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Ambika P. Adhikari

Arizona State University; and, Institute for Integrated Development Studies (IIDS), Nepal,
ambika.adhikari@gmail.com

Keshav Bhattarai

University of Central Missouri, bhattarai@ucmo.edu

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Research Article

Minimizing surface run-off, improving underground water recharging, and on-site rain harvesting in the Kathmandu valley

Keshav Bhattarai¹, Ambika P Adhikari²

1. Department of Physical Sciences; University of Central Missouri

2. Institute for Integrated Development Studies, Nepal

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Abstract

Nepal's political institutions and administrative units were thoroughly restructured in 2015 with the promulgation of the new Constitution. Several rural areas were combined to meet the definition of urban threshold criteria to classify rural areas into urban categories. Accordingly, over 3,900 local political and administrative units were amalgamated into 753 units, of which, 293 units are classified as urban. Within these newly defined urban areas, many natural environments have been converted into impervious surfaces such as paved roads, sidewalks, and building roofs. These impervious surfaces have drastically increased the amount of surface run-offs—often termed as “urban floods” ~under increasing precipitation caused by global climate change. These incidences have negatively impacted to the groundwater recharge processes in the urban areas.

Data on groundwater recharge rates are needed in the context of global climate change to understand the status of groundwater recharge processes in the urban areas of Nepal. However, due to various limitations, this study only focuses around the Kathmandu Valley of Nepal to understand: a) how the expansion of urban, peri-urban, and associated areas have resulted in decreasing groundwater recharges; b) how groundwater is affected by the year-to-year variability of precipitation amount (low and high intensity) with the conversion of the natural landscape into built-up areas; and c) how the changing trends in precipitation and evapotranspiration may impact future groundwater availability. This study is based on a review of the literature and the analysis of secondary data available from the government and various social media and authors' professional experiences. The study ends with some recommendations based on experiences from other parts of the world on groundwater recharge processes.

Keywords: Groundwater, Kathmandu Valley, urban, impervious surface, rainwater, land subsidence.

* Corresponding author; K.Bhattarai (bhattarai@ucmo.edu), AP. Adhikari (ambika@alum.mit.edu)



1. Introduction

In many places, groundwater resources support the livelihoods of the communities and sustain human health. The availability of groundwater is influenced both by natural factors such as spatial distribution of rainfall patterns across and the heterogeneous geology, soil, and topographical characteristics (Prajapati et. al., 2021). Precipitation helps in recharging groundwater through seepages into the ground. However, in the urban areas, when an intense rainfall occurs within a short interval, it fails to seep into underground natural reservoirs due to impervious built-up areas. The rainwater does not reach the aquifers, nor it gets out as baseflow, but it directly flows to streams and rivers as a surface run-off, and eventually drains into the sea and becomes non-fresh water. Through this process, local water source is depleted both by anthropogenic causes and natural processes. Local groundwater levels plummet and then slowly rise up creating a sine-wave form of the water table over time based on the use and recharge of water. Since underground water is usually isolated in constricted spaces when it is pumped out especially in the summer season from locations using high pressures, soils, and rock materials crumble under the surface because they move to fill the gaps created by the removal of water. As groundwater becomes the primary source of water supply for various uses during the lean wet seasons, especially, when rainfall is nominal (Belhassan, 2011), excess of groundwater pumping in the densely populated areas such as in the Kathmandu Valley often leads to land subsidence (Bhattarai et al., 2017) if the underground water stock is not immediately replenished.

Water table can go down due to anthropogenic and natural processes. Pumping out of water for household or other uses is one of the anthropogenic causes that depletes groundwater stored /or floating on top of underground lakes and rivers. Evapotranspiration is not natural causes of groundwater depletion. Naturally, deep-rooted trees take water out and it evaporates into the atmosphere through evapotranspiration. Also, when plants use underground water during the photosynthetic processes, the water table goes down. Groundwater is also influenced by climatic factors because, during rains and intense precipitation within a short interval increases the surface runoff rate resulting in floods, especially in urban areas. At high surface temperatures, groundwater is also lost at a rapid rate due to a high degree of evapotranspiration in presence of deep-rooted broad-leaved trees (Ghiat et. al., 2021), and surface evaporation occurs due to irradiance and high temperature (Buitink et. al., 2020). Large leaf surfaces in windy and warm environmental conditions, evaporate more water than tiny needle surface leaves, such as in coniferous trees. For this reason, broad-leaved plants are planted to drain groundwater in many parts of the world. For example, in the Netherlands, Eastern Cottonwood (*Populus deltoides*) plants are cultivated to drain water while reclaiming sea surfaces (Jacobs et. al., 2014).

