Surface-groundwater interaction in the Kabul region basin

PhD candidate Najibullah Sadid

March 2020

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In 2018, AREU was awarded Best International Social Think Tank by Prospect Magazine.

About the author

Najibullah Sadid is an associate researcher at the Federal Waterways Engineering and Research Institute in Germany. He has been conducting research on hydrosedimentological characteristics of rivers and streams in mountainous environment. He is currently a PhD candidate at the University of Stuttgart, Germany.

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Thanks also go to the hard work of Toby Miller, Shahnaz Faqiri and Ahmad Masoud for their tireless work on editing, formatting and turning a rough draft into a final publication.

Foreword

The Afghanistan Research and Evaluation Unit (AREU) is pleased to present its distinguished audience with a detailed research-based paper titled: Surface-groundwater Interaction in the Kabul Region Basin, authored by PhD candidate Najibullah Sadid, and generously funded by the European Union as part of the EU three-pronged research effort into essential areas of Natural Resources Management (NRM) project.

In the past two decades, groundwater — as the primary water supply source for Kabul residents — has been extensively exploited, causing large drawdowns. The imbalance between groundwater recharge and groundwater use is considered as a key driver for the extreme decline in groundwater. On the other hand, the rapid increase in urbanisation has further limited the marginal share of groundwater regeneration from the surface; hence, the rivers and streams remain the main sources for recharging groundwater.

This research quantifies the groundwater recharge rates in central Kabul, upper Kabul/Paghman, Logar, Shamali and Panjsher sub-basins. The study employs three approaches: (i) basin-scale water budget balance; (ii) river reach length water balance (RLWB); and (iii) groundwater mounding (GWM) using Hantush's 1967 groundwater growth equation to estimate the water surplus/deficit, transmission losses through riverbeds and groundwater recharge rates, respectively.

From water years 2008 to 2018, the basin-scale water was positive for Kabul sub-basin balance only for years 2009, 2011, 2012, 2013 and 2014 for Kabul sub-basin, while for Panjsher sub-basin, a water surplus was observed each year. Field river flow discharge measurements at two or more river sections for RLWB analysis showed various significant transmission rates depending predominantly on the riverbed and bank sediment characteristics. GWM analysis reveals good agreement between observed groundwater growth in rivers' vicinity to wells and calculated groundwater growth for a range of aquifers' specific yield values (0.01 to 0.15) and permeability rates (10 m/day to 60 m/day). The GWM results show a wide spectrum range of recharge rate variations by a maximum of two orders of magnitude for water years 2004 to 2013. The bulk of the groundwater recharge occurs from October to May; however, Paghman, Shakar-Dara and Istalif rivers have shown an extended recharge period from September to July as a result of additional mountain-front recharge.

To utilise the limited recharge period, this paper recommends policy changes including in urban planning/ town planning in adapting water permeable pavements, having river training works allowing optimal bank filtration, and establishing additional recharge basins for surface and subsurface recharge.

I am taking this opportunity to acknowledge the full support of the government of the Islamic Republic of Afghanistan, in particular the ministry of water and energy and their teams for the provision of technical equipment which made this study possible. I hope this paper contributes to better policy planning and opens up the broader space to see how different stakeholders can assist in saving our groundwaters.

Dr Orzala Nemat,

AREU Director

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Abstract

Groundwater—the main water supply source for Kabul residents—has been extensively exploited in the past 2 decades, causing large drawdowns. While the imbalance between groundwater recharge and use is considered a key driver of the decline, the rapid increase in urbanisation has further limited the marginal share of regeneration from the land surface; hence, rivers and streams remain the only recharge sources.

This research quantifies the groundwater recharge rates in central Kabul, upper Kabul/Paghman, Logar, Shamali and Panjsher sub-basins. The study employs three approaches: (i) basin-scale water budget balance; (ii) river reach length water balance (RLWB); and (iii) groundwater mounding (GWM) using Hantush's 1967 groundwater growth equation to estimate the water surplus/deficit, transmission losses through riverbeds and groundwater recharge rates, respectively.[1]

From water years 2008 to 2018, the basin-scale water balance was positive for Kabul sub-basin only for 2009, 2011, 2012, 2013 and 2014, while for Panjsher sub-basin, a water surplus was observed in each year. Field river flow discharge measurements at two or more river sections for RLWB analysis showed various transmission rates depending on the riverbed and bank sediment characteristics. GWM analysis revealed good agreement between observed groundwater growth in rivers' vicinity to wells and calculated groundwater growth for a range of aquifers' specific yield values (0.01 to 0.15) and permeability rates (10 m/day to 60 m/day). The GWM results show a wide range of recharge rates with a maximum of two orders of magnitude for water years 2004 to 2013. The bulk of the groundwater recharge occurs from October to May; however, Paghman, Shakar-Dara and Istalef rivers have shown an extended recharge period from September to July as a result of additional mountain-front recharge. To utilise the limited recharge period, policy changes in urban/town planning in adapting water infiltratible pavements, having river training works that allow optimal bank filtration and establishing additional recharge basins for surface and subsurface recharge are suggested.

Keywords: Kabul groundwater, surface-groundwater interaction, groundwater recharge

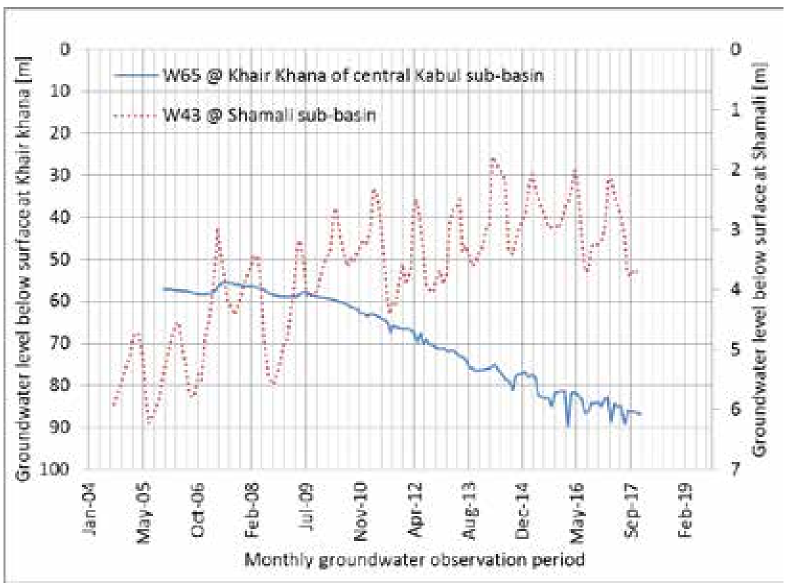
1 M.S. Hantush, "Growth and Decay of Groundwater-Mounds in Response to Uniform Percolation," *Water Resources Research* 3 (1967): 227–234.

1. Introduction

Groundwater levels in most of Afghanistan's basins are undergoing a significant drawdown due to excessive extraction. While large drawdowns are observed in urban areas (e.g., 0.7-1.5 m/yr in central Kabul basin),[2] recent reports have also shown drawdowns in rural areas with limited surface waters for irrigation (e.g., 1.0-1.5 m/yr in southwest Afghanistan).[3] This study quantifies the surface-groundwater interaction in the Kabul region basin and highlights the importance of rivers and streams in groundwater recharge.

The unprecedented groundwater decline endangers the domestic water supply and irrigation for an already overstressed region with strong seasonality of water resources. The metropolitan region of Kabul, home for more than 4.86 million people,[4] is experiencing severe groundwater quantity,[5] and quality, problems.[6] This is of great concern as groundwater is the main domestic water supply source. The groundwater level decline is intensive near the basin boundaries and less dramatic toward the middle of the central Kabul sub-basin, where Kabul River flows and recharges groundwater. The largest groundwater drawdown of about 30 m over 14 years is observed in Khair khana region of central Kabul sub-basin. Meanwhile, for Shamali, Deh Sabz and Logar sub-basins, the groundwater levels have not declined and have even observed some groundwater rise at some wells (Figure 1.1).

Figure 1.1: Example of extreme groundwater drawdown in Khair Khana area located at edges of central Kabul sub-basin (blue in left axis) and groundwater level rise as a result of groundwater regeneration in Shamali sub-basin (red, right axis)



Source: (Sidiqi et al., 2019)

2 T.J. Mack, M.P. Chornack, and M.R. Taher, "Groundwater-Level Trends and Implications for Sustainable Water Use in the Kabul Basin, Afghanistan," *Environment Systems and Decisions* 33 (2013): 457–467.

3 D. Mansfield, "Still Water Runs Deep: Illicit Poppy and the Transformation of the Deserts of Southwest Afghanistan," Afghanistan Research and Evaluation Unit (AREU) Issue Paper No. 40 (Kabul: AREU, 2018).

4 National Statistics and Information Authority (NSIA), *Afghanistan Statistical Year Book 2018-2019* (Kabul: NSIA, 2019).

5 M.H. Sidiqi, A.H. Shirzai, F. Khesrawi, and S.J. Sayedi, "Report of Study and Evaluation of Groundwater Level in Kabul Basin for Years 2011 to 2017," (2019); M.R. Taher, M.P. Chornack, and T.J. Mack, "Groundwater Levels in the Kabul Basin, Afghanistan, 2004–2013," U.S. Geological Survey (USGS) Scientific Investigations Report 2013–1296, (Reston, Virginia: USGS, 2014); M.H. Saffi, A.J. Kohistani, L. Vijselaar, M.N. Eqrar, and M.A. Najaf, "Water Resources Potential, Quality Problems, Challenges and Solutions in Afghanistan (Kabul)", Danish Committee for Aid to Afghan Refugees (DACAAR) Scientific Investigation Report (Kabul: DACAAR, 2013).

6 G. Houben, T. Tünnermeier, N. Eqrar, and T. Himmelsbach, "Hydrogeology of the Kabul Basin (Afghanistan), Part II: Groundwater Geochemistry," *Hydrogeology Journal* 17 (2008): 935–948; Saffi et al., "Water Resources Potential".

Therefore, the groundwater level decline in central Kabul and upper Kabul/Paghman sub-basins is reaching an alarming stage, while the situation in Logar, Shamali, and Deh Sabz sub-basins is stable.

The groundwater level decline is predominantly caused by extraction and regeneration imbalances. Unprecedented groundwater use in Kabul city is associated with the rapid increase in urbanisation, with an estimated expansion rate as high as 13.7 percent between 1999 and 2008.[7] Urban expansion has placed further stresses on the groundwater resources due to increased population; at the same time, the regeneration of groundwater from direct precipitation on the land surface has been significantly decreased, in particular in the urban areas in central Kabul and upper Kabul sub-basins as a result of urbanisation. The increase in paved areas may significantly decrease the groundwater recharge from direct precipitation because more permeable land is turned to impermeable surfaces as the city expands.[8] Direct precipitation on the land surface in the Kabul region contribute marginally to groundwater recharge. However, urbanisation is associated with protection of riverbanks, streambanks and natural drainages from erosion which are the dominant contributors to the groundwater regeneration in Kabul region.[9] As a result, the groundwater level may continue to decline while the rainwater accumulation over the paved surfaces causes man-made flooding. However, impervious surfaces can in turn significantly reduce water losses due to evapotranspiration because the built-up areas protect and limit the soil moisture losses.[10]

Therefore, the surface waters (i.e., lakes, rivers and streams) remain the main sources for groundwater recharge. Groundwater recharge occurs as a result of transmission losses being the dominant hydrological characteristic of intermittent rivers and streams due to a strong gradient between surface and groundwater levels. Surface water infiltration into aquifers is a very slow process depending on the permeability of streambeds and banks, as well as on the aquifer characteristics such as hydraulic conductivity (k), transmissivity (T) and specific yield (Sy). In the upper Kabul sub-basin, infiltration through the riverbed, as studied by flow balance at two gauging stations along the Maidan River, namely at Gulbagh (upstream) and Chehlsutun (downstream), shows a contribution of 72% to the groundwater regeneration.[11] A study by Broshears et al.[12] shows that in the Kabul sub-basin, the groundwater flow path follows the surface water flow direction. Further, Sadid et al. showed that groundwater level fluctuations in wells close to rivers in Kabul basin closely correlate with river's flow discharge variations of rivers, while it weakly correlates with precipitation rates.[13]

Groundwater regeneration from surface waters in Kabul basin faces two major challenges associated with river flow seasonality and modifications. In arid and semi-arid regions of the world, rivers and streams have strong flow seasonality, meaning they cease to flow, or they run dry for considerable time. Accordingly, the groundwater recharge through streambeds and banks is also limited to the flow season. The longer dry periods cause the formation of unsaturated zone between the riverbed

7 A.S. Ahmadi, and Y. Kajita, "Evaluation of Urban Land Development Direction in Kabul City, Afghanistan," *International Journal of Urban and Civil Engineering* 11, no. 2 (2017).

8 e.g., Q. Zhang, L. Miao, H. Wang, J. Hou, and Y. Li, "How Rapid Urbanization Drives Deteriorating Groundwater Quality in a Provincial Capital of China," *Polish Journal of Environmental Studies* 29 (2019): 441–450.

9 Proctor & Redfern Int. Ltd., "Water Supply Sewerage Drainage and Solid Waste Systems for Greater Kabul, Joint Interim Master Plan," *Report for Royal Government of Afghanistan Central Authority for Housing and Town Planning,* (World Health Organization; United Nations Development Programme [unpublished]).

10 M. Minnig, *Impact of Urbanization on Groundwater Recharge: The Case Study of Dübendorf, Switzerland,* Ecole Polytechnique Federale de Lausanne (EPFL), (Lausanne: EPFL, 2017).

11 Proctor & Redfern Int. Ltd., "Water Supply Sewerage".

12 R.E. Broshears, M.A. Akbari, M.P. Chornack, D.K. Mueller, and B.C. Ruddy. *Inventory of Ground-Water Resources in the Kabul Basin, Afghanistan,* U.S. Geological Survey (USGS) Scientific Investigations Report 2005-5090 (Reston, Virginia: USGS, 2005).

13 N. Sadid, S. Haun, and S. Wieprecht, S. "An Overview of Hydro-Sedimentological Characteristics of Intermittent Rivers in Kabul Region of Kabul River Basin," in River Sedimentation, ed. S. Wieprecht (Stuttgart: CRC Press, 2016) and N. Sadid, S. Haun, and S. Wieprecht, S. "An Overview of Hydro-Sedimentological Characteristics of Intermittent Rivers in Kabul Region of Kabul River Basin," in River Sedimentation, ed. S. Wieprecht (Stuttgart: CRC Press, 2017).

and the groundwater level as a result of evapotranspiration from ground surface and water extraction by pumping. The unsaturated zone requires some time after the flow season resumption before an actual groundwater recharge occurs. Therefore, short period rainfalls that cause flash floods may not even regenerate groundwater because the time required for unsaturated zone to become saturated may be much longer than rainfall period. Evidence shows that abrupt rainfall frequency has increased, while the longer-duration precipitation has decreased as a result of climate change.[14] Moreover, the glacier coverage that guarantees flow discharge during dry summers is diminishing. Recent glacier coverage study shows a reduction of 15 percent in just 25 years in Kabul River basin as a result of climate change.[15] Thus, in the future, more perennial rivers may turn to intermittent flow regimes and, accordingly, saturated zones beneath rivers and streams will turn unsaturated.

On the other hand, rivers and streams are constantly losing their natural banks and floodplains due to urbanisation, which intends to serve as natural retention and groundwater recharge basins during flood events. River floodplains may impound a significant amount of floodwater which will gradually infiltrate into the groundwater. Additionally, improper river training works, such as riverbank protection by concrete and stone masonry retaining walls further reduces the riverbanks exposed area to infiltration and thus reduces the groundwater recharge.

Groundwater as the main source for Kabul’s domestic water supply is far from sustainable, neither quantitatively nor qualitatively. One solution is a long-distance supply from outside the Kabul basin. The potential water resources outside central Kabul city can stem from surface, groundwater or a combination of both. Potential groundwater resources nearby are Logar, Upper Kabul or Paghman, Deh Sabz, Shamali and Panjshir sub-basins. To gauge these sources’ sustainability, a study of surface-groundwater interaction is required to quantify the rate of groundwater recharge.

14 V. Aich, N. Akhundzadah, A. Knuerr, A. Khoshbeen, F. Hattermann, H. Paeth, A. Scanlon, and E. Paton. “Climate Change in Afghanistan Deduced from Reanalysis and Coordinated Regional Climate Downscaling Experiment (CORDEX)—South Asia Simulations,” Climate 5, no. 38 (2017); WFD, UNEP, and NEPA, *Climate Change in Afghanistan: What Does It Mean for Rural Livelihoods and Food Security?,* (2016).

15 S.B. Maharjan, E. Joya, T. Bromand, M.M. Rahimi, K.A. Muazafary, M. Bariz, T.C. Sherpa and S.R. Bajracharya. *Status and Decadal Changes of Glaciers in Afghanistan since 1990s.* (Kathmandu: International Centre for Integrated Mountain Development (ICIMOD), 2019).

2. Main objectives of the study

Despite the major contribution of surface water to groundwater regeneration in Kabul region basin, very few researches have quantified the surface-groundwater interaction. The balance between groundwater extraction and recharge can only be revived by quantifying the contribution of surface waters to groundwater recharge. One strategy to combat declining groundwater tables is to re-establish the natural recharge potential through riverbed and banks, as well as establishing additional artificial recharge areas. In order to plan groundwater regeneration strategies, one pre-requisite is to quantify the surface-groundwater relationship. Therefore, in this research work, the main objective is to quantify the surface-groundwater interaction in Kabul region basin, which will serve as a pilot study highlighting the importance of rivers and streams in recharging the groundwater. More specifically, three main objectives are set for this research:

a. What is the recent water balance in the Kabul region that can potentially contribute to groundwater regeneration?

b. How large is surface water transmission loss and its variation along the longitudinal channel reaches of Panjsher, Kabul, Logar, Maidan, Paghman, Shakar-Dara and Istalef rivers due to the water infiltration through streambed and bank?

c. What is the contribution of the infiltrated surface water to the groundwater regeneration? In other words, what percentage of infiltrated water through streambed and banks actively recharges groundwater?

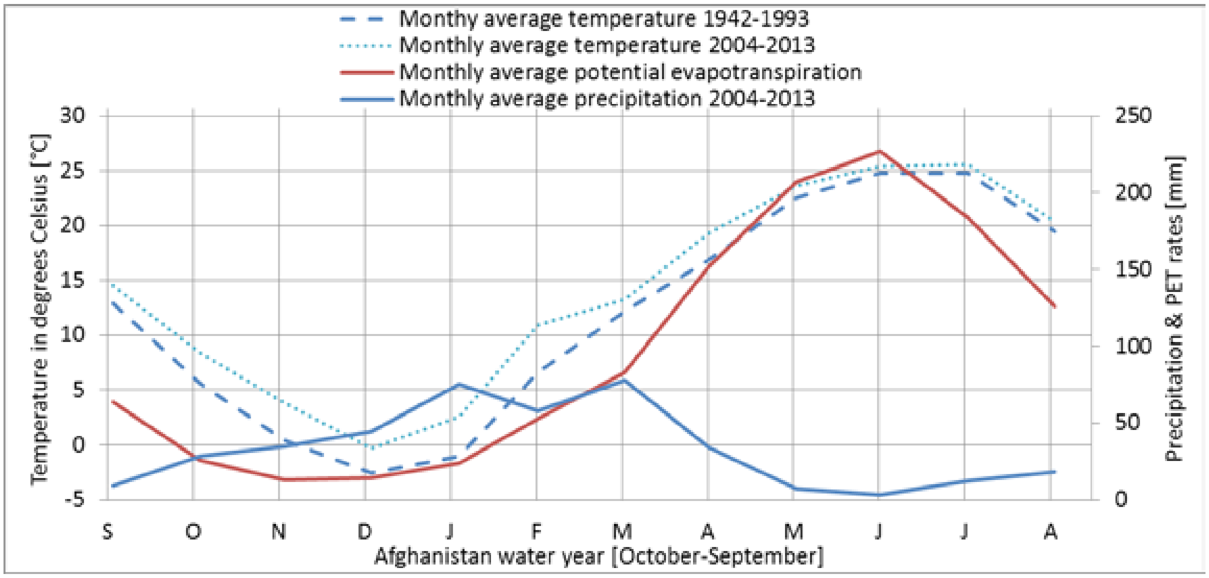
The result of this research work is intended to find out the groundwater recharge rate in central Kabul, Upper Kabul or Paghman, Logar, Deh Sabz and Shamali sub-basins. The findings will reveal how the groundwater recharge rate and duration varies with river flow variations and site-specific parameters such as riverbed and bank size and material properties. The information will help water managers and policy makers understand groundwater recharge potentials, restrictions and opportunities for a sustainable management of groundwater in Kabul.

