Artificial Recharge of Groundwater as a Management Tool for the Kabul Basin, Afghanistan

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ARTIFICIAL RECHARGE OF GROUNDWATER
AS A MANAGEMENT TOOL FOR THE
KABUL BASIN, AFGHANISTAN

A Thesis
Submitted to the Graduate Faculty of the
Louisiana State University and
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Mohammad Farid Masoom
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Abstract

Decades of war and political instability, consecutive droughts, population increase and displacement, caused serious infrastructural damages to water resources of Afghanistan. The main source of water supply for people in Afghanistan is groundwater. However, over-exploitation of groundwater has led to groundwater level declines in most parts of the country. Kabul, the largest city of Afghanistan, is the capital city with a population of 4.5 million and the fifth fastest-growing city in the world. The city has observed groundwater level declines of 5-10 meters (m) since 1980. The decline of about 30 m has also been observed in one of the monitoring wells in the Kabul City. The groundwater level decline will considerably affect life, agriculture and industry in Kabul, Afghanistan.

This study proposes an artificial recharge of groundwater by the surplus flow of the Kabul River in the rainy season, as a management tool for the Kabul Basin, Afghanistan. A direct surface recharge method by means of a recharge basin is suggested to help natural recharge. Computer programs MODFLOW-2005, MODPATH 6 and Groundwater Modeling System (GMS) have been employed in this study. The objective of the study is to increase groundwater storage in the basin so as to reach the sustainable yield. Results indicate that a daily diversion of 75000 cubic meters per day (m$^3$/d) from the Kabul River to the recharge basin during the rainy season, increases the groundwater storage by an annual amount of 9 million cubic meters (Mm$^3$) and fulfills the objective of the study. Results also show that recharged water remains in the groundwater storage sufficient time to ensure water quality improvements.

This study is the first-ever work on evaluating the applicability and effectiveness of artificial recharge in Afghanistan. The approach followed in this thesis is backed by careful review of studies on water resources in Afghanistan, exploring literature on the topic of artificial recharge, and utilization of newest applications of related groundwater computer programs. Therefore, this study suits as an insight for future researches on artificial recharge of groundwater in Afghanistan.
Chapter 1: Introduction

1.1 General Information

Afghanistan is a geologically land-locked country in Central Asia with an estimated population of around 30 million. The vast majority of people of the country reside in rural areas and use agriculture as their means of living. Afghanistan is a mountainous country mainly in northern and central parts with peaks up to 7500 meters (m). These mountains serve as the best water originating bodies for the country, providing the water for five large rivers and hundreds of perennial and ephemeral streams. It is estimated that Afghanistan has 75 billion cubic meters (BCM) of water resources including 55 BCM of surface water and 20 BCM of groundwater. Of this, more than 95 percent is used in irrigation (Qureshi 2002). Most parts of the country have arid to semi-arid climate and cold winters follow hot summers (Broshears et al. 2005). Annual precipitation in Afghanistan ranges from as low as 50 millimeters (mm) in the southwest to as much as 1000 mm in northern Badakhshan province (Tünnermeier et al. 2005).

Decades of war and political instability, consecutive droughts after 2000, population increase and displacement, caused serious infrastructural damages to water resources of Afghanistan and ceased any kind of progress. One of the important needs of the people of Afghanistan aftermath of war is sustainable and reliable sources of water. Country’s fragile economy, lack of professionals in the water sector and inadequacy of social awareness toward diminishing water resources, are the key factors worsening the situation day by day. While the economy of the country depends on water, safe and reliable supplies of water are very rare. Water scarcity, poor water quality and lack of management in water sectors remain as big challenges for the Afghan government. The main source of water supply for people in Afghanistan is groundwater. Groundwater is used for drinking and other domestic uses, irrigation and livestock, industry and public water supply systems. Over-exploitation of groundwater has caused considerable declines in groundwater level all over the country, resulting in drying of many of the shallow wells in large cities in the recent years.

Kabul, the largest city of Afghanistan, is the capital city with a population of 4.5 million and the fifth fastest-growing city in the world (Asian Development Bank [ADB] 2015). The city has observed a high rate of population increase in recent years, mostly because of refugee returns and better job opportunities. More than capacity population for a city originally designed for only 500,000 people, has exacerbated many problems one of which is groundwater availability. Households and industries in Kabul highly depend on groundwater.

Several organizations have been working on groundwater in Afghanistan. German Federal Institute of Geosciences and Natural Resources (BGR), Afghanistan Geological Survey (AGS) and the U.S. Geological Survey (USGS) have been working on Kabul Basin groundwater availability and hydrogeology. Japan International Cooperation Agency (JICA) and Danish Committee for Aid to Afghan Refugees (DACAAR), have also done investigations in water resources in Afghanistan. BGR worked on Hydrogeology of the Kabul Basin. AGS and USGS worked on water level monitoring, groundwater quality and a simulation model for the Kabul Basin. The USGS started its collaboration with AGS in 2004. In a project under the name of “Inventory of
Groundwater Resources in the Kabul Basin, Afghanistan”, USGS-AGS provided a ten-year database for groundwater level and quality of the Kabul Basin. Out of a 148 water level monitoring wells, 69 were selected for measuring water level and water quality.

The landform of Kabul is arid to semi-arid and precipitation rate is about 330 millimeters per year (mm/year). The Kabul Basin is divided into five subbasins. Depth to the water level in Central Kabul City subbasin varies up to 73.34 m (Taher et al. 2014). There has been a decline of 5-10 m in groundwater level in Kabul since 1980. As of November 2004, till 2013, United States Geological Survey (USGS) established an inventory of 148 wells in the Kabul Basin. Water level, chemical, physical and microbiological properties in these wells have been measured. Water need of the Kabul is constantly increasing with increase in population. According to a simulated model of the Kabul Basin by the USGS, excess groundwater withdrawals will result in declining groundwater level and more than half of the shallow wells will become dry (Mack et al. 2010).

Less than a quarter of people in Kabul have access to piped municipal water supply system and the rest solely depend on shallow home-owned and public wells (Saffi 2011). The demand for water has been increasing as a result of population increase, industrial progress in the city and increase in per capita water use. Over-exploitation of groundwater resources in the city of Kabul has been attributed as the main reason for groundwater declines in Central Kabul subbasin (Mack et al. 2010). Natural replenishment of groundwater supplies happens at a very slow rate, so excessive extraction of groundwater at rates greater than natural replenishment results in groundwater level decline in the long term, and if proper steps are not taken to correct the issue, can lead to ultimate mining of groundwater (Asano 1985).

Artificial recharge of groundwater where applicable can be used to help natural replenishment of groundwater and reduce the adverse effects of groundwater decline. Artificial recharge of groundwater is the process in which surface water is put into infiltration basins, ditches or injection wells, where it can infiltrate into the ground and percolate into the aquifer. Artificial recharge is mainly useful for augmenting groundwater, protecting aquifers from saltwater intrusion, reducing land subsidence and improving the quality of injected water and aquifer (Bouwer 2002).

1.2 Problem Statement

The city of Kabul has an area of 480 square kilometers (km²) and is located on both sides of the Kabul River. Kabul drains more than 25% of the annual water flow of Afghanistan. High quality and abundant source of groundwater, once were added values to the city of Kabul. However, over-exploitation of groundwater as a result of population increase has adversely affected both quality and quantity of groundwater in Kabul. There is a high risk that anytime a water related problem such as drought happens, the city will face tremendous outcomes such as water shortage (Japan International Cooperation Agency [JICA] 2007). The USGS report reveals that, during the 10-year monitoring period (2004-2013), water level decline was observed in all but two of 23 monitoring wells in the city of Kabul ranging from a few meters up to 30 m (Mack et al. 2013).

The study by the JICA on groundwater resources in Kabul (2007) shows that, as a result of over-exploitation of groundwater, there is no more groundwater development in the shallow aquifer in the Kabul Basin. Therefore, proper steps as "aggressive
development" scheme toward groundwater development e.g. artificial recharge should be taken. Injecting the excess water of flood or streams in rainy season back to the ground to augment the aquifer storage is considered as a practical option of groundwater management for Kabul, Afghanistan.

1.3 Importance of the Study

The groundwater level decline will considerably affect life, agriculture and industry in Kabul. As their primary source of water, nearly all the population of Kabul rely on groundwater through piped water supply system, home-owned shallow wells, or deeper wells dug for public use. Over-exploitation of groundwater, lack of proper short and long-term management perspectives, and lack of social awareness toward the diminishing water resources in the city conspire together to exacerbate the on-going crisis. A predictive model of groundwater resources shows up to 40 m of water level declines in the city of Kabul in 2057 (Mack et al. 2010).

The decline of groundwater will first affect the people who rely on shallow wells for their daily water use. A decline of several meters dries up shallow wells. In case of deep wells, the decline causes more depth to water level. In both cases, additional costs of digging new wells and more water pumping costs are associated. Families with poor economy who cannot afford the costs would have to find new alternatives such as fetching water from deeper public wells which in most probable case, they need to travel hundreds of meters to have access to water. Another significant impact is that of on agriculture. The decline of groundwater has severely unpleasant effects on crops. Land subsidence is also a major outcome of excess groundwater withdrawals.

1.4 Research Hypotheses

Artificial recharge of groundwater can be introduced as a feasible groundwater management tool to balance the discharge-recharge of groundwater in the city of Kabul. It is believed that the Kabul River has sufficient surplus flow to be used for the artificial recharge study. Artificial recharge of groundwater in the Kabul Basin can help natural replenishment of groundwater storage in order to meet sustainable yield. Moreover, artificial recharge of groundwater is believed to improve groundwater quality.

1.5 Research Objectives

This study will assess the applicability and effectiveness of artificial recharge in Central Kabul subbasin through numerical simulation. Surplus flow in the Kabul River during the rainy season is used for artificial recharge of groundwater. The aim of this thesis is to evaluate the effects of an artificial recharge of groundwater on groundwater storage and quality in Central Kabul subbasin. The study is focused on augmenting the groundwater in such a rate that sustainable yield can be met and groundwater quality is improved.
Chapter 2: Literature Review

2.1 Groundwater

Groundwater is usually referred to the water that is found in fully saturated geologic formations beneath water table (Freeze and Cherry 1979). In other words, the water that happens to be beneath ground surface and fills the pores of sediments and rocks is called groundwater (Department of Water Resources 2003). Groundwater recharge takes place when moisture moves down from land surface toward the water table in unsaturated zone (Harter 2003). This process is called infiltration. Infiltration is a very important component of hydrologic cycle. Precipitation breaks down into several parts of which, infiltration is responsible for replenishment of groundwater resources. Infiltration of water into the ground and the proceeding percolation into ground layers, is called “recharge”. Recharge can occur in several different ways such as direct infiltration of rain and snow, infiltration through stream beds, inflow in subsurface layers from adjacent formations and infiltration from irrigation (Asano 1985). These kinds of groundwater recharge are more precisely called “natural recharge”.

The complex interaction between groundwater and surface water can impact recharge and discharge processes (Sophocleous 2002). Groundwater interacts with all surface water features such as lakes and streams, and a change in one causes change/changes in the other in terms of quantity and quality. Surface waters can recharge groundwater and also affect its quality. Similarly, in many instances, groundwater contributes to streams and lakes by increasing their water and solute (Winter 1998).

In many parts of the world especially in arid and semi-arid areas, groundwater is the main source for most water-consuming activities. However, in most of such areas, groundwater withdrawals exceed natural recharge. Over-pumping of groundwater resources can ultimately result in groundwater depletion. Safe yield, defined as the long-term balance between annual recharge and annual withdrawal, is used to limit the groundwater extractions to protect aquifers from depletion (Sophocleous 1997). Since water is a limited source and societies have no more the luxury of using it only once, reusing water seems reasonable. Water can be reused for irrigation, cooling, non-potable activities, recreational uses and artificial recharge of groundwater. Artificial recharge of groundwater is becoming more important under the consideration of the integrated use of surface water and groundwater (Asano 2006).