Groundwaters are found both in confined and unconfined aquifers which represent a dynamic balance between groundwater storage, recharge, and discharge (Prajapati et al., 2021; Conlon et al., 2005). Confined aquifers are common in urban environments and in areas such as those made from rocks and compact clay where the water level is saturated because impermeable materials are present above and below the water surface, such as in the Great Artesian Basin of Australia (National Water Commission, 2013). When such water resources are drilled, water rushes out easily because of the pressure created by the underground water (USGS, 2022; Sanders, and Thompson, 2020). Confined aquifers recharge quickly when there are surface fissures and earthquake cracks that help the percolation of rainwater or surface recharging. Funneling rainwater from the roof and other clean surfaces into wells helps to easily recharge confined aquifers. Ponds, lagoons, and other landfills are frequently used to recharge confined aquifers. In many places, mechanical gushing is used to recharge groundwaters through deep well injection. Deep well injection is a type of reverse pumping out of water using external energy. This practice can be applicable to areas like the Kathmandu Valley where built-up surfaces such as paved roads, sidewalks, and building roofs have converted natural ground into impervious surfaces causing increased surface runoff, especially during intense rainfall events. Injecting water into underground aquifers requires careful monitoring because of the possibility of pumping in polluted water to the underground aquifers.

Natural recharge of ground water in highly built up areas is limited unless there are interferences by human beings. The groundwater recharge can be naturally and passively achieved through retention ponds or recharging ponds (Figure 1).



Figure 1. A groundwater recharging pond at Gilbert Riparian Preserve, AZ Tempe, USA. Photo by authors

Water recharged through retention ponds is naturally filtered by the ground as they reach underground water bodies via several layers of soils. To help in the recharge and to hold water and avoid flooding, Retention ponds are required in all large

developments and residential areas in the USA to avoid flooding of roads and public areas. For example, urbanized residential area in Gilbert, AZ, USA has successfully implemented such a plan of retaining surface water for recharging (Figure 2).



Figure 2. A retention pond in a residential development,

Recent developments show that using a geotechnical drainage system to

inject water into mines, slopes, and tunnels is possible. Pit drainages (Figure 3) are often done both by natural and artificial processes in areas “where drainage and diversion of drainage flow are problematic” (Edwards et. al., 2106). This could be applicable to the culturally modified landscape of the Kathmandu Valley where a poor drainage system often causes floods during heavy rainfall. Pit drainage could help deflect and redirect flood water. Nature-based processes such as the retention ponds or recharging ponds take a long-time to stabilize the water levels because they work slowly and gradually through seepage and filtration depending upon the geotechnical and environmental conditions of area. By contrast, the mechanical deep-water injection is quick and efficient. However, the deep-water injection requires external energy, hardware, and other tools and human resources. On the other hand, natural recharging processes as described above are passive and work through gravitation, requiring only an initial construction and dedication of land for this purpose.

In urban centers like the Kathmandu Valley, the water injection process (sometimes also called reverse boring) has become necessary as high water usage activities often drain water from the confined aquifers. In many cities, such as Phoenix, Arizona, USA, stringent rules are in place to regulate the recharging of aquifers to avoid contamination while recharging ground water (Silber-Coats and Eden, 2017).

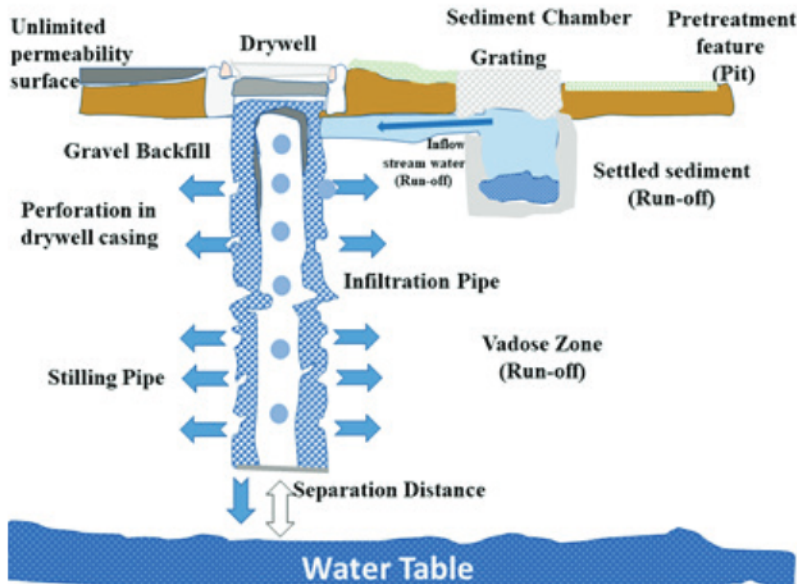


Figure 3. Pit drainage using grass. This drainage system helps seep water underground through dry wells. Drywells are typically backfilled with gravel or cobbles, and water seeps down through walls (Modified and adapted from Edwards et al., (2016)).

