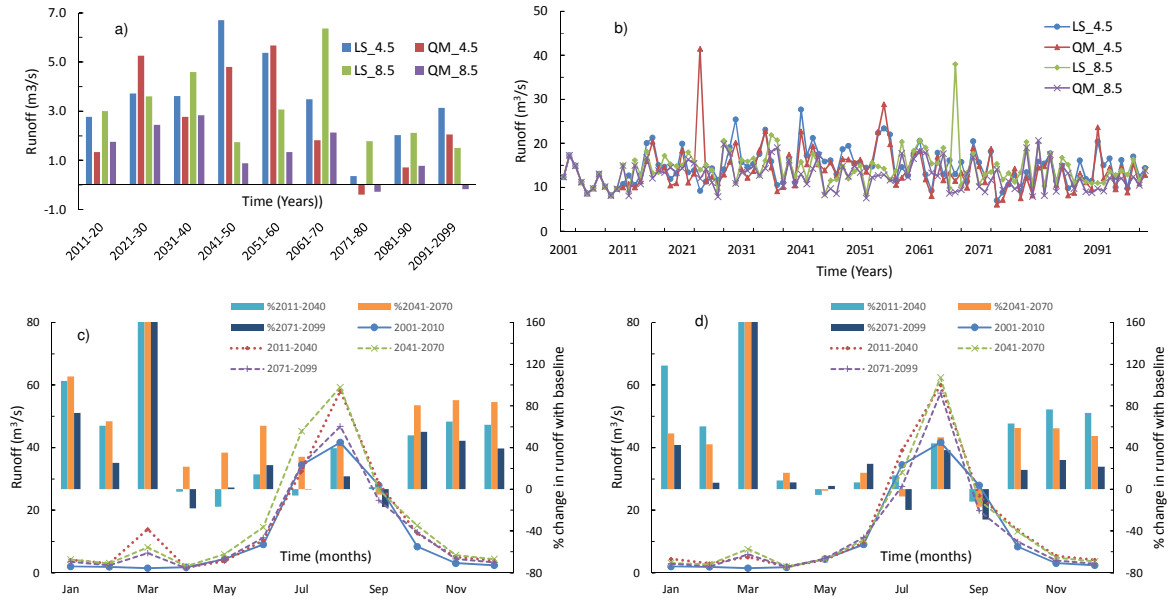


**Figure 3.10** Average monthly change in maximum temperature for NF, MF, and FF with respect to base line period a) under RCP4.5 LS, b) under RCP 4.5 QM, c) under RCP 8.5 LS, d) under RCP 8.5 QM, Average monthly change in minimum temperature for NF, MF, and FF with respect to base line period e) under RCP4.5 LS, f) under RCP 4.5 QM, g) under RCP 8.5 LS, h) under RCP 8.5 QM, Average monthly change in average temperature for NF, MF, and FF with respect to base line period i) under RCP4.5 LS, j) under RCP 4.5 QM, k) under RCP 8.5 LS, l) under RCP 8.5 QM

The change in maximum temperature is expected to increase in all the month except NF case under RCP 4.5. From the above analysis it shows that cooler days are expected to be more cool (September-December, Figure 3.10 e, f) under RCP 8.5, September and December for NF (Figure 3.10 g, h) under RCP 8.5 and hotter days are expected to be more hot (April-August, Figure 3.10 a, b, c, d) for all cases as compared to baseline period.

### 3.4 Effect of climate change on runoff at outlet

When analyzing variation of runoff at outlet of Kathmandu Valley with respect to base line period, the decadal change is expected to increase with due course of time. The highest increase in runoff is expected in 2041-50 under RCP 4.5 LS followed by 2061-70 under RCP 8.5 LS (**Figure 3.11 a**). The runoff values has no any significant trend of increase or decrease similar as precipitation. Runoff also have the similar fluctuation as precipitation which is the major influential factor (**Figure 3.11 c**) for reproducing runoff. The seasonal variation of runoff for the entire Kathmandu Valley shows increase in runoff in August, October-February for all the cases. The rest of the month have different prediction. The month September has expected decrease in runoff for all the cases (**Figure 3.11 b, d**). In the pre and post monsoon period, the percentage change seemed to be higher but value is not so much high. The changes in runoff in month march seems quite different than other, this is due to the higher increase in precipitation predicted by RCM.



**Figure 3.11** a) Average change in decadal runoff with respect to 2001-2010, b) Average expected annual runoff, Average expected monthly runoff (values in m³/s) and % change in runoff with respect to base line period for NF, MF, and FF, c) under RCP 4.5. d) under RCP 8.5

### 3.5 Summary

The performance indicators NS, PBIAS, and  $R^2$  had similar indicator values in the three models used in this study, and the models showed satisfactory performance for runoff simulation. There was close agreement between the monthly observed and calibrated runoff at the watershed scale, and the models accurately captured the flow patterns for most seasons.

Although the three models used similar performance indicators for runoff, the estimated yearly runoff, ET and TWS component values differed among the models.

There were negligible differences in the simulated and observed runoff for the averaged seasonal flow for all the three models, but overestimation of the overall annual runoff by SWAT and BTOPMC and underestimation by the HBV. The runoff simulation was performed based primarily on storm fitting rather than annual total runoff fitting. The runoff fraction varied from 0.55 to 0.59, and the ET component varied from 0.41 to 0.47 of the total precipitation in the three models. The yearly fluctuation in TWS varied from  $\pm 9\%$  to  $\pm 14\%$  of the total precipitation. Considering the variation in the water balance components in the three models, ET had the lowest inter-annual variation, and runoff had the greatest variation. The ET component is primarily driven by radiation and temperature, which does not vary significantly from year to year. The runoff component is primarily driven by precipitation, and relatively small differences in rainfall have a significant impact. The calculation of ET using only temperature as an adjusting parameter in the HBV model led to significantly different results than in the other two models. We used same precipitation, PET, and other climatic parameters, number of sub-basins, and calibration method for all three models. Predictive analyses showed reasonable ranges relative to observational values for runoff, ET, and TWS in all three models. These estimated ranges of values in the water balance components, which can have significant impacts on the available water resources in the KV, provide useful information to guide planning of water resource development projects. Estimates from such model simulations of the available water resources combined with climate impact studies can provide reliable information for water-resource management projects.

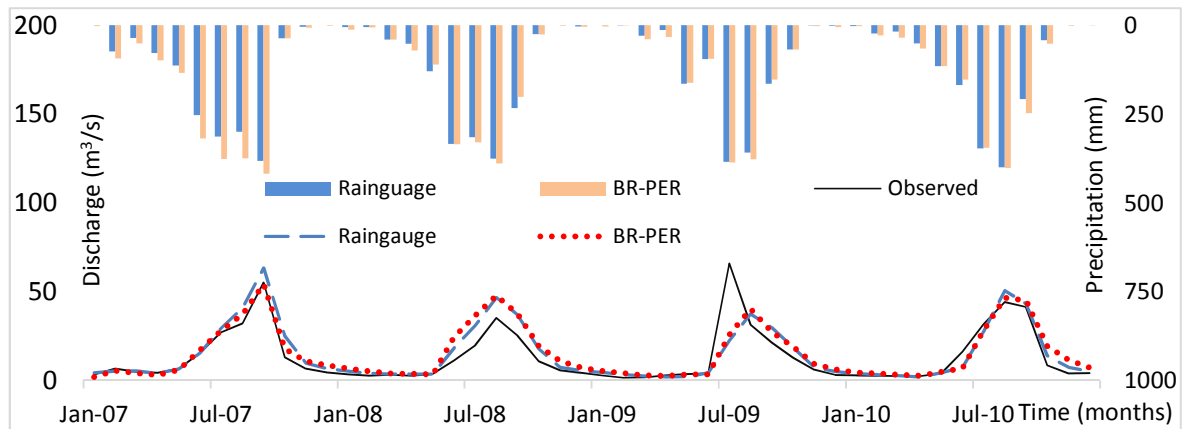
The multi-model techniques representing different runoff, evaporation, and energy balance schemes can be used for more accurate representation of water balance in any basin, and to obtain the ranges of values of each water balance component. In the KV, a possible next step for achieving more reliable water resource assessments would be multi-model analyses that include historical water use and water stress as well as future climate projections.

The expected change in annual precipitation for NF, MF, and FF varies from -1.16%-17.50% under RCP 4.5, and 2.10%-11.02% under RCP 8.5. The expected change in annual maximum, minimum, and mean temperature varies from 2.20%-9.32%, 0.64%-14.68%, 1.67%-11.16% respectively under RCP 4.5. The expected change in annual maximum, minimum, and mean temperature varies from 2.78%-19.13%, 1.47%-32.10%, 2.33%-23.58% respectively under RCP 8.5. Unlike temperature, the observed as well as predicted precipitation has not followed any systematic trend and a large periodic, seasonal and spatial variation. From the analysis, the predicted high flow seems to be high which may cause serious flood in urban area of Kathmandu Valley. There is not so much impact on low season runoff even though expected unpredictable high precipitation and runoff in March.

## EVALUATION OF FRESH WATER FROM MOUNTAIN

### 4.1 Model calibration and validation

Three performance indicator Nash Sutcliffe (NS), Percentage Biasness (PBIAS), and correlation coefficient ( $R^2$ ) as stated in equations (2.8), (2.9), and (2.10) were used to evaluate stream flow simulation in Kathmandu valley near the outlet of the basin of station Khokana (station 550.05). The rain gauge simulation shows superior result than BR-PER during calibration period (2007-2008) having NS 0.8 and  $R^2$  0.95 by rain gauge and NS 0.76 and  $R^2$  0.9 by BR-PER even though both simulation significantly underestimated the peak in 2009. Both simulations have good fit during low season period and BR-PER have high NS and  $R^2$  during validation period (2009-2010) as listed in **Table 4.1**. The satellite-gauge precipitation BR-PER showed the comparable ability to simulate the stream flow in KV compared with the rain gauge data during both calibration and validation period (**Figure 4.1** and **Table 4.1**) at the Khokana station, which is representing almost whole catchment.



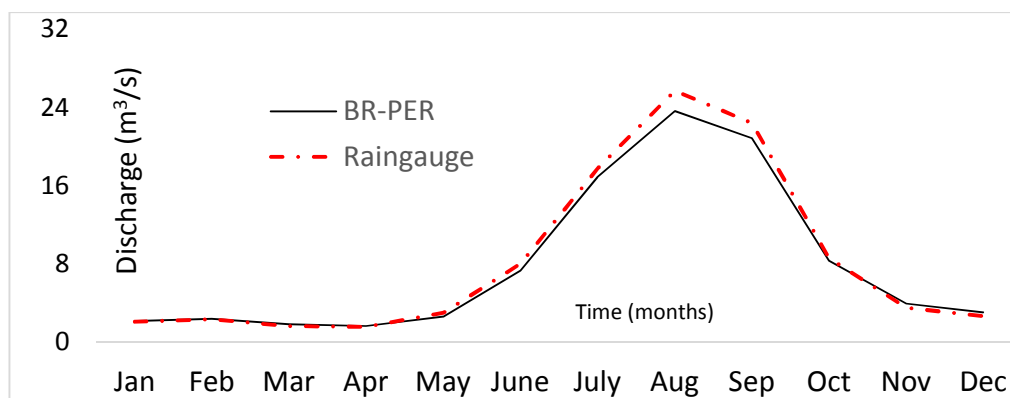
**Figure 4.1** Comparison of observed and simulated monthly streamflow at the Khokana (550.05 station)

**Table 4.1** Performance indicator during calibration and validation period at Khokana station No 550.05

		NS	$R^2$	PBIAS (%)
Calibration (2007-2008)	Rain Gauge	0.8	0.95	-0.3
	BR-PER	0.76	0.90	-0.3
Validation (2009-2010)	Gauge	0.67	0.68	0.03
	BR-PER	0.69	0.7	-0.04

## 4.2 Total inflow from mountainous region to core valley

The discharge simulation at the outlet (Khokana station) and total amount of average (2007-2010) water inflow from mountainous sub watersheds (SW) 1-13 to valley floor (SW-0, also referred as core valley) (**Figure 4.1, 4.2 and 4.4**) using both rain gauge and BR-PER is mostly similar except peak flow. However, because BR-PER inherited the superior ability to capture the rainfall spatial distribution from very high resolution satellite data PERSIANN-CCS than the few rain gauge available in the mountainous regions, BR-PER shows the high ability for stream-flow simulation application in data poor region of KV.



**Figure 4.2** Seasonal variation of total water inflow from mountain to core valley

## 4.3 Spatial distribution of inflow from mountain

Spatial distribution of the predicted average monthly flow from each sub watershed (SW) in the natural conservation zones by rainfall gauge and BR-PER simulation shows the significant difference (**Figure 4.4**) such as -42 % in eight, 31 % in one, 20 % in two, and -29 % in nine taking base as rainfall gauge simulation result. There is no rain gauge in mountains near SW No 1, 2, and 8 and those SW utilized gauge rainfall data from low elevation zone. These rain gauge may be not representing the variation of rainfall on mountain part. The heavy rainfall by rain gauge is high than the BR-PER product in SW No 1 and 2, whereas small in SW No 8 and 9. That shows the wide variability of rainfall input for rain gauge and BR-PER simulation, which causes the significant difference in discharge prediction. In all the watershed moderate rainfall and predicted discharge during lean season flow are almost similar by both rain gauge and BR-PER precipitation product.

While rain gauge simulation, SW No 1 took 2 station data, SW No 2 took 2 station data, and SW No 8 took 1 station data. Similarly for BR-PER simulation SW No 1 took 8 grid data, SW No 2 took 4 grid data, and SW No 8 took 6 grid data. That shows the utilization of spatial distributed precipitation data by BR-PER simulation. We can see the obvious difference in average estimated flow by both simulation and it is difficult to judge which precipitation



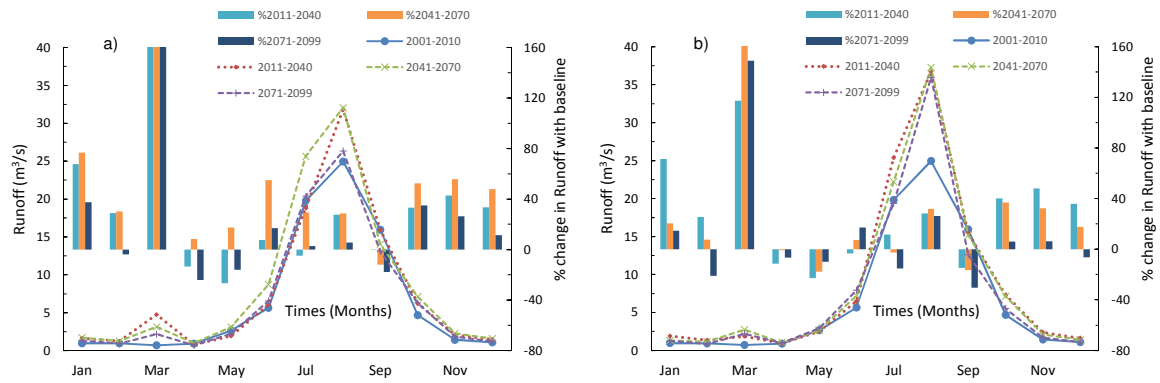
product is correct. However, number of rain gauge is smaller than the number of BR-PER pixel grid in mountainous area and expected to capture spatial distribution of mountainous precipitation properly than point measurement. Currently, only few discharge gauging stations are available at the mountainous area. More discharge gauging station in mountainous region would be necessary to validate this idea.