3. Methodology

3.1. *Study area*

Kabul regional basin is located in an arid to semi-arid climate, with average monthly precipitation rates measured at Kabul airport varying between 0.0 mm to 75 mm, as shown in Figure 3.1. Because Kabul has cold winters, with an average minimum temperature of -2.3°C in January, and hot summers, with an average maximum temperature of 40.2°C in July, the rates of potential evapotranspiration exceed those of precipitation for an extended period. Recent average temperature measurements (2004-2013) indicate an increase in average temperature throughout the year due to climate change.[16]

Figure 3.1: Climate Averages for Kabul based on the Agromet Project Data



PET = potential evapotranspiration.

Source: (MAIL/USGS, 2013)

The Kabul region basin is divided into five groundwater sub-basins, namely central Kabul, upper Kabul/Paghman, Logar, Shamali and Deh Sabz. Kabul River in central Kabul, Paghman, Qargha and Maidan Rivers in upper Kabul/Paghman, Logar River in Logar, Shakar-Dara and Istalef Rivers in Shamali, and Deh Sabz River in Deh Sabz are selected for RLWB and GWM investigations, as shown in Figure 3.2.

The groundwater sub-basins in the Kabul region are formed by prominent bedrock outcrops and crystalline faults.[17] Sub-basins of Kabul and Logar, as well as Shamali and Panjsher, are separated by faults, while central Kabul sub-basin and Deh Sabz sub-basins are separated by mountain ridges resulting from bedrock outcrop. Sub-basins' mountain surroundings and inter-basin ridges have alluvial fan deposits at their flanks ranging from coarse near the source to finer sediment deposits at distal edges.[18] The deposits are primarily composed of Tertiary and Quaternary sediments. The Quaternary sediment deposits of central plain are comprised of alluvium and loess of less than

16 MAIL/United States Geological Survey (USGS). *Agromet Project: Status as of September 2004 to 2013.* (Reston, Virginia: USGS, 2013).

17 R.G. Bohannon. *Geologic and Topographic Maps of the Kabul South 30' x 60' Quadrangle, Afghanistan.* U.S. Geological Survey (USGS) Scientific Investigations Map 3120 (Reston, Virginia: USGS, 2010); Broshears, *Inventory of Ground-Water Resources;* T.J. Mack et al., *Conceptual Model of Water Resources in the Kabul Basin, Afghanistan.* U.S. Geological Survey (USGS) Scientific Investigations Report 2009–5262 (Reston, Virginia: USGS, 2010).

18 Broshears, *Inventory of Ground-Water Resources;* Mack et al., *Conceptual Model of Water Resources.*

80m thickness. The Tertiary deposits have a much larger depth of up to 1,000m and include semi-consolidated conglomerate.[19] Rivers and their floodplains consist of a thin layer of channel alluvium. The Kabul basin aquifer is composed of a primary surficial sedimentary aquifer and an underlying secondary semi-consolidated conglomeritic sediments aquifer.[20] The permeability of the surface aquifer varies between 2.3x 10^{-5} to 1.3 x 10^{-3} m/s;[21] however, for the secondary deep aquifer, much lower permeability values (5.6 x10^{-8} to 1.0x 10^{-6} m/s) are observed.[22] The main characteristics of the Kabul region sub-basins aquifers are listed in Table 3.1.

Table 3.1: Main characteristics of Kabul region aquifers based on the study by Böckh (1971)

Sub-basin	Extent (length x width) [km]	Hydraulic conductivity range [m/s]	Average thickness [m]	Maximum thickness [m]	Aquifer material	Deeper Aquifer
Central Kabul	9 x 2.5	0.5 x 10^{-4} -7.5 x10^{-4}	40 - 80	80	Loam, sand, and gravel	Conglomerates, coarse-grained sandstone
Deh Sabz	17 x 15			80	Alluvium, loess	Conglomerates
Logar	10 x 3	1.4x10^{-4} – 13 x10^{-4}	30- 40	70	Sand, gravel and thin clay layers	Conglomerates, coarse-grained sandstone
Shamali	40 x 10			80	Fan alluvium, alluvium, loess	Conglomerates (<1000m)
Panjsher	22 x 13			80	Alluvium, river channel alluvium	Conglomerates (<1000m)
Upper Kabul/ Paghman	6 x 4	0.2 x 10^{-4} -3.0 x10^{-4}	30 - 70	70	Sand, and gravel	Conglomerates, and sandstone

Groundwater observation in the vicinity wells of Kabul, Paghman, Maidan, Logar, Shakar-Dara, Istalef and Deh Sabz rivers are selected for GWM analysis. The wells with seasonal groundwater table fluctuations are assumed to be predominantly recharged by river flow, while the mountain-front recharge (MFR), that is, recharge from irrigation and recharge from direct precipitation, is assumed to contribute insignificantly to groundwater level fluctuations. The selected wells are further filtered based on the pumping effect on the groundwater level observations, because some of the wells serve as public water supply wells. Therefore, groundwater observations wells are screened for pumping effect and only those with zero or minor pumping effects are considered for GWM analysis.

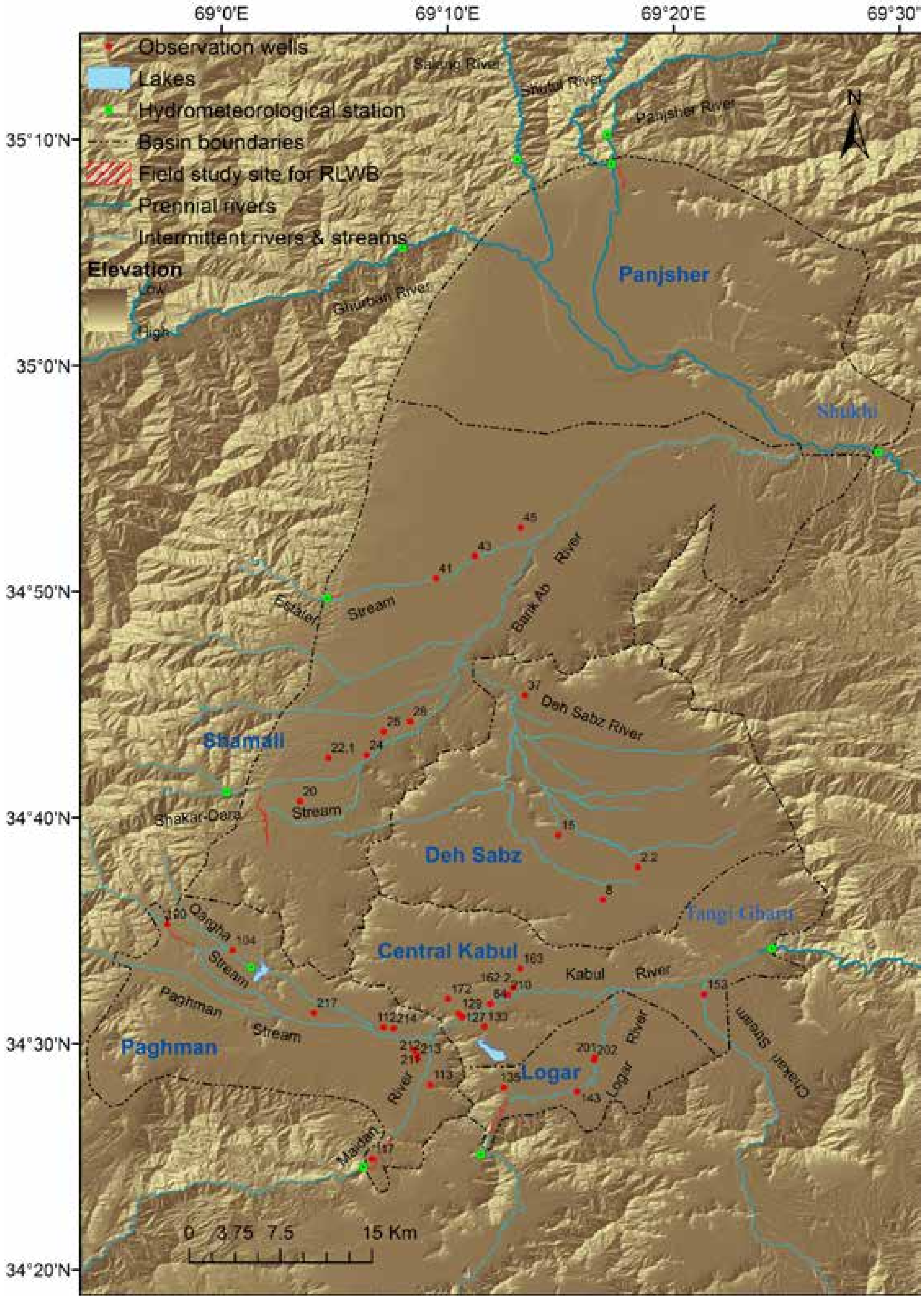
19 J. Homilius, "Geoelectrical Investigations in East Afghanistan*," *Geophysical Prospecting* 17, (1969), 468–487.

20 R.G. Bohannon and K.J. Turner, *Geologic Map of Quadrangle 3468, Chak Wardak-Syahgerd (509) and Kabul (510) Quadrangles, Afghanistan,* U.S. Geological Survey (USGS) Open-File Report 2005-1107- B (Reston, Virginia: USGS, 2007); Mack et al., *Conceptual Model of Water Resources.*

21 E. Böckh, Report on the *Groundwater Resources of the City of Kabul.* Bundesanstalt für Geowissenschaften und Rohstoffe [unpublished] file number 0021016 (1971); Houben, "Hydrogeology of the Kabul Basin".

22 Japan International Cooperation Agency, "The Study on Groundwater Resources Potential in Kabul Basin, in the Islamic Republic of Afghanistan," Final Report, Executive Summary, Sanyu Consultants, Inc. (Kabul; Sanyu, 2011).

Figure 3.2: Kabul region basins and its five sub-basins (central Kabul, upper Kabul/Paghman, Logar, Shamali, Deh Sabz and Panjsher sub-basins)



RLWB = Reach length water balance

Source :(Hillshade based on the U.S. Geological Survey Shuttle Radar Topography Mission data, 2000, 85m resolution)

3.2. *Quantification of surface water infiltration*

Several approaches and methods have been developed and used for quantifying surface –groundwater linkage.[23] The first group of methods typically provides point estimates of infiltration rates through the streambed using controlled experiments,[24] monitoring changes in water content,[25] and heat as tracers of infiltration.[26] The second group of methods uses direct measurements of streamflow during flow events such as RLWB,[27] and flood wave front tracking.[28] These methods estimate transmission loss or streambed infiltration over much larger spatial scales. The third group of methods uses measurements within the groundwater underlying the streambed and therefore estimate groundwater recharge rather than infiltration rates. GWM,[29] and groundwater dating (groundwater tracers including salinity or stable isotopes, i.e., Carbon-14 [14^C]),[30] estimate groundwater recharge representing averages of spatial and temporal values.

For the first group of methods, the data, such as changes in water content, and point infiltration rates are unfortunately not available for Kabul basin. Similarly, for the flood wave tracking in the second group of methods, detailed data of front movement timing and water stage are not available, because the Kabul basin surface water level is measured at only a few river stations located at larger distances from one other. Likewise, the data for groundwater dating are determined by environmental tracers such as salinity, stable isotopes (radon, tritium, 3H/3He, and 14^C). Limited groundwater tracer data are available for Kabul basin,[31] but continued measurement of tracers in surface water bodies near wells that can be studied in terms of surface-groundwater interactions are lacking.

Often more than one method is used for quantification of surface groundwater interaction to improve the confidence of the results obtained using a second method. For Kabul region basins, a continuous streamflow and groundwater level measurements provide sufficient data for RLWB and GWM methods.

3.2.1. Basin-scale water budget balance

The water budget balance is calculated using a basic equation ($dV/dt=E-S$), which shows that variation in water volume (dv) surplus or deficit equals the difference between water input and output over a specific time interval. The input fluxes (E) include the inflow fluxes from rivers flowing into the basin, precipitation rates and rates of sources (e.g., supply from long distance). The output fluxes (s) are comprised of outflow fluxes from rivers flowing out of the basin, evapotranspiration rates and rates of sinks (e.g., water withdrawal for a long-distance supply).

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23 e.g., M. Shanafield and P.G. Cook, "Transmission Losses, Infiltration and Groundwater Recharge through Ephemeral and Intermittent Streambeds: A Review of Applied Methods," *Journal of Hydrology* 511 (2014): 518–529.

24 e.g., D.L. Dunkerley, "Bank Permeability in an Australian Ephemeral Dry-Land Stream: Variation with Stage Resulting from Mud Deposition and Sediment Clogging," *Earth Surface Processes and Landforms* 33, (2008): 226–243.

25 e.g., O. Dahan, B. Tatarsky, Y. Enzel, C. Kulls, M. Seely, and G. Benito, "Dynamics of Flood Water Infiltration and *Ground Water* Recharge in Hyperarid Desert," Ground Water 46, (2008): 450–461.

26 e.g., C.E. Hatch, A.T. Fisher, J.S. Revenaugh, J. Constantz, and C. Ruehl, "Quantifying Surface Water-Groundwater Interactions Using Time Series Analysis of Streambed Thermal Records: Method Development," *Water Resources Research* 42, (2006).

27 e.g., N.M. Schmadel, B.T. Neilson, and D.K. Stevens, "Approaches to Estimate Uncertainty in Longitudinal Channel Water Balances," *Journal of Hydrology* 394, (2010): 357–369.

28 e.g., M. Shanafield, P.G. Cook, P. Brunner, J. McCallum, and C.T. Simmons, "Aquifer Response to Surface Water Transience in Disconnected Streams: Disconnected Aquifer Response To Flood Waves," *Water Resources Research* 48, (2012).

29 Hantush, "Growth and Decay".

30 e.g., A.P. Atkinson, I. Cartwright, B.S. Gilfedder, D.I. Cendón, N.P. Unland, and H. Hofmann, "Using ^{14}C and ^{3}H to Understand Groundwater Flow and Recharge in an Aquifer Window," *Hydrology and Earth Systems Sciences* 18: (2014). 4951–4964.

31 Broshears, "Inventory of Ground-Water Resources"; Houben, "Hydrogeology of the Kabul Basin"; M.H. Saffi, N. Eqrar, and J. Waithaka, "National Alarming on Groundwater Natural Storage Depletion and Water Quality Deterioration of Kabul City and Immediate Response to the Drinking Water Crises," World Bank Meeting sponsored by Danish Committee for Aid to Afghan Refugees (DACAAR), (Kabul: DACAAR, 2019).

$$\frac{dV}{dt} = E - S$$

$$\Delta V = Inflow\ fluxes - Outflow\ Flux + [Precipitation\ - Actual\ evapotranspiration] x basin\ area$$

The inflow and outflow fluxes are the volumetric rates of measured daily flow discharges expressed in m3/month from upstream flowing into the basin and out of the basin respectively. The average monthly precipitation and evapotranspiration rates are multiplied by the basin area to obtain their net volumetric rates in m3/month. The unit time interval for the water balance is 1 month, because the precipitation and evapotranspiration rates are on monthly basis. The monthly average precipitation rates are approximated from the measured precipitation at several hydrometeorological stations within each sub-basin. Monthly average evapotranspiration rates are obtained from actual evapotranspiration (ETa) produced using the operational Simplified Surface Energy Balance (SSEBop) model.[32] The SSEBop model combines evapotranspiration fractions generated from remotely sensed Moderate Resolution Imaging Spectroradiometer (MODIS) thermal imagery, acquired every 8 days, with reference evapotranspiration using a thermal index approach. The groundwater exploitation for domestic water supply is not considered in the water balance equation, because the main objective is to estimate the potential monthly water surplus and deficit over the years 2007 to 2018.

In case of positive (*ΔV*) value, a surplus of water is available that can recharge groundwater, as well as be withdrawn for domestic drinking water demands, long-distance supply and other purposes without causing further decline. A negative value of (*ΔV*) indicates a deficit of water, which is predominantly withdrawn by evapotranspiration from soil moisture that can cause further drawdown of groundwater levels.

In central Kabul, upper Kabul/Paghman and Logar sub-basins, the water balance is calculated from October 2007 to September 2008. The water balance between the gauging stations located in the upper Kabul/Paghman sub-basin, (Paghman River at Qala Malek, Maidan River at Tangi sayedan and Qargha lake outflow), Logar sub-basin (Logar River at Sangi-Naveshta) and central Kabul sub-basin (Kabul River at Tangi Gharo) as shown in Figure 3.2. Unfortunately, for Chakari stream, only historic monthly average data from 1965 to 1980 are available; therefore, for water balancing, historic average monthly flow discharge is assumed. Several sink and sources can be recognised such as Tarakhil canal (withdrawing water from Logar River to central Kabul and Logar sub-basins mainly for irrigation) and Wazir-Abad canal as the main urban drain back to Kabul River. So far, no flow data regarding the sink and sources rates are available. Due to the relatively smaller dimensions of canals draining sinks and sources compared to Kabul River, they are assumed to have marginal contribution to the total water balance and hence the net effect on the water balancing is considered insignificant.

Monthly precipitation is obtained by averaging rates measured in Darul-Aman, Badam Bagh, Tangi-Sayeda, Sangi-Naveshta, and Qala Malek. The monthly average ETa rates are obtained from SSEBop model data for the Bagrami area with mild vegetation that more or less represents an average value for all three sub-basins in consideration. Since ETa rates may vary widely depending on the location and calculation approaches, they are varied by ±25 percent to assess its sensitivity on the water balance calculation.

In Shamali and Panjsher sub-basins, the water balance calculations are performed between the flow discharges measured at several upstream gauging stations in Shamali, Parwan and Kapisa plains and a single outflow gauging station in a bottleneck region of Shukhi in Kapisa province, as shown in Figure 3.2. The main upstream gauging stations for Panjsher River are at Tangi Gulbahar, Ghurband River at Pol-i-Ashawa, Salang River at Bagh-i-Lala and for Shutul River at Bagh-i-Omomi. Three main

32 G.B. Senay, M. Budde, J.P. Verdin, and A.M. Melesse, "A Coupled Remote Sensing and Simplified Surface Energy Balance Approach to Estimate Actual Evapotranspiration from Irrigated Fields," Sensors 7 (2007): 979–1000; G.B. Senay, S. Bohms, R.K. Singh, P.H. Gowda, N.M. Velpuri, H. Alemu, and J.P. Verdin, "Operational Evapotranspiration Mapping Using Remote Sensing and Weather Datasets: A New Parameterization for the SSEB Approach," *Journal of the American Water Resources Association* 49, no. 3, (2013): 577–591.

ungauged streams flow into the plains of Panjsher sub-basin. The similarity of valley morphology and location makes it possible to approximate the flow discharge from Shakar-Dara and Istalef rivers in the Shamali sub-basins. Shakar-Dara, Estalif, Guldara, Farza and Deh Sabz Rivers, as well as several small streams such as Kalakan, flow through small valleys from Safi mountains down to Shamali plains. Among the rivers and streams in the Shamali sub-basin, only Shakar-Dara and Istalef are gauged. The hydrograph for ungauged rivers and streams is approximated based on their catchment area from the gauged rivers, because it is assumed that all valleys down the Safi mountains receive the same rate of precipitation and the soil properties and land cover do not differ significantly. The discharge of ungauged rivers is then simply determined by multiplying the discharge of gauged rivers by the fraction of ungauged catchment area to gauged river catchment area. Lastly, the flow discharge for Deh Sabz River is approximated by a simple rainfall-runoff model using an average precipitation in central Kabul as the main input. Deh Sabz River is an intermittent river flowing as result of precipitation in winter and early spring months and remains dry for the rest of the year.