In unconfined aquifers, the water table is found in the upper areas close to the ground level, and such water tables are directly impacted by drought and rainfall patterns (USGS, 2022). Unconfined aquifers are recharged through lateral and direct percolation of water where water flows along the surfaces through silt and sandy layers such as in the cases of riverbeds of Bagmati, Bishnumati, Manohari, and other rivers of the Kathmandu Valley. When water finds porous surfaces and previous ground, it infiltrates to underground water. During heavy rainfall and flooding, unconfined aquifers become oversaturated. Thus, an unconfined aquifer has a big volume of water during heavy rains because water recharges from nearby sources. Pit recharging may help to retain the excess amount of surface water. Pit seepage is mostly a nature-based recharging process where water seepages through pores. In porous soils, water gets into these pores and the air is often displaced by water, especially, during heavy rainfall because during the heavy rainfall, water pushes air bubbles inside and accelerates the process of recharging.

Plants acquire water from the unconfined and confined aquifers and the groundwater table goes up and down based on the water use and rate of evapotranspiration and rainfall. It goes up slightly when the water infiltrates in because of the rain, but the water level goes down when more water is being pumped out for human use.

Vegetation along the roadside is beneficial for the road because it helps slow erosion. Vegetation also serves in road maintenance if attention is paid in the judicious selections of plant species. Planting more trees helps avoiding drilling holes because deep root system often create a channel for underground water flow (seepage). However, deep, and wider taproot systems can also breaks the foundation of urban structures and road drainage channels.

Other factors that impact groundwater recharge are: how dry the soil is, when it rains, how deep below the earth's surface the water table is, and whether there are any barriers to the water flow. Shallow groundwater systems are made up of sand or gravel such as in the northern part of the Kathmandu Valley where water tables are easy to be recharged and extract for uses. Sands and gravel can help fill the groundwater quickly during large rainfall events. Grass-filled pits help sandy and gravelly surfaces to seep water slowly whereas grass functions as a filter. However, for deep groundwater systems, it can take many years before rainwater reaches deeper water storage. This lag time means there may be water available in groundwater systems even during drought period. The slow water movement means water can be stored in the groundwater system for the long term. Excessive pumping of groundwater for use by big apartments, hospitals, and industrial complexes disrupts the process of groundwater recharging thus inviting the risk of ground subsidence and sinking, and the possible damage to surface structures such as bridges and culverts, roads, and buildings.

Rivers and groundwater systems interact with each other. Based on the local conditions, water can move between groundwater and the river. Anthropogenic activities such as tunneling waters for irrigation and other uses such as large concrete structures often interfere in this process. For example, it has been claimed by the local residents of Kathmandu that Sundhara (Golden waterspout) dried after the construction of the Kathmandu Mall and other physical structures around Sundhara (Bajracharya, 2021). If water flow is not disturbed, the water table mostly recovers and even becomes a part of the connected groundwater system. Recovery of surface levels after extraction happens quite quickly over hours and days, whereas recharge of the whole groundwater system may take many years, such as in the densely settled Kathmandu Valley.

Under these backdrops, this paper looks at the groundwater recharge situation in the Kathmandu Valley. The long-awaited Melamchi Water Supply Project (MWSP) is estimated to supply 170 million liters of fresh water per day (MLD) (MyRepublica, 2022) at the beginning and peak at over 510 MLD after the full completion of the project. However, it has already encountered several unaccountable snags. As MWSP could not meet its goals, the Kathmandu Valley has been facing water crises on

multiple fronts. In an attempt to address the water crises in the Kathmandu Valley caused by the mushrooming apartments, hospitals, educational institutions, hotels, and industries, groundwater has been excessively pumped out to meet the water needs. The result of such indiscriminate pumping of groundwater on one hand and the conversion of the natural landscape into impervious hardscape have seriously hindered groundwater recharging. The Kathmandu's water supply board and the Kathmandu Uptakya Khanepani Limited (KUKL) estimate that the actual demand for water in Kathmandu Valley is "430 million liters per day if water is supplied 24 hours a day" (Xinhua, 2021). KUKL is currently planning to supply 170 MLD from its existing resources and 100 MLD from MWSP. The remaining amount is being drawn from underground using deep boring (Limbu, 2001; Shrestha, 2009), where households are experiencing a drop in the water table level each year (Limbu, 2001). Since over 60 percent of the shallow wells are often contaminated with fecal matter and high numbers of coliform bacteria, more and more agencies in the Kathmandu Valley are going for deep water boring (Limbu, 2001) increasing the probability of land subsidence (Bhattarai et al., 2017).

Record suggests that the Nepal Water Supply Corporation (NWSC) started groundwater withdrawal in Kathmandu in the 1970s. There has been a gradual increase in groundwater extraction rate since then. For example, 9 million liters per day (MLD) was pumped out in 1984, 34 MLD in 1987, and 42 MLD in 1998 despite the warning by the World Bank Study (2008) that categorically stated that only 26.3 MLD of extraction is sustainable. The Asian Development Bank (ADB) also issued a stern warning in 1999, when 58.6 MLD was extracted which was 60 percent more than what was recommended (Limbu, 2001). Groundwater uses by various sectors differ in the Kathmandu Valley. For examples, hotels' uses exceed 8.4 percent, industries' uses exceed 7.9 percent, and the government's uses exceed 5.3 percent in the total water supply used by them. The ADB estimated "over 300 tube wells in the Kathmandu Valley" (Limbu, 2001) are operating without monitoring from the concerned agencies.