SW No 1, 2, and 8 are in high elevation zone with high contributing area (**Figure 2.5 a & Figure 4.4**) from Zone I. These area have high precipitation than other area. Those reason (high elevation zone, high contributing area, and high precipitation) is the major cause for north-east, north-west, and south-east have higher potentiality to harness the water than mid-east and mid-west in KV. The SW No 1 (Shivapuri conservation area), SW No 2 and SW No 8 have higher season flow and higher contribution to total inflow, which are the major potable water supply sources for Kathmandu, Bhaktapur and Lalitpur districts respectively. SW No 4, 5, and 6 have less contribution for fresh water availability than others due to the less contributing area on zone I, low precipitation, and low elevation zone in these area.

#### **4.4 Effect of climate change in water availability**

When analyzing the seasonal variation of water availability from hills of Kathmandu Valley, all cases predicted to increase peak season flow in August. The total water availability from hill predicted to be increase in month October-March, June and decrease in April, May, and September (**Figure 4.3 a, b**). In March, for all the cases, increase in water availability is predicted. The water availability in MF is predicted to increase higher followed by NF and FF respectively under both RCPs. In Kathmandu Valley, the water availability in low flow season seems to be increase, which is the positive to cope with water scarcity problem in dry season. But the predicted increase in high flow season's water availability may be challenging to manage due to several reasons such as already encroached river way, land use change (almost built up area within core valley) etc.

In the previous sub-chapter 4.2 and 4.3, we discussed the water availability from mountain based on the average values estimated by satellite PERSIANN-CCS and ground observed precipitation product over 2007-2010. But in this section, we are discussing water availability only based on the ground observed precipitation product from year 2001-2010, hence values seems to be different. For evaluating the impact of climate change on water availability baseline period is taken as 2001-2010 and the values predicted by bias correction from LS and QM were averaged under similar RCP.



**Figure 4.3** Seasonal variation of total water inflow from mountain to core valley and change in water availability with baseline period (2000-2010), a) under RCP 4.5 and b) under RCP 8.5

SW No 1, 2, 7, and 8 are the major contributor for fresh water from hill to Kathmandu Valley (**Figure 4.5 & 4.6**). The availability of water predicted to be increased in month of August, October-March for all the sub-watersheds under RCP 4.5. The percentage change in water availability in month March for all the sub-watersheds higher as compared to other month. In most of the sub-watersheds, water availability predicted to be decreased in month of September, April, and May under both RCPs. Under RCP 8.5, the change pattern of water availability for all the sub-watershed is similar as RCP 4.5, but the quantity is different.

## 4.5 Summary

The lacking of rain gauges in mountainous region of the KV motivates this study to examine the application of high resolution satellite-gauge merging precipitation data BR-PER for stream-flow simulation and estimating available water resources in mountainous area. BR-PER shows significant improvements of relationship with the rain gauge data compared to the original satellite precipitation product PERSIANN-CCS. Although, the performances of BR-PER depend upon the number of merging rainfall stations, BR-PER shows high potential application for stream-flow simulations in the KV.

BR-PER exploits the ability to capture the rainfall spatial variation from very high resolution satellite data PERSIANN-CCS and shows comparable rainfall magnitude estimations at the station scale with comparable stream flow prediction skill at the whole catchment scale

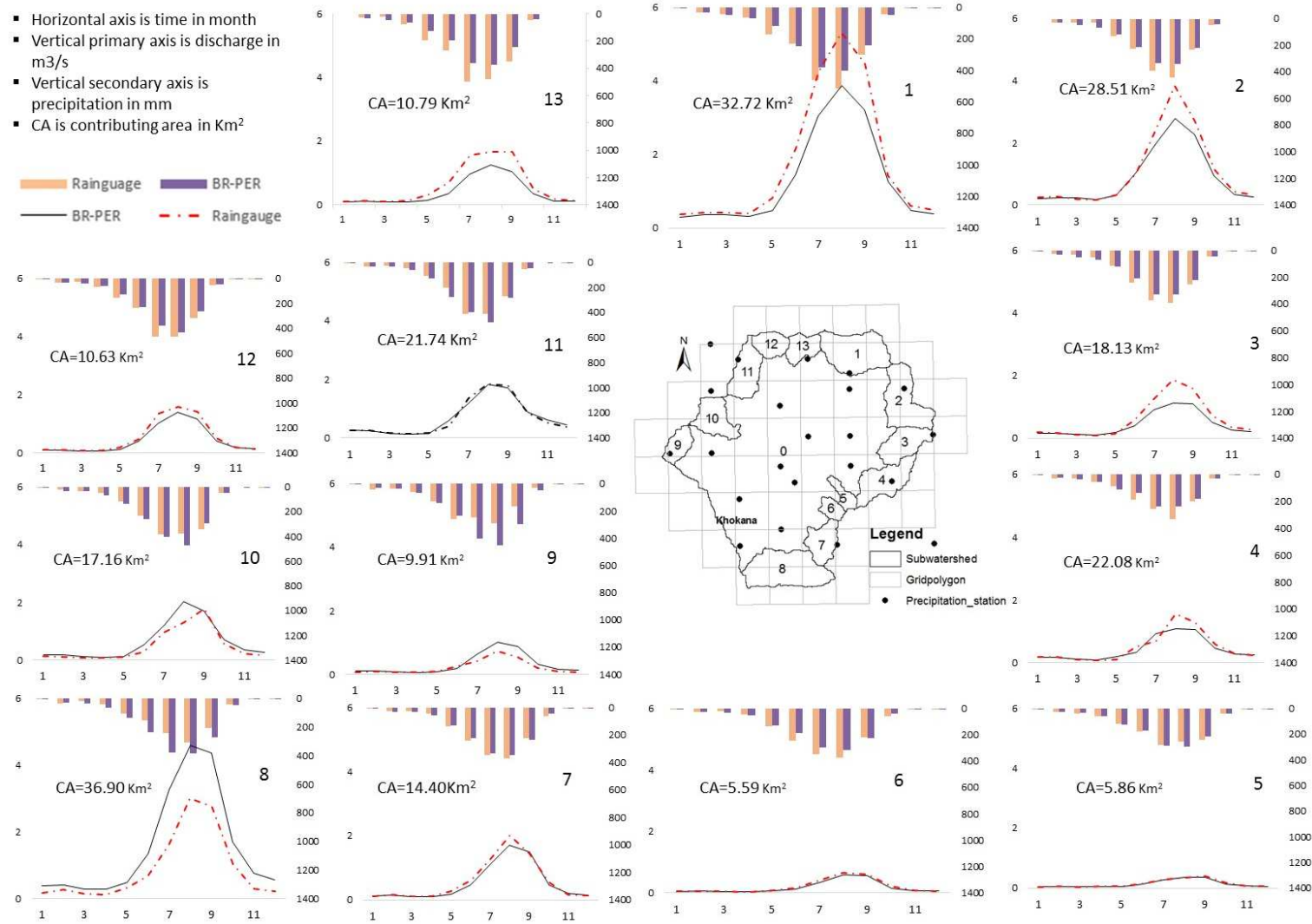
In KV, there is huge demand deficit of 301 MLD and 255 MLD during dry and wet season and KUKL is now worried to tackle this water security problem. KUKL is planning to develop small water reservoir at mountainous region (Zone I) along with small scale water supply

projects. This studies may be supportive documents for decision maker and planner to plan the additional small scale project for potable water supply. Water available for potable water use were estimated using the method described in section 2.4.5 and deducted those available water assuming 10% release as environmental flow (MoWR, 2001) and diverting 20% as the agricultural demand (WECS, 2008). Which shows the possibilities to harness additional 67 MLD and 87 MLD from mountainous region during dry (average of December, January to May) and wet season (average of June, September, October, and November) respectively. Those values are average values of available water estimated by rain gauge and BR-PER precipitation product for year 2007-2010. Which could be the short term solution and can supply potable water to additional 0.49 million and 0.65 million people considering per-capita water consumption rate 135 lpcd during dry and wet season respectively. This additional water harnessing from mountainous region will reduce the recent pressure on ground water abstraction.

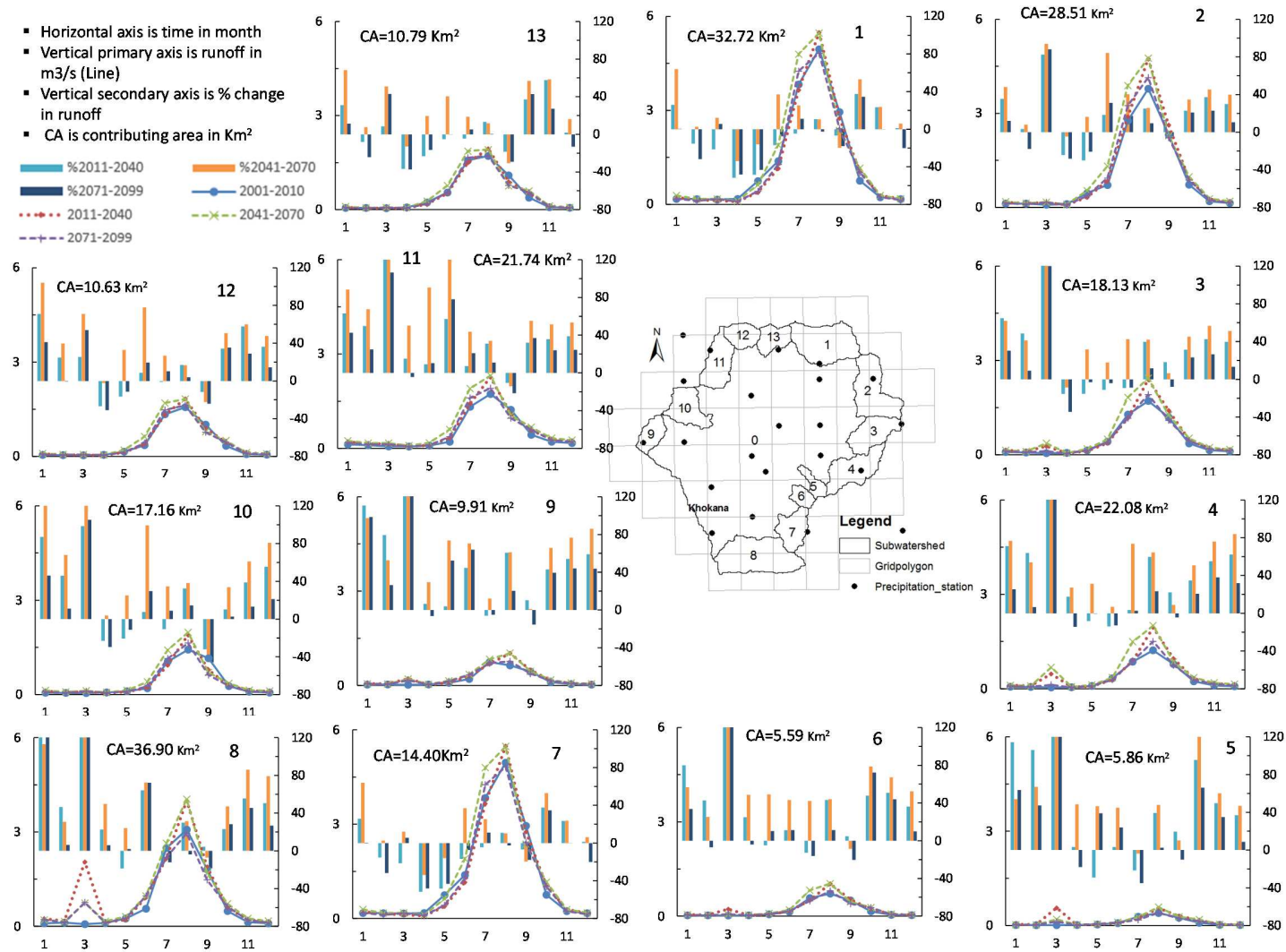
From the climate change perspective, the predicted increase in lean season flow will have positive impact to cope with water scarcity problem but the predicted increase in high season flow could be problematic, which can induce serious inundation in NF, MF, and FF under both RCPs. Hence appropriate adaptation mechanism and strategies need to be implement based on the impact.

- Horizontal axis is time in month
- Vertical primary axis is discharge in m<sup>3</sup>/s
- Vertical secondary axis is precipitation in mm
- CA is contributing area in Km<sup>2</sup>

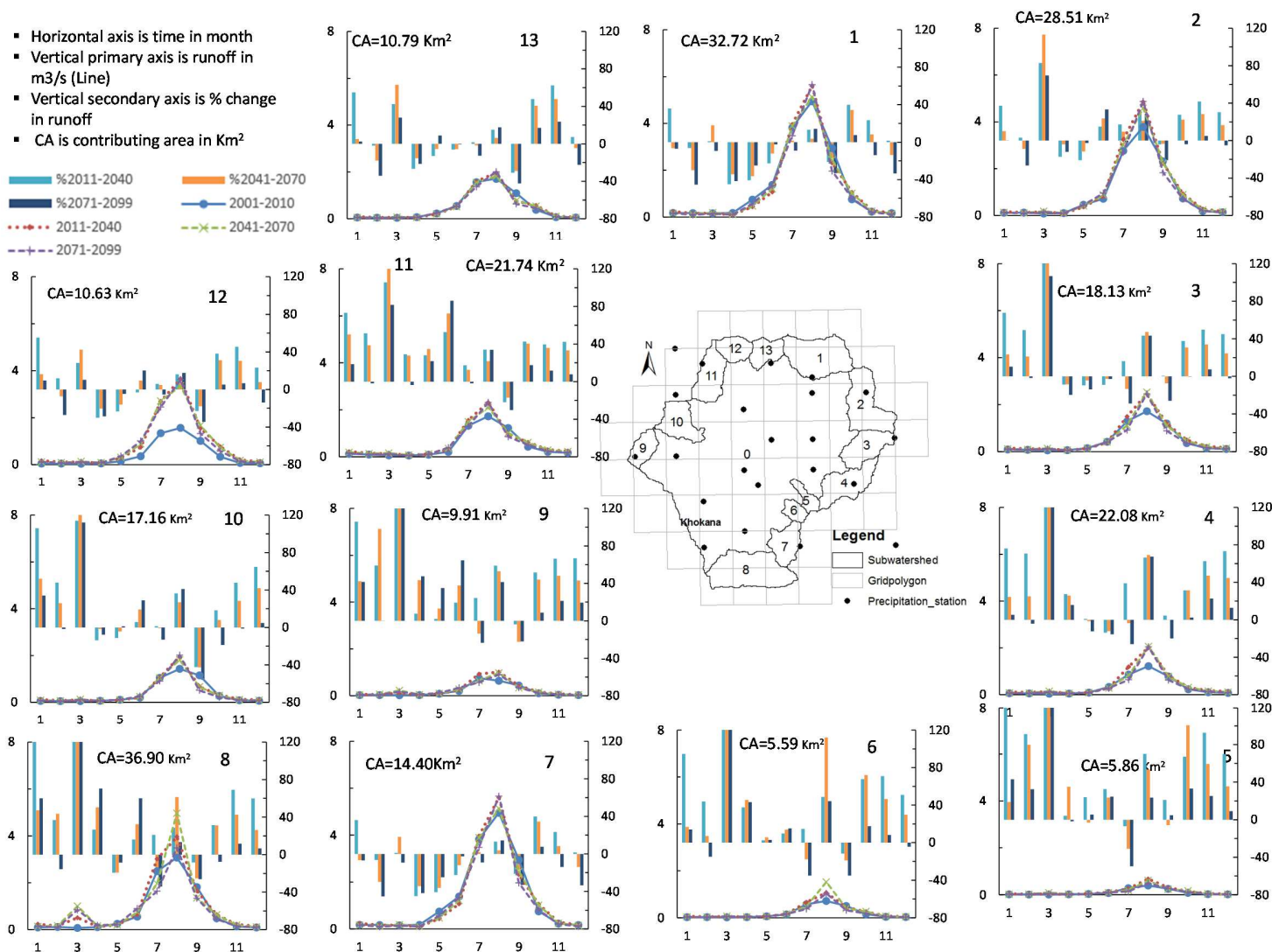
■ Raingauge  
■ BR-PER  
— BR-PER  
- - - Raingauge



**Figure 4.4** Spatial distribution of average fresh water inflow from hill region with contributing area for corresponding points (2007-2010).