2.2 Artificial Recharge of Groundwater

Groundwater recharge can also happen as a result of human intervention to the hydrological cycle i.e. artificial recharge. Artificial recharge is defined as the operations planned and managed by human in order to transfer surface water into the ground (Bear 2007). In other words, it can be described as increasing aquifer storage by artificial means (Phillips 2003). In many parts of the world especially arid and semi-arid regions, groundwater extractions exceed groundwater recharge. Over-exploitation of groundwater resources will result in depletion of the sources along with many other disastrous outcomes. Artificial recharge is one method of altering hydrological cycle so as to
provide groundwater resources with more recharge than what is naturally occurring (Raghunath 2007).

While the principal, and in most cases the only desired result of an artificial recharge project, is augmenting the groundwater resources to provide more water for later extractions; there are several more advantages associated with artificial recharge. Artificial recharge and the subsequent groundwater level rise can stop, reduce and reverse the effects of declining water table in the aquifers. Artificial recharge can be implemented for storing water, reducing land subsidence, improving the quality of injected water (aquifer geo-purification), controlling seawater intrusion and to use aquifer as a conveyance body (Bouwer 2002). Artificial recharge of groundwater is one of the best water resources management tools that has been around for centuries. Evidence shows that from the 5th century AD, farmers in the Middle East, China and India have practiced artificial recharge of groundwater by harvesting floodwater (International Water Resources Association 1983).

Artificial recharge has been an efficient way to put surface water into the ground in the rainy season to use it back in the dry season. Recharge projects have now been implemented around the world for several hundred years. In Scotland and France, the first artificial recharge projects were implemented in 1820 (Jansa 1952). United States, Australia, Israel, Germany, Canada and South Africa are among the countries that have used artificial recharge of groundwater as a water management tool for their groundwater resources.

Taheri and Zare (2011) studied the artificial recharge of groundwater applicability and impacts in a semi-arid region of western Iran called Kangavar Basin. The aim of the study was to evaluate artificial recharge in the area and calculate the safe yield of the aquifer. The study showed positive impacts of the artificial recharge through increased storage of the aquifer and groundwater level rise. Groundwater level declinations as a result of over-exploitation of groundwater in many parts of India urged the government to implement artificial recharge projects throughout the country. Injections wells, infiltration tanks, ditches and canals are being used for artificially recharging groundwater in states of Tamilnadu, Gujarat, Maharashtra and Kerala (Bhattacharya 2010).

The study by the JICA on groundwater resources in Kabul (2007) reveals that, as a result of over-exploitation of groundwater, there is no more groundwater development in the shallow aquifer in the Kabul Basin. Therefore, proper steps as "aggressive development" scheme toward groundwater development e.g. artificial recharge should be taken. Injecting the excess water of flood or streams in rainy season back to the ground to augment the aquifer storage, is considered as a practical option for groundwater management of Kabul, Afghanistan. Japan, China, Iran and India are the Asian countries with large-scale artificial recharge projects. In Europe, Czech Republic is one of the countries experiencing drought and its adverse impact on groundwater storages. Heviánková et al. (2016), suggest that artificial recharge of groundwater with surplus surface water is an optimal solution to overcome the drinking water shortage in the country. France, Greece, Denmark, Netherlands, and Poland are some other European countries implementing artificial recharge as a sustainable water management option (Lallana et al. 2001). Basel, Zurich, and Geneva in Swiss rely on different artificial recharge projects by surplus flow from rivers in the country. The Lee River water is used
for artificial recharge projects in London, England since 1970. In Cape Town, South Africa, artificial recharge schemes are operating for more than 20 years (South Africa Department of Water Affairs 2007). In the United States (U.S.), practicing artificial recharge of groundwater became a broad means to increase groundwater storage in the states of California and New York in around 1930. Various artificial recharge activities have been done by the USGS throughout the U.S. (Aiken and Kuniansky 2002).

The increase in population and consequent increase in demand for water supplies, requires more effective use of water resources. Groundwater will be of great interest if the situations continue as in the past. Since groundwater storages are fixed and one cannot control the precipitation, the only option left for water resources managers is to optimally design, locate and manage pumping and recharge (Asano 1985).

2.3 Methods of Artificial Recharge of Groundwater

Artificial recharge of groundwater projects can be divided into several groups according to the method acquired. Deciding on a method depends on different factors such as the source of water, the quality of water, geological and topographical conditions, type of aquifer, type of soil, economic conditions, etc. (Bear 2007). Generally, groundwater recharge methods can be divided as follows:

- Direct surface recharge
- Direct subsurface recharge
- Indirect subsurface recharge

2.3.1 Direct Surface Recharge

Direct surface recharge utilizes enhancement in infiltration as the tool to increase the recharge to the aquifer. It is one of the simplest and oldest techniques in artificial recharge of groundwater. In this method, surface water moves down to aquifer by passing through the soil. Studies show that from many factors affecting the amount of recharge to the aquifer, area of recharge and length of the time water is in contact with soil are among the most important ones (Asano 1985).

Direct surface recharge of groundwater can be achieved through different techniques. Lands that have a slope of 1 to 3 percent are suitable for recharge by flooding (Asano 1985). The objective of this method is to distribute the water over a thin but large area to provide the underlying aquifer with recharge without disturbing the soil, Figure 2.1. Hashemi et al. (2015) showed that artificial recharge of groundwater by means of floodwater spreading in arid Iran, is an efficient method to increase groundwater resources in arid and semi-arid areas. Their study approved that, provided a balanced pumping, artificial recharge of groundwater through water harvesting, minimizes the effect of excessive groundwater abstraction. Hamdan (2012) studied different artificial recharge methods for Gaza Strip, Palestine. His study concluded that floodwater utilization for artificial recharge of groundwater, is the best option among all, with considerable rise in groundwater level and quality improvement. Ghazavi et al. (2012) studied the impact of artificial recharge of groundwater through floodwater spreading on groundwater level rise and quality in Hajitahere, Iran. The study concluded that infrequent floods in the area are good sources of water for an artificial recharge project and consequently, not only the damages of floods can be minimized, but water table rise
and groundwater quality improvement can be achieved through this project as well. Flooding technique is subjected to contamination (Asano 1985).

![Figure 2.1 Artificial recharge of groundwater by floodwater spreading](image)

Diverting and spreading the surface water to specially designed and constructed basins is another technique used in direct surface recharge of groundwater. This technique allows the water in the basins to infiltrate into the ground through the porous layer at their bottom, Figure 2.2. In some cases, ditches and furrows can be used instead of basins. In non-irrigation season, excess irrigation can be done as a technique for groundwater recharge (Bear 2007). The first artificial recharge of groundwater project by means of surface spreading in the United States was implemented in Orange County, California in 1896 (Lane 1934). Central Arizona Project (CAP) is one of the most successful artificial recharge projects in the U.S. operating for more than 30 years. The project uses surplus flow from Colorado River, Salt Lake, and municipal effluent to artificially recharge aquifers through recharge basins (Jacobs and Holway 2004). Nebraska ranks second in irrigation water withdrawals throughout the United States. Over-exploitation of groundwater in the state has caused substantial groundwater level decline. An evaluation of effects of artificial recharge of groundwater in the area revealed that, water table responses to artificial recharge by a rapid rise. Moreover, the study showed a dramatic improvement in the quality of infiltrated water from spreading basins (Ma and Spalding 1997). Artificial recharge of groundwater through spreading method is also practiced in Los Angeles, California. Surface water from the Colorado River and reclaimed wastewater are used to recharge the groundwater in the area (National Research Council 1994).
Another technique in direct surface recharge of groundwater is using in-channel systems. In-channel systems consist of placing any structure such as dams, weirs, canals, dikes etc. across streams to accumulate the water, spread it out and consequently increasing the wetted area. An increase in the wetted area results in more infiltration into the ground (Bouwer 2002). Direct surface recharge techniques such as flooding and basins are considered off-channel in contrast to in-channel techniques. The Arvari River basin in India experienced severe damages due to over-pumping of groundwater, drought and soil erosion. A number of earth-dams were constructed to capture rainwater flowing the hills in 1985. The long-lasting project has resulted in groundwater level rise and perennial flow in the river basin (Gale 2005). Direct surface recharge method is only applicable when the underlying aquifer is an unconfined one and not an impervious layer.

Figure 2.2 Artificial recharge of groundwater by recharge basins a) top view b) side view
of considerable dimensions exists between the recharge systems and the water table (Bear 2007).

The movement of water in an aquifer is very slow. There may be a period of years until the water recharged to an aquifer reaches pumping wells. During this time, filtering, chemical reactions between particles in the water, decay, ion exchange and adsorption may occur. Therefore, the quality of the water recharged to the aquifer is improved (Bear 2007). On the other hand, a high groundwater flow velocity can adversely affect groundwater quality improvement process. O'Leary et al. (2012) studied the movement of water infiltrated from a recharge basin to wells in Stockton, California. The study observed groundwater level rise in monitoring wells near the project area. However, water particles movement toward pumping wells reached the maximum rate of 13 meters per day (m/d) which posed quality concerns.

Maintenance of high infiltration rates is the key factor, which indicates the economy of the surface spreading technique. Schueler (1987) specifies soils with an infiltration rate of greater than 0.3 m/d as acceptable for implementing artificial recharge by means of surface spreading. According to ASCE, usual infiltration rates for in-channel and off-channel recharge systems are between 0.3 and 3 m/d. Water quality, specially suspended solid content in water, affect infiltration rate (Laverty 1952). Infiltration rate mainly reduces as result of clogging (retention of suspended solids), bacteria and algae growth, dissolved gases in water and some chemical reactions between soil and dissolved solids. Cleaning, drying and scraping the top layer with a defined frequency, can bring back the soil to almost initial infiltration rate. Using the basins in a rotational manner help to recover the infiltration rate. Drying reopens the pores in the soil by killing microbial growth (Raghunath 2007). Test recharge basins are suggested to identify the recharge capacity of the project site before implementing the project (Flanigan et al. 1995). Ali et al. (2017) studied the different factors affecting the infiltration rate in an artificial recharge project in Tunisia. Their study found that number of recharge basins and stream geometry are the two prominent influential factors.

### 2.3.2 Direct Subsurface Recharge

Another method in groundwater recharge is to recharge groundwater by conveying and placing the water directly into an aquifer. This method is called direct subsurface recharge method. Direct subsurface recharge method is used when the aquifer planned to be recharged is confined or an impervious layer exists between the sources for recharge and the aquifer, (Asano 1985).

Direct subsurface recharge of groundwater can be achieved through injection wells designed especially for recharging groundwater. This technique is practiced for injecting water into confining aquifers and when there is an impervious layer of considerable dimensions separating unconfined aquifer and the ground surface. A direct subsurface recharge can be implemented when the land is unavailable or expensive. In some cases, existing pumping wells can be used as recharge wells reducing the costs for new well installations (Bear 2007).

The most important aspect of groundwater recharge through recharge wells is the quality of the water injected. Because the water is injected and placed directly into the aquifer and no filtration takes place through the soil, a water source of poor quality can severely damage the aquifer. It can also damage recharge facilities. Life and effectiveness
of recharge wells are impacted by dissolved gases, suspended solids, temperature, chemical and biological impurities which cause clogging and corrosion of the well screen (Raghunath 2007). Water sources used for recharge wells are usually brought to the quality for drinking before injection, in order to reduce the clogging and to protect the water quality of the aquifer especially in cases the water will be pumped back for drinking purposes (Bouwer 2002). After world war II, Japan started to use direct injection method of artificial recharge to prevent subsidence in some industrial sites. However, the application of direct artificial recharge did not last long, as clogging problems started to adversely impact the projects in great extents. Instead, artificial recharge of groundwater by means of direct surface method is gaining much more attention in Japan. The method is being utilized for sustainable aquifer management in Japan and is considered to be the best method. It is because the river waters used for artificial recharge are not polluted and the country has a lot of precipitation (Hida 2007). Igboekwe and Ruth (2011), studied the applicability and results of artificial recharge of groundwater in Umudike, Nigeria. A direct subsurface recharge method by means of recharge wells was employed for their study. Their study showed that an artificial recharge of groundwater project in the area can restore damages to the groundwater in the area. Groundwater level rise and increase in groundwater storage were the two promising results. Hao et al. (2014) Evaluated the applicability and results of two different artificial recharge methods in middle-upper part of the Yongding River in Beijing, China. Both surface infiltration and direct subsurface method achieved good results for the study area in terms of groundwater level rise and increase in groundwater storage.