The inflow fluxes from Shamali and Deh Sabz sub-basins are considered in two scenarios: (i) the inflow fluxes from Shamali and Deh Sabz are included in the water balance for Panjsher sub-basin; and (ii) the inflow fluxes from Shamali and Deh Sabz are assumed to fully infiltrate in Shamali and Deh Sabz sub-basins and they do not contribute to the water balance in Panjsher sub-basin. The scenario study is aimed to reveal the potential range of Shamali and Deh Sabz sub-basins' contribution to the Panjsher sub-basin water balance. Average monthly precipitation is obtained by averaging rates measured in hydrometeorological stations in Tangi-Gulbahar, Bagh-i-Lala, Bagh-i-Omomi, Pole-Ashawa and Shukhi. The monthly average ETa is obtained from SSEBop model data for Gulbahar area. Unlike Kabul basins, ETa for Panjsher sub-basin in Parwan-Kapisa province does not vary significantly from one location to another, because the vegetation coverage is uniformly distributed. Nonetheless, Panjsher sub-basin ETa rates are varied in a range of ±10 percent to assess its sensitivity on the water balance calculation.

3.2.2. Reach length water balance

RLWB has been widely used for estimating river transmission losses.[33] Transmission losses through streambeds and banks can be determined by measuring the flow discharge at successive river cross-sections. The transmission losses are merely the difference between flow discharges at upstream and downstream cross-sections, while also considering other flow sources and sinks including evaporation rates. The flow discharge measurements can be conducted using an Acoustic Doppler Current Profiler (ADCP) with sufficiently high accuracy. The proportion of transmission losses recharging the groundwater depends on the gradient between surface and groundwater heads, duration of flow season, permeability of streambed and rates of evapotranspiration. The transmission losses obtained using RLWB provide important information about the streambed and banks permeability as well. The optimal study reach for RLWB is a free-flowing river or stream with zero or known rates of sink (water withdrawal) and source (additional inflows from tributaries).

Within the selected reach, several cross-sections can be selected for RLWB in order to investigate the downstream change in the transmission losses along the longitudinal distance of the river or stream. The distance between two adjacent cross-sections should be selected such that significant flow discharge difference between them results. The flow discharge is measured using propeller current meter (PCM) and ADCP devices provided by the Ministry of Energy and Water (MEW). The channel cross-section is divided into several sub-sections of equal widths and for each sub-section; water depth and average flow velocity are measured. The flow discharge for each sub-section is derived by multiplying the average flow velocity with flow area (sub-section's width x water depth). The integration of flow discharge for all sub-sections represents the channel total flow discharge. Thus, during the measurement campaign, the channel wetted width, cross-section area, water depth, and average flow velocity are also obtained. Figure 3.3 shows the field campaigns in Maidan River and Khawja irrigation canal using PCM and ADCP devices respectively.

33 R.A. Payn, M.N. Gooseff, B.L. McGlynn, K.E. Bencala, and S.M. Wondzell, "Channel Water Balance and Exchange with Subsurface Flow along a Mountain Headwater Stream in Montana, United States," *Water Resources Research* 45, (2009).

Figure 3.3: Flow discharge measurement for riverbed transmission loss investigation (a) Maidan River using PCM and (b) Khawja irrigation canal in Kapisa province using ADCP device.

In the upper Kabul sub-basin, Paghman and Maidan rivers are selected for RLWB study. Flow discharge is measured at two locations of Paghman River. The flow is tracked downstream to a third location in Qala Malek gauging station where the river fully dries up. The second and third locations are distanced by 1,460 m and 4,205 m, respectively, from the first measuring location in the downstream direction. Similarly, for Maidan River, flow discharge is measured at a single location in the upstream of gauging station in Tangi-Sayedan (Figure 3.3a) and the river fully dries up downstream of Gulbagh Bridge 2,850 m downstream.

In the Shamali sub-basin, flow discharge in Shakar-Dara and Istalef rivers and irrigation canals are measured. For Shakar-Dara River, flow discharge is measured first at Surkh Belandi area and the flow is tracked downstream where the river fully dries up at a distance of 1,000 m. Further, an irrigation canal diverting water from Shakar-Dara River is measured at three locations respectively at distances 3,000 m, 3,500 m and a fourth location at 4,170 m downstream where the canal fully dries up, is marked. For Istalef River, an irrigation canal is measured at two locations. The first location is the hydrometeorological station, followed by a second location at 950 m downstream and the canal fully dries up further downstream at 3,650 m.

In Logar sub-basin, Logar River is measured at two locations downstream of Sangi-Naveshta hydrometeorological station respectively at distances 3,290 m and 4,080 m downstream of the first location. The river fully dries at third location in the Seya-beni area.

In Panjsher sub-basin, an irrigation canal known as Khawja which conveys water from Panjsher River down to the agricultural land in Parwan-Kapisa plains' northern edge is chosen for the transmission loss investigation. The flow is measured right at the inflow of the canal, followed by a second location at 2,000 m downstream at Puli Wuluswali and a third location at 2,800 m at Puli Khawja Mirali area.

Due to the turbulent flow condition of Panjsher sub-basin rivers during the measurement by the Qliner2 ADCP device, the flow measurement could not obtain the required accuracy. The Qliner2 device was difficult to stabilise on the water surface, which led to measurement errors. Therefore, as an alternative, flow measurement was conducted at three locations on the irrigation canal as shown in Figure 3.3b. The reason why the ADCP device is used in Panjsher sub-basin is because of the large water depths and velocity that makes the rivers as well as the irrigation canal non-wadable for PCM deployment. On the other hand, the Qliner2 device gives much better results when the flow depth is large compared to low water depth conditions. In central Kabul and Deh Sabz sub-basins, flow measurements were not possible, because both were fully or partially dry with limited areas of stagnant water.

The locations of the flow discharge measurements and the locations where the rivers and canals go dry were marked using a GPS. The location coordinate (x,y) point data are used in the ArcGIS tool and subsequently the distance between flow discharge measurement locations, as well as the locations where the rivers and canals fully dry up, are determined. The distances are accurately determined by drawing lines along the actual flow path.

It is worth noting that the time gap between flow discharge measurements of two successive locations does not exceed 30 minutes, although it can be assumed that during late summer and low flow period, the flow discharge does not change significantly within a single day; however, during the snowmelt period, flow discharge may significantly vary during a single day. Nonetheless, even during the early summer months (snowmelt time), the 30-minute gap between flow discharge measurements of two successive locations can be a plausible assumption.

The transmission loss is calculated as the difference of flow discharge between upstream and downstream measurement locations in m^3/s. Transmission loss can be demonstrated with respect to the reach length in $m^3/s*km$ or m^2/s by dividing the transmission loss m^3/s over the distance between upstream and downstream measuring locations. This parameter shows the variation of transmission loss across a channel length. The transmission loss is also represented in terms of channel wetted area in $m^3/s*m^2$ or m/s by dividing the transmission loss over the wetted area of the channel reach. The wetted area of the channel reach is derived by multiplying the average wetted perimeter of upstream and downstream measured cross-sections with the total length of the channel reach. This parameter shows a transmission loss per unit channel wetted area in m/s.

3.3. *Quantification of Groundwater Recharge*

Due to the flow seasonality nature of most of the rivers and streams in Afghanistan, between surface and groundwater table, an unsaturated zone is formed which, after the resumption of the flow in rivers and streams, may become partially or fully saturated. If the surface water flow is long enough, a portion of the infiltrated water through the streambed reaches the aquifer and this process is known as groundwater mounding (GWM). The magnitude of the mound (Δh) in an aquifer of specific (Sy) value is a function of the ratio of the recharge rate (R) to the rate that the aquifer transmissivity (T) allows the water to move away laterally. The groundwater level changes can be relatively accurately calculated from the groundwater level observations. The response of the groundwater mound to fluctuations in stream flow can be used to estimate the changes in the volume of groundwater storage, and infiltrated stream water that has recharged the aquifer. The data required for GWM are the rise in the groundwater level (h), the duration of the surface water flow (t) and the lag time between the flow peak and groundwater level rise to estimate the recharge rate for a flow event. The groundwater level rise is read from groundwater monitoring data before and after a flow event. Similarly, the duration of flow event for every water year can be read from the river hydrograph. The lag time is merely the temporal difference between the peaks of flow discharge and groundwater levels.

Several analytical and finite difference numerical simulation methods (e.g., Modflow) can be used to estimate the groundwater recharge rate. One of the most widely used analytical solutions for GWM analysis is by Hantush, who proposed a two-dimensional groundwater flow equation describing it as growth and decay of mounds in response to uniform percolation as:

$$h^2 - h_0^2 = \mathrm{Z(x,y,t)} = \frac{\nu R}{K_h}\int_0^t \left[erf\left(\frac{\frac{w}{2}+x}{\sqrt{4\nu t}}\right) + erf\left(\frac{\frac{w}{2}-x}{\sqrt{4\nu t}}\right)\right]\left[erf\left(\frac{\frac{l}{2}+y}{\sqrt{4\nu t}}\right) + erf\left(\frac{\frac{l}{2}-y}{\sqrt{4\nu t}}\right)\right] \qquad 3.1$$

$$\nu = \frac{\mathrm{K\bar{b}}}{S_y} \qquad 3.2$$

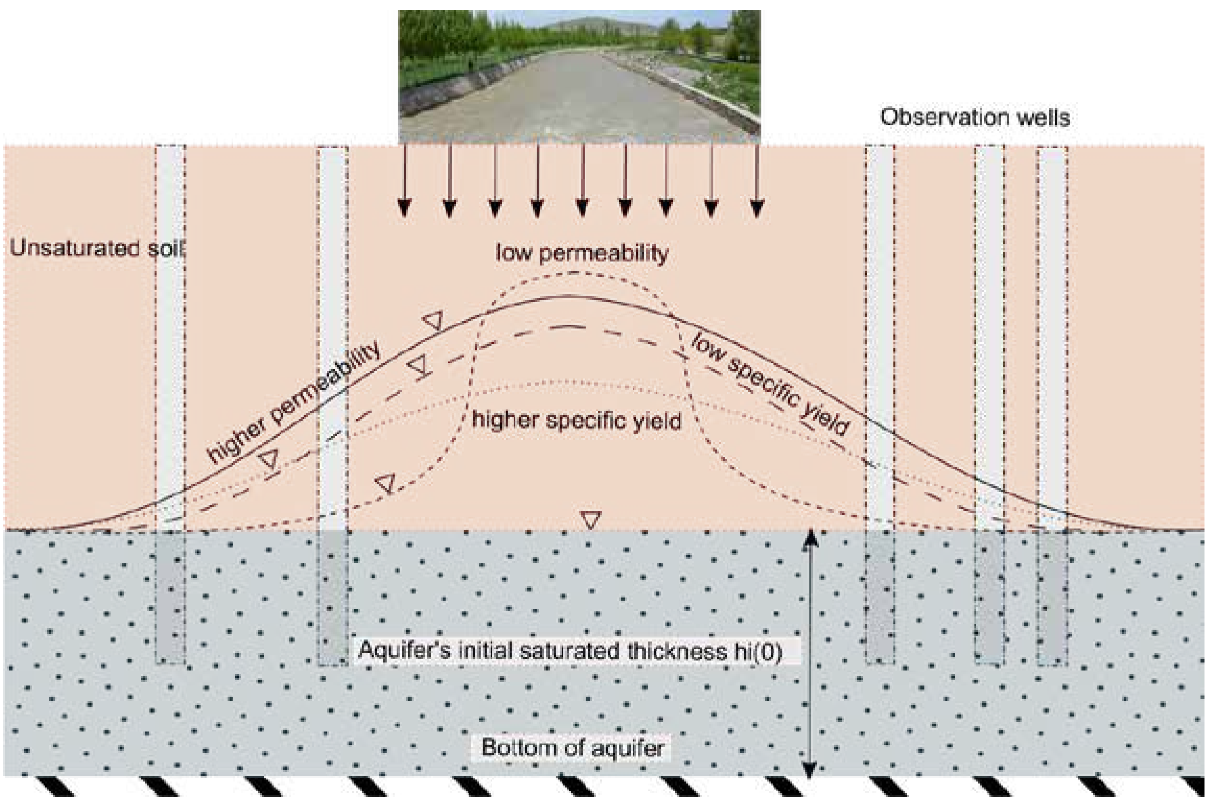
$$\bar{\mathrm{b}} = 0.5[h_i(0) + h(t_1)] \qquad 3.3$$

Where:

(l) and (w) are the dimensions of the recharge area in (y) and (x) direction, respectively; hence, the length and width of the river or stream course in (m). (x,y) is the coordinate of observation points (observation wells). (h) and (h_0) are respectively groundwater head beneath the mound and initial static head prior to the recharge (i.e., initial saturated thickness of aquifer in m). A constant of linearisation ($\bar{b}$) in m is employed in the so-called method of successive approximation to estimate the groundwater mound height. (t) and (t_1) respectively denote the time in (days) since the start of recharge and time used in successive approximation. The aquifer properties are expressed by the horizontal hydraulic conductivity (k_h) in m/day, specific yield (S_y) dimensionless and diffusivity (v) in m^2/day. The error function (erf) also known as Gauss error function and finally (R) is the recharge rate in m/day.[34]

The aquifer sensitivity analysis reveals that by increasing the horizontal hydraulic conductivity value of (K_h), the maximum height of groundwater mound (h) decreases right beneath the basin, but increases in area, as shown in Figure 3.4. The aquifer specific yield (S_y) is a measure of aquifer porosity and is defined as the actual volume of water that can be drained out of a unit volume of aquifer. The maximum mound height decreases when (S_y) increases, because the aquifer stores more water per unit volume compared to when specific yield is lower. More information on the Hantush equation parameters' sensitivity can be obtained from Carleton.[35]

Figure 3.4: Schematic description of groundwater mounding beneath a hypothetical river as recharge basin and the mound shape with respect to high and low (kh) and (Sy) values



The equation is derived based on several assumptions such as (i) the aquifer is unconfined, isotropic and homogeneous; (ii) the groundwater level is horizontal; (iii) the aquifer has an infinite extent;

34 Hantush, "Growth and Decay".

35 G.B. Carleton, "Simulation of Groundwater Mounding Beneath Hypothetical Stormwater Infiltration Basins," U.S. Geological Survey (USGS) Scientific Investigations Report 2010-5102 (Reston, Virginia: USGS, 2010).

and (iv) flow is strictly horizontal.

In the Kabul region basin, the upper shallow aquifer which is in direct contact with surface water, is considered unconfined for all sub-basins.[36] However, recent single well pumping test results in 20 wells with depths between 36 m to 116 m reveal a semi-confined or strongly leaky aquifer type for central Kabul, upper Kabul/Paghman and Logar sub-basins. Nonetheless, the upper shallow aquifer receiving water from rivers can be assumed to be unconfined. In nature, an aquifer is seldom isotropic and homogeneous; rather, it is often anisotropic and heterogeneous. In this study, a heterogeneity of horizontal hydraulic conductivity to vertical hydraulic conductivity is assumed to be a factor of 10, because the clay lenses reported by Böckh[37] may significantly reduce the vertical permeability in the vertical direction even to larger anisotropic values ($K_h/K_v > 10$).

The assumption of horizontal groundwater levels may also contradict the groundwater observations in particular in Shamali, upper Kabul/Paghman sub-basins, because the groundwater levels show relatively strong gradients from the valley-neck toward the basin floor following the ground surface gradient. Since the observations made very close to rivers and streams are predominantly controlled by recharge from surface waters, it is assumed that the sloping groundwater level is not affecting the groundwater growth calculations.

The infinite extent of aquifers assumed in Hantush's equation may have significant effect on the groundwater growth calculation in Kabul region basins, because all sub-basins are bounded by mountains. Thus, the assumption that an aquifer has infinite extent is violated. A rough compromise for infinite extent assumption could be that groundwater is constantly used for water supply and irrigation in Kabul region basins. A continuous groundwater withdrawal may cause the groundwater level growth as result of recharge not to reach the basin boundary. Groundwater observations at wells located far from rivers on the sub-basin boundary confirm this assumption, because the groundwater level is not affected during the recharge period compared to those near the rivers (see Figure 1.1).

The last assumption for strictly horizontal flow is true right after the infiltrated water from riverbed is seeping to groundwater. Right beneath the riverbed, the flow is strongly vertical and further away, and the horizontal component of flow increases, because of higher horizontal permeability compared to vertical permeability of aquifers.

An advantage of Hantush's 1967 analytical method is that since the measured groundwater level changes are used, the method yields actual recharge rates and not infiltration rates. The disadvantage or weakness of this method concerns the assumptions made. In nature, the aquifer's porous medium has often been linked with heterogeneity, as well as changes in geological properties along the longitudinal direction indicating anisotropy. In cases of vertical anisotropy, the height of the groundwater mound is underestimated by Hantush's equation. The anisotropy means various hydraulic conductivities in different directions. Nonetheless, beneath the streambed, the hydraulic conductively is strongly controlled by the alluvial material and therefore, may be less affected by anisotropy.

For this research, an SI version of a spreadsheet by Carletonaquifer thickness, and specific yield. Stormwater-runoff variables that were changed include magnitude of design storm, percentage of impervious area, infiltration-structure depth (maximum depth of standing water[38] is used for calculation of maximum height of groundwater mounds in the center of the basin, as well as at specific distance from the center of the basin. The saturated aquifer thickness hi(0), horizontal hydraulic conductivity (Kh), specific yield (Sy), basin size (length and width), recharge rate (R) and duration (t) are inputs of the spreadsheet. The rivers and streams actually function as a very long rectangular recharge basin. The river course length (L) within each groundwater sub-basin is the

36 Böckh, "Report on the Groundwater Resources of the City of Kabul"; Houben, "Hydrogeology of the Kabul Basin".

37 Böckh, "Report on the Groundwater Resources of the City of Kabul".

38 Carleton, "Simulation of Groundwater Mounding".

basin length, and an average river width (W) is the basin width.

For GWM study, the selected stream reach should have monitoring wells in the vicinity, since the correlation between the rivers' flow event and groundwater level fluctuations are the basis for this investigation. Groundwater level observations are rarely made in Afghanistan and only very limited continuous measurement data are available with the exception of Kabul basin, which has data since 2004 for 70 wells monitored by Afghanistan Geological Survey (AGS) and 10 wells monitored by the Danish Committee for Aid to Afghan Refugees.[39] Often observation wells are used for domestic water supply with installed hand pumps. Data acquired during pumping or after longer pumping show unrealistic fluctuations in groundwater levels and hence are excluded from the analysis. The observation wells considered for GWM study are listed in Table 3.2.

Table 3.2: Observation wells IDs after AGS database, their clear distance from the middle of surface water source, surfaces water widths as well as assumed aquifer properties after Böckh and Johnson.[40]

Central Kabul sub-basin							
Observation wells and their vicinity surface water body					Aquifer properties used		
Well ID	River name	Distance to river [m]	River width (*w*) [m]	River length (*l*) [m]	Saturated thickness h_i [m]	K_h [m/day]	S_y [-]
64	Kabul River	200	58	27,500	56	[10-60]	[0.01-0.15]
127	--	135	38	--	--	--	--
129	--	425	30	--	--	--	--
133	--	957	50	--	--	--	--
152	--	1,018	35	--	--	--	--
162.2	--	596	48	--	--	--	--
163	--	1,790	32	--	--	--	--
172	--	1,810	30	--	--	--	--
210	--	138	38	--	--	--	--
Deh Sabz sub-basin							
2.2	Intermittent rivers and streams	1,200	20	28,000	56	[10-30]	[0.035-0.15]
8	--	890	10	16,500	--	--	--
15	--	1,650	15	--	--	--	--
37	--	617	15	28,000	--	--	--
Upper Kabul/Paghman sub-basin							
113	Maidan River	585	40	14,230	52	[10-30]	[0.035-0.15]
117	--	310	18	--	--	--	--
211	--	1,200	25	--	--	--	--

39 Taher, "Groundwater Levels"; Sidiqi, "Report of Study and Evaluation of Groundwater".

40 Böckh, "Report on the Groundwater Resources of the City of Kabul"; A.I. Johnson, "Specific Yield: Compilation of Specific Yields for Various Materials," Geological Survey Water-Supply Paper 1662-D (Washington, DC: United States Government Printing Office, 1967).