**Figure 4.5** Spatial distribution of average available water from hill (line) region and % change in flow (bar chart) with baseline period (2001-2010) for near future (2011-2040), medium future (2041-2070), and far future (2071-2099) under RCP 4.5



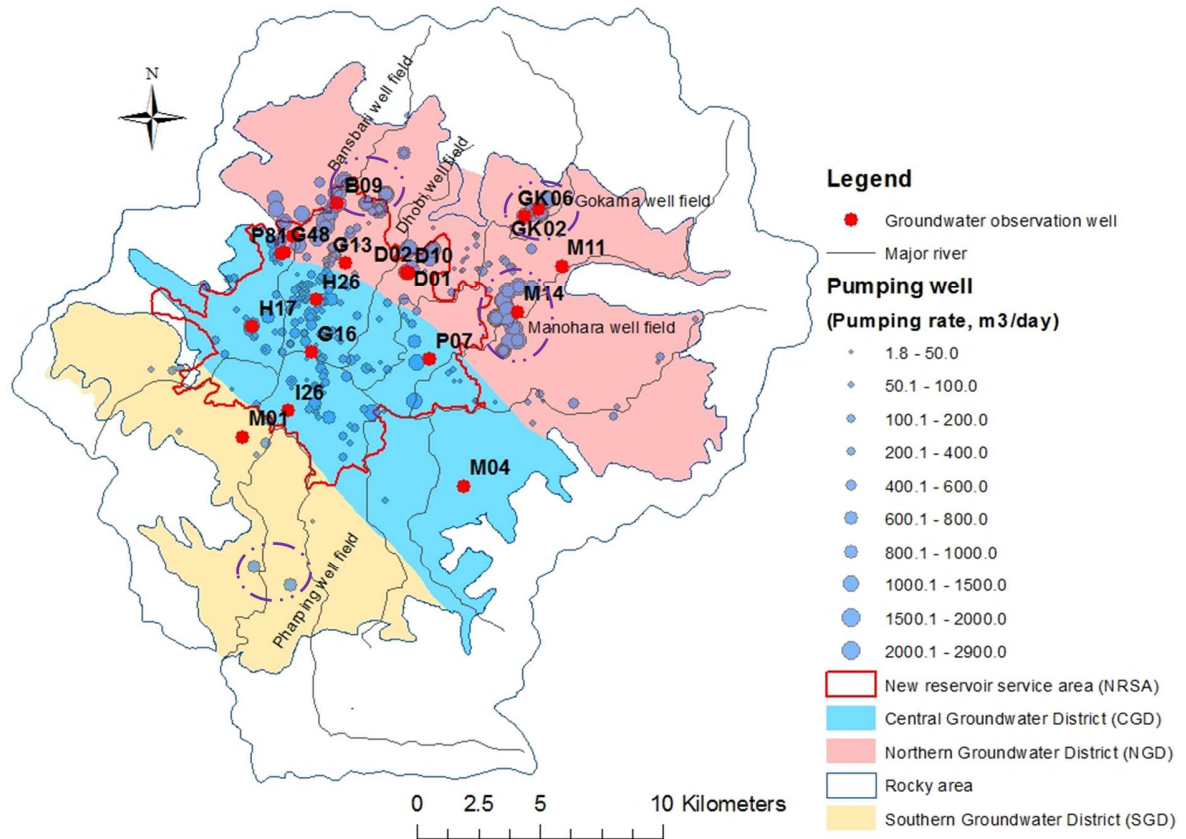
**Figure 4.6** Spatial distribution of average available water (line) from hill region and % change in flow (bar chart) with baseline period (2001-2010) for near future (2011-2040), medium future (2041-2070), and far future (2071-2099) under RCP 8.5

## EVALUATION OF GROUNDWATER SYSTEM

### 5.1 Current rate of pumping

Ground Water Resource Development Board reported 759 deep tube wells (GWRDB, 2012b) are in their record. Among those most of already been abandoned, while only some of these wells were still in use by various water users such as hotels, embassies, government offices, etc. This is a limitation of this research that only 379 pumping wells listed in the GWRDB inventory and their pumping rate of year 2009 were considered while there could be many more new wells while some of these wells have been already abandoned. The majority of 379 pumping wells are located in the central part of the valley, where the KUKL is planning to supply water from off-the-valley source via MWSP, with 153 wells in the NGD, 212 wells in the CGD, and 13 wells in the SGD. The estimated groundwater abstraction from the valley was 143 mld comprising 102, 38, and 3 mld from the central, northern and southern groundwater districts, respectively. Abstraction rates from individual wells ranged from 0.00018 to 2.8 mld with an average of 0.65 mld for the NGD, 0.00028-1.1 mld with an average of 0.18 mld for the CGD, and 0.00042-0.86 mld with an average of 0.24 mld for the SGD (**Figure 5.1**). Higher pumping rates were mainly from the KUKL production wells and three wellfields in Manohara, Bansbari, and Dhobi. The average rate of groundwater heads decline in the KV is about 0.69m/year and is 1.12m/year, 0.72m/year, and 0.23m/year for the NGD, CGD, and SGD, respectively. For the NGD, the average decline of hydraulic heads is 12.35m and is 21.58 m at well B13 and 3.12m at well M12 for the 11 year period. The groundwater heads of CGD has declined by 5.05m at well H17, 6.33m at well P81, 11.6m at well I26, and 8.76m at well M04 and the district average is 7.93m. The SGD has only one observation well M01 with reported 2.57m decline of groundwater heads.

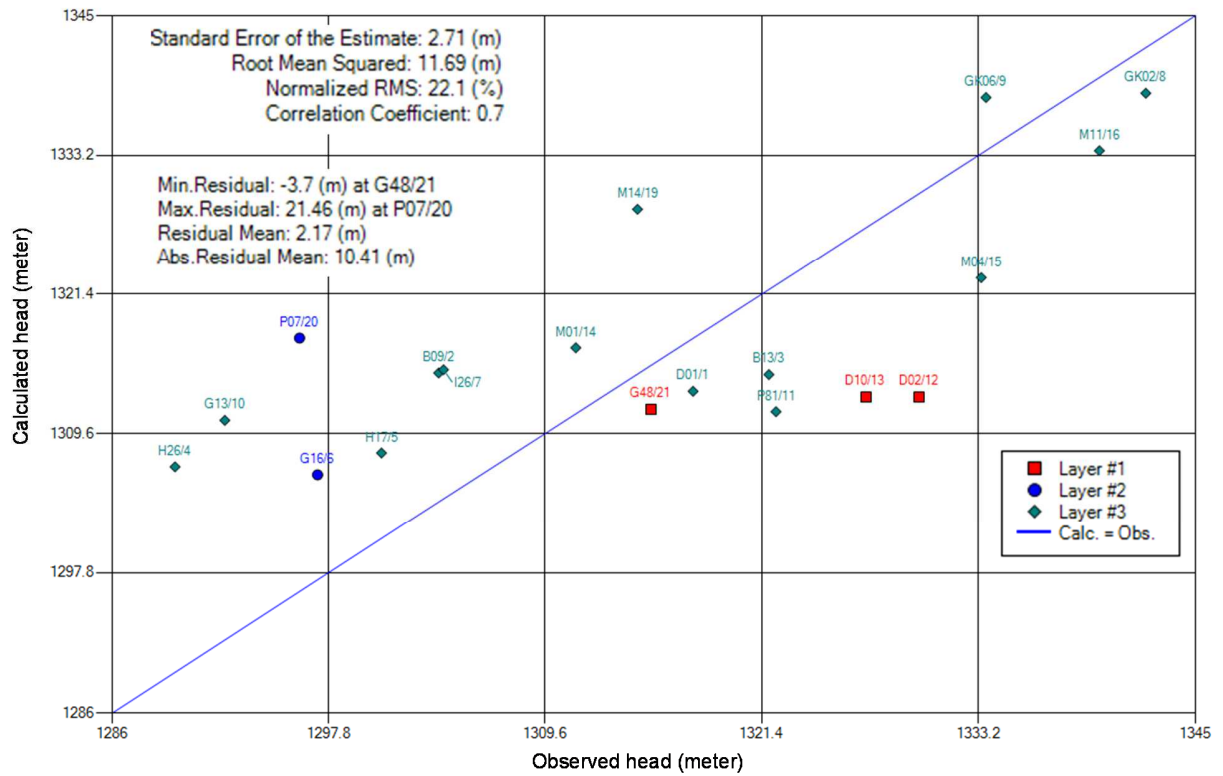




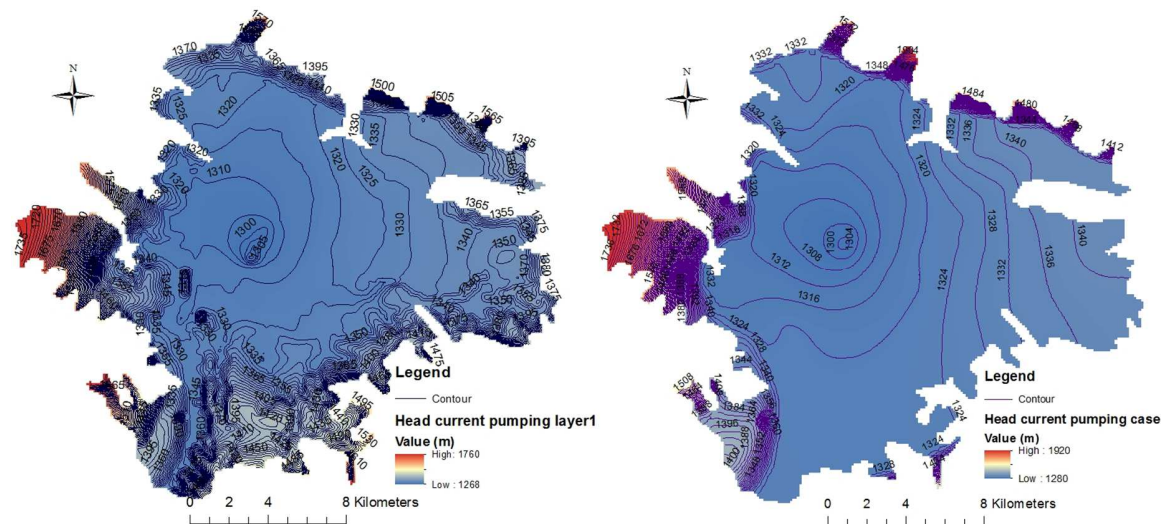
**Figure 5.1** Spatial distribution of pumping wells with abstraction rates at northern, central, and southern groundwater districts of the Kathmandu Valley.

**Figure 5.2** shows the correlation between observed hydraulic heads in January 2003 and the heads generated by the steady-state simulation using 2009 pumping rates. The calibrated groundwater model had a correlation coefficient of 0.70, which is a reasonable model performance considering the limitation of available data and the large uncertainty in subsurface information. The minimum head difference of 3.7 m was observed at well M12 and maximum head difference of 21.47 m at well P07, which is screened in Layer 2. Another well G16 screened in Layer 2 shows a better match. Two wells D10 and D02 located in the close proximity to each other in the NGD demonstrate underestimation of simulated heads in Layer 1. Observation wells H26 and G13 screened in Layer 3 show an overestimation of groundwater heads and may be due to oversimplification of hydrogeology in the western side of the KV. **Figure 5.3** shows the spatial distribution of simulated hydraulic heads in Layers 1 and 3 representing the shallow and deep aquifers. A cone depression is observed in both Layers 1 and 3 in the CGD, but it is slightly shifted due to slightly different locations of the current pumping. For scenario analysis, those results are considered as satisfactory and the groundwater flow model could be further improved with newly collected data.





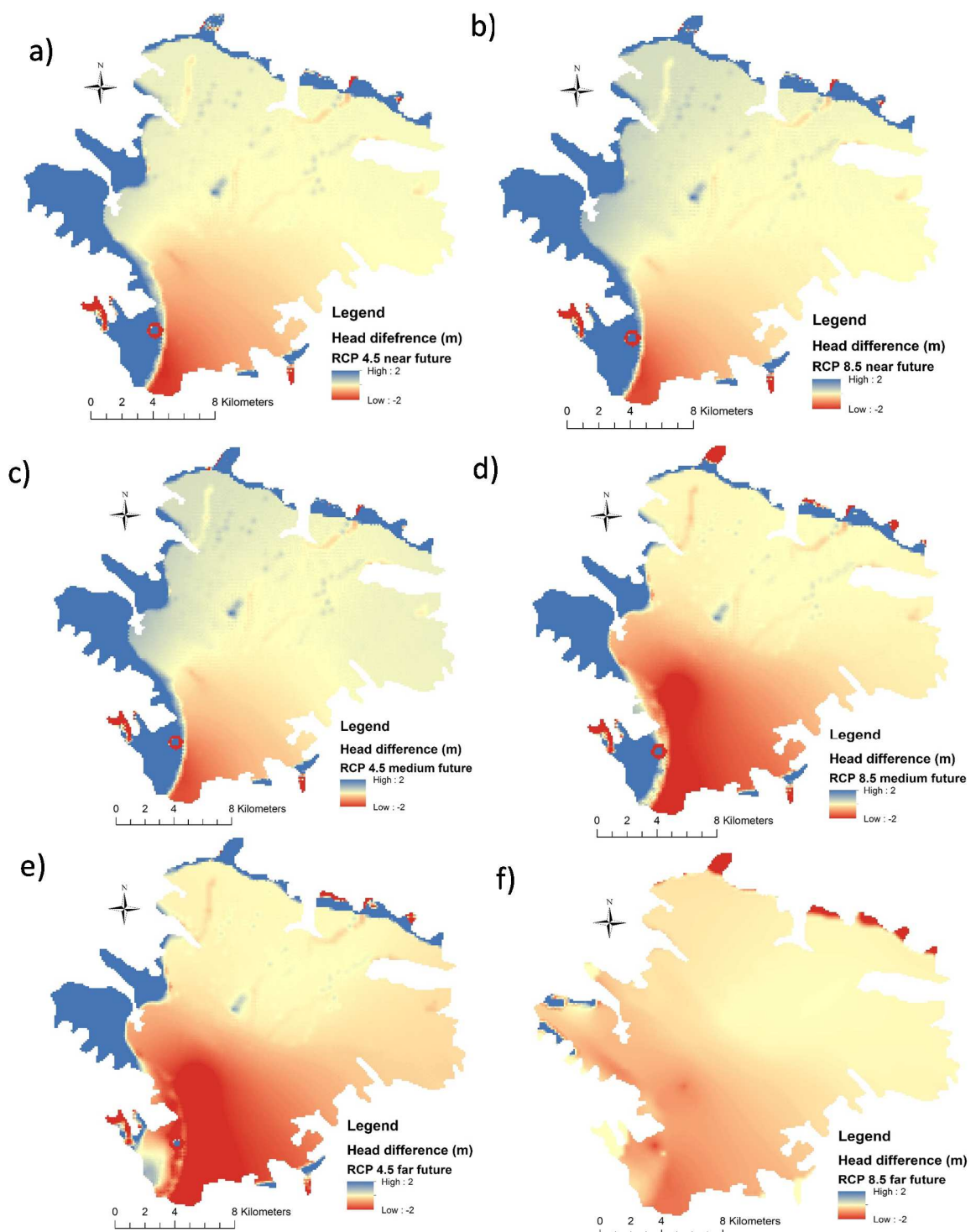
**Figure 5.2** Calibration of hydraulic heads for January 2003 using unpublished observed values from GWRDB (groundwater resources development board).