Costs associated with pretreatment of water, construction of recharge wells and subsequent maintenance, make groundwater recharge by wells more expensive than recharge by surface infiltration, except if the land costs are high or the soil is not suitable for a surface infiltration project. Aquifer storage and recovery (ASR) is a more cost-effective option. In this method, wells are used for both recharging and pumping purposes. These wells can inject, store and pump water in different periods of time to allow recovery of the injected water, Figure 2.3. Using same wells for injecting and pumping, reduces the clogging and is more economical for storing large volumes of water (American Society of Civil Engineers [ASCE] 2011). In 1998, Las Vegas Valley Water District started to use a number of dual-use wells for recharging the principal aquifer to meet present and future water demands. Treated water from Colorado River was recharged to the aquifer through a network of dual-use wells during winter. The recharged water was let to remain in the aquifer and recovered from the storage during summer months when the demand was at its highest (Johnson et al. 1997). High Plains of Texas, which is one of the best agricultural areas in the U.S., experienced groundwater level declines due to excess groundwater withdrawals through irrigation wells in the area. The groundwater formation under High Plains of Texas is Ogallala formation. Direct injection of water collected in playa lakes into the Ogallala formation was considered as the best option to increase the groundwater storage. For this purpose, a number of irrigation wells were used to recharge the formation with lake water. Subsequently, the same wells were used to withdraw water for irrigation in dry periods (Valliant 1964).
Indirect Subsurface Recharge

Indirect subsurface groundwater recharge is the method in which groundwater table near a river, lake or stream is lowered by pumping water through wells and galleries near them (Raghunath 2007). The process allows more recharge to the aquifer from lakes, rivers and streams by inducing the movement of water towards wells. Inducing the movement of water from surface resources by means of indirect subsurface method has two goals; first, recharging the aquifer with the river water, second, purification and filtration of the river water through the process it undergoes while traveling to the pumping installations (Bear 2007). This method is of good benefit when surface waters have poor quality and the subsurface reservoirs are small. Inducing the movement of water from a stream that has considerable amount of contamination may seriously affect the quality of water pumped from the adjacent wells (Patel and Shah 2008). A special type of indirect subsurface recharge method in which the source water is a river is called riverbank filtration (RBF), Figure 2.4. There are numerous aspects controlling the success of an RBF method. Source water quality, groundwater quality, pumping rate, soil type, travel time for water particles to travel from river’s bank to pumping wells, and finally, well type have a substantial impact on RBF performance (Ray et al. 2002). Farmers in the Tamilnadu state of India have been implementing indirect subsurface recharge for many years. They use this method to induce the flow toward their irrigation wells (Sakthivadivel 2007). Shamsuddin et al. (2014) studied the possibility of RBF method in Langat River basin, Malaysia. Their study showed quality improvements in infiltrated water; however, extracted water from pumping wells did not meet drinking water quality standards. Hamdan et al. (2013) carried on a study to evaluate the effectiveness of RBF by Nile River water in Awsan city of Egypt. They concluded that infiltrated water can be extracted from wells 50 meters away and be used for drinking purpose after simple chlorination.
There are some other methods of recharging groundwater e.g. aquifer modification, and the combination of surface and subsurface methods which are not discussed in this study. In brief, direct surface recharge of groundwater by means of surface spreading is the most affordable option. The method ensures considerable improvement in groundwater quantity and enhances groundwater quality during the infiltration process. Direct injection methods can be very useful in strategic locations if the source of freshwater is available for artificial recharge (Kimrey 1989).

2.4 Source of Water for Artificial Recharge of Groundwater

Source of water for an artificial recharge of groundwater project varies according to the technique acquired and the subsequent use of the recovered water. Water from different surface reservoirs with varying qualities can be considered for being artificially recharged into an aquifer. Usually, water from storm/flood runoff, municipal wastewater treatment plants and excess irrigation water are used to recharge groundwater. Pretreatment may be needed to bring the source water to the quality suitable for recharge and ensuring the quality for the intended extraction (American Society of Civil Engineers [ASCE] 2011). Water quality analyses of possible sources for an artificial recharge project along with quality analyses of the groundwater must be done before attempting to implement an artificial recharge project (New Hampshire Department of Environmental Services 2012). From the standpoint of source water quality, an understanding of required water quality, geochemical processes and anthropogenic activities effects, is important prior to decide on artificial recharge method to be implemented in a specific area (Gale 2005). Sarma and Xu (2017) have discussed the reliability of artificial recharge of groundwater in arid Namibia. Their study found different factors impacting the recharge in the area. The study proposes that use of rapid runoff is a reliable source of water for the artificial recharge project in terms of quality.
2.5 Identifying the Suitable Site

Identifying a suitable site for a recharge facility installation requires a precise investigation of several determining factors. An ideal site for a recharge project ensures an economical and effective outcome. The method of recharge and the intended use of extracted water have great weight in determining a suitable location. American Society of Civil Engineers (ASCE), defines the following characteristics as the significant elements in selecting a site for a recharge project:

- Geology
- Hydrology
- Topography
- Meteorology
- Vegetation cover
- Land use
- Distance to the source of water for recharge
- Distance to the area of use, etc.

Methods in Geographic Information System (GIS) applications can be utilized to prepare a suitability analysis of the aforementioned factors and decide on the most suitable location for a recharge project.

2.6 Disadvantages of Artificial Recharge of Groundwater

While artificial recharge of groundwater has many advantages such as groundwater level rise, increase in groundwater storage, groundwater quality improvement and land subsidence prevention, there exists some undesired outcomes associated with artificial recharge of groundwater. The most important disadvantage is the high risk of contamination of groundwater through recharge wells. One should be extra-careful when examining each case as he/she may permanently damage an aquifer water quality if the recharging water source is polluted with non-degradable or toxic pollutants (Bear 2007). Injected water can drastically damage the aquifer if the source water quality is inferior to some specific standards. The scale of an artificial recharge project also plays an important role. A small-scale artificial recharge project may not meet the groundwater storage requirement and economically will not be considered feasible. Excessive artificial recharge of groundwater can cause land uplift. Zhang et al. (2015) studied the adverse effects of artificial recharge in Shanghai, China. Their study focused on land uplift as a result of continuous artificial recharge and restrictions on groundwater extraction. Their study found that excess artificial recharge and the resultant groundwater level rise has caused land uplift in many areas.

2.7 Modeling in Groundwater Management

Anderson et al. (2015) define a model as "any device that represents an approximation of a field situation". Scientists and water resources engineers use computer models to better understand the groundwater flow conditions and get an insight into future of the ground reservoirs. The emergence of high-speed computers has encouraged the use of computer simulations as water management tool. A mathematical
computer model uses a governing equation to simulate groundwater flow to show the physical process that happens in the system. While most groundwater modeling studies are intended for predicting the outcomes of a proposed action, there are two other significant goals of a groundwater modeling study; a groundwater model can be utilized to study the generic geologic settings and also to interpret parameters that control the system (Anderson et al. 2015).

Modeling of a groundwater system involves three elements: data, conceptualization and modeling (Yang et al. 2010). A computer simulation model for a groundwater system can be used for different purposes. For example, by describing the factors that have effect on recharge, a model can hand over important perspective about the hydrologic system. A predictive model can investigate how changes in climate, land use and other elements impact recharge (Healy 2010).

United States Geological Survey (USGS) has developed one of the most popular groundwater flow models, MODFLOW. MODFLOW is a three-dimensional finite-difference groundwater model that can simulate a groundwater system. This model uses a block-centered finite-difference approach to solve three-dimensional flow equations. A variety of packages, codes and features have been created by USGS that can be integrated with MODFLOW. This groundwater modeling system is more flexible in defining aquifer layers (confined, unconfined or both), aquifer properties, hydraulic conductivity and transmissivity (Konikow and Reilly 1999).

2.8 Modeling Artificial Recharge of Groundwater

Mirlas et al. (2015) used the groundwater flow model MODFLOW to assess the quantity of artificial recharge for an agricultural area in southeastern Kazakhstan. The MODFLOW program was hired to simulate and assess the results of a proposed artificial recharge project by means of infiltration basins. Findings showed that artificial recharge in the area helps to rise groundwater level and prevent the inflow of contaminated water from irrigation areas. Chitsazan and Movahedian (2015) combined groundwater flow model MODFLOW and Groundwater Modeling System (GMS) to study the effects of artificial recharge in Gotvand Plain aquifer, western Iran. Results showed that artificial recharge has been effective in the area. Groundwater level rise and groundwater storage improvement were seen in the area. Pliakas et al. (2005), employed MODFLOW to simulate an artificial recharge project in Xanthi plain, Thrace, Greece. The artificial recharge was achieved by activating an old streambed of a river as a cost-effective option. Jonoski et al. (1997) presented a methodology to investigate the impacts of the artificial recharge on groundwater levels and travel time for water particles to reach the nearest pumping well. Their methodology hired a coupled groundwater simulation-optimization model to determine optimal pumping system. Al-Assa’d and Abdulla (2010) investigated the applicability of different artificial recharge methods in Mujib Basin, Jordan. The groundwater flow model MODFLOW was used in their study to simulate various scenarios. MODFLOW model helped to determine optimal extraction and recharge rates. Hunt (2003) investigated lake-groundwater interaction modeling using the LAK3 package in MODFLOW-2000. He found that using the LAK3 package in MODFLOW-2000 is the best technique to simulate the lake-groundwater interaction. The lake package can further be used to simulate an artificial recharge basin. El-Zehairy et al.
(2017) utilized lake package in MODFLOW to disclose the interaction between artificial lake and groundwater in artificial Lake Turawa, Poland.

2.9 Particle Tracking

Particle tracking is a broadly applied practice to study the movement of imaginary particles. Particle tracking in groundwater is used to compute flow pathways, evaluate water quality and determine travel time for water particles to reach a specified location. Groundwater particle tracking is commonly used to map areas that contribute to recharging pumping wells (USEPA 1994). Crandall et al. (2008) utilized particle tracking to investigate flow path and travel time for groundwater particles to travel from a recharge area to a water supply well near Tampa, Florida. The results illustrated that travel time for particles to reach the water supply well ranges from a few hours to nearly 130 years. They used this result to evaluate the quality of the water that ultimately reaches the water supply well. Kauffman et al. (2001) investigated the concentration of nitrate in water supply wells in Kirkwood-Cohansey aquifer system in Southern New Jersey by means of particle tracking. Haitjema (1995) used particle tracking to investigate groundwater residence time for semi-confined and unconfined aquifers under steady-state conditions.