One of the authors of this paper has observed the groundwater studies of Japan International Cooperation Agency (JICA) in Nepal since the 1980s. JICA's (1990) studies predicted between 27,000 - 40,000 MLD recharge rate mainly in the northern region along the buffer zones of the rivers and rivulets. The same study revealed that because of the deposition of thick impermeable clay (black soil, or Kalimati in Nepali) in the southern portion of the Valley, the recharge is difficult, where the rate of depletion of groundwater via deep boring has been rapid.

2. The issues of the Kathmandu Valley

Especially since the 1980's, many people living in the Kathmandu Valley have found the use of ground water as cost effective (Pandey et. al., 2010) as the Kathmandu Upatyaka Khanepani Limited (KUKL) has been able to meet only 19 percent of the total demand of drinking water during the dry seasons and 31 percent during the rainy seasons (Thapa et al. 2018) from the regular water supply using the surface water sources. The dependence on groundwaters for industries, hotel, and hospital uses (Lamichhane and Shakya, 2019) began to grow since then. Pandey and Kazama (2014) and Shrestha et al. (2017) have estimated that Kathmandu Valley groundwater recharges between 4.6 and 14.6 million cubic meters per year (MCum³/year), but it is not uniform across the entire watershed of the Kathmandu Valley.

3. The Kathmandu Watershed

Using a triangulated irregular network (TIN) surface created in ArcGIS Pro 3.0 utilizing 30m x 30m resolution digital data with three-time surface (z) factor exaggeration, we drew the Kathmandu Watershed to exactly delineate where and how actually water drains into the Kathmandu Valley from northern landscape, and laid the geology of the landscape over this surface (Figure 4. a-b). Lamichhane et al. (2019); Thapa et al. (2016); JICA (1990) have made some attempts to map the Kathmandu Valley's groundwater recharge areas. Groundwaters recharge either from precipitation or from natural water sources such as rivers and their territories. Precipitation in Kathmandu's watershed ranges from 4.2 mm in December to 402.1 mm in July with a total annual rainfall of 1,533 mm per year (Shrestha, 2009). Over 80 percent of precipitation occurs between June and September and contributes 456.01 million m³ per year of surface water that flows at the southern tip from the surface area of 738 sq. km. covering a perimeter of 149 km (Figure 4) of the watershed. The flow becomes minimum and almost non-existent during the non-rainy seasons. Within the valley, traditionally, many stone waterspouts, wells, and Rajkulos (royal wells) (Figure 4a) were used to sustain the water needs of the Kathmandu denizens.

The tradition of stone waterspouts and Rajkulos in the Kathmandu Valley started from the Kirat period (900 B. C. to 300 A. D.) (Acharya, 2018). Lichhavi kings (300 - 900 A. D) gave continuity to this tradition with some improvements including the digging of wells in the nearby settlements to meet local water needs, and this work was regarded as Kirti which means 'fame'.

To assure that the local water supply system is robust, the Malla rule (1201 - 1779

waterspouts that too only during the wet seasons, 280 are dried, and 94 disappeared. A report by NGOFUWS (2006) revealed that about 400 stone spouts and several hundred traditional dug-wells in the Kathmandu Valley are now dry. Until 1991, people of Patan, Kathmandu, and Bhaktapur, used stone waterspouts to meet their water needs. However, today, only 100 waterspouts are functional in Lalitpur, 60 in Bhaktapur, and 40 in Kathmandu districts (Ghimire, 2022). Water does not flow in 373 waterspouts. According to Padma Sundar Joshi, a city planner, and researcher of stone spouts, around 100,000 people are getting water from existing stone spouts (Ghimire, 2022).

In Patan, there is one Manga Hiti (Manga waterspout) where water 24 hours a day. This spout was established by the grandson of king Mandev in 570 BS. Another stone waterspout located in Handigaun, Kathmandu near Satyanarayan Temple has been in operation since 500 BS. According to Sushil Shrestha, Expert, Stone Waterspouts, in Lalitpur alone, there are at least 54 waterspouts on which water flows 24 hours a day. In Bhaktapur, there are 82 stone waterspouts where only 8 waterspouts serve water, and in Kathmandu, only 10 percent of the spouts yield water. According to Padma Sundar Joshi, of all the waterspouts of the Kathmandu Valley, it is possible to make 50 percent of the spouts generate water 24 hours a day. Poudel (2020) studied the stone waterspouts of the Lalitpur district. During his studies between 2006 and 2019 within the area of Lalitpur Municipality, he found that Iku Hiti flowed perennially during the study period. Though he found Sundhara Hiti operating only during the monsoon seasons, Sauga Hiti and Maka Hiti are now completely dry. He observed that other spouts were either operating seasonally or are completely dried out making it hard to meet the water demand of the Kathmandu Valley.