**Figure 5.3** Spatial distribution of simulated hydraulic heads in the shallow (left) and deep (right) aquifers in the three groundwater districts within the Kathmandu Valley using the calibrated model. Head values are in meters above mean sea level.

## 5.2 Impact of climate change on groundwater system

Groundwater is the one of the major contributor of water supply in Kathmandu Valley. The increasing trend of pumping resulted decrease in groundwater head as explained earlier. In this section, we tried to estimate the impact of climate change especially in groundwater system. For this, recharge (percolation) values for each re-defined zone (**Figure 2.9 a**) were estimated by SWAT model for NF, MF, and FF and applied in the groundwater model. The change in recharge values for each zone varies from 1.28-31.78%, 8.35-40.18%, and -7.25-12.70% under RCP 4.5 and 3.54-37.96, -5.25-20.93%, and -14.79-7.33% under RCP 8.5 for NF, MF, and FF respectively. Which shows there is not a significant change in recharge component due to climate change. The change in head with baseline period for NF, MF, and FF seems to be varied from -1m to 1 m (**Figure 5.4 a-f**), even though we can see high values in the boundary of the groundwater basin which may be due to the several uncertainties like higher fluctuation of elevation in short distance, geological properties may be not well represented. These are the major limitation of the groundwater model and can be improved in future.



**Figure 5.4** Head changes between the baseline and a) near future RCP 4.5, b) near future RCP 8.5, c) medium future RCP 4.5, d) medium future RCP 8.5, e) far future RCP 4.5, and f) far future RCP 8.5

### 5.3 Summary

This study demonstrates an investigation of water resources management scenarios in the Kathmandu Valley using a groundwater flow model developed with limited available data. Groundwater models are useful tools that can make use of available data and guide new data collection in the critical areas for improving simulation results while answering practical question. Initially the model was calibrated for the steady state condition and spatial distribution of hydraulic head were evaluated. The cone depression has been found in central ground water district in both shallow and deep aquifer. The model was used to simulate the spatial distribution of hydraulic heads for the different climate changes scenarios and recommend policy options.

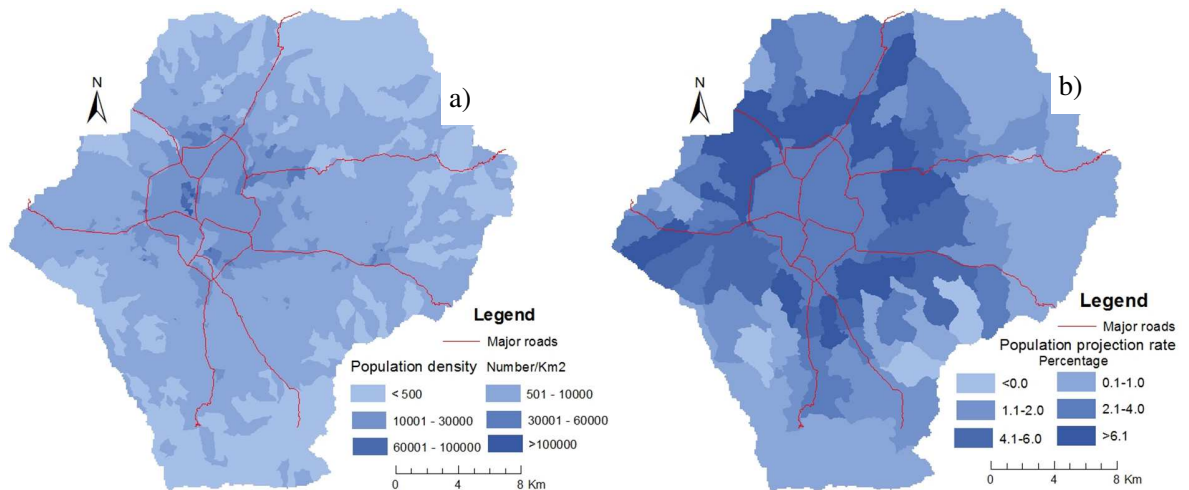
From the analysis, it is clear that impact of climate change will not be so much significant as compared to the increase in pumping rate. Hence appropriate adaptation technologies like managed aquifer recharge (MAR) can be applied to enhance the recharge process and appropriate monitoring and regulation is most to protect the depleting aquifer.

Despite using the advanced modeling technology with available KV data, the current model setup is only the first attempt to represent complex aquifer system of the KV watershed. The first limitation of this study is the lack of up-to-date groundwater abstraction information from active pumping wells and 379 pumping wells of 759 existing well on the record were implemented using estimated 2009 pumping rates. Having reliable data can indicate the decline of hydraulic heads and identify areas of potential concern. A sparse observation wells monitoring network and lack of river discharge data was the second major limitation of this study. To calibrate the groundwater flow model, the 2003 groundwater head observation data was used as the most complete dataset while river discharge data was unavailable to calibrate surface-groundwater interactions on the majority of perennial streams. Two river gauging stations allowed to match river losses to groundwater between simulated and observed discharges on river reach, but this is insufficient for the rest of KV watershed. In this study, we simplified the surface geological information into six subgroups and these boundaries were assigned in all three layers. Currently, we included the low permeable zone in the model based on perennial rivers that originate in these area and utilizing isotope tracers we help to quantify groundwater contribution from the low permeable areas to the three layer aquifer system. Having more detailed geological and hydrogeological information should resolve problematic areas of the future models by using more vertical layers with finer spatial grids. In addition, we assumed a steady-state situation in the KV aquifer system that is acceptable for evaluating change of groundwater heads. However, the decline of groundwater heads with different rates is seem at all available observation wells and the transient model will be useful to determine the response time of the groundwater system to pumping in future studies.

## EVALUATION OF HOUSEHOLD WATER SECURITY

### 6.1 Water security index

Water security at household level were estimated for both basic human water requirement and economic growth using the eq. (2.14) considering 50 lpcd and 135 lpcd as per capita demand respectively. In this study, 2011 population data from census were taken as the base year and population for future periods were projected based on the projection rate estimated by CBS, which were used to estimate the demand for different time period. Results show higher population density inside the ring road and along the major road networks (**Figure 6.1 a**). The percentage annual growth rate adopted for this study is as shown in **Figure 6.1 b**; the higher value in the periphery of the ring-road, where several infrastructures (e.g., road, hospital, and school) were already developed and free land space is available for residence.



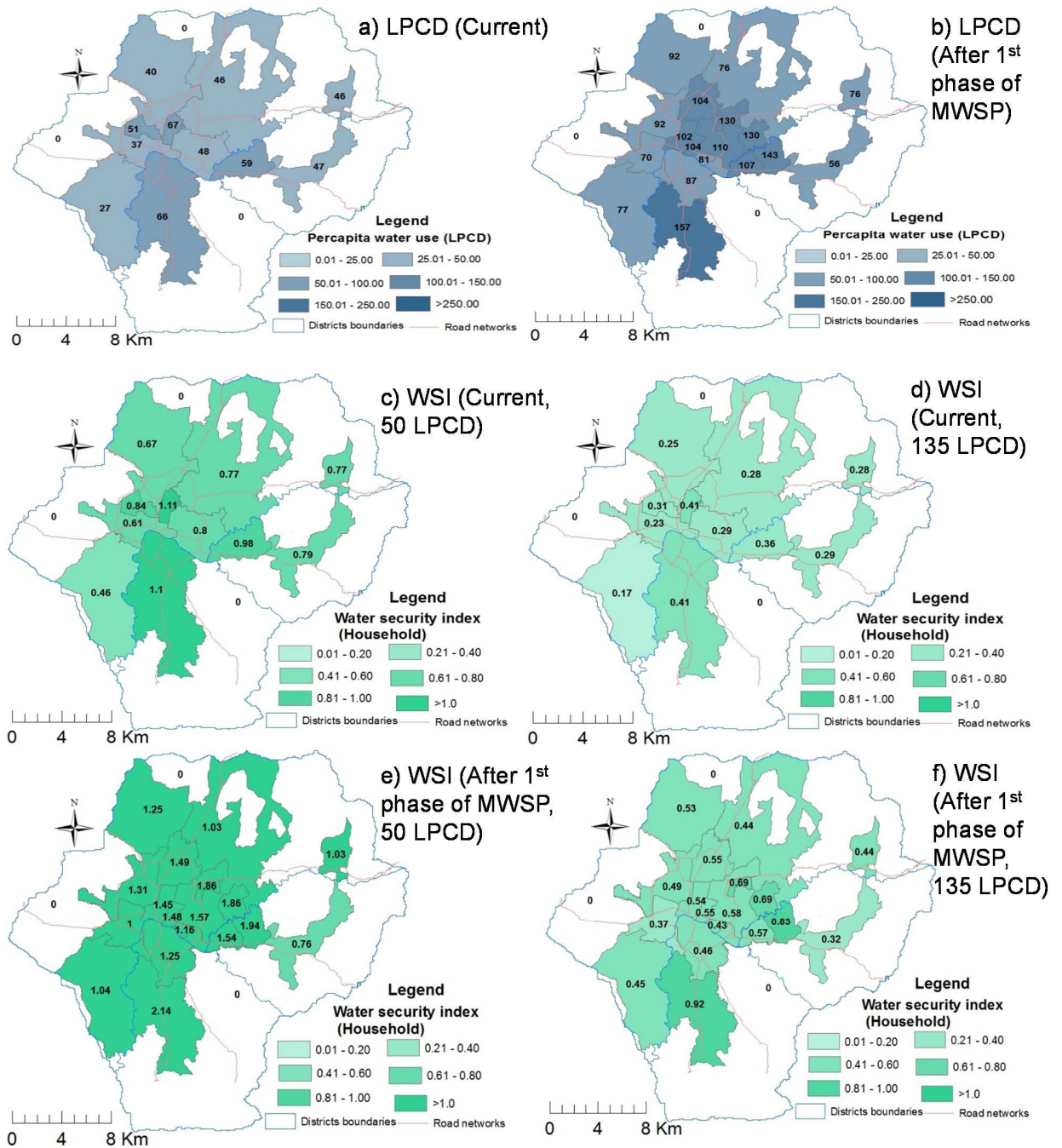
**Figure 6.1** Adopted population for estimating current and future population a) ward-wise population density for base year 2011, b) adopted ward/VDC wise percentage annual growth rate

#### 6.1.1 Current situation and after first phase of Melamchi water supply project

KUKL has planned to serve the KV through existing as well as new service reservoirs as shown in **Figure 2.10**. In the year 2016, all the service areas have limited water supply through existing reservoirs, only the SA B-5, 6, 7, and 10 met the basic human water requirement (**Figure 6.2 a**). None of the SAs met the water required for economic growth. After the first phase of MWSP, water supply situation is expected to improve significantly within the inner part of the ring road as that area will be served with water from new reservoirs (red dots in **Figure 2.10 b**) through the improved distribution network (**Figure 6.2 b**). After first phase of MWSP, all the SAs could meet the basic human water requirement and only SAs B-5 and B-6



could meet the required water for economic growth. This shows that even after the 170 MLD additional water, most of the SAs will face water scarcity.



**Figure 6.2** Per capita water supply (lpcd) in each service area a) current, b) After first phase of MWSP and Household water security index c) Current (Basic), d) Current (Economic Growth), e) After first phase of MWSP (Basic), f) After first phase of MWSP (Economic

For year 2016

All the area could not meet the demand for economic growth but nearly sufficient to meet the basic human water requirement for SAs B-5, 6, 7, and 10. Which shows the WSI for 50 lpcd demand is greater than 0.7 in all SAs except B-2, 3, and 9 as presented in **Figure 6.2 c**. Similarly for 135 lpcd demand WSI is less than 0.5 in all the SAs as presented in **Figure 6.2 d**. Which shows that water supply from KUKL is not sufficient to meet both basic as well as economic growth requirement in almost all SAs.

For year 2018

After the first phase of MWSP, water security situation for all SAs will significantly improve and WSI is greater than 1.0 in all the SAs except B-4 for 50 lpcd demand as presented in **Figure 6.2 e**. Even though water is not sufficient to meet the demand of economic growth, which is clearly shown by WSI less than 1.0 in all the SAs as presented in **Figure 6.2 f**.

#### *6.1.2 After Second phase of Melamchi water supply project and future*

After second phase of MWSP i.e. in year 2024, water supply situation in the area served by new reservoir is expected to improve significantly and reach up to 317 lpcd, whereas the area served by existing reservoir is expected to deteriorate further and reach up to 52 lpcd. The reason behind this is the high demand as population growth rate is expected to be higher outside the ring road area where most of the SAs are served by existing reservoir lies. In addition, rather than increasing supply, it is expected to deteriorate further due to old pipe networks. From those **Figure 6.3 a & b**, it is clear that there is some inequity in water distribution in respective service area, which may lead to social conflict. The available more than 135 lpcd of available per capita water inside the ring road, it can be re-distributed to service area served by existing reservoirs.

For year 2024

After the second phase of MWSP, all the SA served with both new and old reservoirs have water security index greater than 1.0 for 50 lpcd demand and nearly equal to 1.0 in SAs B-2, 3, and 4 as presented in **Figure 6.3 c**. The SAs served by new reservoir have WSI greater than 1.0 but SAs served by existing reservoir have less than 0.5 in all except B-6 for 135 lpcd demand as presented in **Figure 6.3 d**.