Computer programs designed for particle tracking can determine particles’ travel time and pathway based on velocity vectors that are computed from cell-by-cell flow rates of a numerical flow model (Bair et al. 1990). The USGS has designed a particle tracking post processing model MODPATH, to work with MODFLOW (Harbaugh 2005). MODPATH uses the output of steady state or transient simulation of MODFLOW to compute paths of particles that move through a groundwater system. MODPATH assigns a set of “imaginary” particles at desired regions and computes the pathway and time associated with each particle (Pollock 2012). Gusyev et al. (2014) applied a particle tracking analysis by MODPATH to compute groundwater particles’ flow pathlines and their corresponding tritium concentration in western Lake Taupo catchment (WLTC). Abdel-Fattah et al. (2008) employed MODPATH to illustrate the travel time for water particles to travel from a bank infiltration site to a well in El Paso, Texas, US. Buxton et al. (1991) used MODPATH particle tracking to investigate the potential aquifer recharge areas on Long Island, New York.
Chapter 3: Description of the Study Area

3.1 General Background

The study area is the Kabul Basin, Afghanistan. The Kabul Basin is a valley between Kohe Safi Mountains in the east and Paghman Mountains in the west. The basin covers an area of 3,600 km² and is divided into five main subbasins: Kabul River, Paghman River, Logar River, Chakari River, Panjsher River, Salang River, Ghorband River and Istalef River are the major rivers in the basin, Figure 3.1. Groundwater flow in the Kabul Basin is mainly through saturated alluvium and a small amount of flow is believed to be through the weathered bedrock and fractures in bedrock. The Kabul Basin is bounded by mountain chains. Subbasins are separated by outcrops of bedrocks except for Shomali and Panjsher subbasins in the north, and Central Kabul and Logar subbasins in the south (Mack et al. 2010). According to Bohannon and Tuner (2007), Kabul valley is filled with less than 80 m Quaternary sediments and 800 m thick underlying Tertiary sediments and rocks. Fan alluvial developed on the sides of the mountains surrounding the subbasins.

Most data gathering activities in Afghanistan were interrupted from 1980 to 2003 because of war and civil conflicts. Tünnermeier et al. (2005) describe that Kabul has a low annual precipitation of 330 mm/year. The evaporation rate is relatively high in comparison to annual precipitation and is about 1600 mm/year. Therefore, on an annual basis, the net direct groundwater recharge by precipitation is approximately zero. Leakage from streams and irrigation is believed to be the main source of groundwater recharge in the basin. Transmissivity is estimated about 10 to 8,000 m²/d and hydraulic conductivity of the basin ranges from 10 m/d to 70 m/d. During the worst droughts in Afghanistan starting in 2000, the annual precipitation rate was as low as 175 mm (International Water Management Institute, 2002). According to Banks and Soldad (as cited in Broshears et al. 2005) water level elevation has declined from 4 m to 6 m after 3 to 4 years of drought.

3.2 Location

The study area is the Kabul Basin which is a valley between Kohe Safi Mountains in the east and Paghman Mountains in the west. The Kabul Basin is divided into the following subbasins; Shomali, Panjsher, Paghman and Upper Kabul, Central Kabul, Deh Sabz and finally Logar. The Kabul Basin is bounded by mountain chains. Subbasins are separated by outcrops of bedrocks except for Shomali and Panjsher subbasins in the north, and Central Kabul and Logar subbasins in the south (Akbari et al. 2007), Figure 3.2. Artificial recharge of groundwater is applied in Central Kabul subbasin that provides water for Kabul. Depth to groundwater in Kabul varies considerably and is typically between 30 m to 70 m (Asian Development Bank [ADB] 2015).
Figure 3.1 Rivers in the Kabul Basin, Afghanistan
Note: Modified from (Mack et al. 2010)
Figure 3.2 Subbasins in the Kabul Basin, Afghanistan
Note: Modified from (Mack et al. 2010)
3.3 Topography and Geology

The Kabul Basin has been created as a result of movements of plates in Late Paleocene (Houben et al. 2009). Landforms inside the Kabul Basin range from arid to semi-arid and are tectonically active. Subbasins are separated by outcrops of bedrocks except for Shomali and Panjsher subbasins in the north, and Central Kabul and Logar subbasins in the south, Figure 3.2. Sediments from bedrock outcrops and surficial deposits have accumulated in the central plains of the subbasins. The slope from the center of the subbasins to the adjacent mountains is gentle and alluvial fans can be observed on the flanks of the surrounding mountains and rims of the subbasins (Mack et al. 2010).

3.3.1 Topography

Fluvial processes and tectonic activities have had great impacts on the topography of the Kabul Basin. The Kabul Basin is surrounded by mountains. Kohe Safi Mountains to the east is as high as 3000 m and Paghman Mountains reach up to 4400 m in height in the west of the study area. The outcrops separating the subbasins range from 200 m to 500 m high from the adjacent valley floor. Central plains in Central Kabul and Logar subbasins is about 1800 m and in Paghman and Upper Kabul subbasin is about 2200 m. The border with Shomali area is delineated with ephemeral streams flowing from Paghman Mountains (Mack et al. 2010). The city of Kabul is located in the south of the Kabul Basin along the confluence of the Paghman Stream, Logar River and Kabul River. The topography of the Central Kabul is almost flat. The direction of flow of Kabul River is toward the east where finally Logar River joins it (Broshears et al. 2005), Figure 3.2.

3.3.2 Geology

Plate movements of Late Paleocene age have resulted in the emergence of the Kabul Basin. Metamorphic rocks surround and underlay the basin. A system of faults in the west, east and southeast intersects the Kabul Block (Tünnermeier & Houben, 2005). According to Homilius (1969), the north and west edges of the basin are mainly composed of Precambrian gneisses, mica slates, amphibolites, quartzites and marbles. Surficial geology and topography of the Kabul Basin is presented in Figure 3.3.

Location of the Kabul Basin is in the north-central part of the Kabul Block. Erosion and faulting of the crystalline rocks have formed the basin. Surrounding mountains and hills were uplifted as a result of faulting. The erosion of this highlands and the deposition in the basin has created the present landform (Broshears et al. 2005). The west rim of the Kabul Block is marked by Chaman-Paghman fault system, The Paghman fault trends north and northeast which is defined by linear, continuous fault scarps on piedmont alluvium in the western part of the Kabul Basin. Geomorphic evidence shows that Paghman fault had a recent sustained movement during much of Quaternary time. Eastern margin of the Kabul Basin is marked by few discontinuous linear scraps identifying normal faults that are part of an extensional system (Ruleman et al. 2007). Figure 3.4 shows a planar view and cross-section of the of generalized structure, geology and hydrology of the Kabul Basin.
An accumulation of Quaternary and Tertiary sediments and rocks forms the filling of the valleys in the Kabul Basin. According to Broshears et al. (2005); Japan International Cooperation Agency [JICA] (2007); Tünnermeier et al. (2005), Quaternary sediments are about 80 m thick; whereas, the underlying tertiary sediments are estimated about 800 m in thickness in the city of Kabul. In some areas of the basin, sediments may be as thick as 1000 m (Böckh 1971). Tünnermeier et al. (2005) divide the basin sediments as follow:

a) The molasse-type Butkhak series of the Upper Miocene which have been formed after early Tertiary alpidic uplift of the Hindukush and mainly consist of red sandstone, gravels, conglomerates and breccias.

b) The Pliocene Kabul series in the central part of the basin which are mainly argillaceous beds, lacustrine silts and fine sand lenses.

c) Main aquifers inside the Kabul Basin which consist of Quaternary terrace sediments of middle and younger Pleistocene.

d) Loess deposits reaching their highest thickness at the edges of the basin.

According to Bohannon and Turner (2007), the mountains surrounding the basin are primarily composed of Paleoproterozoic gneiss and Late Permian through Late Triassic rocks (as cited in Mack et al. 2010). Metamorphic core-complex rocks forming inter-basin ridges are Paleoproterozoic gneiss. Paleoproterozoic gneiss and migmatite of the Sherdarwaza Series and low-grade schist and quartzite of the Walayati Series make basement rocks in the Kohe Safi on the east of the Kabul Basin. Not much information is available about the composition of the rocks beneath the valley-fill sediments, but probably they are similar to the predominant Sherdarwaza bedrock surrounding and inside the Kabul Basin (Mack et al. 2010).

3.4 Climate and Hydrology

The climate in the Kabul Basin is arid to semi-arid with hot summers and cold winters. Most of the precipitation happens in winter and early spring. Precipitation in the Kabul Basin varies in each subbasin. Precipitation in the area increases with increase in altitude northward, mostly because of snow. For example, average precipitation at South Salang is more than 2.5 times the precipitation in Kabul (World Bank 2010). Figure 3.5 shows precipitation and evapotranspiration at Kabul, Afghanistan. Average precipitation rate and evapotranspiration rate in Kabul is 330 mm/year and 1600 mm/year respectively (Houben et al. 2009). Figures 3.6 and 3.7 show the seasonal precipitation and evapotranspiration in the Kabul City. Figure 3.6 demonstrates that very little precipitation happens during summer and fall; whereas, 88% of the precipitation in Kabul happens during winter and spring months. Evapotranspiration rate in the Kabul City is high reaching its maximum value of 240 millimeters per month in July. Figure 3.7 shows that winter has the least (5%) and summer the greatest (52%) of evapotranspiration in the Kabul City.

Streamflow in the Kabul Basin varies both seasonally and annually. In spring, when snow in mountains melts, the streamflow is more than half of the total annual streamflow (Mack et al. 2010). There are numerous stream gages located in the Kabul Basin, Figure 3.8. The two stream gages that provide streamflow data for this study are; Kabul River at Tangi Saidan, Figure 3.9, and Paghman Stream at Puli Sukhta, Figure 3.10. The Paghman Stream originates from Paghman Mountains and flows west to east.
Figure 3.3 Surficial geology and topography of the Kabul Basin, Afghanistan (Mack et al. 2010)
Figure 3.4 Planar view (A) and generalized hydrogeologic cross section (B) of the Kabul Basin, Afghanistan (Mack et al. 2010)
and later joins Kabul River approximately at the point where the Kabul River starts flowing east, Figure 3.1 (Mack et al. 2010). The Kabul River flows eastward till leaves the country and enters Pakistan, Figure 3.1. The ample flow in the Kabul River during the rainy season can be utilized in an artificial recharge project to improve groundwater storage; otherwise, the water leaves the country and finally empties to the Indus River. Not only for artificial recharge, but the Kabul River basin has the potential for hydroelectric power development, irrigated agriculture development, and urban and industrial water supply projects. Kabul River basin is not the largest nor the most important agricultural area in the country; however, agricultural development in the area is likely to be successful due to close proximity to major markets in Kabul. The average flow of the Kabul River is eight times more than the water required to irrigate 352000 hectares agricultural site in the area. (World Bank 2010). The Kabul River finally crosses to Pakistan after Kunar River joins it. In 2005, Pakistan started to draft a water treaty with Afghanistan that did not make any progress due to lack of data on rivers in the Kabul Basin. The only time the two countries negotiated water issues dates back to 2013 without any follow up. The World Bank has been trying to assist both Afghanistan and Pakistan to discuss a water treaty for the Kabul Basin (Kakakhel 2017).

![Figure 3.5 Monthly precipitation and evapotranspiration in the Kabul City, Afghanistan](image)

**Figure 3.5** Monthly precipitation and evapotranspiration in the Kabul City, Afghanistan

**Note:** Data adapted from (World Bank 2010)
Seasonal Precipitation in the Kabul City, Afghanistan

- Spring: 49%
- Summer: 5%
- Fall: 7%
- Winter: 39%

Note: Data adapted from (World Bank 2010)

---

Seasonal Evapotranspiration in the Kabul City, Afghanistan

- Spring: 22%
- Summer: 52%
- Fall: 21%
- Winter: 5%

Note: Data adapted from (World Bank 2010)
Figure 3.8 Streamgages in the Kabul Basin, Afghanistan
Note: Modified from ((Mack et al. 2010))
Figure 3.9 Monthly Streamflow of Kabul River at Tangi Saidan
Note: Data adapted from (Mack et al. 2010)

Figure 3.10 Monthly Streamflow of Paghman Stream at Puli Sukhta
Note: Data adapted from (Mack et al. 2010)
Chapter 4: Methodology

Artificial recharge of groundwater by means of diversion from nearby surface water, in a period of the year with surplus streamflow in the Kabul River (rainy season), is applied and evaluated by the aid of computer programs; Groundwater Modeling System GMS v10.2 (Aquaveo Inc.), Modular finite-difference groundwater flow model MODFLOW-2005 (Harbaugh 2005), and particle tracking post processing model MODPATH 6 (Pollock 2012). The programs were used in constructing and predicting the success of the project. Brief descriptions of the computer programs GMS v10.2, MODFLOW-2005 and MODPATH 6 are provided in the following sections. Later in this chapter, a detailed explanation of all steps and procedures used to implement artificial recharge in the study area will be discussed. The following flowchart illustrates the steps followed in this study, Figure 4.1.