4. The increasing water demand of the Kathmandu Valley

Population of the Kathmandu Valley has increased from 1.11 million in 1991, 1.65 million in 2001, and 2.53 million in 2011 (Thapa et al., 2018). In 2021, the urban population in the Kathmandu Valley increased to 2.71 million unaccounted for the floating population and non-urban population. Altogether there are 437,324 households with 780,521 families in urban areas of the Valley. These comprise of 90,699 households with 134,152 families in Bhaktapur, 70,849 households with 108,453 families in Lalitpur, and 275,806 households with 573,916 families in Kathmandu district (CBS, 2021). As the population density of the Kathmandu Valley has increased to 20,288 per sq. km. (2021), many houses are built, and stone waterspouts and wells are encroached on or badly mismanaged by new concrete structures. These new structures have led several stone waterspouts, wells, and ponds to become dry and inoperative. With the growth in population, water demand has

increased from 35.1 MLD in 1998, to 155 MLD in 2000, 320 MLD in 2009, and 370 MLD in 2015 (Thapa et al., 2016; Thapa et al., 2018), and 470 MLD today (Shrestha et al., 2022), and it is projected that if the floating population of the Kathmandu is accounted for, even 510 MLD (GoN and ADB, 2021) would be barely sufficient meet the needs of the Valley population. In 2015, as the shortage of drinking water started, the KUKL authorized private individuals to supply potable water to Kathmandu's dwellers. However, the private organizations could serve only 31 percent of the valley denizens during the rainy and winter seasons, and this service was shrunken to 19 percent during the dry seasons (Thapa et al., 2016). KUKL used to collect 65.3 MLD water in the dry season and 131 MLD in the wet season from various sources such as rivers and groundwaters to serve Kathmandu residents (Prajapati et al. 2021; Gautam et al., 2017).

As KUKL was unable to meet the demand of the Kathmandu denizens, private individuals started deep well boring in the Kathmandu Valley. Side effects of such unregulated pumping of groundwaters were noticed as early as the 1980s. Despite these side effect of ground subsidence, the number of private wells and deep boring continued in the Kathmandu Valley. "Extraction of groundwater has increased from 2.3 million liters per day (MLD) in 1979 to 80 MLD in 2011" (Shrestha et al, 2016 in Bhattarai et al. 2017) to meet the growing demand of water (Bhattarai et al., 2017). The Government of Nepal (GoN) has been attempting to complete an ambitious Melamchi Water Supply Project (MWSP) by diverting water from Melamchi River of Sindhupalchowk district since 1998 to ease the water shortage of the Kathmandu Valley by increasing the supply up to 500+ MLD (GoN and ADB, 2021). However, its full benefit has yet to be experienced by the Kathmandu denizens. Eventually, this can relieve the pressures on the groundwater aquifers to deep water pumping out using the high-powered engine.

5. Aquifers

The Kathmandu Valley Watershed has shallow aquifer in the north. The geology there is composed of igneous and metamorphic rocks. In the southern and western parts of the Valley, the geology contains sedimentary rocks (Dhital, 2015; Sakai, 2001) and black soils (Nepali word "Kalimati") (Chapagain et al., 2010). The southern part is a "compact fluvial-lacustrine layer of Quaternary-Pleistocene sediments composed of sand, silt, clay, and gravel" (Shakya et al, 2019:1). The presence of silt, sand, and gravel make the soil porous for unconfined aquifers. Both shallow to deep aquifers are found in this southern region. The depth of deep tube wells varies from 30 to 300 m, and the deep aquifers yield water ranging from 3000 to 400,000 liters per day (Pandey et al, 2012).

JICA (1990) has divided the aquifers of the Kathmandu Valley into the northern groundwater district (NGD), formed by the deposits of sand and gravel beds, the central groundwater district (CGD) with thick (200 m) impermeable black 'Kalimati' clay, and the southern groundwater district (SGD) comprises carbonate rocks classified as lower permeability layers (Chapagain et al., 2010). "Groundwater in the Valley is extracted from both shallow (0–60 m depth) and deep (>60m depth) aquifers" (Shakya et al., 2019:2; Chapagain et al., 2010). The deep and shallow aquifers are distinguished by a thick aquitard of approximately 200 m of clay distributed mostly toward the central Valley. The yield of the aquifer decreases as one goes farther away from the valley (Chapagain et al., 2010).