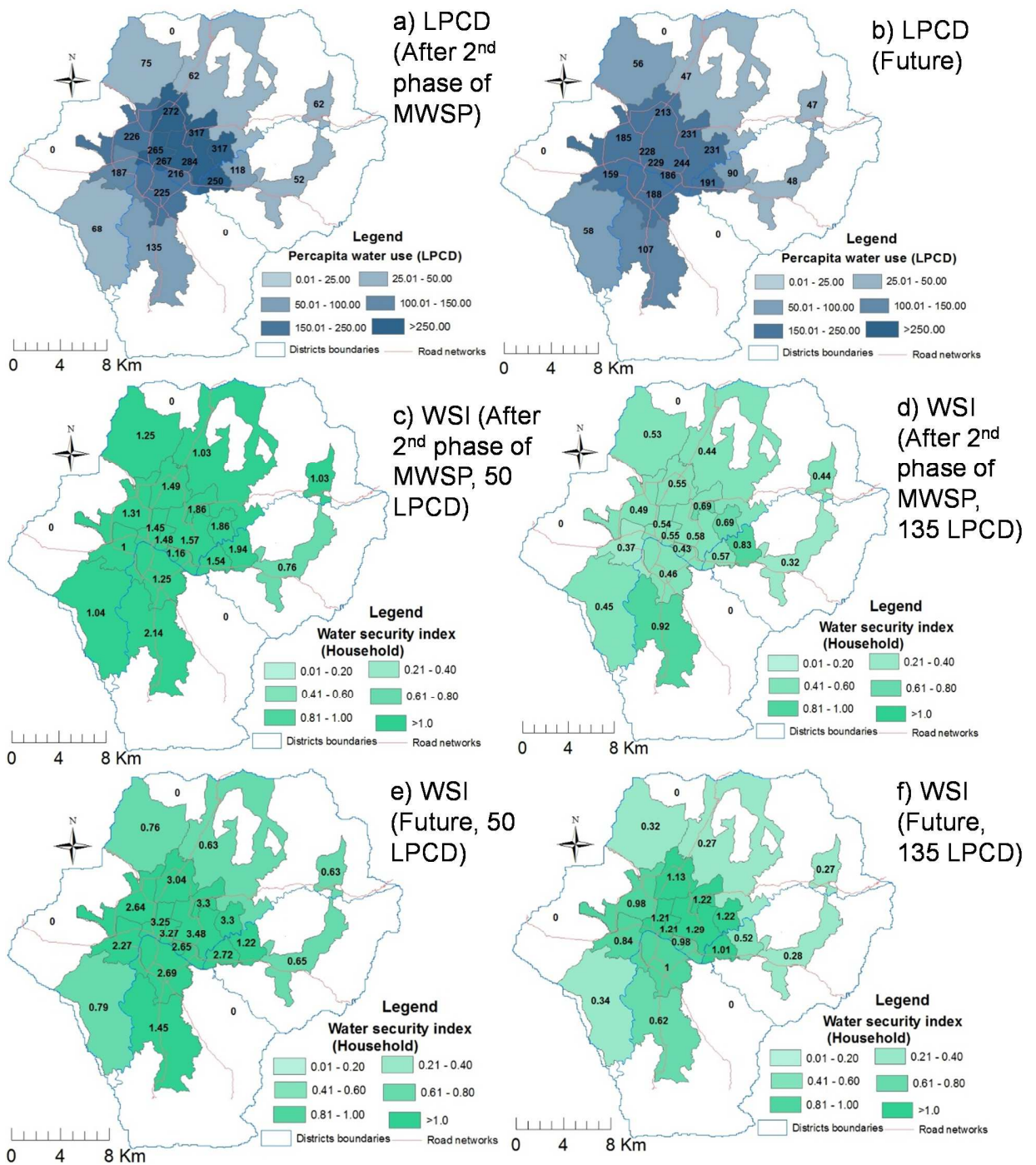
For year 2030

In the future situation, all the SA served with new reservoirs have water security index greater than 1.0 for basic human requirement as 50 lpcd demand as presented in **Figure 6.3 e**.

But the SAs served by existing reservoir have WSI around 0.7 except B-6 for 50 lpcd demand. Similarly, for 135 lpcd demand, all the SAs served by new reservoir have WSI greater than 1.0 but SAs served by existing reservoir have around 0.3 for all except B-6 as presented in **Figure 6.3 f**.

Those results from four cases show, there is mostly water deficit situation in the SAs served by existing reservoir, which is likely to be improved after completion of MWSP. It is also clear that there could be inequality in water distribution from concerned authorities, and hence there is possibility of reallocation of available water by expanding the SAs served by new reservoir for equitable distribution of potable water within KUKL SA.





**Figure 6.3** Per capita water supply (lpcd) in each service area) After second phase of MWSP, b) Post-MWSP (By year 2030 or sustainable development target year) and Household water security index c) After first phase of MWSP (Economic growth), After second phase of MWSP (Basic), e) After second phase of MWSP (Economic Growth), f) Future (Basic), h) Future (Economic growth)

## 6.2 Analysis of pumping scenario simulation

**Figure 5.3** shows changes in hydraulic heads between the baseline and the five simulated scenarios summarized in **Table 2.2**. The results of the first scenario show an average increase of hydraulic heads by 3.37 m across the three groundwater districts and by 3.20 m, 2.77 m, and 4.49 m in NGD, CGD and SGD, respectively (**Figure 6.4 b**). The reduction of pumping is considered after the implementation of the first phase of the MWSP and indicates the significant increase in the northwestern part than the central part of the valley.

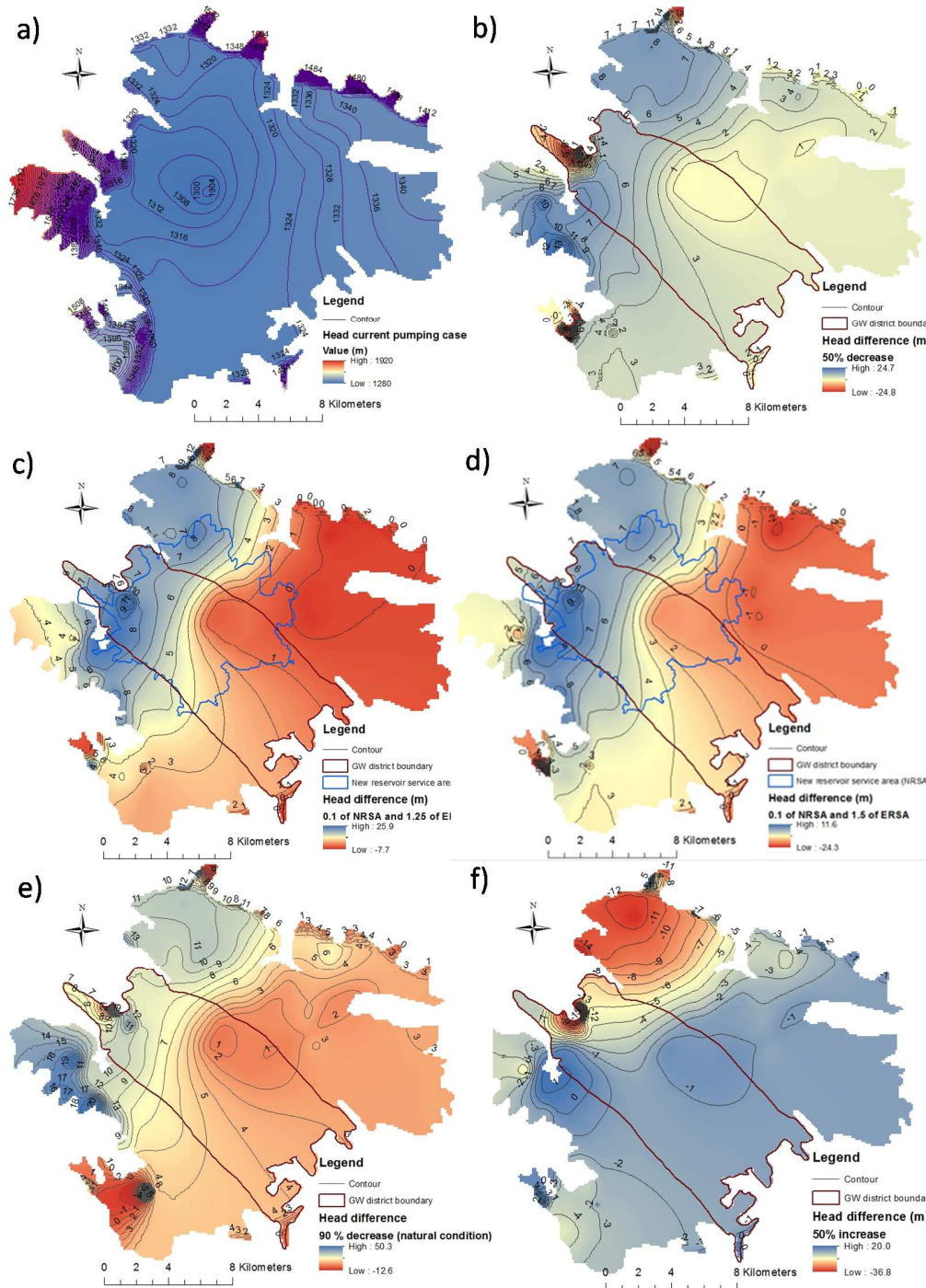
In the second scenario (**Figure 6.4 c**) after the implementation of the second phase of MWSP, the new RSA receives a sufficient amount of water and hence there is possibilities to reduce pumping significantly, hence assumed as natural condition. In contrast, the water deficit becomes worse in the existing RSA, leading to an increase of pumping by 25%. As a result, there is a significant increase (up to 11m) in hydraulic heads inside the new RSA outlined by the blue line, mainly the central-western part of the valley. The increase of pumping by 25% in the existing RSA increase in head (up to 7 m) in northeastern part of the valley at nearby Bansbari well field, but it results in the decrease of heads in the northeastern part of the valley (**Fig. 6.4 c**). The average increase of hydraulic heads is 2.24m, 3.59m, 4.25m in the NGD, CGD, and SGD, respectively. The average increase of head is 3.15m for entire valley cases due to significant decrease in pumping inside the new RSA, where most of the pumping well occurs, and the water deficit is substantially reduced inside the new RSA in this scenario.

In the third scenario, in the existing RSA the situation would deteriorate due to unmet total demand and increased pumping by 50% in the existing RSA. In this scenario, hydraulic heads decrease in the northeastern part of the valley and increase in the central and northwestern parts (**Figure 6.4 d**). The average change of hydraulic heads is 1.62m, 3.47m, and 4.2m in the NGD, CGD, and SGD, respectively. The average change of heads for the valley is 2.83m. These results indicate that there is a significant impact on groundwater system after the completion of MWSP, especially if proper regulatory mechanisms are able to curb the pumping amount from deep aquifers by substituting it with the piped water supply to meet water deficit.

In the optimistic scenario, the MWSP is completed on stipulated time and the water supply is redistributed across all sub-districts of both new and existing RSAs, fully satisfying all water demands. The natural pumping in the entire valley leads to increases in hydraulic heads by 5.48m in an average and 5.06m for the NGD, 4.83m for the CGD, and 7.11m in SGD (**Figure 6.4 e**). The highest increase in SGD is due to the significant reduction in pumping in two wells in Southern part (Pharping well).

For the pessimistic scenario, there is a severe water deficit with a possible increase in pumping by 150% of the current state in the entire valley, e.g. the MWSP is not completed on

time. The average decrease of hydraulic heads is -2.97m for the KV and is -4.0m, -2.19m, and -2.19m in the NGD, CGD, and SGD, respectively (**Figure 6.4 f**).

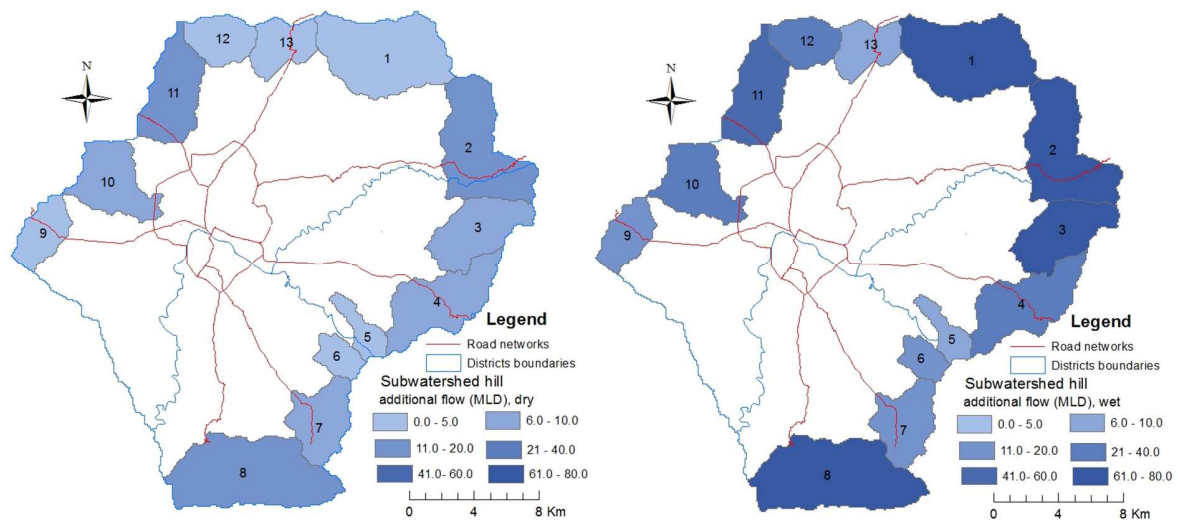


**Figure 6.4** Simulated heads in the baseline scenario (a) and head changes between the baseline and b) 50% reduction, c) natural (10% increase in new and 25% increase in existing RSAs, d) natural in new and 50% increase in existing RSAs, e) optimistic, and f) pessimistic scenario

### 6.3 Development of management option

#### 6.3.1 Surface water management

The conservation zone has fresh water available and can be used for water supply. KUKL is also using those areas for supplying the potable water for KV as shown in **Figure 2.10**. SWAT model was applied to estimate the total amount of available water (flow) and deducted with the water already used by KUKL. The sub-watershed (SW) No 1, 2, and 8 have higher amount of water available than other and mostly used by KUKL for supplying water to Kathmandu, Bhaktapur, and Lalitpur districts, respectively. From the predictive analysis, it indicates additional 0, 12, 10, 10, 3, 3, 8, 12, 5, 9, 13, 4, and 1 MLD in dry season, and additional 61, 66, 70, 31, 10, 12, 12, 71, 17, 37, 46, 27, and 10 MLD wet season from SW No 1 to 13 respectively can be harnessed for the water supply in KV after deducting the already used water by KUKL (**Figure 6.5**). This result indicates there is a possibility to harness total additional 88 MLD and 470 MLD water in both dry (average of December, January to May) and wet (average of June-November) seasons respectively for the period 2001-2010. But the information about how much water is recently harnessed through respective sub-watershed by community outside the KUKL service area is not available. Hence the concerned authority can prepare inventory of those uses of sources and coordination with other community-based organizations working on this sector by KUKL for reallocate the resources to cover the whole KV.