212	--	990	25	--	--	--	--
213	--	830	25	--	--	--	--
100	Paghman River	120	20	24,800	50	[10-30]	[0.035-0.15]
104	--	150	5	7,000	--	--	--
112	--	715	28	24,800	--	--	--
214	--	725	25	--	--	--	--
217	--	915	20	--	--	--	--
Logar sub-basin							
135	Logar River	1,000	20	20,000	58	[10-110]	[0.025-0.15]
143	--	160	25	--	--	--	--
201	--	80	20	--	--	--	--
202	--	100	30	--	--	--	--
Shamali sub-basin							
20	Shakar-Dara/ Barikab	1600	25	60,000	40	[10-60]	[0.01-0.15]
22.1	--	1,900	16	--	--	--	--
24	--	355	16	--	--	--	--
25	--	840	20	--	--	--	--
28	--	690	17	--	--	--	--
41	Istalef/ Barikab	140	20	23,400	--	--	--
43	--	145	15	--	--	--	--
45	--	1,250	15	--	--	--	--

The procedure for GWM analysis is described in following four steps:

1. The groundwater level data are checked for each water year's maximum and minimum water levels. The maximum water levels usually occur between March and June and the minimum water levels occur between August and October, as shown in the example for groundwater observations in Well 64 in central Kabul sub-basin in Figure 3.5a.

2. For each water year, the lowest groundwater level is taken as a reference for calculating the net change as a result of withdrawal (negative change) or recharge (positive). The groundwater levels are subtracted from the lowest reference level until the next year's minimum point is reached. The calculation procedure is repeated by taking the next year's lowest groundwater level as the reference. The groundwater level change with time shows a growth phase when it is positively increasing, and a decay phase, when it declines. The groundwater level growth phase is associated with recharge processes from surface waters, irrigations and direct precipitation and the decay phase is indicative of mound spreading and extraction. The duration of groundwater level growth is calculated based on the time difference between the start and end (Figure 3.5b).

3. Solving for Hantush's equation (3.1), groundwater growth is fitted with mounding levels by changing the recharge rates within the growth duration. The recharge rate is adjusted on the monthly basis when required to achieve best agreement with the measured level growth (Figure 3.5c).

4. The recharge rates are subsequently verified with the changes in flow discharge using the measured river's hydrograph, precipitation and evapotranspiration rates. This comparison is essential because the effect of groundwater recharge from the surface water and irrigation or direct precipitation can be recognised. Although the contribution of each recharge source cannot be quantified from this comparison, nonetheless, a qualitative influence of other recharge sources can be observed (Figure 3.5d).

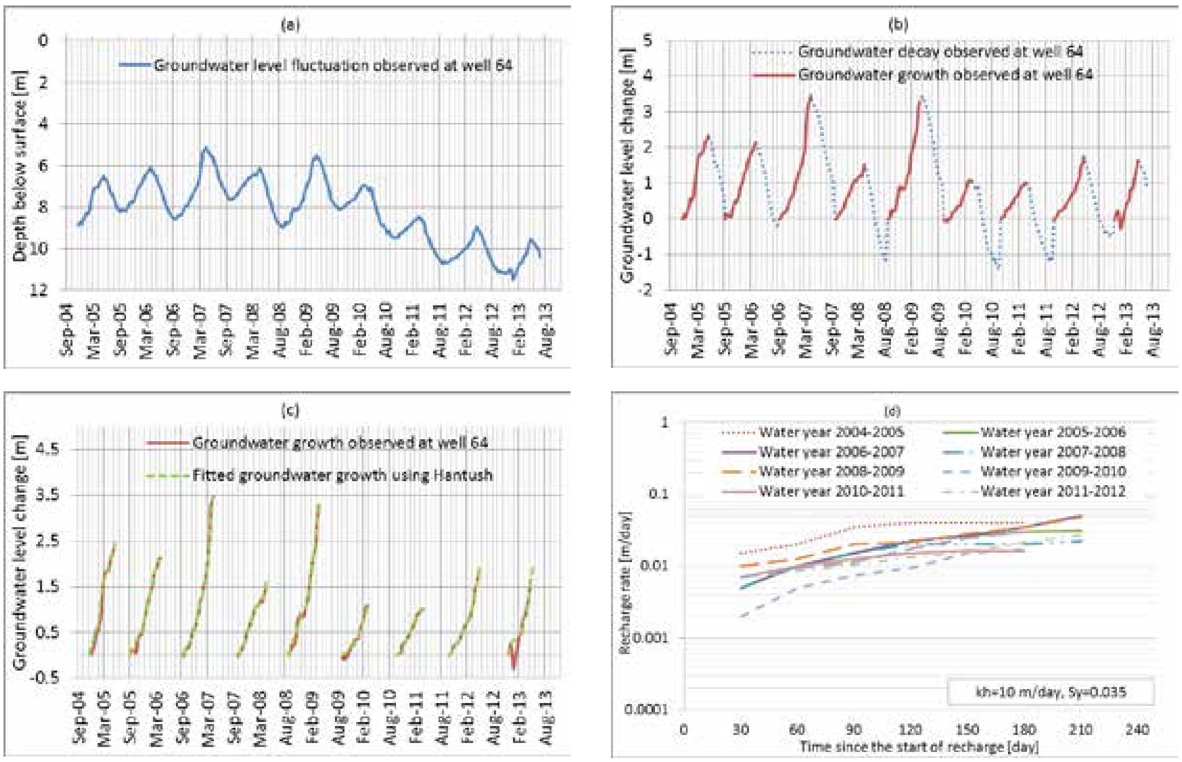


Figure 3.5: Steps for groundwater recharge estimation using groundwater mounding approach by Hantush, (1967)(a) measured groundwater levels for well 64 located at 200 m from Kabul river (b) groundwater growth (solid red line) and decay (dotted blue line) (c) fitted calculated groundwater growth using Hantush equation and (d) groundwater recharge rates fulfilling the groundwater growth for water years 2004 to 2013.

Source: Groundwater data (Sidiqi et al., 2019)

As mentioned earlier and extensively studied by Carleton,[41] the Hantush equation is sensitive to hydraulic conductivity (soil permeability), soil specific yield (soil porosity), initial aquifer thickness (saturated soil thickness) and basin dimensions (basin length and width). In nature, the values of (K_h) usually vary by several orders of magnitude at any given site. The (K_h) values for Kabul region basins reported by Böckh[42] vary by at least one order of magnitude; therefore, their values are varied between 10 m/day to 110 m/day. The values of specific yield (S_y) can also vary widely depending primarily on the soil characteristics such as grain sizes, porosity, soil texture, and soil compaction as result of cementation. The value of (S_y) for any aquifer can vary by at least a factor of two as reported by Johnson.[43] Böckh[44] reported a (S_y) value of 0.075 for the shallow aquifer and much lower value of 0.025 for the lower layer of conglomerates in Kabul region basins. Therefore, the value of (S_y) is varied between as low as 0.01 to 0.15 to cover a large spectrum of its variations and to assess the sensitivity of (S_y) on the determination of recharge rates. Nonetheless, for achieving more accuracy, more comprehensive aquifer pumping tests are required to determine the values of (K_h) and (S_y) and their range of variations for all sub-basins in Kabul region. Therefore, the value of (S_y) is varied between as low as 0.01 to 0.15 to cover a large spectrum of its variations and to assess the sensitivity of (S_y) on the determination of recharge rates. Nonetheless, for achieving more accuracy, more comprehensive aquifer pumping tests are required to determine the values of (K_h) and (S_y) and their range of variations for all sub-basins in Kabul region.

Initial thickness of saturated soil or aquifer thickness can vary by several factors. A basin floor may have the largest (hi) thickness while it decreases gradually toward the boundary. For Kabul region, sufficient information regarding the (hi) thicknesses is available; thus, (hi) is excluded from sensitivity analysis. Basin length (l) and width (w) cannot vary significantly, because site measurements can be easily conducted. Nonetheless, rivers and streams may strongly vary their widths that can influence the total recharge per unit cross-section area. In this research, an average river width is assumed. A sensitivity analysis of (K_h) and (S_y) will reveal their influence for the estimation of a mean recharge rate for each sub-basin.

Table 3.3 summary of the sensitivity analysis parameters change from a reference analysis.

Sub-basin	Parameters	Reference analysis	Sensitivity analysis I	Sensitivity analysis II	Sensitivity analysis III	Sensitivity analysis IV	Sensitivity analysis V
Central Kabul	Kh (m/day)	10	10	60	60	60	30
	Sy (-)	0.035	0.070	0.010	0.035	0.15	0.15
Logar	Kh (m/day)	10	110	10	30		
	Sy (-)	0.025	0.025	0.07	0.15		
Upper Kabul/ Paghman	Kh (m/day)	10	30	30			
	Sy (-)	0.035	0.035	0.15			
Shamali	Kh (m/day)	10	60	60	60		
	Sy (-)	0.05	0.035	0.01	0.15		
Deh Sabz	Kh (m/day)	10	30	30			
	Sy (-)	0035	0.035	0.15			

41 Carleton, "Simulation of Groundwater Mounding".

42 Böckh, "Report on the Groundwater Resources of the City of Kabul".

43 Johnson, "Specific Yield".

44 Böckh, "Report on the Groundwater Resources of the City of Kabul".

4. Study Results

4.1. *Water budget balance*

The water budget balance results for Kabul region river networks in Kabul, upper Kabul or Paghman and Logar sub-basins and Parwan-Kapisa river networks in Panjsher sub-basins are shown in Figure 4.1 (a & b) and Figure 4.2 (a & b), respectively. Figures 4.1 (a) and 4.2 (a) show sum of inflow fluxes, outflow flux and the difference between them in m^3/s on the left vertical axis and monthly average rates of precipitation and ETa in mm on the right vertical axis. Figures 4.1 (b) and 4.2 (b) show volumetric rates of monthly average precipitation and ETa in m^3 on the right vertical axis and the volumetric average transmission loss in m^3 on the left vertical axis. The blue-shaded regions extending out of pink shaded-areas represent the contribution of rainfall to the groundwater regeneration. The blue-shaded regions behind the pink-shaded areas indicate larger ETa rates than rainfall rates; thus, precipitated water is lost due to higher evapotranspiration before infiltrating into the groundwater.

4.1.1. Kabul region

In Kabul region, the rainfall contribution to the groundwater regeneration lasts from November to April during which the ETa rates are the lowest compared to the rest of the year. The second contributor to the groundwater regeneration is the transmission losses through riverbed and banks as result of infiltration. The transmission loss is the difference between inflow fluxes and outflow flux. The inflow fluxes for Kabul region are the sum of average daily flow discharges measured at Sangi-Naveshta, Tangi-Sayedan, Qala Malek, Bandi-Amir Ghazi and outflow of Qargha lakes, respectively, for Logar, Maidan, Paghman and Chakari rivers. The outflow flux is the average daily discharges measured at Tangi-Gharo station further downstream of Kabul River. The green-shaded regions in Figure 4.1(a) represent the difference between inflow fluxes and outflow flux. All positive fluxes difference values indicate transmission loss between upstream and downstream river network stations. Highest transmission losses are observed between months November to April. The lowest is between June to October both as water is diverted for irrigation and both upstream and downstream reaches become dry. The negative values of the flux differences indicate a downstream increase in flow fluxes occurring between March and May. During this time, early spring rainfall on the urban region of Kabul leads to considerable runoff, which is drained by canals such as Wazir Abad to Kabul River. Unfortunately, flow data of urban drainage canals is not available; therefore, transmission loss for this period cannot be estimated. This of course does not mean that water is not lost as a result of infiltration during this period; rather, the negative flux differences make the transmission loss calculation impossible.

The net volumetric water surplus or deficit in m^3 is plotted in Figure 4.1(b) as a function of volumetric rates of precipitation and ETa. From November to April, a net water balance surplus (positive) is observed, with a deficit from May to October.

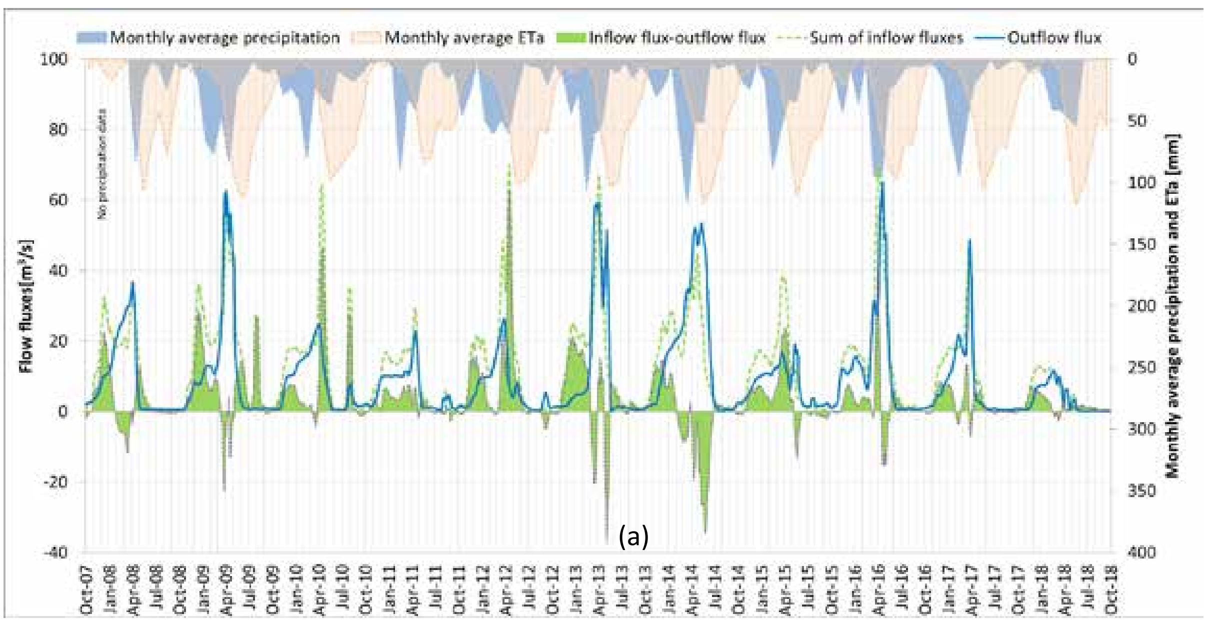
The ETa for this study is estimated based on the SSEBop model[45] that varies widely depending primarily on the land surface vegetation cover. The values of ETa for Kabul region are assumed from Bagrami area located between the central Kabul urban area and the rural area in Logar sub-basin with temperate vegetation. The ETa values may therefore be overestimated for the Kabul urban region with much less vegetation cover. Thus, the water budget balance is also calculated subsequently for a 25 percent reduction and 25 percent increase in ETa rates. The reduced ETa rates significantly increase the net water surplus and have resulted in intensive decrease in net water deficit, while, as a result of 25 percent increase in Eta rates, water deficit is observed for all investigated years, except a marginal surplus for year 2013. The net volumetric water surplus and deficit for all three ETa cases are summarised in Table 4.1.

45 Senay, "Operational Evapotranspiration Mapping".

Table 4.1: Yearly water balance surplus and deficit for Kabul region basin (Upper Kabul/Paghman, central Kabul and Logar sub-basins)

year	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018
Surplus 106(m^3)	128.6*	313.2	196.2	250.1	332.9	378.6	209.9	260.5	206.3	188.6	18.46**
Deficit 106(m^3)	156.3	221.0	218.2	217.6	295.9	260.2	198.8	264.5	224.7	233.4	330.4
25% reduction in ETa											
Surplus 106(m^3)	147.5*	356.9	219.1	272.1	363.2	406.4	235.9	295.0	251.1	198.7	20.8**
Deficit 106(m^3)	104.6	138.0	127.9	153.0	194.8	177.4	129.8	179.1	148.1	134.5	232.2
25% increase in ETa											
Surplus 106(m^3)	112.0*	280.7	178.2	228.1	302.5	350.8	194.7	234.2	168.9	178.6	16.1**
Deficit 106(m^3)	210.4	315.4	313.4	282.2	397.2	349.9	278.6	358.0	306.6	332.2	428.8

*No Precipitation data are available for January to March 2008. **Precipitation data for year 2018 are limited to January to September only.



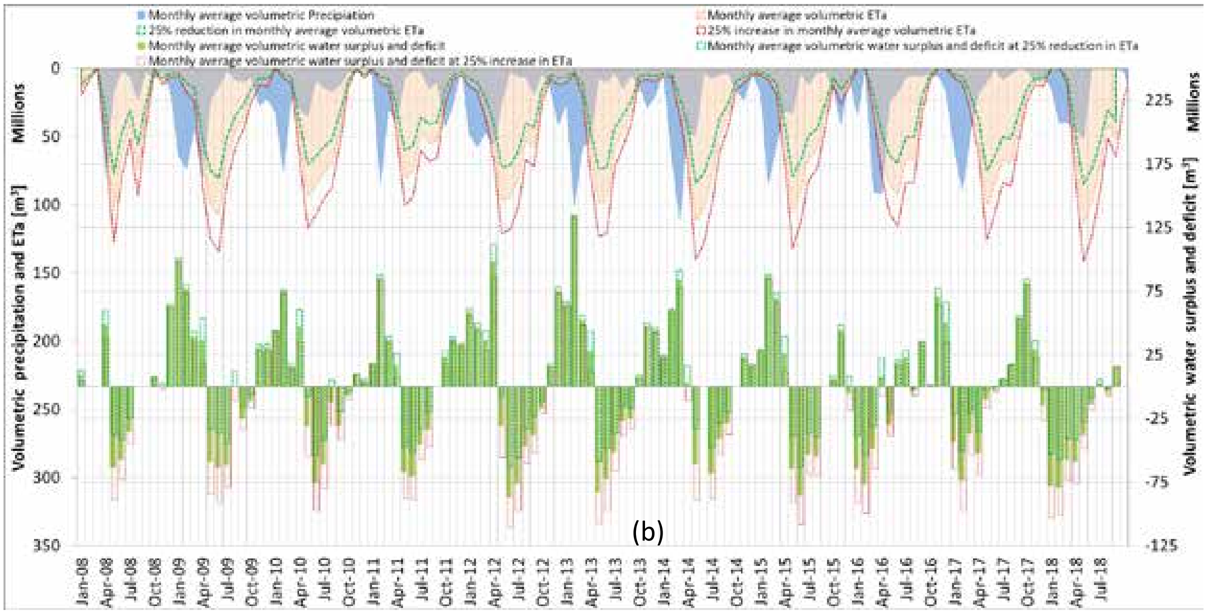


Figure 4.1: Basin-scale water budget balance for Kabul basin (central Kabul, upper Kabu/Paghman and logar sub-basins) (a) Daily average inflow fluxes, outflow fluxes and average monthy rates of ETa and precipitations (b) volumetric rates of ETa and precipitation as well as total water surplus and deficit

Sources: Precipitation data from MEW and MAIL; River hydrographs data from MEW; ETa data from U.S Geological Survey (USGS) and Earth Resources Observation and Science (EROS)

As shown, in Kabul region, the rates of precipitation and their timing are crucial elements of the water balance. The precipitation levels during the winter and early spring months are the most important for generating a water surplus that may partly be recharging groundwater. All other precipitation in the summer and late summer months may evaporate from the land surface and will not take part in groundwater regeneration. In years with a water deficit, not only groundwater recharge will reduce but the domestic water supply from groundwater may additionally lead to further decline of groundwater levels. Therefore, it is very important to leverage years with a water surplus for groundwater recharge by establishing suitable conditions in the river system scale, as well as by establishing additional artificial recharge basins.

4.1.2. Parwan-Kapisa region (Panjsher sub-basin)

The monthly average ETa values are much larger compared to Kabul basin, because of dense vegetation cover in Panjsher sub-basin. The highest ETa occurs between April to October; the rest of the year, the rate of ETa is significantly decreased as a result of drops in air temperature and vegetation cover. Most importantly, during this low ETa period, most of the year's total precipitation occurs, which significantly contributes to the positive water balance in Panjsher sub-basin.