The aquifers of the Kathmandu Valley's watershed have different types of soils; for examples, Dystrochrepts, Haplumbrepts, Haplustalfs, and Rhodustalfs (Figure 4b). Dystrochrepts are formed from mica gneiss and schist which contains clay and primary minerals. These soils have the least morphological development on which the thinness and coarse texture of the sola accumulation may occur beneath the cambic horizons in vertical cracks in the structurally rigid, isovolumetrically weathered saprolite. Several unconfined aquifers exist within such structures. The source of clay is relatively easily weathered plagioclase (Rice et al., 1985). Haplumbrepts, Haplustalfs, and Rhodustalfs contain calcareous materials and are found along the foothills of the hillocks facilitating the process of groundwater recharging in unconfined aquifers. Haplumbrepts and Haplustalfs types of soils are found along densely populated area, where the surfaces have "Kalimati" that invites interference by humans for groundwater recharge through deep-ground injections. In the northern areas, the soil has low base saturation with a minimum horizon, but as the topography changes to a plain valley, the soil becomes compact with a thick dark horizon. In the northern region, if soils are not disturbed, groundwater recharge becomes normal, but the compaction of soil with the constructions of various structures leads to surface and sub-surface run-off, where deep water injection remains the only solution to recharge groundwaters.

The Kathmandu Valley Watershed (KVW) is drained by Bagmati river and its tributaries such as Bishnumati, Hanumante, Dhobi Khola, Manohara, Balkhu, and Nakhhu covering an area of 613 km² ranging in elevation from 1,212 to 2,762 meters above the mean sea level (Figures 4 and 5). These rivers have many tributaries, many of which are seasonal. The total river run a length of the KVW is 2,710 kilometers (km). Some are very short (0.36 km) while Bagmati has the maximum continuous length of 60 km within the delineated watershed area (Figure 5a). Within the KVW,

denser settlements are found along the valley where many buildings including tall apartments, industries, hospitals, and hotels are located. These structures are associated with the deep-water (30 – 350 meters) pumping using high powered pumps.

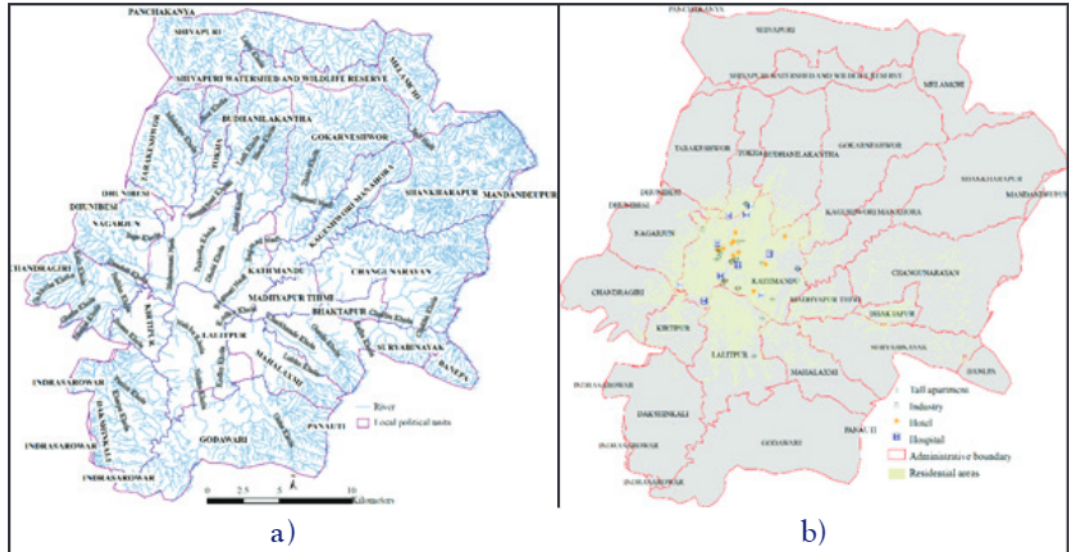


Figure 5. Kathmandu Valley: (a) River systems contributing to groundwater recharge and (b) Locations of tall apartments, industries, hotels, hospitals, and settlements concentrations where most groundwater pumping activities are confined.

In addition, many large and small structures are built by encroaching riverbeds and floodplains, and even by burying ponds, and sites of stone waterspouts. Satellite images taken in 2022 and Google Earth have revealed that overtime, more than 5,677 structures have been built (excluding bridges and culvert) within the distances of 25 meters from various water bodies. The area of such structures ranges from 5 sq. meters to 9,500 sq. meters (Figure 6b). Most of these structures are found in the plain areas of the valley (Figure 6a) that remain the potential sources for groundwater recharge. The land subsidence that happened in Kathmandu in the 1970s near the Bishnumati River in Hyummur neighborhood between Kalimati and Jaisi Deval may repeat again if judicious groundwater recharging is not carried out soon. Judicious ground recharging is also essential to avoid the contamination of various biological activities such as the nutrient washed away from tree root systems and the seepages from drain fields from the septic tanks connected to toilets.