Figure 4.1 Flowchart of the steps in artificial recharge of groundwater
4.1 Description of Groundwater Modeling System

The Groundwater Modeling System (GMS v10.2) graphical user interface, is a comprehensive environment that performs groundwater simulations. GMS supports various codes including but not limited to MODFLOW and MODPATH. The GMS interface is divided into twelve modules. These modules are 2D grid module, 3D grid modules, 2D mesh grid, 3D mesh grid, 2D scatter point module, 3D scatter point module, solid module, borehole module, TIN (Triangulated Irregular Network) module, map module, GIS (Geographic Information System) module and finally UGrid (Unstructured Grid) module. A module exists for each data type that GMS supports (GMS User Manual 2017). In this study, the implementation of artificial recharge of groundwater is achieved through modeling of recharge basin by using GMS software.

4.2 Description of MODFLOW-2005

Modular finite-difference groundwater flow model MODFLOW was first developed in 1983 by the USGS. Since then, the model has been continuously revised and improved. While the first version of the program was called MODFLOW-88, the last two version of the program are MODFLOW-2005 and MODFLOW 6. MODFLOW-2005 is coded in Fortran 90 (Brainerd et al. 1990). The program supports both steady state and transient flows and can deal with regular and irregular grid layers of confined, unconfined or combination of the two. Every single part of a simulation is represented by a single package. Recharge, evapotranspiration, rivers, wells, drains, etc. can be introduced to groundwater model with a single package. Defining hydraulic characteristics of groundwater flow process in a system, such as storage terms, horizontal and vertical hydraulic conductivities are also part of the simulation process in MODFLOW-2005 (Harbaugh 2005).

MODFLOW-2005 employs the following partial-differential equation to simulate the three-dimensional movement of groundwater of non-varying density in a porous media (earth material):

\[
\frac{\partial}{\partial x} (K_{xx} \frac{\partial h}{\partial x}) + \frac{\partial}{\partial y} (K_{yy} \frac{\partial h}{\partial y}) + \frac{\partial}{\partial z} (K_{zz} \frac{\partial h}{\partial z}) + W = S_s \frac{\partial h}{\partial t},
\]

(4-1)

where

- \( K_{xx}, K_{yy}, K_{zz} \): hydraulic conductivity components along x, y, and z coordinates, respectively, assumed parallel to the major axes of hydraulic conductivity (L/T)
- \( h \): potentiometric head (L)
- \( W \): Volumetric flux per unit volume (recharge or accretion) (1/T)
- \( S_s \): specific storage of the porous medium (1/L)
- \( t \): time (T)

Combining equation (4-1) with flow and head conditions at the boundaries of an aquifer, and specifying initial-head conditions, creates a mathematical representation of a groundwater flow system, the solution of which provides an algebraic expression giving \( h(x,y,z,t) \). If derivatives of \( h \) with respect to time and space are substituted in equation (4-1), the boundary conditions, initial conditions and the equation itself are satisfied. An
analytical solution of the equation (4-1) can become very tedious for complex systems and use of numerical methods is encouraged to deal with the problems of this kind. One highly appreciated approach is to make use of the finite-difference method. In a finite-difference approach to numerically solve the equation (4-1), the continuous system is replaced by a set of discrete points in space and time. The partial derivatives in equation (4-1) are replaced by some terms that are computed according to the differences in head values at these discrete points. The discretization convention is that the system is composed of grids of blocks called cells and their three-dimensional location is specified using i, j, k indices representing row, column and layer respectively (Harbaugh 2005).

In this study, the simulation of artificial recharge of groundwater in the Kabul Basin is achieved by employing the Lake Package (LAK3) in MODFLOW-2005. The Lake Package in MODFLOW-2005 simulates the artificial lake (that represents the recharge basin in this study) and allows the head in the lake to fall and rise as a result of interaction with groundwater (Merritt and Konikow 2000).

**4.3 Description of Particle Tracking Post Processing Model MODPATH**

The USGS has designed a particle tracking post processing model MODPATH, to work with MODFLOW (Harbaugh 2005). MODPATH uses the output of steady state or transient simulation of MODFLOW to compute paths of particles that move through a groundwater system. MODPATH assigns a set of “imaginary” particles at desired regions and computes the travel path and time associated with each particle. MODPATH enables the user to track particles in a groundwater flow system either forward or backward. Options are available to specify an arbitrary location to stop the particle tracking, or MODPATH stops the tracking when particles reach flow boundaries. The user also has the ability to declare a time for the particle tracking to start and stop. For simulations in which the final stress period is steady state, the option is provided to either stop or continue the particle tracking till indefinite time. However, for simulations in which the final stress period is transient, MODPATH stops the particle tracking at the end of MODFLOW simulation (Pollock 2012).

MODPATH input files are composed of a set of MODFLOW input and output files plus some data files specific to MODPATH. MODFLOW files are; cell-by-cell flow file, discretization file and head output file. Specific files to MODPATH are; a basic data file, starting location file, simulation file and name file. MODPATH produces different output files according to the preferences of the user. Following is a list of output files MODPATH creates:

- Listing file: similar to MODFLOW listing file, a summary of MODPATH input files and results for each simulation.
- Debug files: troubleshooting files that can help to find errors.
- Particle coordinates output file: These files show the movement of particle through the simulation time. MODPATH can provide four types of particle output files namely, endpoint, pathline, timeseries, and advective observation files (Pollock 2012).

In this study, MODPATH version 6 is used for particle tracking to observe the time and flow path of particles from the recharge basin to the model boundary and a withdrawal well.
4.4 The USGS Groundwater Flow Model for the Kabul Basin, Afghanistan

The USGS groundwater flow model of the Kabul Basin is developed upon integrated analysis of historical data, hydrogeological data and recently collected data. This model is a steady state model that simulates groundwater flow in the unconfined shallow Quaternary aquifer and underlying Neogene aquifer. The model consists of four layers. Layer 1 of the model represents Quaternary sediments which is almost 80 m thick in the basin, layers 2 and layer 3 are each 500 m thick and represent the underlying Tertiary (Neogene) semi-consolidated bedrock in the subbasins and include bedrock at the perimeters of the subbasins, layer 4 is 1,000 m thick and represents the underlying bedrock at depth, Figure 4.2. The numerical model MODFLOW-2000 has been used in developing the groundwater flow model for the Kabul Basin, Afghanistan. Each cell in the model represents an area of 400 m × 400 m.

4.4.1 Boundary Conditions and Stresses

Different MODFLOW-2000 packages have been used to simulate boundary conditions and various stresses in the Kabul Basin, Afghanistan. Streamflow, recharge, agriculture and domestic water use compose the stresses in the aquifer. Parameters responsible for recharge are infiltration from precipitation, leakage from rivers, leakage from perennial streams and lateral inflows from upland areas.

4.4.2 Hydraulic Properties

The geology of the area is divided into eight major zones according to hydraulic conductivity and storage characteristics. Table 4.1 summarizes hydraulic characteristics of the Kabul Basin, Afghanistan.

4.5 Site Selection

In artificial recharge of groundwater, surplus streamflow in rainy season is used to augment aquifers. Kabul River flows 15 times greater than dry seasons through Kabul. This huge amount of water in Kabul River is the best source to improve aquifer storage. Being one of the world’s most water-stressed cities, Kabul relies on groundwater from four aquifers in the Central Kabul subbasin. Increasing annual recharge to aquifers in the Central Kabul subbasin is considered as a low-cost solution to rural, urban and agricultural water improvement (Asian Development Bank [ADB] 2015).

Because the focus of this study is the Kabul City, the artificial recharge project is located in Central Kabul subbasin to improve the aquifers that provide water for Kabul City. According to Asian Development Bank [ADB] (2015) south of the Central Kabul subbasin can be a feasible choice for an artificial recharge project. The specific location of the recharge facilities in this study was based on depth to groundwater level and distance to the sources water. Longest distance to groundwater in the area happens at a distance of about 1 kilometer (km) south of the Upper Kabul River in Qala-i Zaman Khan. More depths to groundwater level provides more unsaturated zone through which infiltration from recharge facilities will take place. Surplus flow from Upper Kabul River will be used for artificial recharge in this area, to improve groundwater storage so as to...
Figure 4.2 Generalized Hydrogeologic representation, including numerical model layers of the Kabul Basin, Afghanistan.

Note1: Geology codes from Bohannon and Turner, 2007; and Lindsay and others, 2005

Note2: Redrawn from (Mack et al. 2010)
Table 4.1 Hydraulic characteristics of sediment and rock aquifers in the Kabul Basin, Afghanistan.

<table>
<thead>
<tr>
<th>Sediment or rock unit</th>
<th>Hydraulic conductivity (m/d)¹</th>
<th>Model layer(s)</th>
<th>Horizontal hydraulic conductivity (m/d)</th>
<th>Vertical hydraulic conductivity (m/d)</th>
<th>Porosity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fan alluvium and colluvium</td>
<td>-</td>
<td>1</td>
<td>50</td>
<td>5</td>
<td>0.28</td>
</tr>
<tr>
<td>River channel sediments</td>
<td>388.80</td>
<td>1</td>
<td>100</td>
<td>10</td>
<td>0.3</td>
</tr>
<tr>
<td>Loess</td>
<td>34.56</td>
<td>1</td>
<td>20</td>
<td>2</td>
<td>0.28</td>
</tr>
<tr>
<td>Unconsolidated conglomerates</td>
<td>-</td>
<td>1</td>
<td>3</td>
<td>0.3</td>
<td>0.28</td>
</tr>
<tr>
<td>Upper Neogene</td>
<td>8.64</td>
<td>1,2</td>
<td>1</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>Lower Neogene</td>
<td>-</td>
<td>3,4</td>
<td>3</td>
<td>0.3</td>
<td>0.1</td>
</tr>
<tr>
<td>Sedimentary rocks</td>
<td>-</td>
<td>4</td>
<td>0.1</td>
<td>0.1</td>
<td>0.01</td>
</tr>
<tr>
<td>Metamorphic and igneous rocks</td>
<td>-</td>
<td>4</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
</tr>
</tbody>
</table>

¹ Reported by Bockh (1971)
Note: Adapted data from (Mack et al. 2010)

meet sustainable yield of the aquifer. The horizontal hydraulic conductivity in the area is 20 m/d and vertical hydraulic conductivity is 2 m/d. The porosity of the soil in the area is about 0.3. Soil type in the area is loess which is composed of roughly 20% of clay and equal portions of silt and sand.

4.6 Steps in Application of Artificial Recharge to the Study Area

In performing the artificial recharge of groundwater to the study area, Central Kabul subbasin, numerous steps have been taken. These steps will be discussed in detail in upcoming sections. The first two steps are cautious modifications to the original model files.

4.6.1 MODFLOW-2000 to MODFLOW-2005

The USGS groundwater flow model for the Kabul Basin is created based on MODFLOW-2000. In order to avoid experiencing any kind of inconsistency in future steps of the implementation of artificial recharge to the study area, an attempt is done to upgrade the model files from MODFLOW-2000 to MODFLOW-2005. Although GMS interface supports both versions of the program, there were doubts if MODPATH particle
tracking results will be correct, as particle tracking program for locally refined models is based on MODFLOW-2005. In this process, the USGS MF2KtoMF05UC converter program was used. MODFLOW-2005 has slightly different format compared to MODFLOW-2000. It also provides new Observation-Process input files (Harbaugh 2007).