The inflow and outflow fluxes show a predominant snowmelt flow regime, with a single flow peak in June. In Panjsher sub-basin, the inflow and outflow fluxes can be studied in two periods. During the high flow periods (April to August), the outflow flux is larger than inflow fluxes except for the years 2009, 2014 and 2018. The anomaly in larger outflow flux than inflow fluxes may have two reasons. First, a systematic measuring error either in upstream or downstream gauging stations may have led to an underestimation of flow discharge at the former or an overestimation at the latter. Therefore, an assessment of flow discharge estimation methodology should be performed to find out to what extent the measurement error may have influenced the larger outflow flux at Shukhi station. Secondly, the larger outflow flux during high flow period may be explained by the exfiltration of groundwater at the edge of Panjsher sub-basin in Shukhi area of Kapisa province. The aquifer thickness in the bottleneck valley decreases drastically and, accordingly, the storage capacity compared to Panjsher sub-basin. The groundwater level observation in Shukhi area shows a water level as low as 2.5m on the edges of the valley.[46] Groundwater simulation results by Modflow also show the groundwater flow direction toward Shukhi with significant gradient from Panjsher sub-basin.[47] One may argue about different inflow and outflow flux behaviour for 2009, 2014 and 2018 compared to the rest of the years. The rate of the exfiltration at Shukhi may be dependent on the degree of Panjsher sub-basin groundwater storage saturation. When the Panjsher sub-basin groundwater does not reach full storage saturation, the exfiltration may not occur; therefore, the outflow flux is less than the inflow fluxes. Roughly 16 percent of irrigation water in Parwan and Kapisa provinces is supplied by the groundwater;[48] therefore, there is continuous extraction and recharge of groundwater storage in Panjsher sub-basin. Nonetheless, a comprehensive investigation is required to verify first whether exfiltration occurs and, if it does occur, at what rate.

Thus, in this study, for the period at which the outflow flux is larger than inflow fluxes are excluded from the water balance analysis. Although the transmission losses rates cannot be estimated for the period with inflow fluxes are smaller than outflow fluxes; they do occur as in years 2009, 2014, and 2018 that large transmission losses are observed during high flow periods. The transmission losses, however, can be estimated for the late summer and winter months (September to April), because the inflow fluxes for this period are often larger than outflow fluxes.

The volumetric water surplus and deficit as a result of the water budget balance for Panjsher sub-basin is shown in Figure 4.2 (b). The monthly volumetric water surplus and deficit is calculated for those months with positive flux differences between inflow and outflow; thus, periods with negative fluxes between inflow and outflow (larger outflow fluxes than inflow fluxes) are excluded from the investigation. Additionally, to understand the sensitivity of ETa values, monthly averages are increased by 10 percent and subsequently decreased by 10 percent. The volumetric water surplus (positive) and deficit (negative) are shown in million m^3 by green column charts. The sensitivity of the ETa is shown by orange and mint dashed lines for a 10 percent increase and 10 percent decrease, respectively.

The results of water balance for the case including the inflow fluxes from Shamali and Deh Sabz are shown by column charts in mint. For all cases in Panjsher sub-basin, the surplus of water exceeds the deficit, mainly due to the larger precipitation rates compared to Kabul region basin, despite larger ETa values. Larger water surplus is observed for the months February to April, during which precipitation rates are highest and ETa rates are lowest, while the water deficit occurs during the months June to September with the highest ETa rates and irrigation demand. The variation of ETa rates by ±10 percent revealed only marginal changes in the net water surplus and deficit.

The water surplus shows significant increase when the inflow fluxes from Shamali and Deh Sabz sub-basins are included. A summary of yearly water surplus and deficit is listed in Table 4.2.

46 Saffi, “Water Resources Potential”.

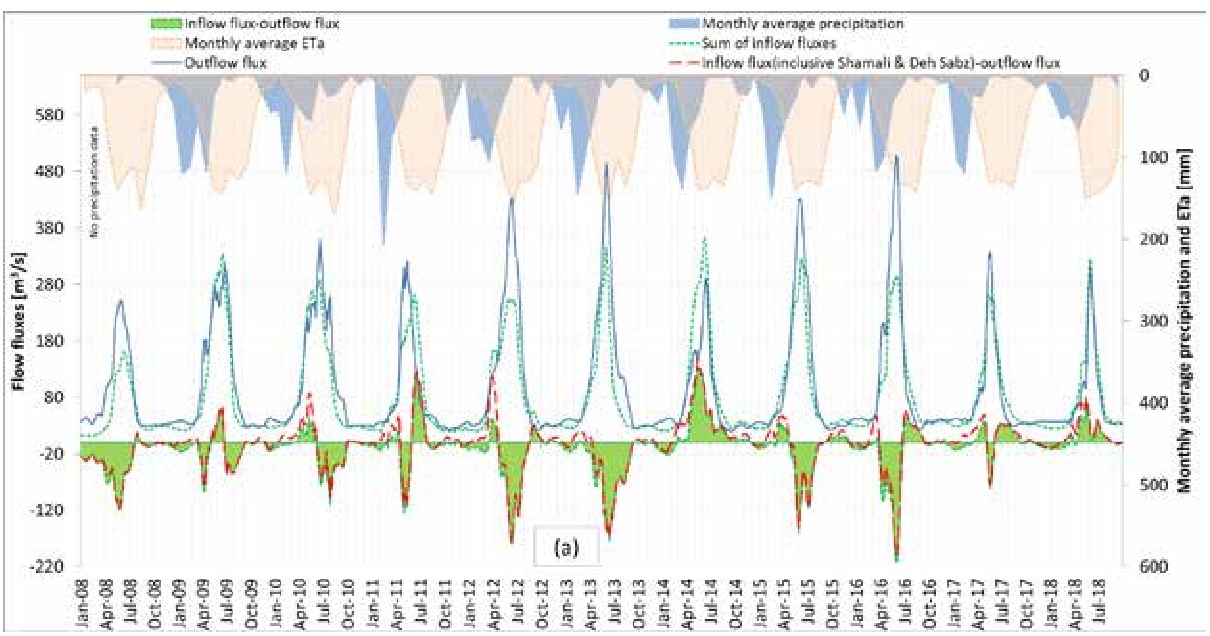
47 Mack, *Conceptual Model of Water Resources*.

48 S.S. Shobair, “Current Drought Situation in Afghanistan, Drought Assessment and Mitigation in Southwest Asia,” International Water Management Institute (2001).

Table 4.2: Yearly water balance surplus and deficit for Panjsher sub-basin (Parwan-Kapisa)

year	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018
Surplus $10^6(m^3)$	0.0*	111.2	99.3	431.7	193.3	66.8	682.7	202.9	140.0	107.7	186.8**
Deficit $10^6(m^3)$	56.6	61.7	85.2	74.0	40.9	107.2	9.4	133.8	0.0	30.0	48.2
With inflow fluxes from Shamali and Deh Sabz											
Surplus $10^6(m^3)$	0.0*	201.8	326.5	577.6	474.3	169.4	915.9	364.8	265.2	306.6	320.1**
Deficit $10^6(m^3)$	57.8	60.9	61.8	95.1	65.8	99.6	3.5	123.9	29.1	5.8	46.6
10% reduction in ETa											
Surplus $10^6(m^3)$	0.0*	123.6	107.9	445.9	202.6	68.6	705.0	208.4	154.9	122.9	203.5**
Deficit $10^6(m^3)$	48.2	54.0	71.0	66.1	35.6	94.3	6.3	118.6	0.0	21	41.1
10% increase in ETa											
Surplus $10^6(m^3)$	0.0*	102.3	90.6	417.5	184.3	65.1	660.5	197.5	125.1	92.6	170.2**
Deficit $10^6(m^3)$	65.1	73.0	99.5	81.9	46.2	120.1	12.6	249.1	0.0	39.0	55.2

*No precipitation data are available for January to May of 2008. **Precipitation data for year 2018 are limited to January to September only.



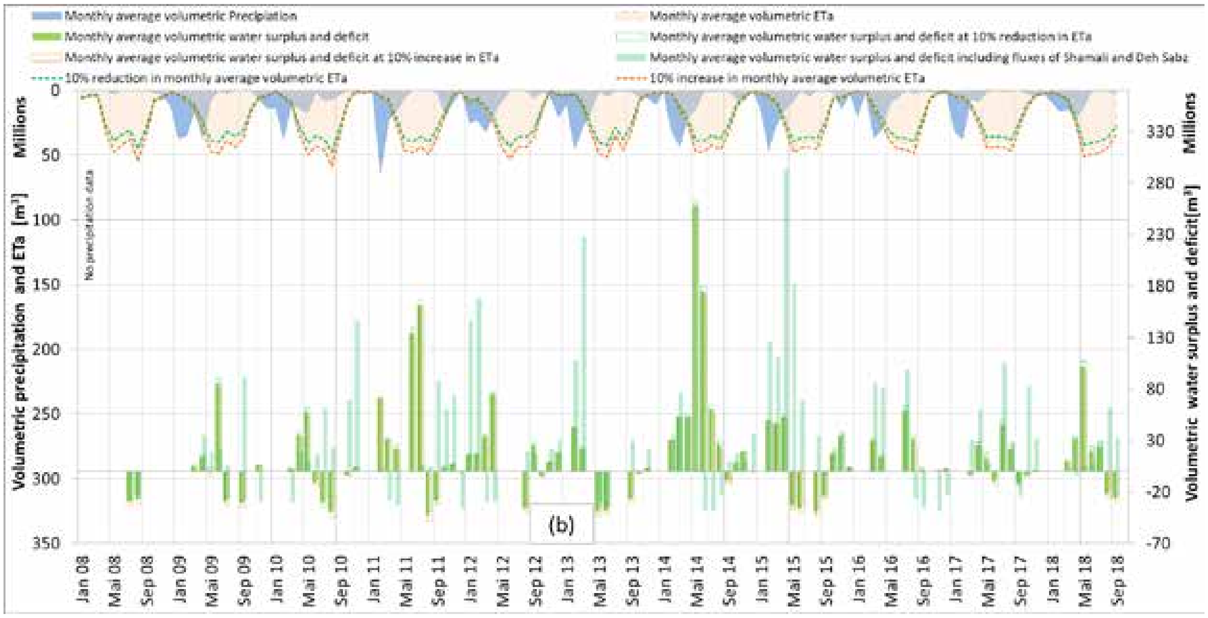


Figure 4.2: Basin-scale water budget balance for Panjsher sub-basin (a) Daily average inflow fluxes, outflow fluxes and average monthy rates of ETa and precipitations (b) volumetric rates of ETa and precipitation as well as total water surplus and deficit

Sources: Precipitation data from MEW and MAIL; River hydrographs data MEW; ETa data from USGS and EROS

Unlike Kabul basin, in Panjsher sub-basin, the water balance for 2008-2018 shows large surpluses. Despite the fact that, due to the anomaly of larger outflow flux than inflow fluxes for the summer periods (June-October), water surplus in the form of river transmission losses (inflow-outflow fluxes) is excluded from the water balance analysis, a surplus of water is shown for almost all investigated years. Water deficits only occur during late summer (July-October), with high ETa rates and almost zero precipitation rates. The rest of year, the water budget shows a surplus that significantly contributes to groundwater regeneration in Panjsher sub-basin. The larger outflow fluxes as opposed to inflow fluxes at the outflow edge of sub-basin boundary in Shukhi area are indicative of full aquifer storage regeneration that even leads to exfiltration back to surface water during high flow periods.

As shown, the water balance is strongly influenced by the rates of ETa. Unfortunately, ETa observation data do not exist for Kabul region that can validate the SSEBop approach utilised in this research. Therefore, the water surplus and deficit values for the investigated years should be considered as relative values. The error in ETa estimates may be larger for central Kabul and upper Kabul sub-basins compared to Panjsher sub-basin, because Kabul province has large built-up (paved) area, and less vegetated area that can strongly affect the ETa rates. In Panjsher sub-basin, the land surface has large uniformly distributed vegetated area that can serve for more uniform distribution of ETa as well. However, the SSEBop approach uncertainty may influence both sub-basins with the same degree.

4.2. *Reach length water balance results*

The RLWB results for upper Kabul/Paghman, Shamali, Logar and Panjsher sub-basins are summarised in Table 3.3. Key parameters are upstream (US) section discharge, downstream (DS) section discharge, reach length, wetted perimeter, maximum water depth, and average section velocity and transmission loss per unit wetted area.

In the upper Kabul/ Paghman sub-basin, the transmission loss for the investigated Maidan River and Paghman River reaches varies from 1.0x 10^{-5} m/s and 5.63x10^{-5} m/s, respectively. The larger transmission loss rates of about a factor five for Paghman River compared to Maidan River can be roughly explained by very coarse riverbed sediments (i.e., cobbles to sand) compared to riverbed sediments of Maidan River containing significant amount of fine sediments (i.e., clay and silt). Similarly, in Shamali sub-basin, the transmission loss rates vary between 4.2x 10^{-5} m/s and 1.0x 10^{-4} m/s for Shakar-Dara and it ranges between 5.1x10^{-5} m/s and 1.39x10^{-4} m/s for the Istalef River irrigation channel. The transmission loss rates are similar to Paghman River, because both Shakar-Dara and Istalef rivers have strong hydro-sedimentological similarities.

In Logar sub-basin, the transmission losses of Logar River vary between 9.7x10^{-6} m/s and 3.0x10^{-5} m/s. The transmission loss rates are smaller than Shakar-Dara, Istalef and Paghman rivers, but are similar to Maidan River, because Logar riverbed also has a significant amount of fine sediments. Usually Logar River dries up from July to October, but the exfiltration of groundwater from the marshland upstream of Sangi-Naveshta station partially supplies water to the river that is eventually lost around 6.5 km downstream. In Panjsher sub-basin, an irrigation canal locally known as canal Khawja is investigated. The transmission loss rates of canal Khawja within the study reach vary between 2.0x10^{-5} m/s and 8.2 x10^{-5} m/s. The Khawja irrigation canal-bed is predominantly sandy to silty with relatively good permeability that allows infiltration into the groundwater; however, the stone masonry walls of the canal hinder bank filtration. Due to the difference in riverbed materials of rivers in Panjsher sub-basin with predominantly gravel-beds compared to irrigation canals, the transmission loss rate of Khawja canal provides a rough estimate of minimum transmission loss rates.

The transmission losses for rivers and canals in Shamali, upper Kabul/Paghman and Logar sub-basins also represent a rough estimate of minimum transmission loss, because the study is conducted during July to August, with minimum flow discharge. The transmission loss of water during this period is not fully occurring in groundwater regeneration, because a significant part of the water is lost due to high rates of evaporation from the soil column.

Table 4.3: Summary of reach length water balance for rivers, streams and irrigation canals in upper Kabul/Paghman, Shamali, Logar and Panjsher sub-basins

River/canal	US discharge (m^3/s)	DS discharge (m^3/s)	Reach length (m)	Wetted perimeter (m)	Maximum depth (m)	Average flow velocity (m/s)	Transmission loss per unit wetted area (m^3/sm^2)
Upper Kabul/ Paghman sub-basin							
Paghman River reach 1	0.37	0.18	1,460	2.8	0.32	0.51	5.63 $x10^{-05}$
Paghman River reach 2	0.18	0.00	2,745	1.8	0.40	0.35	3.66 $x10^{-05}$
Maidan River	0.20	0.00	2,850	7.0	0.30	0.15	1.00 $x10^{-05}$
Shamali sub-basin							
Shakar-Dara River	0.13	0.00	1,000	1.5	0.23	0.5	8.67 $x10^{-05}$
Shakar-Dara (irrigation channel) reach 1	0.53	0.39	500	2.8	0.33	0.7	1.00 $x10^{-04}$
Shakar-Dara (irrigation channel) reach 2	0.39	0.10	3,000	2.3	0.35	0.5	4.20 $x10^{-05}$
Shakar-Dara (irrigation channel) reach 3	0.1	0.00	670	2.2	0.19	0.3	6.78 $x10^{-05}$
Istalef River/ irrigation channel reach 1	1.05	0.28	950	3.7	0.49	0.73	1.39 $x10^{-04}$
Istalef River/ irrigation channel	0.28	0.0	2,700	2.2	0.33	0.45	5.10 $x10^{-05}$
Logar sub-basin							
Logar River reach 1	0.14	0.07	3,290	1.4	0.22	0.42	9.67 $x10^{-05}$
Logar River reach 2	0.07	0.00	790	3.0	0.26	0.11	2.95 $x10^{-05}$
Panjsher sub-basin							
Canal Khawja reach 1	9.34	8.99	2,000	10.0	1.35	0.80	2.03 $x10^{-05}$
Canal Khawja reach 2	8.99	8.022	800	7.0	1.24	0.77	8.22 $x10^{-05}$

4.3. Groundwater mounding analysis results

Recharge rates are determined by fitting the change in groundwater levels with the growth rates from the Hantush (1967) equation. The recharge rates fulfilling the groundwater change in a specific well are represented by a single dashed line identified by a well ID (as given by the AGS database) and their distance from the nearby water body (river or stream) in semi-logarithmic diagrams. The results for each well cover a 10-year spectrum of groundwater growth from 2004 to 2013. The groundwater level change varies from one water year to another depending on the river water year discharge magnitude and flow period, as well as on rate of precipitation that can partially contribute to the groundwater level growth. Therefore, for each water year, the associated recharge rates reproducing the groundwater change are shown by the same colour. The variation over the recharge period in days indicate which rate reproduces the given groundwater level growth under certain horizontal hydraulic conductivity (kh), specific yield (Sy), initial saturated thickness of aquifer, and the dimension of water body. As an example, if the recharge at day 180 is 0.1 m/day, it means a constant recharge rate of 0.1 m/day over the whole period of 180 days must persist in order to fulfil the groundwater growth observed at a specific observation well. The recharge rates are determined on a monthly basis (30 days), because the groundwater level measurements are also conducted every month except for well number 64; therefore, the first rates of recharge are provided at the end of every 30 days.

4.3.1. Central Kabul sub-basin

In the central Kabul sub-basin, the recharge rates fulfilling the observed groundwater level growth are shown in Figure 3.3 (a), (b), (c), (d), (e) and (f), respectively, for (kh=60 m/day; Sy=0.01), (kh=60 m/day; Sy=0.035), (kh=10 m/day; Sy=0.035), (kh=10 m/day; Sy=0.07), (kh=30 m/day; Sy=0.15) and (kh=60 m/day; Sy=0.15).

In general, for most of the water years, the groundwater recharges occur from 150 to 210 days, up to a maximum of 240 days. The recharge rates vary significantly, as well as for wells close to river (e.g., W127 and W210) and those located much farther from river (e.g., W172 and W163). Highest variations are observed right at the beginning of the recharge period to 90 days and decreases afterwards. Theoretically, recharge rates should be much lower at the initial period, increase to a certain value and remain constant for the rest of period analogous to surface water level rise in Kabul River. Two reasons may lie behind intensive rate variations at the initial recharge period. The observation wells are often installed with hand pumps and used for public water supply; therefore, the observed groundwater levels may not be static but dynamic. The dynamic groundwater levels may be affected by pumping; therefore, the groundwater level growth may lack accuracy. In central Kabul sub-basin, only four wells (W64, W127, W129 and W133) have more or less static groundwater level observations, and the recharge rate obtained for these for wells show normal behaviour. For example, groundwater observation at W64 is well reproduced by lower recharge rates at initial recharge period, while the rates achieve a constant value by the end of recharge period, as shown by dashed green line in Figure 4.3.