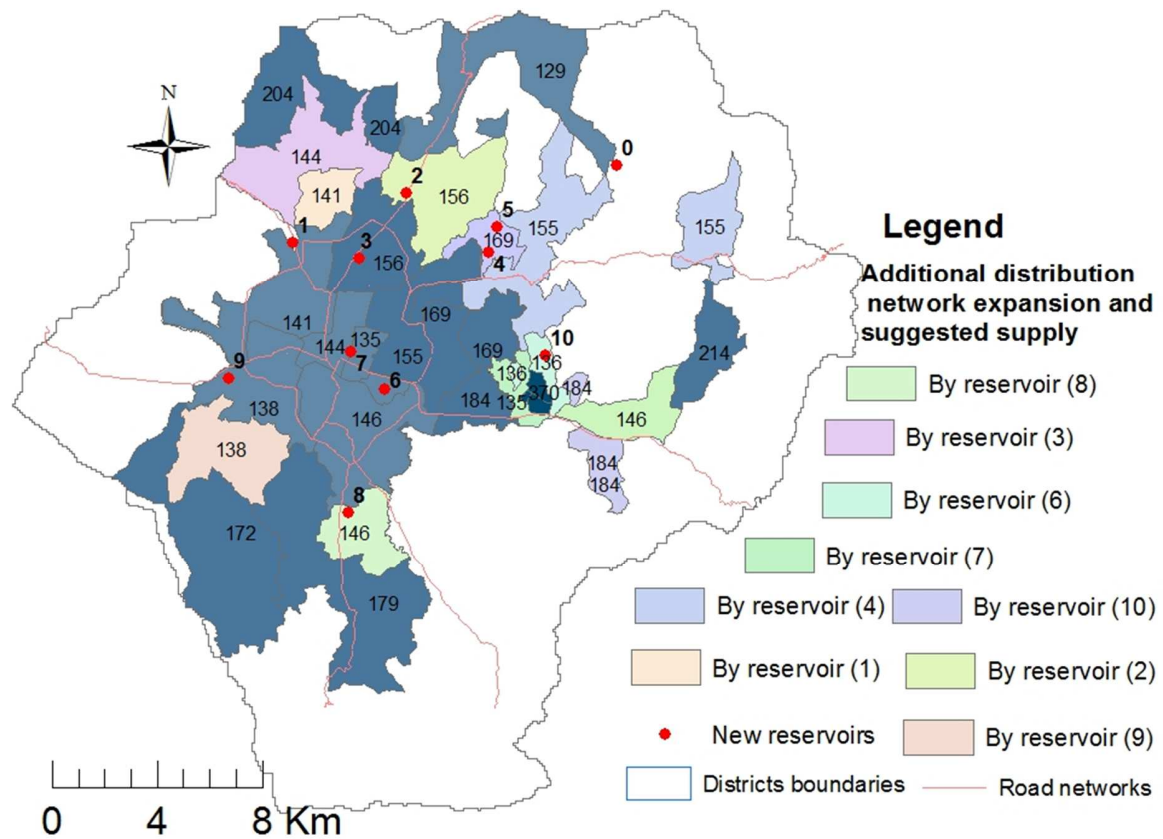


**Figure 6.5** Additional freshwater available for supply after deducting KUKL existing supply in MLD a) for dry season and b) for wet season

The per capita water supplied in the SAs served by new reservoir is comparatively high by 2030 than the SAs served by existing reservoir. For equitable distribution of the water, the re-distribution proposed in this study is based on following criteria: distance from the reservoirs,



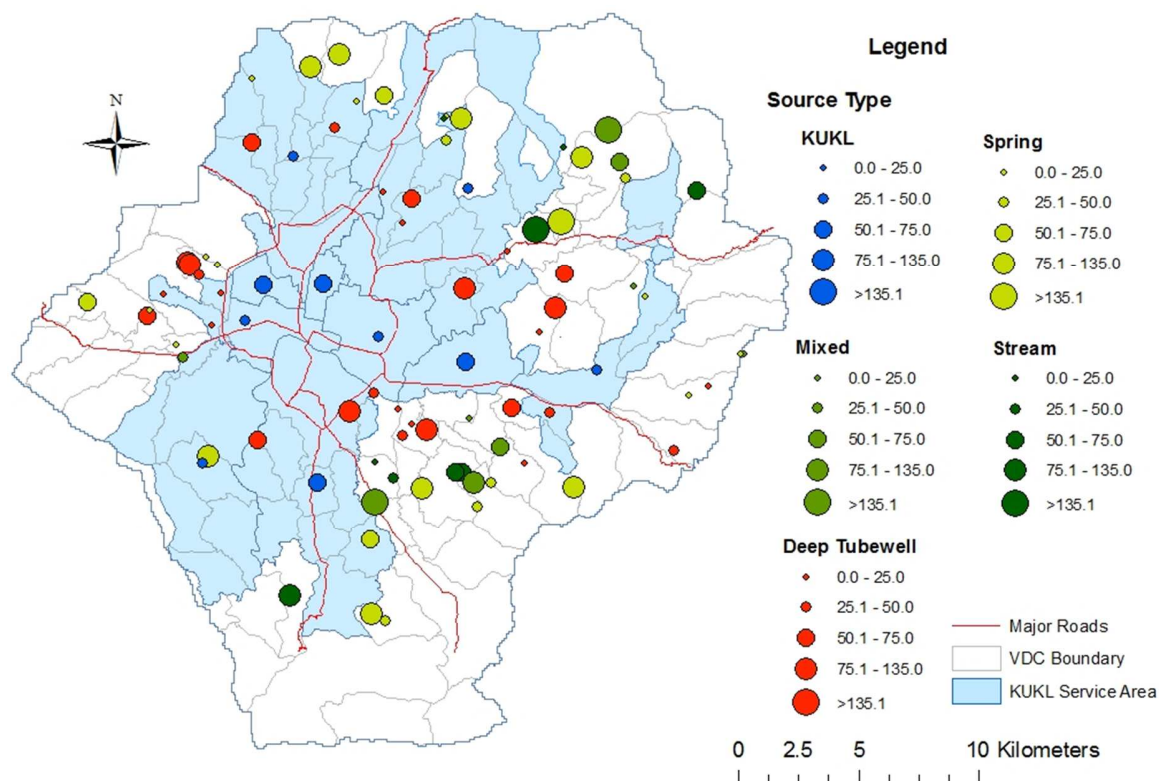
availability of pipe networks, administrative boundaries, and ensuring about 135 lpcd water availability in each service area. The possible water re-distribution is shown by different colour than the original service area colour (light blue) as shown in **Figure 6.6**. SA B-3 have good amount of water available from MWSP and existing network. After re-distributing water from surplus to deficit reservoir of existing reservoir SAs, it is seen that 90% of water harnessed for SA B-3 from KUKL can be used for expansion of SA in no service area zone. Similarly, the water available in SA B-5 can also be used for SAs expansion. Re-distributing available water in new reservoir in the way shown in **Figure 6.6** can serve additional 1.21 million people in periphery of current improved distribution network considering 135 lpcd as demand. Those re distribution is done with existing available resources and MWSP water. The additional water available from hills and existing networks surplus water from SA B-3 and B-5 can be used for expanding the KUKL's existing SAs with good quality of water for the entire KV.



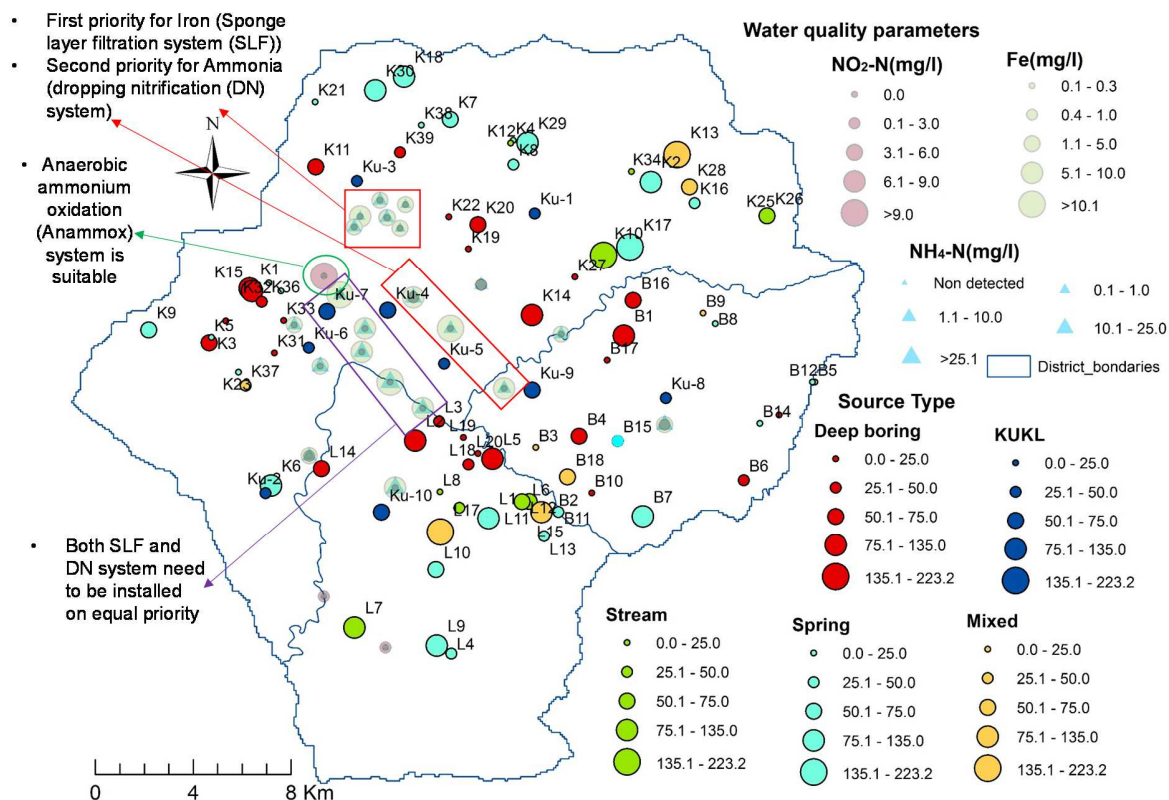
**Figure 6.6** Water redistribution scenario by respective reservoir (values in lpcd) with improved distribution network in KV (reservoir 0 means the main reservoir at Sundarijal, which receives water from MWSP)

The fresh water available in mountainous area (**Figure 6.5**) and proposed water redistribution (**Figure 6.6**) shows the possible strategy for the equitable distribution. Hence we

tried to prepare inventory of community based water supply scheme across the valley. From the preliminary inventory analysis it is clear that, the area outside the KUKL service area have around 80 number of schemes and spatially distributed very well (**Figure 6.7**). The community based schemes have different sources like spring, deep tube well, mixed (spring and stream, spring and deep tube well, stream and deep tube well). As per the preliminary inventory, 29 deep tube well, 28 spring, 10 stream, and 10 mixed water sources are managed by community. Most of the spring and stream sources are in foot hills of the mountain and deep tube wells in the peri-urban areas. These data shows that, schemes near by the sub-watershed having good amount of water availability (**Figure 6.4**) have larger circle (large amount of water supply per capita). Around 13% of total scheme have less water supply per capita i.e. <25 lpcd and similarly around 23% have in between 25-50 lpcd. Even though community managed water supply scheme have better water availability than KUKL system. In general it can be say that, the people living in foot hills are getting good amount of water than peri-urban areas and core city area except foot hills of Bhaktapur district (Central-East). The reason behind this is the less fresh water availability in this area (**Figure 6.4**). The concerned authority can update the inventory and integrate with the KUKL system to achieve the equitable distribution especially after the completion of Melamchi project.



**Figure 6.7** Spatial distribution of community based water supply schemes with KUKL system showing water supply per-capita and types of source



**Figure 6.8** Spatial distribution of water quality parameter along with community managed water supply schemes with KUKL system

Water quality parameter is very important to know the suitability of available water and their purpose of use. The **Figure 6.8** shows the spatial distribution of water quality parameter ammonia-nitrogen, iron, and nitrite-nitrogen along with community managed water supply scheme. The central part of Kathmandu valley deep groundwater system have contamination of mainly ammonia and iron and those data were obtained from SATREPS, WaSH-Mia, Nepal project working group-2. Those contaminants need to be treat to make it usable for different purpose. The researcher at university of Yamanshi are developing several locally fitted compatible and decentralized (LCD) treatment system, which have been already installed in several places of Kathmandu Valley. The types of LCD and their performance, targeted contaminants are presented in Table 6.1. Most of the deep tube wells were contaminated by iron and ammonia, hence based on contaminants level, sponge filtration layer (SFL) for iron removal and dropping nitrification (DN) system for ammonia removal need to be install. In northern part, iron content is higher than ammonia, hence SFL need to be installed first and in central part both need to installed equally. It is highly recommended to install both the system in same place to remove both iron and ammonia and make it usable for bathing and washing. Hence project can select nearby community managed deep tube well to install the SLF and DN system, which could be sustainable in long run rather than the private wells. If community wants to use treated water for drinking purpose, in addition to SLF and DN, Hydrogenotrophic Denitrification (HD) system is necessary.

**Table 6.1** Developed locally fitted compatible and decentralized (LCD) treatment system installed with their performance

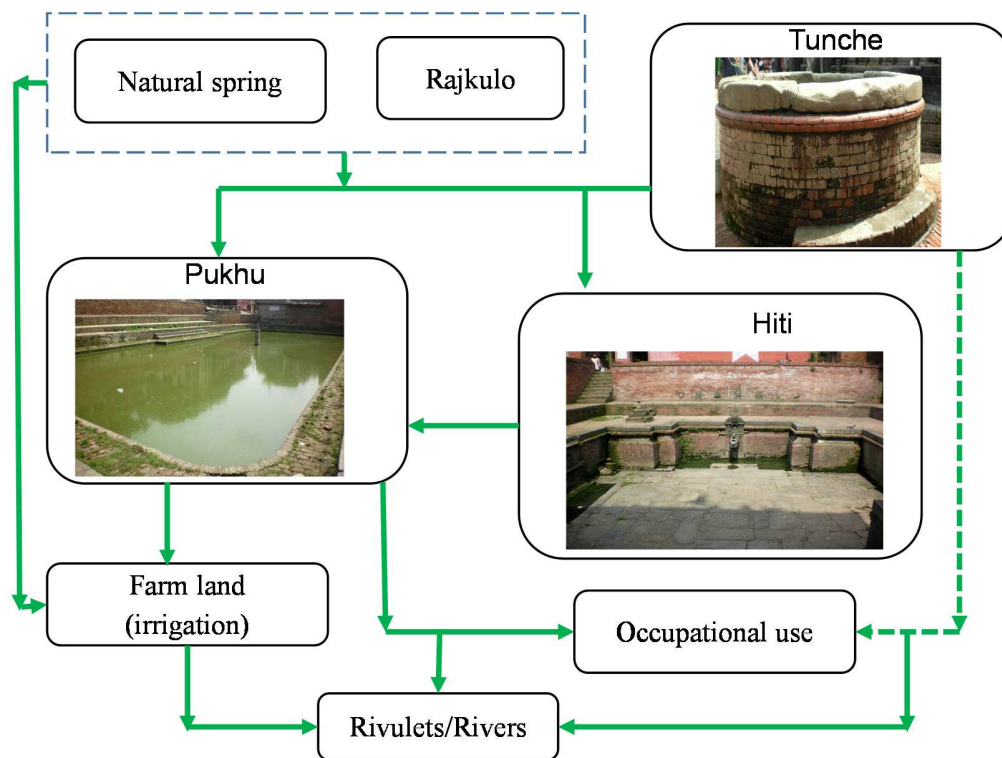
Unit name	Target contaminant	Capacity in single unit	Efficiency	Experimental site	Water use		
		[Liter/Day]	[%]		Washing	Bathing	Drinking
Sponge Layer Filtration (SLF)	Iron, Turbidity	864-1000	70-100%	Jwagal, IOE	○	○	×
Sand filtration (SF)	Turbidity	864-1000	> 99%	Jwagal, Hotel Kido	○	○	×
Dropping Nitrification (DN)	Ammonia	864-1000	> 99%	Jwagal, Chyasal	○	○	○
Hydrogenotrophic Denitrification (HD)	Nitrate	1000	50% (Latest data)	Jwagal, Thimi	○	○	○
Anaerobic ammonium oxidation (Anammox)	Ammonia, Nitrite	N.D	N.D	Jwagal	○	○	×
Constructed Wetland (CW)	Ammonia	N.D	N.D	Jwagal	○	△	×
N.D:Not designed							

### 6.3.2 Groundwater management

Those above analysis shows declining trend of groundwater level. Which is crucial and can lead to land subsidence problem. The model based study shows, there is possibility to increase average hydraulic head from +2.83 m to +5.48 m in various stage of the MWSP implementation and decline of hydraulic head by -2.97 m for increased pumping rate with no implementation of the MWSP. Recent model based studies shows the possibilities of 1.6mm/year average land subsidence in Kathmandu Valley (Shrestha et al., 2017). That shows reduction of pumping has significant impact for recovery of already depleted aquifer, which can be achieved through implementation of MWSP. A cone depression is observed in both Layers 1 (shallow aquifer) and 3 (deep aquifer) in the CGD (**Figure 6.4**), and this area has significant decrease in water level. Those area in basically Shankmul and Patan area (central part of the city), where almost 90% of land is paved with building and roads. Hence recharging the groundwater system could be one of the option to recover the groundwater depletion, which is quite difficult due to availability of limited open space suitable for recharge. There could be several option for recovering the groundwater level in KV, in this thesis we are just discussing one possible option to recharge shallow aquifer in core old settlement like Patan, Lalitpur. Hence based on the previous literature and primary observation of core settlement of Patan area, utilization of traditional existing infrastructure could be the one of the option. Therefore we tried to evaluate and describe one of the potential groundwater management option.