4.6.2 Modification of Original MODFLOW Packages

Hydraulic input parameters such as horizontal hydraulic conductivity, vertical hydraulic conductivity and recharge of the model were originally introduced to the model through cluster numbers in a zone file and corresponding parameter values in a parameter value file. A multiplier packages were also used to multiply the parameter values by specific numbers where required. The author observed GMS having difficulty reading these files and extracting the portions of the files required when creating a locally refined model. An effort is made to create individual files for horizontal hydraulic conductivity and vertical hydraulic conductivity of each layer, and also recharge rate for the first layer. Consequently, GMS was able to read the aforementioned parameters directly from corresponding files; therefore, there remained no more need for the zone and multiplier packages.

4.6.3 Local Grid Refinement (LGR)

Refinement of grids in a model may be needed for achieving more accurate results at a specific local area of a model. A global refinement of the entire model domain can result in intensive computations and also a waste of time when only a specific local area of the model is of concern. On the other hand, traditional Telescopic Mesh Refinement (TMR) in which a one-way coupling link imposes coarser grid simulation on the finer local grid boundaries, often includes substantial undetected differences in heads and fluxes across the boundaries. Local Grid Refinement (LGR) in MODFLOW-2005, allows one or more, finer local grids be embedded in a coarser global grid in a groundwater flow simulation. The coarser grid is called the parent model and the finer grid is called the child model. The two-way coupling associated with LGR facilitates feedback between parent and child model and ensures consistency in boundary conditions along the interface of the two. (Mehl and Hill 2006).

Local Grid Refinement (LGR) in MODFLOW-2005 allows grid refinements of both horizontal and vertical. User can define one horizontal refinement ratio; whereas, vertical refinement ratio of each layer can be different. In general terms, increase in refinement ratio decreases the error in both child and parent models. However, there is an optimal level of refinement to be achieved (Mehl and Hill 2006).

Another very useful option associated with LGR in MODFLOW-2005 is the ability to save coupling flux and head boundary conditions and use them later to run each model independently. LGR saves coupling flux and head boundary conditions in Boundary Flow and Head (BFH) package. Care must be taken when using BFH package in instances that a change in either model affects the boundary conditions (Mehl and Hill 2006).

As stated in MODFLOW-LGR documentation (Mehl and Hill 2006), user may need to modify some input files for the cells that form the interface between parent and
child model. The reason is, the interface cells are no longer in the same old size and volume as before, and now are truncated, Figure 4.3; whereas, stress packages such as Recharge, General Head Boundary, River and Evapotranspiration still contain the original cell size, and fluxes are computed based on original cell size. The document provides the following options to handle stresses in the interface cell:

1) No change. This option is not recommended because the stresses in the interface are counted twice (based on original cell size), Figure 4.4b.

2) Neglect the volume of stress lost in the boundary of child model and account only for parent cells at the boundary. This option can be used with the assumption that neglected stress is relatively small in comparison to total stress in the system, Figure 4.4c.

3) Account for the stress in the child interface area and also truncated parent cells by modifying the stress in the adjacent parent cell, Figure 4.4d.

4) Account for the stress in the child interface area and also truncated parent cells by modifying the stress in the adjacent child cell, Figure 4.4e.

Explanation

- Node of the parent model only
- Node of the child model only. The parent model is inactivated here after the initial parent simulation, so the parent model has a hole in it.
- Specified-head boundary node of the child model determined by interpolation from the parent solution at the shared nodes
- Internal child-grid fluxes
- Fluxes summed to provide parent-flux boundary condition

Figure 4.3 Two-dimensional view of a locally refined grid. (b) detailed Interface area showing flux balance across the boundary. White area shows cells at the interface.

Note: Redrawn from (Mehl and Hill 2006)
Accordingly, if either option three or four is used, the stresses can be modified in either parent or child model. Testing of the four above-mentioned options has shown that the last two provide closer results to globally refined model results (Mehl and Hill 2006).

The model used in this study originally had cell size of 400 m by 400 m. In order to get more reliable results, the study area is locally refined into child cells of size 16 m by 16 m. For this purpose, Local Grid Refinement (LGR) in MODFLOW-2005 is used. Each parent model cell is horizontally divided into 25 by 25 child cells (horizontal refinement ratio of 1:25). It means, instead of one former parent cell of area 160000 square meter (m$^2$), now there is 625 new child cells of area 256 m$^2$ each, Figure 4.5. Likewise, the study area is vertically divided into child layers. Each parent model layer is represented by five child model layers (vertical refinement ratio of 1:5). Refinement ratios presented above have been found through numerous trials and finally, the ratios with the least errors were selected. The author also found that a vertical refinement of all parent model layers (as opposed to only first layer) gives a better result.

![Diagram](image)

**Explanation**
- □ Area for which recharge is not included in the MODFLOW calculations
- ■ Area where recharge is accounted for
- ⬤ Recharge rate in Recharge Package file
- Q Net recharge to the entire area

Figure 4.4 Schematic view of different options for handling recharge at the interface.

Note: Redrawn from (Mehl and Hill 2006)

The only stress at the interface of the child and the parent model that had to be modified according to LGR documentation was the recharge rates. Recharge rates have been adjusted according to all the four options discussed earlier for recharge package modification at the interface. Finally, it was observed that the option 4 provides the best
result. In order to adjust the recharge rates for the child cells at the interface, the following equations have been used (Mehl and Hill 2006):

\[
\begin{align*}
R_{\text{adjustedChild}} &= R \times 1.5, \\
R_{\text{adjustedChildC}} &= R \times 2.25,
\end{align*}
\]

where
- \( R \) is the original recharge rate over the entire parent cell area
- \( R_{\text{adjustedChild}} \) is the adjusted rate in the interface cell of the child model
- \( R_{\text{adjustedChildC}} \) is the adjusted rate in the interface corner of the child model

4.6.4 Method for Artificial Recharge of Groundwater

The artificial recharge method for this study is a direct surface recharge method. This method is the most common and affordable method of artificial recharge and requires less technical equipment and efforts. Since the source water for the artificial recharge in the study area is river water, direct surface method must be used and a direct injection method is not applicable. Artificial recharge of groundwater is applied to the study area by means of an artificial lake that represents the recharge basin.
4.6.5 Simulation of Artificial Recharge by Means of an Artificial Lake

After locally refining the study area, the artificial recharge is applied to the model by means of an artificial lake Figure 4.6. In order to do so, the Lake Package (LAK3) in MODFLOW-2005 was employed. The LAK3 package in MODFLOW-2005 can handle lake-groundwater interactions, allowing the lake to expand and contract. The head in the lake can rise or fall as a result of interaction with groundwater. The model can calculate the stage in the lake upon user preference. A gaging station can be added to the lake to calculate the stage in the lake after each time step. The stages will be written to MODFLOW Gage Package (GAGE) file. Gage package facilitates monitoring the stage at the lake and in defining the optimal flow rate to/from the lake (Merritt and Konikow 2000).

In this study, the artificial recharge of groundwater in Central Kabul subbasin is applied to the study area during four months of March-June, in which the surplus streamflow from the Kabul River can be diverted to the artificial recharge basin to augment aquifers, Figure 4.7. During this four months, flow in the Kabul River composes nearly 80% of the total Kabul River flow of all year (Mack et al. 2010). In rest of the year, there is very less flow in the river reaching a minimum of 1 cubic meter per second in September. In order to meet the sustainable yield requirement in the Central Kabul subbasin, the production capacity needs to be increased from existing 3.15 million cubic meters per year (Mm³/year) to 12.5 Mm³/year (World Bank 2010). This means that an approximate rate of 75000 m³/d of water needs to be directed to the recharge basin during the months that artificial recharge is being applied. Due to elevation difference, water needs to be pumped to the area of artificial recharge.
Artificial recharge basin dimensions were adjusted in accordance with the augmentation rate of 75000 m³/d. The lake that represents the artificial recharge basin should have dimensions able to handle the inflow. An overflow from the lake as well as a low stage in the lake is not desired. A deep basin increases the effects of clogging. Furthermore, all time during the artificial recharge period, the flow must be from the recharge basin to groundwater. Flow from groundwater to the recharge basin should be thoroughly considered while designing the recharge basin. Groundwater level rise happening as a result of artificial recharge can limit, and in some occasions, stop infiltration form recharge basin to groundwater. Based on all above-mentioned criteria, in order to reduce consequent clogging in the basin, have shorter drying time and prevent groundwater flow to the recharge basin, a shallow basin was preferred to a deep one. Results in the MODFLOW Gage Package were very helpful in defining the dimensions of the lake, since dimensions were determined based on securing the maximum stage in the lake during the artificial recharge period, through a trial and error process.

### 4.6.6 Artificial Recharge Scenarios

A number of scenarios were developed to find optimal recharge basin dimensions, Table 4.2. In scenario 1, artificial recharge is applied by a 200 m × 200 m recharge basin. In scenario 2, dimensions are 300 m × 300 m. In scenario 3, recharge basin dimensions are increased to 350 m × 350 m. In scenario 4, recharge is applied to a 380 m × 380 m recharge basin. In scenario 5, seven 5-meter spaced 50 m × 380 m basins were used as recharge basins. Finally, in scenario 6, dimensions were further increased to 400 m × 400 m. As stated earlier, a shallow recharge basin is preferred in this study. The depth of the
Table 4.2 Scenarios for artificial recharge basin

<table>
<thead>
<tr>
<th>Scenarios</th>
<th>Number of basins</th>
<th>Length (m) × Width (m)</th>
<th>Depth (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>200 × 200</td>
<td>0.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.7</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1.2</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>300 × 300</td>
<td>0.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.7</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1.2</td>
</tr>
<tr>
<td>3</td>
<td>1</td>
<td>350 × 350</td>
<td>0.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.7</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1.2</td>
</tr>
<tr>
<td>4</td>
<td>1</td>
<td>380 × 380</td>
<td>0.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.7</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1.0</td>
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<td></td>
<td>1.2</td>
</tr>
<tr>
<td>5</td>
<td>7</td>
<td>50 × 380</td>
<td>0.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.7</td>
</tr>
<tr>
<td></td>
<td></td>
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</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1.2</td>
</tr>
<tr>
<td>6</td>
<td>1</td>
<td>400 × 400</td>
<td>0.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.7</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1.2</td>
</tr>
</tbody>
</table>

recharge basin varies from a minimum of 0.5 m to a maximum of 1.2 m. The logic behind this choice is to find the minimum area that can handle the recharge rate of 75000 m$^3$/d, bearing in mind that depth of the basin should not exceed 1.2 meter in order to prevent and/or minimize undesired outcomes e.g. clogging.

4.6.7 Stress Periods

The model is run for approximately one year through three stress periods. The first stress period is as short as 0.1 day. This stress period is added to check everything in the model works fine before applying the artificial recharge. The second stress period is 120 days and represented the artificial recharge period. An approximate rate of 75000 m$^3$/d is applied as inflow to the recharge basin in this period. At the beginning of this stress period, the recharge basin is assumed to be completely empty. The third stress period is 240 days and shows the remaining months of the year without artificial recharge, Table 4.3.
Table 4.3 Stress periods and corresponding artificial recharge.