Among the various ways to recharge the groundwater is to manage the surrounding watershed areas well. One immediate remedial measures to support groundwater recharging is the need for cross checking the structures that are built on or nearby the waterbodies to assure that: a) these structures have not affected the spring water resources; b) no environmental disasters impact human settlements; c) such settlements do not contaminate nearby waterbodies, and such contaminations do not become the major causes for cholera and other water borne disease outbreaks. With these precautions, probably, groundwater recharging using rainwaters may become one of the major feasible options.

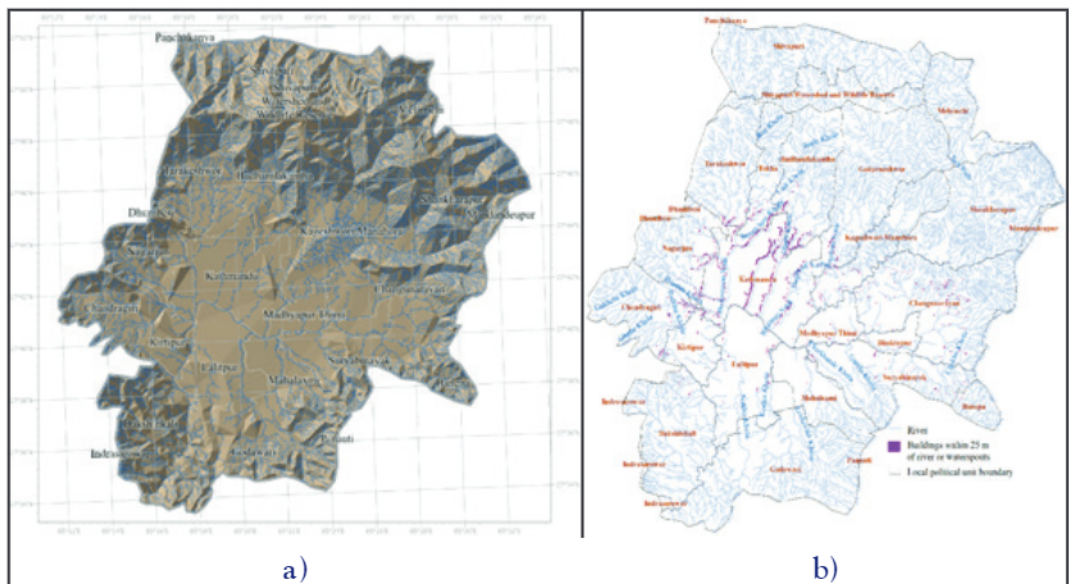


Figure 6. Kathmandu Valley: (a) Watershed with river systems, and (b) Locations where structures are built either on or above the rivers, waterspouts, or within 25 meters within water sources. These structures occupy an area of 75,3327 square meters. These structures disturb the process of groundwater recharge leading to ground subsidence (Figure 7).