In Kathmandu Valley, mainly in old Newari settlement three types of water bodies are in existence. Those are stone spouts (Hiti), drag well (Tunche), and Pond (Pukhu). Among these Hiti and Tunche are freshwater bodies that supply potable water, and the water is mainly supplied through royal canal (Gautam et al., 2017). Water from Hiti and Tunche was observed to be used for drinking, cooking, washing, cleaning and animal feeding as well as for small scale farming too. Recently due to un-functional status of royal canal (Rajkulo), groundwater (mainly from shallow aquifer) are supplying water to those Hiti and Tunche. These are the indigenous water management system (IWMS), most of them are non-functional in recent days, hence need to be revitalized for proper use of available resources. The below **Figure 6.9** shows the cascade reusability framework of IWMS, those framework can be utilized for optimized use of available resources. Those framework also can work as groundwater recharge system for other Tunches and Hitis in lower elevation than that of the previous Pukhus. KVWSMB in collaboration with local level institution can enforce such system to revitalized the existing system and participatory water managed practice may manage water effectively and efficiently. As an initial work, KVWSMB may start the inventory of Tunche, Hitis, Pukhus, spring sources, and Rajkulo to assess the possibility of cascade reusability, revitalization and uses of those structure for augmenting the groundwater system.



**Figure 6.9** Cascading reusability framework of indigenous water management system practiced in typical Newari settlement in Kathmandu Valley to recharge the groundwater system (modified from (Gautam et al., 2017))

### 6.3.3 *Conjunctive use for sustainable management*

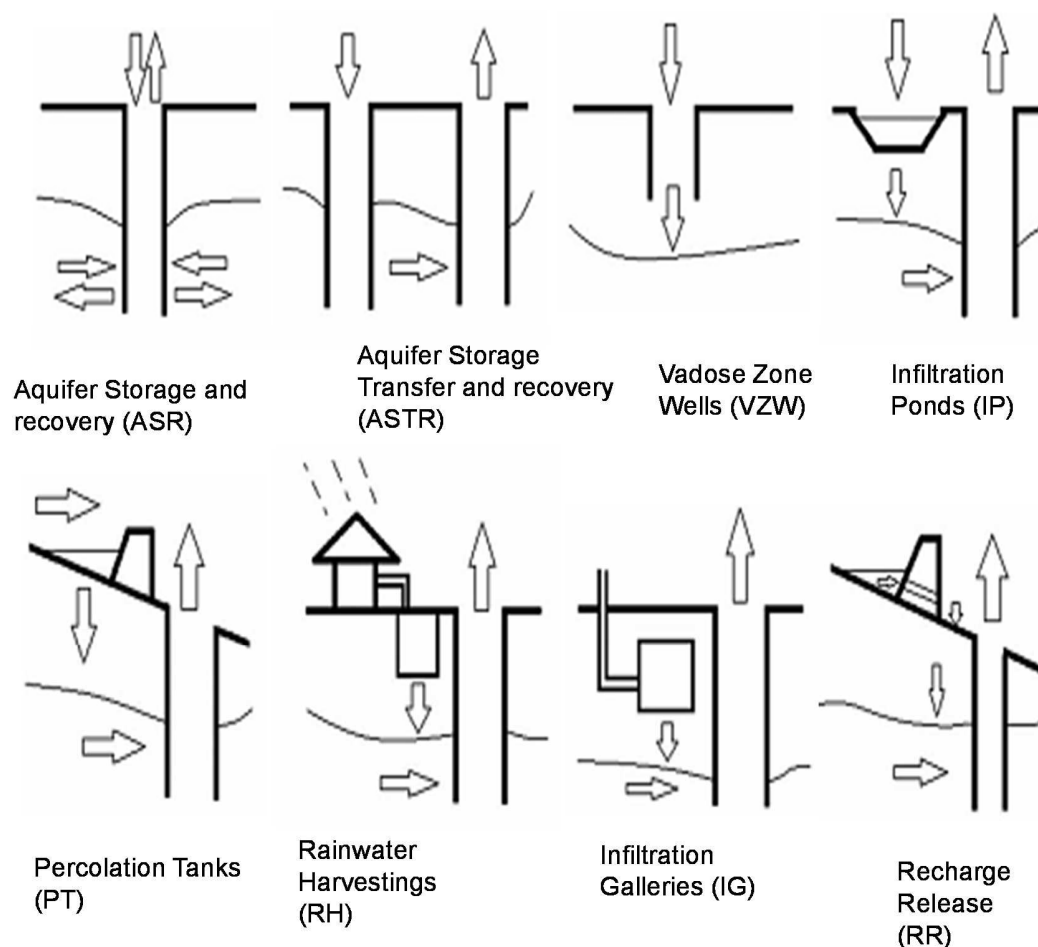
Sustainable management of both available surface and groundwater has become challenging due to several reason such as high population growth rate, improper land use planning, poorly managed infrastructure, and several seen and unseen reasons. There could be several management option, managed aquifer recharge (MAR) could be one of the potential option based on the available literature and their applicability. In this section we are trying to explain one of the conjunctive use of surface and groundwater through managed aquifer recharge (MAR) techniques. MAR refers to intentional infiltration of surface water or harvested rainwater into aquifer for further recovery or environmental uses (Dillon et al., 2009).

As we know, Kathmandu Valley is on acute shortage since long time, hence KUKL is supplying water through both surface and groundwater system. Groundwater level is declining in trend, wells are drying every year, and dry season flow is also decreasing (some section of river seemed to be almost dry) due to over use of both surface and groundwater. MAR can be used as to address the shortage and contribute to sustainable water resources management practices, which can be establish depending upon the source of recharged water, the selection of recharge method and site, the type of water treatment system, and ultimate purpose of the recovered water. All these are closely related and integrated. In case of Kathmandu Valley, the main purpose of recovered water is to use for drinking and domestic purpose. Hence source of water and its quality is major but there is no any strong rules, regulation, and guidelines prevail for MAR with reclaimed water. MAR system is combination of natural and engineered processes. Surface water (usually from lake or river) or harvested rainwater is pumped/provided to the infiltration area, pretreated if necessary, and infiltrated to the aquifer by suitable method (Kurki et al., 2013) and hence can be stated as conjunctive use of surface and groundwater. This system can work as alternate methods to recover and supply potable water to the system. Design of MAR system is site specific and different types in existence, few of them are presented with figures and details as described in Yuan et al. (2016).

In Kathmandu Valley, several deep wells are in abandoned condition, which can be used for aquifer storage and recovery (ASR) and aquifer storage, transport and recovery (ASTR) MAR system. ASR is the underground storage of water through injection and recovery from the same well, whereas ASTR is from separate well. These two method could be cost effective MAR system in Kathmandu Valley and can be implemented by KUKL easily. Another possible MAR techniques in Kathmandu Valley is rainwater harvesting (RH), in which rainwater is collected and redirected to a deep with the percolation and then reused for further process. KVWSMB can motivate individual households to make RH in each household voluntarily, which is efficient to augment the natural filtration of rainwater to underground formation, and is beneficial to restore the hydrological cycle in urban areas (Kim et al., 2012) like Kathmandu Valley. KUKL have several production well named as Bansbari well field, Manohara well field, Gokarna well field, Dhobi well field and Pharping well field (**Figure 5.1**)

and have space to construct infiltration galleries (IG). IG are percolation trenches in which permeable medium has internal void space to facilitate infiltration. Mainly those IG can be used to store water during wet season, which help to recharge the groundwater system and from production well water can be supplied for use.

Most of the river passing through Kathmandu valley does not have sufficient amount of water in dry season to maintain the environment flow. This will lead to environment pollution as well as stress to groundwater system due to increased pumping through well. In this situation, two MAR system: infiltration ponds (IP) and recharge release (RR) can be applicable. IP is large pond that are either excavated or located in an area surrounded by a bank, which can help to increase the base flow to stream system. For this, KVWSMB can identify the several location, which are suitable for IP along the major river of Kathmandu valley. Water can be stored during wet season in those IPs and could be effect means to recharge groundwater as well as to maintain base flow to river. In RR system, dams are built on ephemeral streams to detain flood water, the release rate of water downward can be slowed, which can help to maintain the environmental flow during dry season as well as recharging the underlying aquifers. Several locations suitable for RR (like Sundarijal area, Mahadev River area, Bishnumati River area etc.) in hill can be identify and possible system can be developed for augmenting the recharge. Government of Nepal already identified one of the possible area and planning to construct Dhap dam at Sundarijal for RR to maintain environmental flow during dry season.



**Figure 6.10** various type of managed aquifer recharge (MAR) system adapted from (Yuan et al., 2016)

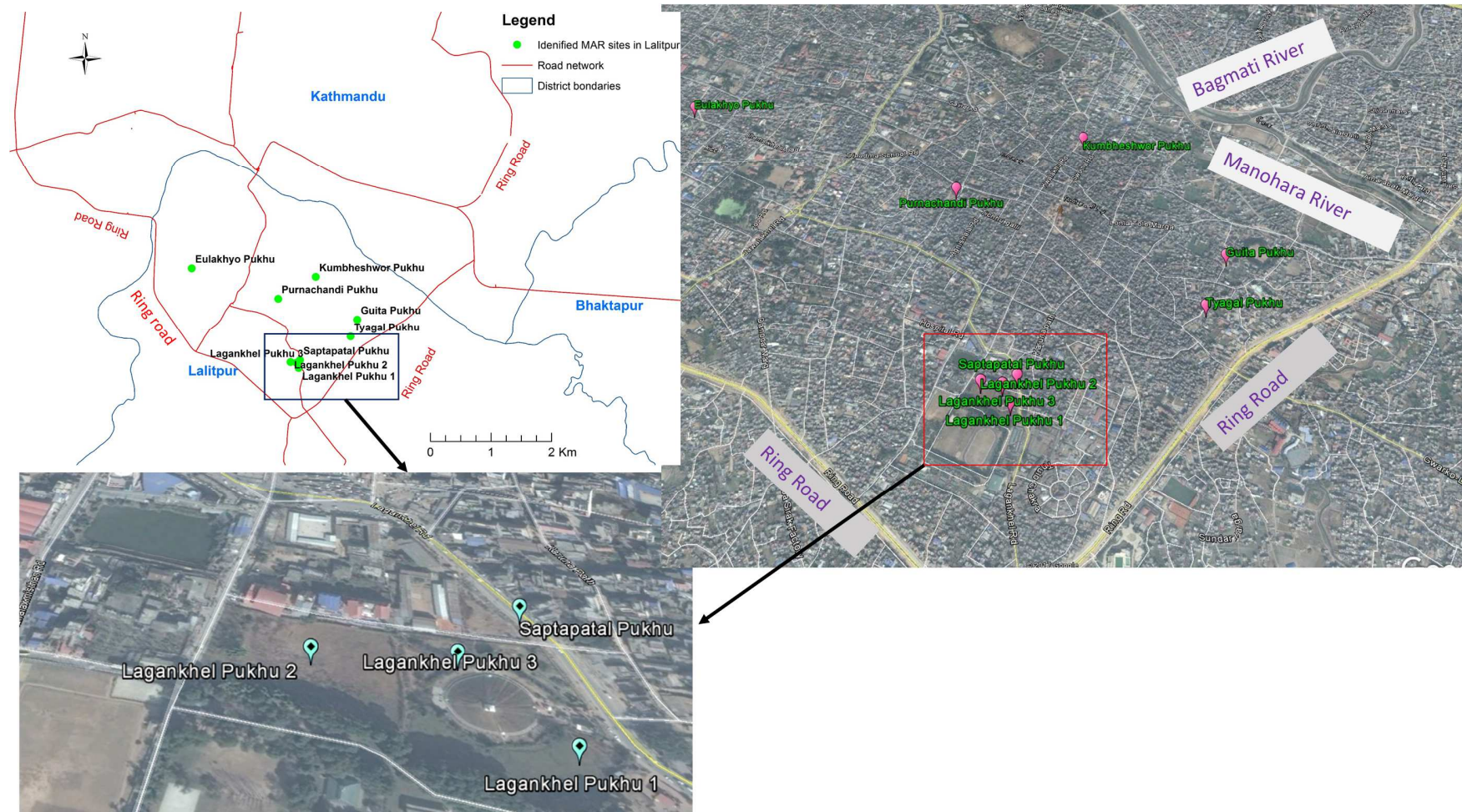
Most of the above discussed MAR techniques are in general. In this study, we are trying to identify some of the potential sites, where recharge can be done to enhance water production from nearby sources. In this preliminary studies, we are just trying enlist few ponds characteristics that can be used as infiltration ponds to recharge the groundwater system in Patan area as shown in **Figure 6.11**. The data shows the potentiality of recharge, hence the detail analysis of cost benefit analysis, detail technical design, law and regulation need to be formulated by concerned authorities. From the preliminary analysis it is clear that, most of the identified potential MAR site seems to be favorable for recharging the groundwater system. While designing the recharge system, it can create contamination and hence need to meet the quality requirement. As per regulation of [KVWSMB, \(2014\)](#) , only rainwater can be used for recharging the groundwater system in Kathmandu Valley, which need to be implement strictly to restrict the groundwater contamination in KV.