<table>
<thead>
<tr>
<th>Stress Period</th>
<th>Length (day)</th>
<th>Time Step</th>
<th>Length (day)</th>
<th>Artificial recharge</th>
<th>Artificial recharge rate (m$^3$/d)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stress period 1</td>
<td>0.1</td>
<td>1</td>
<td>0.1</td>
<td>No</td>
<td>-</td>
</tr>
<tr>
<td>Stress period 2</td>
<td>120</td>
<td>1</td>
<td>30</td>
<td>Yes</td>
<td>75000</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>30</td>
<td>Yes</td>
<td>75000</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>30</td>
<td>Yes</td>
<td>75000</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4</td>
<td>30</td>
<td>Yes</td>
<td>75000</td>
</tr>
<tr>
<td>Stress period 3</td>
<td>240</td>
<td>1</td>
<td>60</td>
<td>No</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>60</td>
<td>No</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>60</td>
<td>No</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4</td>
<td>60</td>
<td>No</td>
<td>-</td>
</tr>
</tbody>
</table>

4.6.8 Particle Tracking

The USGS MODPATH 6 particle tracking is used in this study to observe the flow path of “imaginary” water particles from the recharge basin to the model boundary. MODFLOW simulation results of the groundwater model run after applying artificial recharge, are provided for MODPATH as input files along with other input files specific to MODPATH. MODPATH automatically generated 2646 particles and their starting locations between the range of locations provided by the user. For this study, MODPATH is let to run indefinite time to compute the time it takes for each particle to reach the model boundary and a withdrawal well. Two output files are created based on simulation result; a pathline file, which includes the coordinates along the path of each particle, and an endpoint file, in which information about the initial and final location and time for each particle can be found.
Chapter 5: Results and Discussions

The goal of this study was to investigate the applicability and effectiveness of artificial recharge of groundwater in Central Kabul subbasin. The very first step in applying artificial recharge to the study area was to refine local model area. Secondly, artificial recharge was applied and finally, a particle tracking completed the study. The method hired for artificial recharge of groundwater in this study was direct surface recharge.

5.1 Local Grid Refinement Results

The USGS groundwater flow model for the Kabul Basin, Afghanistan, is considered a coarse model according to its cell size. It was important to divide the cells in the study area to smaller cells so as to have better results. This process is done through locally refining grids capability of MODFLOW-2005 called LGR. As documentation of shared node local grid refinement of MODFLOW-2005 states, there is an optimal refinement ratio to be achieved. Generally, the increase in refinement ratio decreases the parent and child model errors. However, the sudden decrease in cell size at the interface of parent and child model can introduce new error to the system. Different refinement ratios have been tried in this study. Table 5.1 shows the numerical errors associated with a few numbers of the refinement ratios tried.

<table>
<thead>
<tr>
<th>Number</th>
<th>Parent model cell size (m)</th>
<th>Child model cell size (m)</th>
<th>Refinement ratio</th>
<th>Parent model percent discrepancy (%)</th>
<th>Child model percent discrepancy (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>400.00</td>
<td></td>
<td>No refinement</td>
<td>-0.21</td>
<td>-</td>
</tr>
<tr>
<td>2</td>
<td>400.00</td>
<td>133.33</td>
<td>1:3</td>
<td>-0.12</td>
<td>200.00</td>
</tr>
<tr>
<td>3</td>
<td>400.00</td>
<td>44.44</td>
<td>1:9</td>
<td>-0.05</td>
<td>-11.23</td>
</tr>
<tr>
<td>4</td>
<td>400.00</td>
<td>19.05</td>
<td>1:21</td>
<td>-0.02</td>
<td>-5.78</td>
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<tr>
<td>5</td>
<td>400.00</td>
<td>16.00</td>
<td>1:25</td>
<td>-0.01</td>
<td>0.00</td>
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<tr>
<td>6</td>
<td>400.00</td>
<td>12.12</td>
<td>1:33</td>
<td>-0.17</td>
<td>23.58</td>
</tr>
<tr>
<td>7</td>
<td>400.00</td>
<td>10.25</td>
<td>1:39</td>
<td>0.35</td>
<td>-28.47</td>
</tr>
</tbody>
</table>

The row numbered 5 in Table 5.1 shows that the least errors in parent and child model are achieved when a refinement ratio of 1:25 was used. It should be mentioned that refinement was applied to all layers of the model. The author experienced that, among different solvers in MODFLOW-2005, the Preconditioned Conjugate Gradient (PCG) solver worked best with LGR in this study. Figure 5.1 represents an excerpt of outputs from parent and child model after refinement. Subsequently, Figure 5.2 shows a
Figure 5.1 a) Parent model result after refinement b) Child model result after refinement
visual representation of the locally refined study area, before and after model run for head calculation.

Figure 5.1a and 5.1b are budget parts of MODFLOW simulation results for parent and child model at the end of the simulation time corresponding to time step 4 of stress period 3. Each budget mainly consists of two parts; describing what enters the groundwater system and what leaves the groundwater system, calculated both in whole (e.g. \(L^3\)) and in unit time (e.g. \(L^3/T\)). Storage term is always zero for a steady state
simulation. Constant head is the head value that does not change during simulation. Constant head value is zero for parent model since there is no direct contact between aquifers and surface waters. However, for child model, it is not zero because it contains boundary fluxes across child and parent model. Head dependent boundary shows the amount of water that enters or leaves groundwater system, depending on a user-specified reference head in boundaries. General head boundary package is used only in parent model to calculate head dependent boundary. Parent model flux in boundary is defined by parent flux b. c. term. For child model, the value is included in constant head term. Recharge to/from the groundwater system is shown by recharge term in the results. Wells term shows the groundwater abstractions (or injections) from wells in the model. Seepage from streambed is demonstrated by stream leakage term. Since the model runs on a steady state simulation, the sum of all inflows and outflows must become zero. Finally, the figure shows numerical errors (percent discrepancies) for both parent and child model as -0.01 and 0.00 respectively.

Last two figures both show the model results after the model was run with the optimal refinement ratio (1:25), that was found after numerous trials. Considering the original error of the parent model which was -0.21 (Table 5.1), It can be concluded that, local grid refinement and using PCG solver has improved parent model error to about 96%. Following is the four key points learned from local grid refinement in this study:

- Although greater refinement ratio decreases both parent and child model error but, can also introduce error to the system because of the abrupt change of cell dimensions at the interface of child and parent model. Therefore, there is an optimal refinement ratio that can be found based on the purpose of refinement.
- Local grid refinement helps to achieve more accurate result in the child model area of the parent model. In return, the feedback from the child model helps to get more accurate result for the parent model.
- Based on experience gained in this study, a vertical refinement of all parent model layers (as opposed to refining only the first layer of parent model) produces better results.
- Local grid refinement can achieve most of the goals of global grid refinement when applied to a specific area of interest and additionally, save time and effort.

5.2 Artificial Recharge of Groundwater Results

In this study, direct surface recharge of groundwater water was employed as artificial recharge method. Water was diverted from the Kabul River during the four months of March, April, May and June. Daily withdrawal rate from the Kabul River to the recharge basin was set according to sustainable yield requirement. A daily flow rate of 75000 m$^3$/d was diverted from the river to the recharge basin during the recharge period.

While an artificial recharge project may have various objectives, the primary goal of artificial recharge in the study area was to improve the groundwater storage. The results showed that by allocating 75000 m$^3$/d of water from the Kabul River to the recharge basin during the four months of artificial recharge period, the annual sustainable yield can be achieved. However, deciding on an optimal artificial recharge basin was a
rigorous procedure. Six different scenarios were evaluated based on their ability to accommodate the required flow rate from the Kabul River, Table 5.2.

Table 5.2 Results of scenarios for artificial recharge basin

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Number of basins</th>
<th>Length (m) × Width (m)</th>
<th>Depth (m)</th>
<th>Average daily recharge (m³)</th>
<th>Cumulative recharge at the end of recharge period (m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>200 × 200</td>
<td>0.5</td>
<td>10000</td>
<td>1200000</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.7</td>
<td>14000</td>
<td>1680000</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1.0</td>
<td>20000</td>
<td>2400000</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1.2</td>
<td>24500</td>
<td>2940000</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>300 × 300</td>
<td>0.5</td>
<td>24000</td>
<td>2880000</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.7</td>
<td>32000</td>
<td>3840000</td>
</tr>
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<td>46000</td>
<td>5520000</td>
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<td></td>
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<td>1.2</td>
<td>56500</td>
<td>6780000</td>
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<tr>
<td>3</td>
<td>1</td>
<td>350 × 350</td>
<td>0.5</td>
<td>30500</td>
<td>3660000</td>
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<td></td>
<td></td>
<td></td>
<td>0.7</td>
<td>41000</td>
<td>4920000</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1.0</td>
<td>59000</td>
<td>7080000</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1.2</td>
<td>72000</td>
<td>8640000</td>
</tr>
<tr>
<td>4</td>
<td>1</td>
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<td>5040000</td>
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<td>0.7</td>
<td>56000</td>
<td>6720000</td>
</tr>
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<td>9240000</td>
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<td>89000</td>
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<tr>
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<td>7</td>
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<td>0.5</td>
<td>41000</td>
<td>4920000</td>
</tr>
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The six scenarios represent six different artificial recharge basins in terms of their area. Furthermore, each scenario is divided into four more parts according to their depths. As stated earlier, the objective is to find the optimal recharge basin dimensions that can accommodate the required flow rate. Best recharge basin will be the one that can accommodate the daily flow of 75000 m³ in the smallest area with a depth not exceeding 1.2 m. It should be mentioned that depth is more important than area and plays a major role in the long-term effectiveness of an artificial recharge project. Therefore, depth is given priority over the area.

Table 5.2 shows that the first three scenarios failed to provide the required dimensions for an artificial recharge basin able to accommodate the required daily flow.
Scenario 4 with a recharge basin area of 380 m × 380 m and a depth of 1 m could accommodate 77000 m³ of flow on a daily basis which is a little greater than required 75000 m³. After scenario 4 proved successful, scenario 5 was developed to check if the recharge basin in scenario 4 can be replaced by seven 5-meter spaced 50 m × 380 m recharge basins, since narrower basins provide more lateral infiltration and cause less clogging effects. Results showed that scenario 5 with a depth of 1 m could accommodate 73000 m³ which is slightly smaller than required flow and needs a little more depth. Scenario 6 was also based on scenario 4. The objective in scenario 6 was to check if it is possible to increase the area by 20 m on each side and decrease the depth for long-term benefit. However, scenario 6 failed to be acceptable for an artificial recharge project since groundwater inflow to the recharge basin was observed during artificial recharge period. Larger areas than of scenario 6 were not considered after scenario 6 failed, Figure 5.3. Overall, Scenario 4 proved to be the best artificial recharge basin with dimensions 380 m × 380 m × 1 m (0.1444 km²). Scenario 5 can also be a good alternative if small modifications are made. Figure 5.4 shows dimensions of the recharge basins in the Scenario 4 and scenario 5. Figure 5.5 shows percent effectiveness of each scenario.

Figure 5.3 Average daily recharge for each scenario

Figure 5.6 is an excerpt from the results of scenario 4 with an inflow rate of 75000 m³/d, at the end of the first year. Artificial recharge was applied to the study area during stress period 2, which consists of four time-steps. The length of this stress period is 120 days which is roughly four months. The model results at the end of stress period 2, indicated that there is a daily seepage of about 75000 m³/d from the recharge basin to groundwater, Figure 5.6a. The same amount of artificial recharge was happening from
Figure 5.4 Recharge basins for scenario 4 and scenario 5

Figure 5.5 Percent effectiveness of different recharge scenarios
### Volumetric Budget for Entire Model at End of Time Step 4 in Stress Period 2

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Figure 5.6 a) Model results at the end of stress period 2 b) Model results at the end of stress period 3
the lake to groundwater through every time-step in the stress period 2 (not shown in Figure 5.6). At the end of the stress period 2, an amount of 9 Mm$^3$ of water was infiltrated through seepage from the recharge basin to groundwater. This amount is sufficient to improve groundwater storage in the area to meet sustainable yield requirement. The results in Figure 5.6 show that, during stress period 3 (after recharge period) which is 240 days and corresponds to the time in the year after recharge period, there is no seepage from the lake to groundwater.