Secondly, the recharge variations spectrum is strongly controlled by the aquifer's (kh) and (Sy) values. Higher (kh) and lower (Sy) values lead to much lower variation in recharge compared to lower (kh) and higher (Sy) values. Therefore, those values of (Kh) and (Sy) where realistic recharge rate variations result may better represent the natural conditions. The controlling parameters for recharge variations are predominantly the aquifer properties; thus, the Hantush groundwater recharge equation is run for a range of (kh) and (Sy) values to determine the sensitivity of these parameters. A close agreement between recharge rates fulfilling the groundwater level growth in wells close to river and those far from river are considered optimum. As shown in Figure 4.3 (b) and (c), for instance, an increase in (kh) value from 10 m/day to 60 m/day resulted in fewer variations in recharge rates compared to a (kh) value of 10 m/day, because higher kh values mean that the infiltrated water moves faster and increases the extent of groundwater mounding; therefore, the change in recharge rate for wells close to the river and those far from the river reduces. Similarly, the sensitivity of (Sy) value is analysed for a range of values between 0.01 and 0.15. The results indicate that lower (Sy) values lead to smaller recharge variations, as can be observed in Figure 4.3, in particular during the initial phase of recharge period (30 to 90 days) compared to larger (Sy) values. Since the higher (Sy) value means that aquifer stores more water per unit volume of aquifer, therefore with a given recharge rate, the mounding height or groundwater level growth would be lower in the lateral extent. Thus, higher recharge rates are required to impose groundwater level growth compared to (Sy) values. The sensitivity of aquifer properties reveals non-linear changes in groundwater level growth, because this is expressed by a non-linear equation. On average, for central Kabul sub-basin, a recharge rate of 0.025 m/day, 0.056 m/day, 0.046 m/day, 0.14 m/day, 0.23 m/day and 0.18 m/day can be estimated that meets the groundwater level growth observations in all wells respectively for (kh=60 m/day, Sy=0.01), (kh=60 m/day, Sy=0.035), (kh=10 m/day, Sy=0.035), (kh=10 m/day, Sy=0.07), (kh=30 m/day, Sy=0.15) and (kh=60 m/day, Sy=0.15).

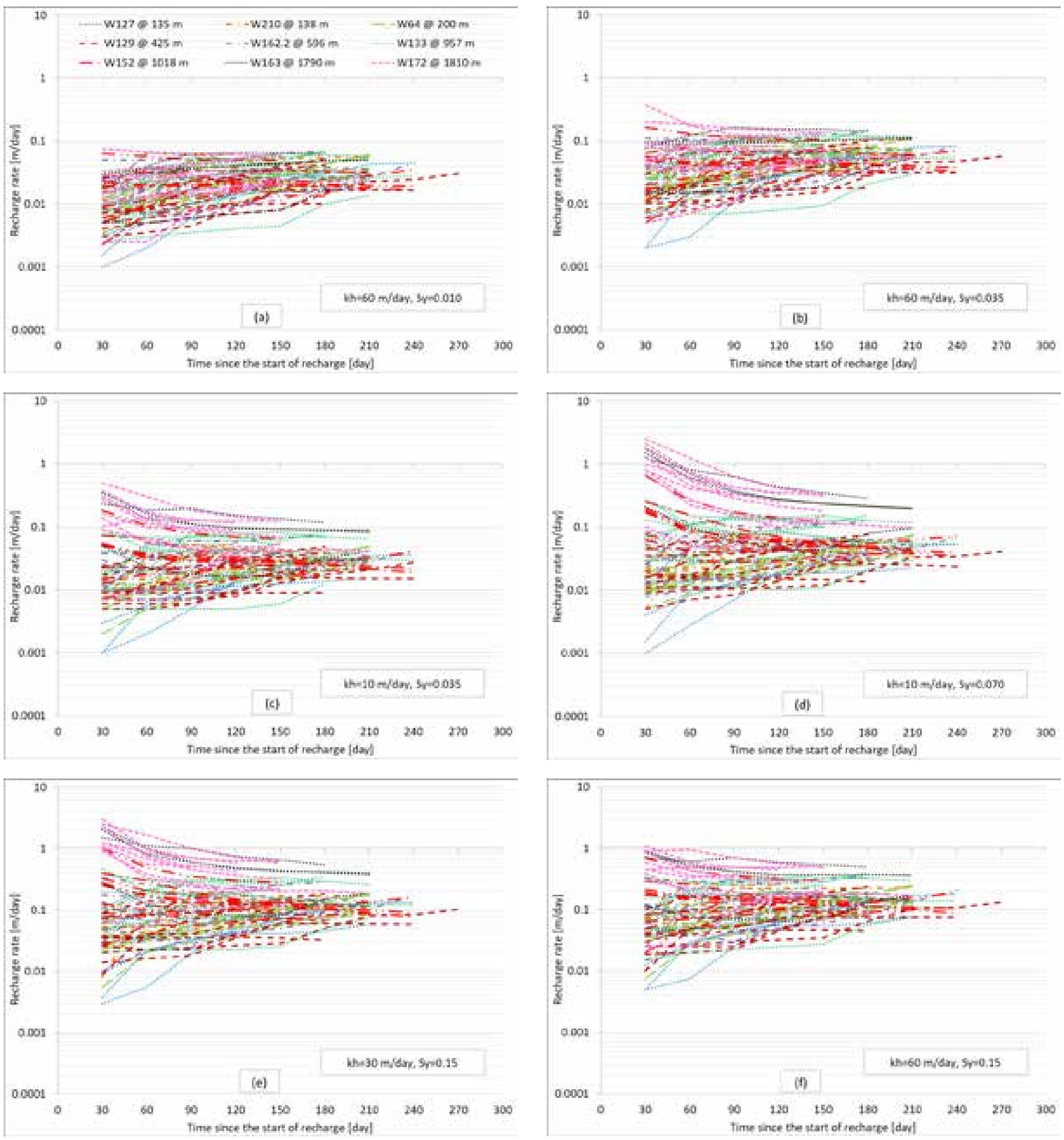


Figure 4.3: Groundwater recharge rate variations fulfilling the groundwater growth in central Kabul sub-basin for four combination of (kh) and (Sy) values (a) kh=60 m/day, Sy=0.01 (b) kh=60 m/day, Sy=0.035 (c) kh=10 m/day, Sy=0.035 (d) kh=10 m/day, Sy=0.07 (e) kh=30 m/day, Sy=0.15 and (f) kh=60 m/day, Sy=0.15

Beside of the recharge rate, the timing of groundwater recharge and its interdependency with the water balance parameters are of utmost importance. Figure 4.4 shows the recharge rate variations with respect to river flow discharge, precipitation and ETa rates for central Kabul sub-basin. As expected, recharge rates are strongly controlled by flow discharge, but the duration is limited by the ETa. This indicates that larger flow in the river leads to higher recharge rates until the ETa rates significantly increase, which leads to stoppage of groundwater recharge, because, due to the higher ETa rates, the infiltrated river water is lost before reaching groundwater. Most of groundwater recharge occurs between October to May with highest recharge rates between January and March, when the ETa rates are low. In central Kabul sub-basin, precipitation, in particular that occurring in summer (June to September), does not contribute to groundwater regeneration. For the rest of year, the contribution of precipitation on groundwater recharge is assumed to be limited to run-off generation in rivers and streams.

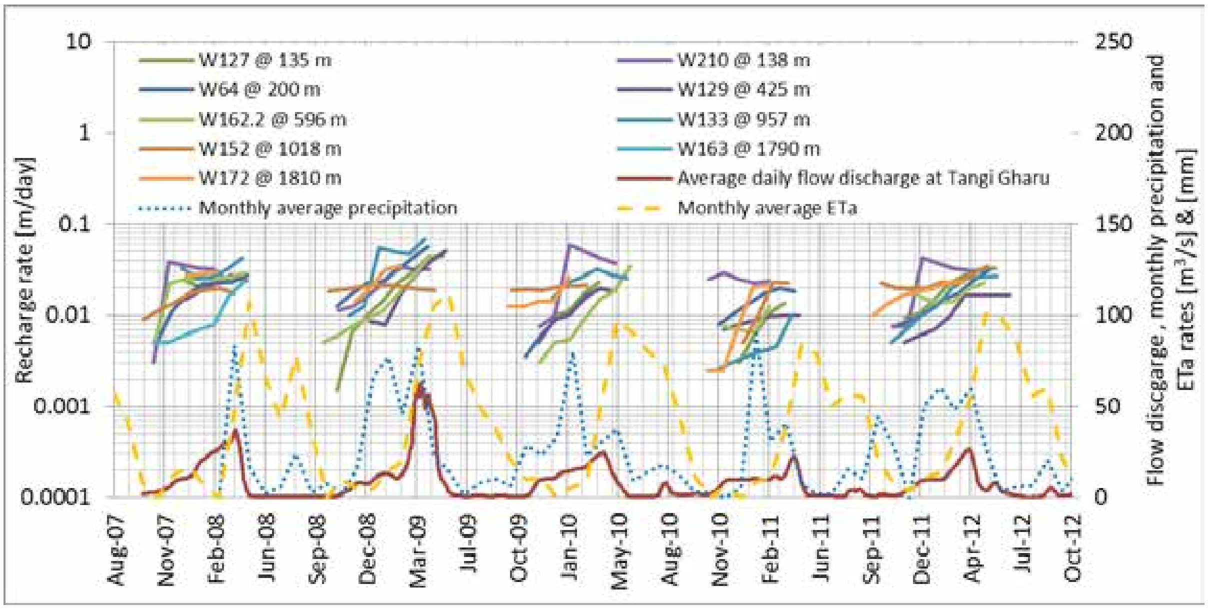


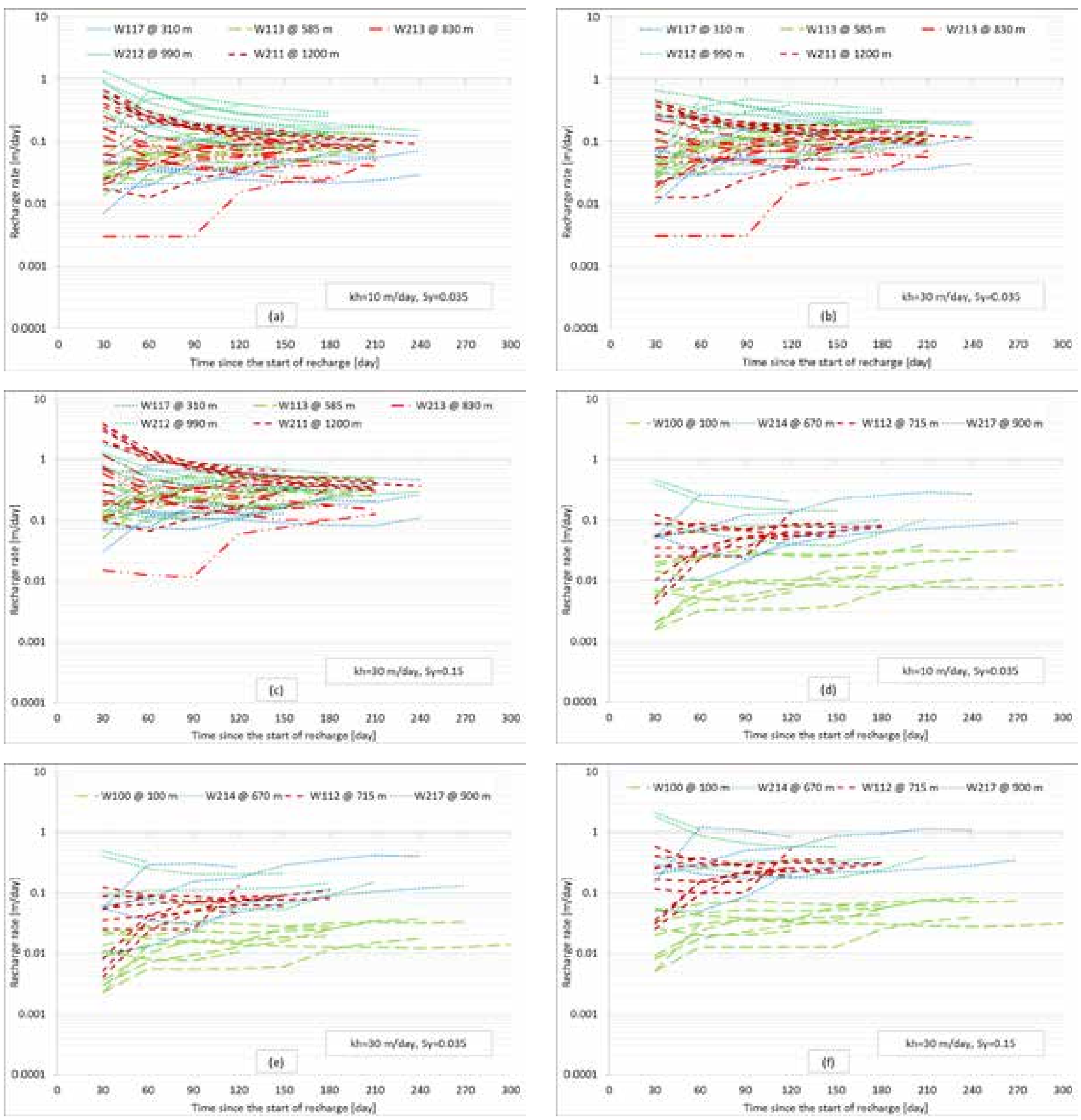
Figure 4.4: Groundwater recharge rate variations with respect to river flow discharge, precipitation and ETa rates for central Kabul sub-basin.

Sources: Precipitation data from MEW and MAIL; River hydrograph data from MEW; ETa data from USGS and EROS

4.3.2. Upper Kabul/Paghman sub-basin

In upper Kabul/Paghman sub-basin, the groundwater recharge rates are estimated based on the groundwater level growth in wells close to Maidan and Paghman rivers respectively in Figures 4.5 (a b & c) and (d, e f & g). Similar to central Kabul sub-basin, the recharge rate variations for upper Kabul/Paghman sub-basin are in the range of two orders of magnitude between 0.01 m/day to 1.0 m/day for wells close to Maidan River and between 0.003 to 0.3 for wells close to lower Paghman river respectively. The recharge rate for different (kh) and (Sy) values for the only well in Qargha River (upstream of Qargha lake inflow) shows a variation between 0.005 to 0.5 m/day. In average for Maidan River, a recharge rate of 0.136 m/day, 0.138 m/day and 0.44 m/day respectively for (kh=10 m/day, Sy=0.035), (kh=30 m/day, Sy=0.035) and (kh=30 m/day, Sy=0.15) result. Similarly, for Paghman River in the lower Paghman sub-basin, an average recharge rate of 0.078 m/day, 0.097 m/day and 0.32 m/day respectively for (kh=10 m/day, Sy=0.035), (kh=30 m/day, Sy=0.035) and (kh=30 m/day, Sy=0.15) can be estimated. In the upper Qargha area, recharge rates of 0.1 m/day, 0.16 m/day, 0.2 m/day and 0.39 m/day respectively for (kh=10 m/day, Sy=0.035), (kh=30 m/day, Sy=0.035), (kh=15 m/day, Sy=0.075) and (kh=30 m/day, Sy=0.15) can be estimated for Qargha River in the upper Paghman sub-basin area.

As shown, the recharge duration from Paghman River can be about 60 days longer compared to Maidan River, in particular for wells 100 and 104, which are located further upstream of upper Kabul/Paghman sub-basin. Field observations and flow discharge measurements at Qala Malek hydrometeorological station reveal that the river goes dry for 4 to 6 months. The drying pattern of Paghman River is from downstream and extends to upstream in the late summer months, therefore even when the downstream reach of Paghman River is already dry, the upper reach continues to recharge the groundwater. The groundwater level in the upper Kabul/Paghman sub-basin has strong gradient from Paghman valley toward central Kabul, causing the groundwater flow to follow surface water flow. The subsurface groundwater flow due to MFR in turn contributes to groundwater level growth in the downstream region of upper Kabul/Paghman sub-basin. The field observation for this study also supports the idea that the river still flows in the upstream reaches, while the downstream reach is fully dry (see Table 3.3).



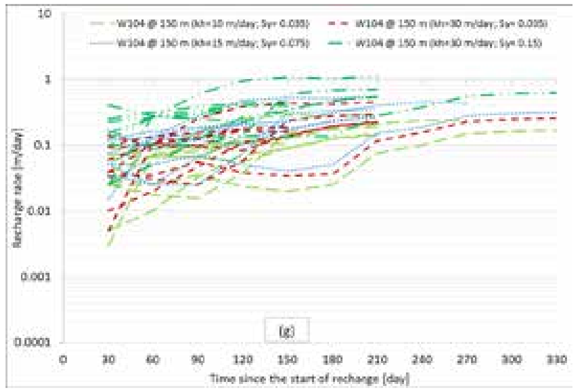


Figure 4.5: Groundwater recharge rate variations fulfilling the groundwater growth in upper Kabul/ Paghman sub-basin for various combination of (kh) and (Sy) values (a) Maidan River (kh=10 m/day, Sy=0.035) (b) Maidan River (kh=60 m/day, Sy=0.035) (c) Maidan River (kh=30 m/day, Sy=0.15) and (d) Paghman River (kh=10 m/day, Sy=0.035), (e) Paghman River (kh=30 m/day, Sy=0.035), (f) Paghman River (kh=30 m/day, Sy=0.15), and (g) Qargha River

In upper Kabul/Paghman sub-basins, higher variations in recharge rates are observed for Paghman and Qargha rivers compared to Maidan River. The distinct behaviour is predominantly a result of MFR, which significantly contributes to total groundwater recharge originating from winter snow cap reserves of Safi Mountains, while for Maidan River, the catchment barely receives snow in winter primarily due its much lower elevations. Therefore, a more comprehensive groundwater modelling approach is needed to separately quantify the MFR contribution in upper Kabul/Paghman sub-basins.

4.3.3. Logar sub-basin

In Logar sub-basin, the groundwater recharge rates are estimated based on the groundwater level growth in wells close to Logar River. The recharge rate variations are respectively shown for (kh= 10 m/day; Sy=0.025), (kh= 110 m/day; Sy=0.025), (kh= 10 m/day; Sy=0.07) and (kh= 60 m/day; Sy=0.15) in Figures 4.6 (a), (b) (c) and (d). The recharge rates vary by one order of magnitude between 0.01 to 0.2 m/day, 0.04 to 0.4 m/day, 0.04 to 0.5 m/day and 0.1 to 1 m/day respectively for four sets of (kh) and (Sy) values, as mentioned above. On average, recharge rates are 0.075 m/day, 0.18 m/day 0.15 m/day and 0.41 m/day respectively for (kh= 10 m/day; Sy=0.025), (kh= 110 m/day; Sy=0.025), (kh= 10 m/day; Sy=0.07) and (kh= 60 m/day; Sy=0.15). The recharge rate variations for Logar River in Logar sub-basin reveal the lowest variations among all sub-basins. The results for the largest (kh= 60 and 110 m/day) value show lower recharge variations for wells both close to and far from Logar River, as well as for different water years (2004 to 2013). Logar sub-basin reveals that both higher (kh) and (Sy) values produce good agreement between measured and calculated groundwater growth. The only rate at which the variations in recharge increase is for (kh=10 m/day and Sy=0.07), which indicates that lower Kh values and larger Sy values do not represent the aquifer property in Logar sub-basin. Recharge rate results for (kh= 60 m/day; Sy=0.15) agree well with the observation of Proctor & Redfern Int. Ltd.,[49] despite the different method used for determination of recharge rate.