**Table 6.2** Some identified potential MAR sites for infiltration pond in Patan area

Name	Location	Location		Rehab Activiti es in past	Recharge Condition				Cost	Social Inclusion (during and After rehab)	Availability of Recharge Structure			Further Work
											Nat ural Sou rce	Rainwater Harvesting		
		Longit ude	Latitude		Baseme nt	Geologic al Conditio n	Hydrogeol ogical Condition	Recharge through Pond				Open Space	Big Str uct ure	
Tyagal Pukhu	Tyagal	27.668	85.331	Yes	Open	S	NF	Yes	M	Yes	No	Partial ly Yes	No	Need
Guita Pukhu	Balkumari, Guita Tole	27.670	85.332	Yes	Partially Sealed	NF	NF	Partially	L	Yes	No	Yes	Yes	Conserva tion
Kumbhesh wor Pukhu	Bangalamu khi Temple	27.676	85.326	No	Sealed	NF	S	No	H	Yes	No	Yes	No	Need
Purnachan di Pukhu	Ga Bahal	27.673	85.320	Yes	Open	NF	F	Yes	M	Yes	No	No	Yes	Need
Saptapatal Pukhu	Lagankhel	27.665	85.323	No	Open	F	S	Yes	H	Conflict	No	Yes	No	Need
Eulakhyo Pukhu	Thado Dhunga, Yaulakhel	27.677	85.307	Yes	Open	F	G	Yes	M	Yes	No	Yes	Yes	Need
Lagankhel Pukhu 1	Lagankhel	27.664	85.323	No	Open	F	S	Yes	M	Yes	No	Yes	No	Need
Lagankhel Pukhu 2	Lagankhel	27.665	85.322	No	Open	F	S	Yes	M	Yes	No	Yes	No	Need
Lagankhel Pukhu 3	Lagankhel	27.665	85.323	No	Open	F	S	Yes	H	Yes	No	Yes	No	Need

Where, S is Satisfactory, NF is Not favorable, F is Favorable, G is Good, L is Low, M is Medium, H is High

Source-KVWMSB, ongoing study, unpublished, personal communication with hydrogeologist of KVWSMB



**Figure 6.11** Location map of identified managed aquifer recharge (MAR) sites in Patan area in Lalitpur district



## 6.4 Summary

This study analysed water security situation using a water demand and supply based indicator for current and different time periods corresponding to the MWSP phases. From the results, it can be concluded that the water security situation is likely to improve gradually and meet all the water demands within KUKL SA. However, current strategy for water distribution will lead to unequal distribution. The available water and distribution strategy could not cover the entire valley, and subsequently may result in social conflict. As a way out, it is suggested to re-distribute freshwater from the reservoirs by expanding KUKL's existing distribution network improvement area as in **Figure 6.5**. It helps reach out to additional 1.21 million people in the valley with water supply services. Similarly, 88 MLD in dry and 470 MLD in wet season can be additionally harnessed from the hill area, and those freshwater can be used to expand the KUKL service area to whole KV.

As the ultimate goal of KUKL is to supply potable water for all the residents within the entire KV, it is an appropriate time for KUKL to start preparing an inventory of community-based and other agency-supplied water infrastructures outside the existing SAs. Those infrastructures can later be integrated with KUKL system for proper management of freshwater supply system throughout the valley.

In groundwater model simulations representing various stages of implementation of the Melamchi Water Supply Project (MWSP), estimates of groundwater abstraction rates played a critical role in the analysis of the impacts of MWSP. The first phase of MWSP partially fulfills water demand of both new and existing RSAs, while after the second phase of MWSP, the water demand of the new RSA is fully met and the existing RSA still faces water deficit. Despite getting sufficient amount of utility water, there is still a possibility to abstract groundwater using the available infrastructure. As a result, the spatially averaged changes in hydraulic head ranged from +2.83m to +5.48m in various stages of the MWSP implementation, and -2.97m for increased pumping rates with no implementation of the MWSP

These findings demonstrate an improvement of groundwater management with the implementation of the MWSP considering the proper regulations of groundwater pumping. Based on these results, it is recommended that, after the first phase of the MWSP, the Kathmandu Valley Water Supply Management Board (KVWSMB) motivate groundwater users to voluntarily reduce their pumping rates by up to 50% for the sustainable management of groundwater. However, after the second phase of MWSP, appropriate regulation on groundwater pumping needs to be implement based on the accessibility of piped water supply and enforced with appropriate regulatory and monetary mechanisms. Such regulatory mechanism could be monetary incentives to install meters to monitor pumping rates. For example, the KVWSMB may aim to impose a higher price for groundwater pumping license

in the new reservoir service area (RSA), medium price in the existing RSA, and free of charge in the areas having neither new nor existing public water supply based on the price and availability of water. Currently, several rules, regulations, and strategies exist for regulating water supply and sanitation in the valley; however, the situation has not improved over past decades. The historical trend of observed hydraulic heads demonstrates a steady decline by 0.69 m/year due to increasing groundwater abstraction in the valley. Combining the current depletion of the aquifer system with increasing water demand in the future may results in the overexploitation of groundwater resources. The MWSP is the key project to combat the present water deficit, but the investigations of the MWSP scenarios on the groundwater system are lacking. In this regard, the current study attempts to evaluate the implication of MWSP in groundwater system by investigating the potable water deficit calculated from water demand and supply and giving answers to water management questions such as “What may be the impacts of possible legislative interventions that responsible regulatory authority can undertake after the completion of MWSP?”

Those analysis indicates the significant contribution of MWSP to secure the water security in KV. Even though, those MWSP is not sufficient to cover whole KV, hence need to develop the additional water supply project from surrounding hills. In addition to this groundwater management is also important to recover the groundwater level as well as to achieve the water security. Cascade reusability of IWMS could help to recharge the groundwater system in old settlement and recover the water level, the detail investigation is necessary to identify the potential site, operation mechanism, quantity that can be recharged etc. Managed aquifer recharge system such as ASR, ASTR, RH, IP, IG and RR can be used as a conjunctive use of both surface and ground water to address water shortage in KV which can contribute for sustainable management of water resources. Implementation of MAR is often hampered by the absence of a clear economic case for the investment to construct and operate the system (Maliva, 2014). KVWSMB can evaluate economic and technical feasibility of different MAR at different location using cost benefit analysis to implement the MAR system. The detail investigation of appropriateness of MAR system and their location is necessary to evaluate the functionality of the system.



## SUMMARY OF THE STUDY

### 7.1 Summary

Two third of population live under water scarcity globally and nearly half of those population live in India and China (Mekonnen and Hoekstra, 2016). Water security becoming threat to sustainable development of human society because of increasing population, increasing demand during the last few decade. In addition to this, climate change also affecting the society and people are trying to adapt with those changes. Nepal is also facing water scarcity mainly in city areas for potable water due to rapidly increased population, urbanization and increased demand. Kathmandu Valley, capital city of Nepal is also facing the severe water scarcity threat, which need to be address through research and water resources project development activities.

The increased potable water demand from 35.1 to 370 MLD within 27 year and increased urbanization resulted the degraded water quality in both surface and groundwater. In addition to this, groundwater pumping increased significantly resulting decline in water level around 1.0 m/year. Which become serious problem, hence GoN has planned to supply additional 510 MLD water through off the valley source Melamchi. In this regard, this study tried to contribute to know the situation of water availability in different component of hydrological cycle applying both surface and groundwater model to resolve the water security problem in KV with different climatic and non-climatic scenarios. This study, therefore, aims to address water resources status, their response, and how those spatial distribution of water security will affect with different climate change, supply management, and groundwater management scenario.

This study contributed mainly on water quantity aspect, their variability with climate change, effect of population change, contribution of mega project (MWSP), variability of water security situation in due course of time with development, and identification of few water management option to achieve the water security in KV. The flow of study with major contribution of study are summarized as:

- The variability of available water component in different hydrological cycle is necessary to know the water balance component. This studies attempted to quantify the available water component for whole watershed using multi model (SWAT, BTOPMC, and HBV) and how those components are varying with expected climate change were identified using SWAT model.
- After knowing the holistic water balance component, this studies focused on the potable water supply. As we know, the river system in KV is extremely polluted and hence fresh water that is suitable for drinking were quantified using SWAT model. In addition to this, applicability of satellite precipitation product PERSIANN-CCS was also identified. The impact on climate change on those available fresh water resources from hills were quantified.

- The status of the groundwater component is not well understood, hence need to know the aquifer behavior. Groundwater flow model in Visual MODFLOW Flex environment were prepared. There could be potential impact on pumping after MWSP, hence based on water deficit status after MWSP different pumping scenarios were developed. The model based spatial distribution of change in head under different pumping scenarios as well as on different climate change scenarios were prepared.
- After knowing current status and impact of climate change on both surface and groundwater, this study identified the contribution of MWSP to secure the water security. The spatial distribution of water security index and water supplied per capita in due course of time along with progress of project were mapped and contribution of those project were identified to achieve the SDG in KV.
- Knowing the current status, impact of climate change, and impact of MWSP in both surface and groundwater, it was found that both sources are in risk and hence need to manage in sustainable manner. Few sustainable management option for both surface and groundwater as well as conjunctive use were identified as an adaptation strategies for water secure KV.

## 7.2 Findings and conclusions

From the perspective of sustainable management of water resources (surface and groundwater) in Kathmandu Valley, surface and groundwater modeling strategies were adapted. Those model based studies achieved above stated five objectives and concluded findings as follows:

1. In Kathmandu Valley, the population growth, urbanization, improper land use planning, poorly regulated groundwater withdrawal regulation, poor and old utility infrastructure are leading water insecurity and pressure on both surface and groundwater. Those resulted the reduction in water resources availability (per capita), change in water availability due to climate change, decline in groundwater level, less recharge, increment in pumping, and possibility of land subsidence.
2. The water balance component, annual precipitation average over 2001-2010 found as 1538 mm, runoff fraction varies from 0.55-0.59 and evapotranspiration varied from 0.41-0.47 of the total precipitation applying multi-model approaches. The annual fluctuation of total water storage component varies from  $\pm 10\%$  to  $\pm 14\%$  of total precipitation.
3. Evapotranspiration have the lowest inter annual variation and runoff have greatest variation in Kathmandu Valley. The predictive analysis by applying multi-model approach shows streams are supplemented by groundwater through October to March and rest of the month groundwater is recharged by the precipitation. The recharge values have been found less as compared to precipitation.

4. The climatic parameter temperature has been expected to increasing with due course of time, unlike precipitation has no any trend of increasing or decreasing based on the ACCESS 1.0 product. The average increase in maximum temperature is expected as 0.58, 1.20, and 1.95 °c under RCP 4.5 and 0.71, 2.10, and 3.82 °c under RCP 8.5 for NF, MF, and FF respectively with respect to baseline period. Similarly, the average increase in minimum temperature is expected as 0.11, 0.91, and 1.67 °c under RCP 4.5 and 0.22, 1.95, and 3.71 °c under RCP 8.5 for NF, MF, and FF respectively with respect to baseline period. The average increase in precipitation is expected as 101.88, 218.92, and 23.90 mm under RCP 4.5 and 129.08, 93.91, and 68.08 under RCP 8.5 for NF, MF, and FF with respect to base line period. The maximum temperature expected to increase in hot days and minimum temperature expected to decrease in cold days, which means warm days could be warmer and cold days may be colder. In all the cases, rainfall is predicted in month March, which may be unexpected.
5. The runoff components expected to increase except April, May, July, and September at outlet of Kathmandu Valley. This shows the not significant impact on water availability but could inundate valley due to flooding in monsoon period.
6. The high resolution satellite precipitation product PERSIANN-CCS has potential applicability in Kathmandu valley after bias correction, which could reproduce comparable rainfall magnitude at the station scale with comparable stream flow production at the whole catchment scale.
7. Based on the PERSIANN-CCS and gauged rainfall, the average (2007-2010) data shows possibility to harness additional 67 MLD and 87 MLD, which can serve additional 0.49 and 0.65 million of additional people in Kathmandu Valley during dry and wet season respectively. In addition to this, it shows North-East, North-West, and South-East of valley have higher potential of water availability than Mid-East and Mid-West in valley.
8. Water available through mountain as compared with baseline period seems to be increase in both dry and wet season. It is predicted to be increase by 61% and 40% under RCP 4.5 and 31% and 52% under RCP 8.5 during dry and wet season respectively for near future. The increased percentage flow in month March seems to be high, which leads the change in water availability during dry season is higher. In this study only ACCESS 1.0 data used, which is the limitation of the study.
9. Water security condition in 2016 is very severe, which caused pressure on groundwater system. If MWSP finished on stipulated time frame, water security situation is projected to be improve significantly after first phase for all the service area as compared to 2016. After second phase of MWSP and for future, the situation become different, which shows new reservoir service area is projected to be fully satisfied whereas old reservoir service area seems to be worsen. If KUKL supplied as their 2016 planning, there could be in-equality in current distribution. Which may lead the conflict among users and also could not cover the whole Kathmandu Valley. The MWSP could

be the key project to combat the present and future water deficit and the re allocation of available resources is necessary for the equitable distribution of water among service areas.

10. The data of groundwater level from 2003-2014 shows a steady decline of water level by 0.69 m/year due to increased groundwater abstraction. The projected increased water demand in future may result in the overexploitation of the groundwater resources. There is possibility of recovery of groundwater hydraulic head after implementation of MWSP. The model based study shows, there is possibility to increase average hydraulic head from +2.83 m to +5.48 m in various stage of the MWSP implementation and decline of hydraulic head by -2.97 m for increased pumping rate with no implementation of the MWSP. The model based study shows, there is not significant change in percolation and also not a significant change in hydraulic head due to climate change.
11. For the sustainable management of both surface and groundwater system, reallocation of water from KUKL to different service area is necessary. Inventory of community based water supply schemes will help to know the situation outside the KUKL service area, which will helpful to plan the few small scale water supply schemes in hill of Kathmandu Valley to expand their service area in whole valley. Those reallocation and additional scheme could be the management of surface water for securing water security. In addition to this, cascading reusability of traditional infrastructure for recharging the groundwater system could be the groundwater management option. The conjunctive use of both surface and groundwater can be promoted by adopting suitable MAR techniques throughout the valley as per their applicability.

### **7.3 Recommendation**

Based on the model based study of water availability and future projection for population, climate change impact and implication of MWSP in both surface and groundwater, following recommendation were summarized:

- ❖ The estimated values of water balance components, water available from hills of Kathmandu Valley can provide significant insights of available water resources. Those information can be used to guide, plan, and develop the new water resources project. In this study, climate data from ACCESS 1.0 only used hence several other GCMs can be used for better understanding of climate change. In addition to this, several anthropogenic affect can be incorporate
- ❖ It is recommended to make inventory of all the community based small water supply schemes (both surface and groundwater) by KUKL or KVWSMB. Based on the water availability, few small scales need to be developed from hill for supplying sufficient water in whole valley area.

- ❖ After first phase of the MWSP, KVWSMB can motivate groundwater users to voluntarily reduce their pumping rates up to 50% and appropriate regulation on groundwater pumping need to be enforced after second phase of MWSP. Appropriate regulatory and monetary mechanism such as monetary incentives to install meters to monitor pumping rates and different rate for pumped water based on the accessibility of piped water supply. KVWSMB may aim to impose a higher price for groundwater pumping license in the new reservoir service area (RSA), medium price in the existing RSA, and free of charge in the areas having neither new nor existing public water supply based on the price and availability of water
- ❖ KVWSMB can perform inventory of available stone spouts, ponds, dug wells, and conveyance canal to understand their status, size, performance and possibility of expansion or revitalization. These can be used for recharging the groundwater system for both shallow and deep aquifer. KVWSMB can identify the possible location of MAR techniques, their appropriateness, financial and economic aspect of MAR, technical consequences, design methods suitable for Kathmandu Valley, policies and regulation formulation to enhance the groundwater recharge for the sustainable management of available water resources.

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