Results in Figure 5.6 show that, during the recharge period and after it, there is no seepage from groundwater to the artificial recharge basin. This indicates that the flow direction is only from the lake to the groundwater and no time during artificial recharge period, groundwater flows to the lake. Figure 5.6 also shows that natural recharge in the model area is as small as 68544 m$^3$; whereas artificial recharge is big as 9 Mm$^3$ on an annual basis. However, it should be noted that model area does not encompass whole Central Kabul subbasin, and natural recharge in the subbasin is certainly much higher. Annual Artificial recharge of 9 Mm$^3$ corresponds to roughly 20% of the recharge from precipitation and 0.3% of the total recharge in the whole Kabul Basin, Afghanistan. Percent discrepancy (numerical error) of 0.01 proves that the model was successful in performing a steady state simulation.

Groundwater level rise of 1-2 m was observed in the vicinity of the recharge basin right after recharge period. However, at the end of the simulation, groundwater levels returned back to the same elevation or lower than pre-recharge period. This can be explained as, for a consistent groundwater level rise, the artificial recharge must be applied for several years. In this study, because of lack of appropriate data, the artificial recharge was not extended beyond one year. Running the simulation with a little data for a long period would question the reliability of the results. The results further proved that groundwater level rise under the recharge basin and nearby areas does not limit the artificial recharge for the simulation time. However, in an artificial recharge of several years, groundwater level rise may limit the infiltration from recharge basins.

Infiltration rate from the recharge basin to groundwater calculated based on daily flow and area of the basin is 0.5 m/d. This number is among usual infiltration rates according to ASCE (2011) and in acceptable range according to Schueler (1987). However, the infiltration rate will most likely decrease over time as a result of clogging and groundwater level rise.

Evaporation from a recharge basin ranges from 0.3 m/year in humid climates to 2.5 m/year in dry climates (ASCE 2011). Since the recharge period corresponds to the rainy season in the study area and evaporation is very small than infiltration, the evaporation loss is ignored.

5.3 MODPATH Particle Tracking Results

MODPATH particle tracking post processing program was hired to compute flow path of particles from the recharge basin to the model boundary and nearest well. A total of 2646 “imaginary” particles were released at the beginning of the simulation. MODPATH helped to get two important results; firstly, the influence area of the recharge basin and secondly, travel time for each particle to reach model boundary or nearest well.

The results from MODPATH output shows that groundwater flow from under the recharge basin is dominantly due north-east. All particles moved in northeast direction
until they reached the model boundary. Figure 5.7 depicts the influence area of the recharge basin.

Travel time for each particle to terminate either in model boundary or nearest well was computed by MODPATH. Travel time results from MODPATH particle tracking indicated that the shortest and longest time it takes for an “imaginary” water particle to travel from the recharge basin to the model boundary are approximately 11 and 23 years, respectively. For an “imaginary” water particle to reach the nearest well from the same recharge basin, the shortest and longest travel times are calculated as approximately 16 and 23 years, respectively. Table 5.3 shows shortest, longest, average and median for particles terminated either at the model boundary 1 km from the onset of the basin or at the nearest well. The results prove that the water infiltrated through the recharge basin remains sufficient time under ground and ensures that the water extracted later, will be of better quality. A very short travel time, as well as a very long travel time, can question the feasibility and efficiency of an artificial recharge project.

![Figure 5.7 Flow path of particles from the recharge basin](image)

**Table 5.3 Travel time for particles from the lake to nearest well and model boundary**

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<th>Terminated at the nearest well (years)</th>
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<tr>
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<td>Largest</td>
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<tr>
<td>Average</td>
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<tr>
<td>Median</td>
<td>15.76</td>
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In brief, the approach followed in this study was based on many factors. Firstly, local grid refinement of the study area was necessary to obtain better results. After local
grid refinement, the artificial recharge basin in this model was represented by 570 child cells; whereas, it would have been represented with only one cell without a local grid refinement. Obviously, applying a high recharge rate at only one cell of a model will pose uncertainty and doubt in the results. Secondly, in order to simulate the artificial recharge in the area, an artificial lake was introduced to the model to represent the recharge basin. As mentioned earlier, the lake-groundwater interaction through seepage from the lake best represents an artificial recharge basin. Moreover, the stage in the lake can vary according to the interaction of lake with groundwater. Thirdly, a very important aspect of an artificial recharge project is the quality of water used to recharge groundwater. In a direct surface method of artificial recharge of groundwater, the physical and chemical processes that take place during infiltration and percolation of water through soil, help to improve the quality of water that reaches the aquifer and subsequently withdrawal wells. As the source water for artificial recharge in this study was river water -that obviously needs quality improvement-, direct surface recharge method is believed to be able to achieve this goal. Finally, particle tracking helped to investigate the influence area of the artificial recharge basin and travel time for the “imaginary” water particles to reach the model boundary. Particle tracking was a significant part of this study to make sure that water from the recharge basin stays sufficient time under ground for quality improvement.
Chapter 6: Summary and Conclusions

Decades of war and political instability, consecutive droughts after 2000, population increase and displacement, caused serious infrastructural damages to water resources of Afghanistan and ceased any kind of progress. One of the important needs of the people of Afghanistan aftermath of war, is sustainable and reliable sources of water. The main source of water supply for people in Afghanistan is groundwater. Groundwater is used for drinking and other domestic uses, irrigation and livestock, industry and public water supply systems. Over-exploitation of groundwater has caused considerable declines in groundwater level all over the country, leading to drying of many of the shallow wells in large cities in the recent years.

Kabul, the largest city of Afghanistan, is the capital city with a population of 4.5 million and the fifth fastest-growing city in the world (Asian Development Bank [ADB] 2015). The city has observed a high rate of population increase in recent years. Households and industries in Kabul highly depend on groundwater. Several organizations have been working on groundwater in Afghanistan. German Federal Institute of Geosciences and Natural Resources (BGR), Afghanistan Geological Survey (AGS), the U.S. Geological Survey (USGS), Afghanistan Ministry of Energy and Water (MEW), Japan International Cooperation Agency (JICA), Danish Committee for Aid to Afghan Refugees (DACAAR), World Bank (WB) and Asian Development Bank (ADB) have done investigations in water resources in Afghanistan. While once high quality and abundant sources of groundwater, were added values to Kabul, now all the aforementioned organizations agree on an on-going groundwater crisis in Kabul. Water scarcity is a big challenge awaiting Kabul. There has been a decline of 5-10 m in groundwater level in Kabul since 1980. Water level decline was observed in all but two of 23 USGS monitoring wells in the city of Kabul ranging from a few meters up to 30 m (Mack et al. 2013). A predictive model of groundwater resources shows up to 40 m of water level declines in the city of Kabul in 2057 (Mack et al. 2010). The situation will drastically affect life, agriculture and industry in Kabul.

The study by the JICA on groundwater resources in Kabul (2007) reveals that, as a result of over-exploitation of groundwater, there is no more groundwater development in the shallow aquifer in the Kabul Basin. Therefore, proper steps as "aggressive development" scheme toward groundwater development e.g. artificial recharge should be taken. Injecting the excess water of flood or streams in rainy season back to the ground to augment the aquifer storage is considered as a practical option for groundwater management of Kabul, Afghanistan.

This study suggests an artificial recharge by the excess water of the Kabul River during the rainy season, in Central Kabul subbasin, Afghanistan. The ample flow in the Kabul River during the rainy season can be utilized in an artificial recharge project to improve groundwater storage; otherwise, the water leaves the country and finally empties to the Indus River. Studies by World Bank (2010) and Asian Development Bank (2015), show that the river has the potential for artificial recharge of groundwater, hydroelectric power development, irrigated agriculture development, and urban and industrial water supply projects.

It is believed that artificial recharge of groundwater can help natural recharge and replenish groundwater in Kabul. While there are numerous benefits of an artificial
recharge project, this study is focused on increasing groundwater storage in the area. The artificial recharge method applied in the study area is direct surface recharge in which, the water diverted to the recharge basin is let to infiltrate to ground through the soil. The method ensures considerable improvement in groundwater quantity and enhances groundwater quality during infiltration process (Kimrey 1989).

After locally refining the study area, the artificial recharge is applied to the USGS Kabul groundwater flow model by means of an artificial lake. Computer programs MODFLOW-2005 and GMS 10.2 are acquired to simulate the artificial recharge in the study area. The objective is to meet the sustainable yield requirement in the Central Kabul subbasin. Therefore, the production capacity needs to be increased to 12.5 Mm³/year (World Bank 2010). This means that an approximate rate of 75000 m³/d of water needs to be directed to the artificial lake during the rainy months of March-June. Computer program MODPATH 6 particle tracking is used in this study to observe the flow path of “imaginary” water particles from the recharge basin.

Among six scenarios, the artificial recharge basin with an area of 0.1444 km² was selected based on optimal results. Simulation results represent improvements in groundwater storage in the study area. Results show that at the end of the artificial recharge period, an amount of 9 Mm³ of water was infiltrated through seepage from the recharge basin to groundwater. This amount is sufficient to improve groundwater storage in the area to meet sustainable yield requirement. Groundwater level rise of 1-2 m was observed in the vicinity of the recharge basin right after recharge period. However, at the end of the simulation, groundwater levels returned back to the same elevation or lower than the pre-recharge period. Particle tracking results indicate that the water infiltrated through the recharge basin remains sufficient time underground and ensures that the water extracted later, will be of better quality.

This study proves that an artificial recharge project by means of surface spreading of the surplus flow from the Kabul River is an efficient water resources management tool for the Kabul Basin, Afghanistan. Results of this study indicate that the approach undertaken fits the real situation in the site. However, as in many scientific researches, this study includes limitations. Lack of appropriate data for the study was a major constraint in this research. Data collecting activities were interrupted in Afghanistan during war. The model used for this study was built by historic data of about 30 years ago and a portion of new data collected by the USGS during 2004-2007 in the Kabul Basin, Afghanistan. Additionally, the model is not calibrated due to lack and/or inaccessibility of recent observation data. This limitation impeded the study to go on for a longer time to observe the long-term impacts of artificial recharge on groundwater storage and groundwater level rise and posed uncertainties to the study.

Notwithstanding the shortcomings in this study, it is the first-ever study of applicability and effectiveness of artificial recharge of groundwater as a management tool in Afghanistan in general, and in the Kabul Basin in particular. The approach followed in this thesis is backed by careful review of studies on water resources in Afghanistan; exploring literature on the topic of artificial recharge, and utilization of newest applications of related groundwater computer programs. Therefore, this study suits as an insight for future researches on artificial recharge of groundwater in Afghanistan in order to increase groundwater storage, groundwater level rise, water quality improvement and land subsidence prevention. The main goal of this study was to prove that an artificial
recharge project in the study area is applicable and effective. However, to measure its extent of effectiveness, more efforts are required in the future. For the future implementation of artificial recharge of groundwater in the area, it is recommended that a thorough investigation of soil properties and other in-situ/laboratory measurements be done. It is also recommended to utilize a calibrated groundwater flow model that is built and calibrated with sufficient data. Finally, it is recommended to construct test recharge basins to examine the effectiveness of the project before any attempt to construct actual facilities.

This research can lead to new studies on the applicability of artificial recharge of groundwater in different parts of Afghanistan using the surplus flow of rivers during the rainy season. The research can be extended to study various effects of artificial recharge of groundwater e.g. land subsidence prevention.
References


Mehl, S. W. and M. C. Hill (2006). MODFLOW-2005, the US Geological Survey modular ground-water model-documentation of shared node local grid refinement (LGR) and the boundary flow and head (BFH) package.


Vita

Mohammad Farid Masoom citizen of Afghanistan, received his bachelor’s degree in Civil Engineering from Engineering Faculty of Kabul University. Thereafter, he worked as a civil engineer in construction companies in Afghanistan for four years. In 2016, he received a United States Department of State’s Fulbright Foreign Student Scholarship to study his master’s degree in Civil Engineering with a concentration in Water Resources Engineering at the Louisiana State University. He will receive his master’s in May 2018.