49 Proctor & Redfern Int. Ltd., “Water Supply Sewerage”.

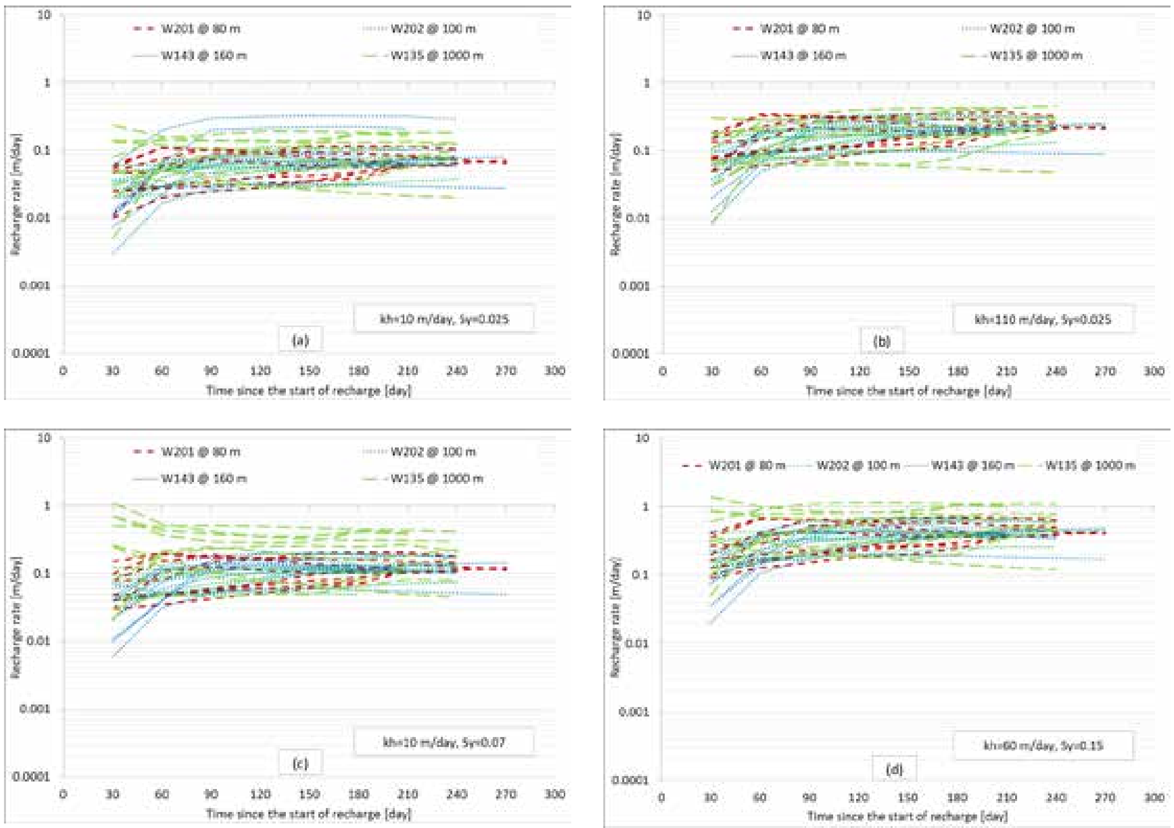


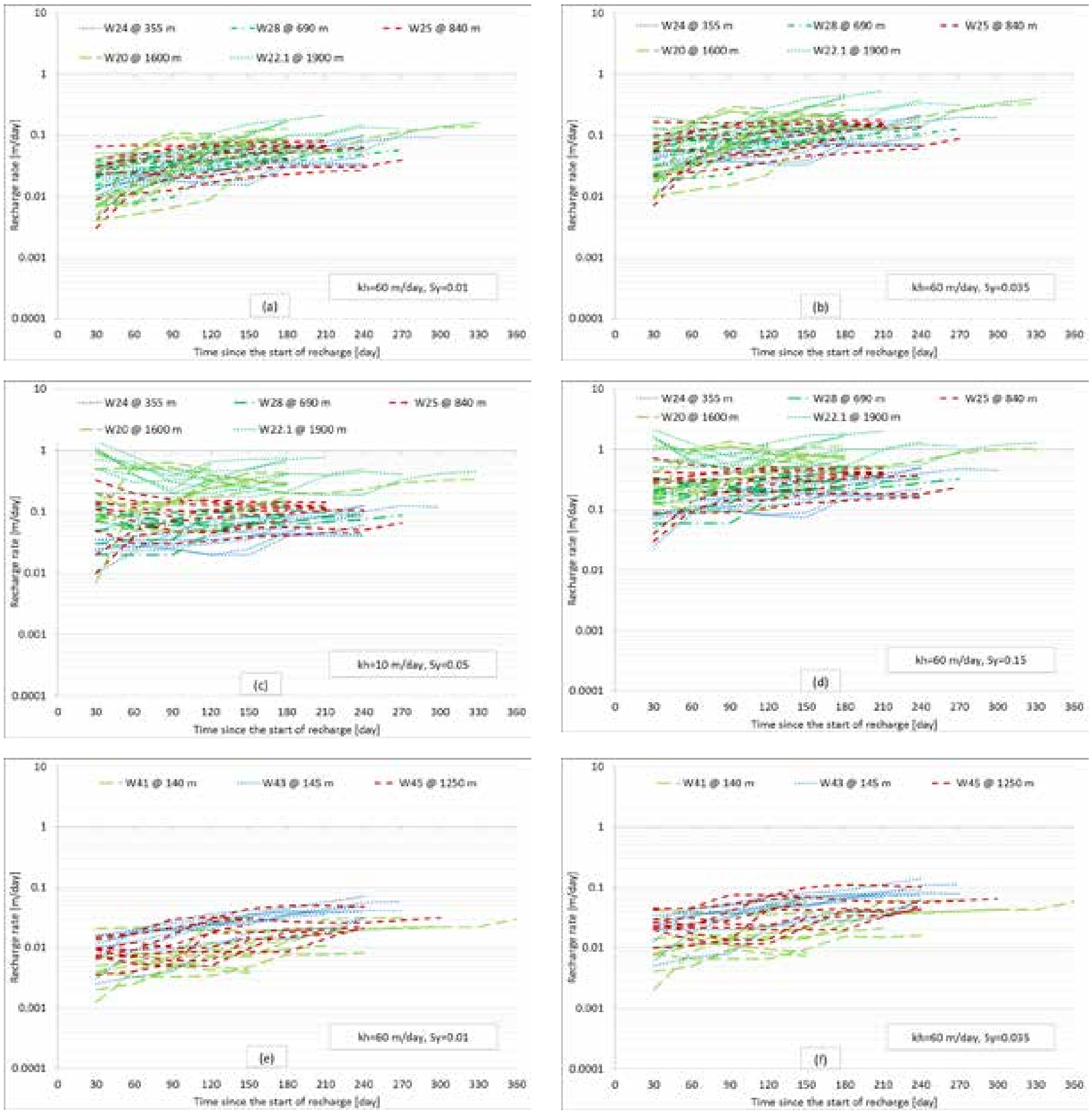
Figure 4.6: Groundwater recharge rate variations fulfilling the groundwater growth in Logar sub-basin for three combinations of (kh) and (Sy) values (a) kh=10 m/day, Sy=0.025 (b) kh=110 m/day, Sy=0.025 (c) kh=10 m/day, Sy=0.07 and (d) kh=60 m/day, Sy=0.15

4.3.4. Shamali sub-basin

In Shamali sub-basin, the groundwater recharge rates are estimated based on the groundwater level growth in wells close to Shakar-Dara and Istalef rivers for (kh= 60 m/day; Sy=0.01), (kh= 60 m/day; Sy=0.035), (kh= 10 m/day; Sy=0.05) and (kh= 60 m/day; Sy=0.15) respectively in Figures 4.7 (a, b, c & d) and (e, f, g & h). As shown, the variations of recharge rates shrink from less than two orders of magnitude for (kh= 10 m/day; Sy=0.05) to less than one order of magnitude for (kh= 60 m/day; Sy=0.035) and (kh= 60 m/day; Sy=0.01) for both Shakar-Dara and Istalef rivers. Since both larger (kh) value and lower (Sy) value serves for faster spreading of infiltrated surface water into the groundwater, the results for larger (kh=60 m/day) and lower (Sy= 0.035 and 0.01) values reflect lower recharge variations for wells located at different distances from the rivers. The increasing trend right at the beginning of recharge period for lower Sy value and higher Kh value is more realistic, because the rate of recharge follows the flow discharge in rivers that gradually increases. The results for higher Sy value of 0.15 and Kh value 60 m/day shows much larger recharge rates primarily because of higher Sy value.

Average recharge rates for Shakar-Dara River can be estimated to be in the range of 0.048, 0.12, 0.18 and 0.44 m/day, while for Istalef River lower recharge rates of 0.02, 0.038, 0.043, and 0.12 m/day are respectively estimated for (kh= 60 m/day; Sy=0.01), (kh= 60 m/day; Sy=0.035), (kh= 10 m/day; Sy=0.05), and (kh= 60 m/day; Sy=0.15).

Similar to Paghman River, Shakar-Dara and Istalef rivers are also flowing through narrow valleys. While both rivers dry up in the downstream reaches, their upstream reaches remain flowing throughout the year, which ensures an MFR. Thus, the groundwater recharge from the upstream reaches continues beyond the dry summer periods of about 300 days for some rich water years. The upstream regions near the valley-neck may be influenced by summer recharge much more than those areas further downstream, because, at the latter, the infiltrated water spreads in larger extents, thus causing lower groundwater growth. This may explain why larger recharge must come from Shakar-Dara River compared to Istalef River, because groundwater level growth for the former is from wells located in upstream region.



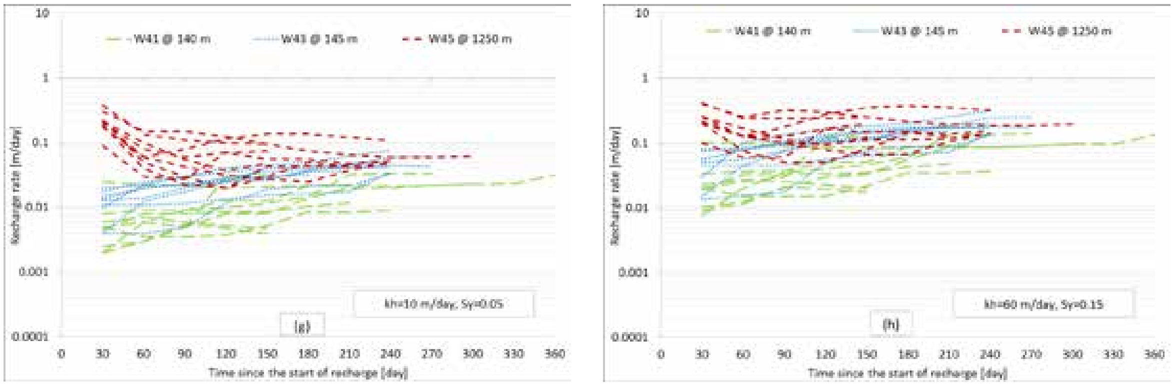
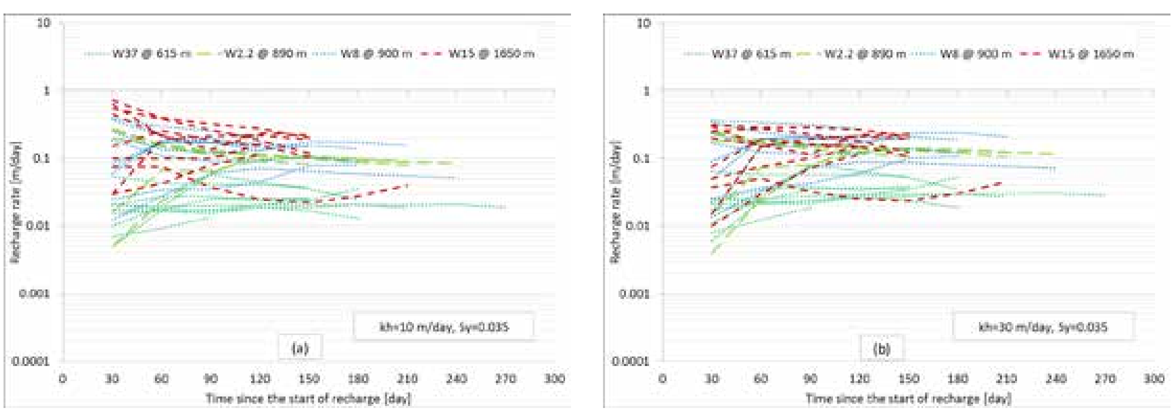


Figure 4.7: Groundwater recharge rate variations fulfilling the groundwater growth in Shamali sub-basin for four combinations of (kh) and (Sy) values (a) Shakar-Dara (kh=60 m/day, Sy=0.01) (b) Shakar-Dara (kh=60 m/day, Sy=0.035) (c) Shakar-Dara (kh=10 m/day, Sy=0.05) (d) (kh=60 m/day, Sy=0.15) (e) Istalef (kh=60 m/day, Sy=0.01) (f) Istalef (kh=60 m/day, Sy=0.035) (f) Istalef (kh=10 m/ day, Sy=0.05) and (h) (kh=60 m/day, Sy=0.15)

4.3.5. Deh Sabz sub-basin

In Deh Sabz sub-basin, the groundwater recharge rates are estimated based on the groundwater level growth in wells close to intermittent rivers and irrigation channels in this sub-basin. The recharge rates are estimated for (kh= 10 m/day; Sy=0.035), (kh= 30 m/day; Sy=0.035) and (kh= 30 m/day; Sy=0.15), as shown in Figures 4.8 (a) (b) and (c), respectively. Recharge rates vary by two orders of magnitude between 0.008 to 0.8 m/day, 0.008 to 0.3 m/day and 0.04 to 1.4 m/day, respectively, for (kh= 10 m/day; Sy=0.035), (kh= 30 m/day; Sy=0.035) and (kh= 30 m/day; Sy=0.15). On average, recharge rates of about 0.12 m/day, and 0.57 m/day can be estimated for three sets of Sy and Kh values for Deh Sabz sub-basin. In Deh Sabz sub-basin, the recharge duration can be as short as 150 days, because the rivers flow as a result of direct precipitation; therefore, the flow regime in rivers is more seasonal and lacks snowmelt, because even its elevated areas lack a prolonged snow cover. Longer recharge periods at some locations may be strongly dependent on the land irrigation that can contribute to groundwater recharge. The irrigation water is partly supplied from Kabul and Logar rivers via irrigation channels.



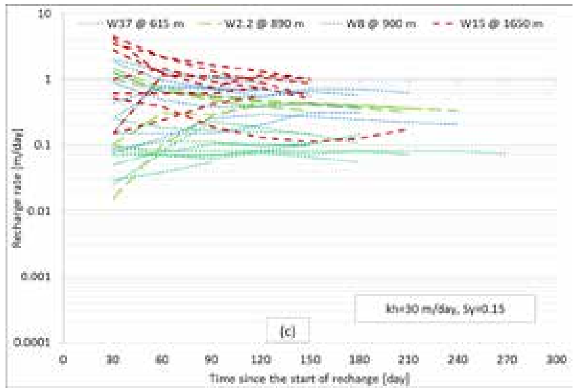


Figure 4.8: Groundwater recharge rate variations fulfilling the groundwater growth in Deh Sabz sub-basin for two combinations of (kh) and (Sy) values (a) kh=10 m/day, Sy=0.035 and (b) kh=30 m/day, Sy=0.035 (c) kh=30 m/day, Sy=0.15

The recharge rate estimates are merely based on the groundwater level growth with a fundamental assumption that a rise is caused predominantly by surface water infiltration from rivers. This assumption may lead to overestimation of recharge rates for those sub-basins with larger agricultural land, because infiltration from irrigated land may significantly contribute to groundwater regeneration. However, irrigation starts at the summer months, during which the rates of evapotranspiration are highest compared to the rest of year; thus, the infiltrated water may evaporate before reaching groundwater. Losses from irrigation channels as well as from particular crop fields such as rice with longer standing water durations contribute to groundwater recharge, even during summer.

Secondly, the MFR is also contributing to groundwater recharge, in particular in Shamali and upper Kabul/Paghman sub-basins, with the snow-covered Safi mountains and Deh Sabz sub-basin. Mountains receive more precipitation compared to basin floor; in particular, due to the cooler air on the elevations, orographic precipitation occurs. The water from rain and snowmelt finds its way through fractures of rock blocks down to the basin floor aquifer. Therefore, not taking the MFR into account in groundwater growth can lead to overestimation of recharge rates from rivers.

Thirdly, the direct precipitation on the land surface may also contribute to groundwater recharge, in particular in Shamali, Logar, Deh Sabz and upper Kabul/Paghman sub-basins, where large permeable land surfaces are still available. The precipitation from November to April can contribute to groundwater recharge, because during this period, the rates of evapotranspiration are the lowest in Kabul region. Fortunately, most of the water year's precipitation occurs also in winter and early spring months, which, depending on their intensity and duration, may contribute to groundwater level rise.

The volumetric groundwater recharge rate in m^3/s is then calculated by multiplying the average recharge rate by an average river dimension (river width x river length in the sub-basin), as listed in Table 3.2 for all investigated rivers. The average volumetric groundwater recharge rate from the investigated rivers and streams are compared with the results by Proctor & Redfern Int. Ltd.[50] in Table 4.3.

50 Proctor & Redfern Int. Ltd., "Water Supply Sewerage".

Table 4.4: Groundwater recharge rate comparison with the study by Proctor & Redfern Int. Ltd (1972) and Böckh (1971)as reported by (Tünnermeier et al., 2005).

Sub-basin	Rivers	This study [m³/s]				Proctor & Redfern Int Ltd (1972) [m³/s]
Central Kabul		Kh = 10 m/day, Sy=0.035	Kh= 60 m/day, Sy=0.035	Kh=10 m/day, Sy=0.07	Kh=30 m/day, Sy=0.15	
	Kabul River	0.59	0.72	1.80	2.94	0.82
Upper Kabul/ Paghman		Kh = 10 m/day, Sy=0.035	Kh= 30 m/day, Sy=0.035		Kh=30 m/day, Sy=0.15	
	Maidan River	0.57	0.56		1.8	
	Paghman River	0.27	0.34		1.12	0.48
Logar		Kh = 10 m/day, Sy=0.025	Kh= 10 m/day, Sy=0.07	Kh=110 m/day, Sy=0.025	Kh=30 m/day, Sy=0.15	
	Logar River	0.35	0.67	0.85	1.90	2.16
Deh Sabz		Kh = 10 m/day, Sy=0.035	Kh = 30 m/day, Sy=0.035		Kh=30 m/day, Sy=0.15	
	Deh Sabz River	0.50	0.50		2.47	
Shamali		Kh = 60 m/day, Sy=0.01	Kh = 60 m/day, Sy=0.035	Kh = 10 m/day, Sy=0.05	Kh=30 m/day, Sy=0.15	
	Shakar-Dara River	0.66	1.60	2.56	6.1	
	Istalef River	0.10	0.21	0.23	0.62	

The values in Table 4.3 show a rough estimation of volumetric recharge rates for the investigated rivers in all five sub-basins in Kabul region. The uncertainty in river width and length estimation can affect the results. The river width, which actively allows groundwater recharge, may change from one location to another along the river course as well as with the change in flow discharge, that is, the river width increases with rising flow in the river. Similarly, there is uncertainty in estimation of river length, which actively contributes to groundwater recharge in a sub-basin. Some river courses are strongly meandered (e.g., Logar River and downstream of Kabul River), which causes in nature an overlapping of groundwater level growths. In this study, river courses, including meanders, are considered as active river length contributing to groundwater recharge. Another important factor in estimating total volume of groundwater recharge is the duration. Therefore, for instance, despite relatively good recharge rates in Deh Sabz sub-basin, their relatively short period leads to lower total groundwater volume.

Nonetheless, the comparison indicates average recharge rates for central Kabul and upper Kabul/Paghman sub-basins of (kh= 60 m/day, Sy= 0.035), with values reported by Proctor & Redfern Int. Ltd.[51] In Logar sub-basin, however, good agreement is achieved with (kh= 30 m/day, Sy= 0.15). In short, the recharge rates derived from fitting Hantush's equation with measured groundwater growth in vicinity wells are sensitive to (kh) and (Sy) values. A comprehensive pumping test campaign is required to improve the accuracy of (kh) and (Sy) values. Pumping tests in the past for Kabul region are conducted using single wells with no observation wells, which make it hard to derive a good estimation of (Sy) values. Thus, it is strongly recommended to conduct future pumping tests with multiple observation wells in order to properly detect the so-called cone of groundwater depression, which in turn allows good estimation of (Sy) values.

51 Proctor & Redfern Int. Ltd., "Water Supply Sewerage".

5. Conclusions and policy recommendations

5.1. *Conclusions*

As the study results suggest, groundwater sustainability in Kabul region basins faces many challenges but there are also opportunities. If central Kabul sub-basin is viewed as integral part of its four neighbouring sub-basins, it becomes clear that area's with groundwater availability is not located farther away from largest extraction areas. A long-distance water supply from neighbouring Panjsher, Shamali and Logar sub-basins can bridge the gap between groundwater availability and use and therefore, can strongly reduce the stress on groundwater in central Kabul sub-basin.

The basin-scale water balance revealed that water surplus and deficit are varying strongly from one water year to another depending largely on the rates of precipitation and evapotranspiration. The variation of precipitation rates is the dominant factor in water balance, while the ETa rates do not vary considerably. Surplus of water is observed in years 2009, 2011 to 2014 for central Kabul, upper Kabul/Paghman, and Logar sub-basins. While the years with more water surplus can contribute more to groundwater recharge, the dry years may further shrink the groundwater levels, because, in the latter, the groundwater extraction cannot be compensated by the limited recharge rates.

The situation in Panjsher sub-basin (Parwan and Kapisa provinces) is more promising, with water surplus throughout 2008-2018. Water balance for Panjsher sub-basin revealed that the groundwater exfiltration occurs during peak flows right at the downstream of the sub-basin in Shukhi bottleneck region. The outflow flux of Panjsher River at Shukhi station shows much larger rates compared to sum of inflow fluxes from Panjsher, Salang, Ghurband and Shutul rivers measured respectively at upstream stations of Tangi Gulbahar, Pol-i-Ashawa, Bagh-i-Lala and Bagh-i-Omomi. The groundwater exfiltration is also supported by as low as 2.5m groundwater level observations in Shukhi region. Nevertheless, a comprehensive investigation is required to study whether the larger outflow flux measured at Shukhi gauging station is due to exfiltration or a systematic error in measurement methodology is causing this anomaly. Despite expected uncertainties in rates of precipitation and evapotranspiration, the water balance analysis provided information about water surpluses and deficits affecting groundwater regeneration.

The RLWB is conducted by measuring flow discharge at two or more locations of the rivers, streams and irrigation canals in Maidan and Paghman rivers in upper Kabul/Paghman, Logar rivers in Logar, Shakar-Dara and Istalef rivers in Shamali and in Khawja irrigation canal in Panjsher sub-basins. The field measurements are conducted during July and August. During this period, the rivers and streams are drying up in Kabul region, because agricultural demand is at its highest and most water is diverted for irrigation; in addition, evapotranspiration rates are their peak, meaning the transmission losses determined during summer months stand for a minimum rate. For a comprehensive river transmission loss investigation, RLWB should be conducted at during March-May in order to avoid the effect of evapotranspiration. Nonetheless, the resulting transmission losses reveal that riverbed and bank sediment properties are one of the main controlling parameters, that is, rivers and streams with coarse sediments and natural banks show larger transmission losses.

The groundwater mounding analysis is performed using Hantush's 1967 groundwater growth equation. The monthly measured groundwater level changes from 2004 to 2013 for wells close to rivers and streams in all five sub-basins are used to determine the corresponding recharge rates of rivers and streams that can induce the observed groundwater growth. The recharge rates show variations of up to two orders of magnitude between observations made at different wells (located at different distance from the river) as well as due to various river flows for the different water years (2004-2013). The groundwater mounding is strongly controlled by (Sy) and (Kh) values; thus, a sensitivity analysis of both parameters reveals that the best agreement between observed groundwater level growth and calculation is achieved for 0.025 to 0.15 and 30 m/day to 60 m/day respectively. The recharge rates vary in duration based on the water year, namely wet water years may elongate recharge duration. Similarly, a wet year induces larger groundwater growth, which is reflected also by larger recharge rates compared to a dry year with lower recharge rates, because not only duration but also magnitude of flow discharge affects recharge rates. The second source of recharge variations is the wells' distance from rivers and streams. The wells closer to the surface water sources are influenced the most, while wells at further distances are less affected by river water infiltration. In case groundwater growth in distanced wells and close wells are similar, the recharge rate in Hantush's equation must be increased in order to induce a stronger groundwater growth at larger distances from the river.

The relationship between recharge, river flow, precipitation and ETa indicates that river flow is the main driver of discharge in most of sub-basins, while a higher ETa is the main driving parameter for recharge stoppage. In Shamali and upper Kabul/Paghman sub-basins, the flow down the valleys such as Paghman, Shakar-Dara and Istalef induces a subsurface groundwater recharge even during summer months, despite the rivers being dry at their downstream reaches. The coarse alluvial fan sediments, with higher permeability and large groundwater level gradients downslope, allow the surface water at uppermost reaches to flow into the subsurface and contribute to the groundwater recharge during summer months. The subsurface flow in turn reduces the water loss as result of evapotranspiration during the high ETa summer period. Groundwater recharges for most of the sub-basins occur between October and May, with highest rates between January and April.

5.2. *Policy recommendations for an improved groundwater regeneration*

Rivers and streams in Kabul region basins have strong seasonality and remain partially or fully dry for the rest of year, except rivers in Panjsher sub-basin that can be termed as perennial rivers. Therefore, it is of utmost importance to have optimal condition for the groundwater recharge during the flow period. The optimal recharge condition can be achieved by adaptation of new policies and their implementation by the following sectors:

- **Urban planning/ town planning (Kabul municipality)**

Kabul is a fast-growing city with urban area expansion rate of 13.7 percent between 1999 and 2008.[52] The expansion in urban areas are directly affecting groundwater recharge from precipitation, because the areas exposed to infiltration are converted permanently to housing areas. The urban area expansion is associated with increases in paved areas of roads, streets and walkways. More importantly, urbanisation is associated with protection of riverbanks, streambanks and drainages from erosion, which otherwise serve as natural infiltration basins. The heavily protected urban drainages convey the collected surface runoff water much faster into the Kabul River, where, after a short residence, it will leave the basin; similarly, in the areas where the drainages have poor connectivity, the accumulated water on the surface is easily evaporated without contributing to groundwater regeneration. The direct precipitation on the land surface may have marginal contribution to the groundwater regeneration, but the drainages collecting the water from urban area's catchment can contribute.

The paved areas either fully abstract water infiltration or strongly reduce the infiltration rates. The outcome of a complete sealing of surfaces by paving is already affecting the Kabul inhabitants in the form of flooding even during a very moderate precipitation for a few hours. Moreover, the accumulation of water on the surface endangers the lives and properties of people and restricts the regeneration of groundwater.

One strategy to cope with this kind of man-made flooding is to adapt a permeable pavement and drainage design practice that allows rainwater infiltration either through porous pavers or through gaps between impermeable blocks. The permeable pavements can be used for all roads of low traffic load and walkways. In the scale of households, families should be made aware of the benefits of permeable pavements in terms of groundwater recharge potentials and their effects on avoidance of rainwater accumulation flooding. The permeable pavement and drainage practice should be

52 Ahmadi and Kajita, "Evaluation of Urban Land Development

applied to all future projects of Kabul city's expansion, as well as to those existing places requiring replacement or repair.

- **Adaptation of river training works**

River training works (RTWs) including riverbank protections have been largely practiced focusing unidirectionally on the protection aspects of the RTWs, while the ecological and the surface-groundwater interaction aspects are largely ignored. In Kabul region, riverbanks are increasingly protected by stone masonry walls mainly to avoid bank erosion and to ensure flood protection. The protections are often achieved by building stone masonry retaining walls with gaps filled with cement mortar, hence, fully hindering the relationship between the riverbank with flora and fauna and the surface water-groundwater. Kabul River, Maidan River, parts of Paghman and Istalef rivers are good examples of such bank protections. While groundwater recharge as a result of direct precipitation on the land surface have minor contributions to the total groundwater regeneration, rivers and streams are making the bulk of groundwater recharge. Worldwide, a new trend of rivers and streams' re-naturalisation is observed, in which the relationship between water bodies and their surroundings are re-established by removing the obstacles (i.e., weirs, retaining walls, etc.), not only to improve groundwater recharge, but also to achieve ecologically good status and improve water quality.

In Afghanistan, RTWs are done by several administrations such as Ministry of Urban Development and Land, Ministry of Rural Rehabilitation and Development, Ministry of Energy and Water, Ministry of Agriculture Irrigation and Livestock (MAIL) and city municipalities; therefore, on the government level, a new policy concerning the RTWs is required to replace the old-fashion practices with ecologically friendly ones. In particular, concerning achieving more recharge area for surface water infiltration, riverbanks should be protected by permeable measures (i.e., by rip-raps, vegetation) instead of stone masonry walls to allow river bank filtrations and habitat for biodiversity. If for instance, the stone masonry bank protection of Kabul River is replaced by a permeable protection, groundwater recharge will increase by 10 percent to 15 percent.

- **Artificial recharge**

While urbanisation in Kabul region has reduced the infiltratible surface for groundwater regenerations that cannot be fully revertible, there are measures that can partially compensate the groundwater recharge. There are three common methods used as artificial groundwater recharge. The first method is known as direct surface recharge which allows water infiltration into groundwater by passing through the porous medium (soil). Since the infiltration occurs from the surface, this method requires land surfaces that can be used as infiltration basins. A prerequisite for establishing infiltration basins is to make sure the area is infiltratible (soil is permeable); otherwise, ponding water may contribute to more water loss due to evaporation. The basins are often established within the river system, namely the floodplains of the river system function as natural retention basins. On one hand, they reduce the flood peaks by spreading the floodwater over a large basin area and on the other hand, they allow groundwater recharge. In central Kabul sub-basin, the river floodplains have been heavily urbanised (often by illegal settlement); therefore, re-establishing river floodplain retention basins is increasingly becoming challenging. Reclaiming the natural floodplains of rivers is therefore a prerequisite. However, upper Kabul/Paghman, Shamali, Logar and Deh Sabz sub-basins provide large land surfaces for direct recharge. In Shamali sub-basin, people traditionally divert water from the rivers and streams in ponds to first attract wild ducks and other migratory birds and eventually hunt them. These ponds may have been established for other purposes, but allow a significant amount of water to infiltrate and recharge groundwater.

A second method for direct recharge of groundwater is the injection of surface water to aquifers known as direct subsurface recharge. This method can be applied in particular to central Kabul basin, where the land availability for surface recharge is limited. Since in this method, a direct connection between surface water and the aquifer is established, the risk of polluting the groundwater by the surface water is high. Additionally, direct subsurface recharge implementation is associated with higher costs, because, for this method, recharge wells must be constructed. Direct subsurface recharge can be implemented on different scales. At smaller scales, such as public and private buildings, rainwater harvesting and snow storage in shallow wells can function as artificial groundwater regeneration, as well as helping reduce water accumulations on the surface. One advantage of subsurface direct groundwater recharge is minimisation of water lost due to evaporation, because the water is stored in wells with large depth-to-surface area ratios. The hand-dug shallow wells traditionally exist in yards of private and some public buildings in Kabul that were used for groundwater withdrawal for drinking and irrigation. These wells now are mostly dry, but the structure can be easily adapted for rainwater /snow storage. In this regard, public awareness and supportive policies such as reduction in water supply costs for those families who have established a recharge well in their yard can be examined.

In a short period of time, re-naturalisation of riverbanks (re-establishment of river water linkage with surrounding soil) will directly increase the groundwater recharge in Kabul region basins. In the long run, more research work is needed on determining specific locations for functioning infiltration basins.

Literatures

Ahmadi, A.S., and Y. Kajita. “Evaluation of Urban Land Development Direction in Kabul City, Afghanistan.” *International Journal of Urban and Civil Engineering* 11, no. 2 (2017).

Aich, V., et al. “Climate Change in Afghanistan Deduced from Reanalysis and Coordinated Regional Climate Downscaling Experiment (CORDEX)—South Asia Simulations.” *Climate* 5, no. 38 (2017).

Atkinson, A.P., I. Cartwright, B.S. Gilfedder, D.I. Cendón, N.P. Unland, and H. Hofmann. “Using 14C and 3H to Understand Groundwater Flow and Recharge in an Aquifer Window.” *Hydrology and Earth Systems Sciences* 18 (2014): 4951–4964.

Böckh, E. *Report on the Groundwater Resources of the City of Kabul*. Bundesanstalt für Geowissenschaften und Rohstoffe [unpublished] file number 0021016 (1971).

Bohannon, R.G. *Geologic and Topographic Maps of the Kabul South 30’ x 60’ Quadrangle, Afghanistan*. U.S. Geological Survey (USGS) Scientific Investigations Map 3120 (Reston, Virginia: USGS, 2010).

Bohannon, R.G., and K.J. Turner. *Geologic Map of Quadrangle 3468, Chak Wardak-Syahgerd (509) and Kabul (510) Quadrangles, Afghanistan*. U.S. Geological Survey (USGS) Open-File Report 2005-1107- B (Reston, Virginia: USGS, 2007).

Broshears, R.E., M.A. Akbari, M.P. Chornack, D.K. Mueller, and B.C. Ruddy. *Inventory of Ground-Water Resources in the Kabul Basin, Afghanistan*. U.S. Geological Survey (USGS) Scientific Investigations Report 2005-5090 (Reston, Virginia: USGS, 2005).

Carleton, G.B. *Simulation of Groundwater Mounding Beneath Hypothetical Stormwater Infiltration Basins*. U.S. Geological Survey (USGS) Scientific Investigations Report 2010-5102 (Reston, Virginia: USGS, 2010).

Dahan, O., B. Tatarsky, Y. Enzel, C. Kulls, M. Seely, and G. Benito. “Dynamics of Flood Water Infiltration and Ground Water Recharge in Hyperarid Desert.” *Ground Water* 46 (2008): 450–461.

Dunkerley, D.L. “Bank Permeability in an Australian Ephemeral Dry-Land Stream: Variation with Stage Resulting from Mud Deposition and Sediment Clogging.” *Earth Surface Processes and Landforms* 33 (2008): 226–243.

Hantush, M.S. “Growth and Decay of Groundwater-Mounds in Response to Uniform Percolation.” *Water Resources Research* 3 (1967): 227–234.

Hatch, C.E., A.T. Fisher, J.S. Revenaugh, J. Constantz, and C. Ruehl. “Quantifying Surface Water-Groundwater Interactions Using Time Series Analysis of Streambed Thermal Records: Method Development.” *Water Resources Research* 42 (2006).

Homilius, J. “Geoelectrical Investigations in East Afghanistan*.” *Geophysical Prospecting* 17 (1969): 468–487.

Houben, G., T. Tünnermeier, N. Eqrar, and T. Himmelsbach. “Hydrogeology of the Kabul Basin (Afghanistan), Part II: Groundwater Geochemistry.” *Hydrogeology Journal* 17 (2008): 935–948.

Japan International Cooperation Agency. “The Study on Groundwater Resources Potential in Kabul Basin, in the Islamic Republic of Afghanistan.” Final Report, Executive Summary, Sanyu Consultants, Inc. (Kabul; Sanyu, 2011).

Johnson, A.I. “Specific Yield: Compilation of Specific Yields for Various Materials.” Geological Survey Water-Supply Paper 1662-D (Washington, DC: United States Government Printing Office, 1967).

Mack, T.J., et al. *Conceptual Model of Water Resources in the Kabul Basin, Afghanistan*. U.S. Geological Survey (USGS) Scientific Investigations Report 2009–5262 (Reston, Virginia: USGS, 2010).

Mack, T.J., M.P. Chornack, and M.R. Taher. “Groundwater-Level Trends and Implications for Sustainable Water Use in the Kabul Basin, Afghanistan.” *Environment Systems and Decisions* 33 (2013): 457–467.

Maharjan, S.B., et al. *Status and Decadal Changes of Glaciers in Afghanistan since 1990s*. (Kathmandu: International Centre for Integrated Mountain Development (ICIMOD), 2019).

MAIL/United States Geological Survey (USGS). *Agromet Project: Status as of September 2004 to 2013*. (Reston, Virginia: USGS, 2013).

Mansfield, D. “Still Water Runs Deep: Illicit Poppy and the Transformation of the Deserts of Southwest Afghanistan.” Afghanistan Research and Evaluation Unit (AREU) Issue Paper No. 40 (Kabul: AREU, 2018).

Minnig, M. *Impact of Urbanization on Groundwater Recharge: The Case Study of Dübendorf, Switzerland, Ecole Polytechnique Federale de Lausanne (EPFL)*. (Lausanne: EPFL, 2017).

National Statistics and Information Authority (NSIA), Afghanistan Statistical Year Book 2018-2019. (Kabul: NSIA, 2019).

Payn, R.A., M.N. Gooseff, B.L. McGlynn, K.E. Bencala, and S.M. Wondzell. “Channel Water Balance and Exchange with Subsurface Flow along a Mountain Headwater Stream in Montana, United States.” *Water Resources Research* 45 (2009).

Proctor & Redfern Int. Ltd. “Water Supply Sewerage Drainage and Solid Waste Systems for Greater Kabul, Joint Interim Master Plan.” Report for Royal Government of Afghanistan Central Authority for Housing and Town Planning. (World Health Organization; United Nations Development Programme [unpublished]).

Sadid, N., S. Haun, and S. Wieprecht, S. “An Overview of Hydro-Sedimentological Characteristics of Intermittent Rivers in Kabul Region of Kabul River Basin,” in River Sedimentation, ed. S. Wieprecht (Stuttgart: CRC Press, 2016).

Sadid, N., Haun, S., and Wieprecht, S. (2017). An overview of hydro-sedimentological characteristics of intermittent rivers in Kabul region of Kabul river basin. International Journal of River Basin Management . 0, 1–13.

Saffi, M.H., A.J. Kohistani, L. Vijselaar, M.N. Eqrar, and M.A. Najaf. “Water Resources Potential, Quality Problems, Challenges and Solutions in Afghanistan (Kabul).” Danish Committee for Aid to Afghan Refugees (DACAAR) Scientific Investigation Report. (Kabul: DACAAR, 2013).

Saffi, M.H., N. Eqrar, and J. Waithaka. “National Alarming on Groundwater Natural Storage Depletion and Water Quality Deterioration of Kabul City and Immediate Response to the Drinking Water Crises.” World Bank Meeting sponsored by Danish Committee for Aid to Afghan Refugees (DACAAR). (Kabul: DACAAR, 2019).

Schmadel, N.M., B.T. Neilson, and D.K. Stevens. “Approaches to Estimate Uncertainty in Longitudinal Channel Water Balances.” *Journal of Hydrology* 394 (2010): 357–369.

Senay, G.B., M. Budde, J.P. Verdin, and A.M. Melesse. “A Coupled Remote Sensing and Simplified Surface Energy Balance Approach to Estimate Actual Evapotranspiration from Irrigated Fields.” *Sensors* 7 (2007): 979–1000.

Senay, G.B., S. Bohms, R.K. Singh, P.H. Gowda, N.M. Velpuri, H. Alemu, and J.P. Verdin. “Operational Evapotranspiration Mapping Using Remote Sensing and Weather Datasets: A New Parameterization for the SSEB Approach.” *Journal of the American Water Resources Association* 49, no. 3 (2013): 577–591.

Shanafield, M., and P.G. Cook. “Transmission Losses, Infiltration and Groundwater Recharge through Ephemeral and Intermittent Streambeds: A Review of Applied Methods.” *Journal of Hydrology* 511 (2014): 518–529.

Shanafield, M., P.G. Cook, P. Brunner, J. McCallum, and C.T. Simmons. “Aquifer Response to Surface Water Transience in Disconnected Streams: Disconnected Aquifer Response to Flood Waves.” *Water Resources Research* 48 (2012).

Shobair, S.S. “Current Drought Situation in Afghanistan, Drought Assessment and Mitigation in Southwest Asia.” International Water Management Institute (2001).

Sidiqi, M.H., Shirzai, A.H., Khesrawi, F., and Sayedi, S.J. *Report of Study and Evaluation of Groundwater Level in Kabul Basin for Years 2011 to 2017*. (2019).

Taher, M.R., M.P. Chornack, and T.J. Mack. “Groundwater Levels in the Kabul Basin, Afghanistan, 2004–2013.” U.S. Geological Survey (USGS) Scientific Investigations Report 2013–1296. (Reston, Virginia: USGS, 2014).

WFD, UNEP, and NEPA. *Climate Change in Afghanistan: What Does It Mean for Rural Livelihoods and Food Security?*. (2016).

Zhang, Q., L. Miao, H. Wang, J. Hou, and Y. Li. “How Rapid Urbanization Drives Deteriorating Groundwater Quality in a Provincial Capital of China.” *Polish Journal of Environmental Studies* 29 (2019): 441–450.

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