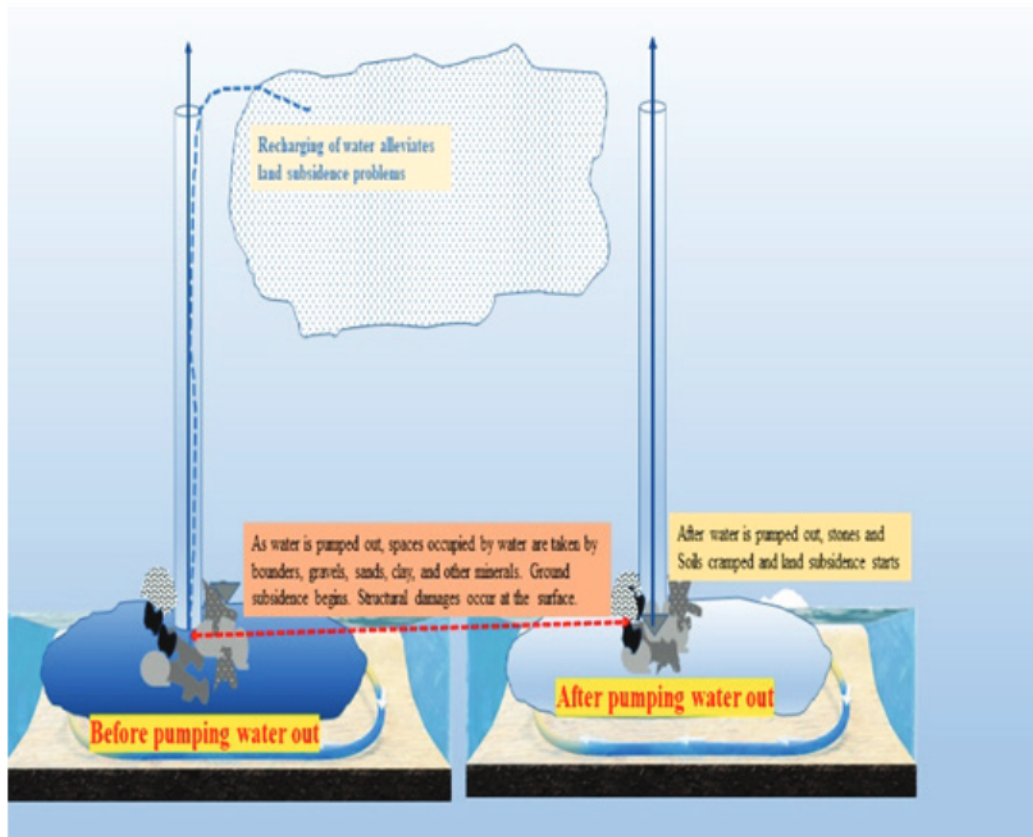


Figure 7. When water is pumped out, stones, gravels, sands, and soil particle occupy the spaces taken by these materials and land subsidence starts.

6. Harvesting rainwater

Harvesting rainwater for drinking, irrigation, industrial uses, firefighting, construction, aquaculture, groundwater recharge, has become a preferred practice in many cities across the world. For example, a almost 42 percent of South Australian population uses rainwaters for drinking purposes (Shrestha, 2009). “In Bangladesh, rainwater is a major alternative source of drinking water in arsenic-affected areas” (Shrestha, 2009:1). Singapore has been most successful in utilizing rainwater for human use. Each month, the Changi (Singapore International) Airport harvests 63,500 tons of rainwater for “flushing toilets and cooling the terminal buildings” and saves USD 390,000 each year from importing water (Shrestha, 2009) from Malaysia and Indonesia. The Gansu Province of China harvests rainwater to irrigate 236,400 hectares of land each year (Shrestha, 2009).

Recharging groundwater from rainwaters for two contiguous years have resulted in the increase of water level by 5 to 10 meters in the state of Jaipur (Rajasthan) Jaipur India (Mahnot et al. 2003). The shortages of drinking water have been apparent in the Kathmandu Valley since the 1980s as the population increased (Figure 8). Every day in the Valley, the underground water extracted is six times more than its recharging rate (Limbu, 2001; Shrestha, 2017, Shrestha, 2009). An immediate consequence of the depletion of shallow groundwater aquifers is that dug wells, hand pumps, and traditional stone spouts can no longer provide water as they once did. The groundwater quality is also a concern, chemical pollutants such as arsenic, ammonia, and nitrate have been detected in deep aquifers in many areas of the Valley (Shrestha et al., 2017). Increasing population on one hand and heatwave and dry years that have depleted water sources on the other have threatened the water supplies not only in Nepal, but all over the world. Harvesting rainwater has been an option to recharge ground waters. However, the rainwater also is not free from pollution (DIW, 2022).

Shrestha (2009) from his decade-long research revealed that in some extreme events the Kathmandu Valley receives up to 1,900 mm of rainfall annually. This heavy rainfall has been both curse and blessing for the Kathmandu Valley. It is a curse in the sense that as many areas of the Kathmandu Valley have become impervious due to the construction of roads, buildings, and other structures, they have increased to the surface run-off during the rainy seasons. The flood of each rainy season often brings clay particles that get deposited on the road surfaces. As the Kathmandu Valley's roads become dry in winter and summer, vehicles plying on the road crush these floods deposited clay particles into fine grain. During the rainy season, these crushed particles make roads in Kathmandu muddy and contaminated with chemicals. During the dry seasons, these fine-grained particles become parts of aerosols and PM10 and PM2.5 materials. Heavy rainfall also often becomes blessing because it washes away road dirt and it offers opportunities to harvest approximately 1.2 billion cum³/year or "3,353 million liters of rainwaters per day (MLD) from 640 sq.km area" (Shrestha, 2009:2) within the urban environment. This is more than the "present water demand" (Shrestha 2009:2) (Figure 8). During his long-term studies, in some years, Shrestha (2009) has observed exceptionally high (to be exact in his word, "2,500 mm") annual rainfall in the valley. Shrestha (2009:2) and UN-HABITAT (2006) argue that almost 80 percent of "total rainfall on a building can be collected easily" (Shrestha 2009:2). Theoretically, "a building with a roof area of 100 sq. m could collect up to 200 cu. m of rainwater per year" (Shrestha 2009:2). It is estimated that a person needs about 35 cubic meters (cum) of water each year. A 100 square meter roof surface can sustain a five-member family annual of 175 Cum³ water needs if that water can be collected and stored safely and properly treated for various uses.

Exploring the possibilities of harvesting rainwaters, in this paper, we have integrated information from three sources:

- a. Information from the decades-long findings of Shrestha (2009), who observed rainfall in the Kathmandu Valley from 2005 till today.
- b. The number of household information and number of members in a family residing within the urban classified areas from the Census Bureau of Statistics.
- c. We digitized the entire buildings of the Kathmandu Valley that occupy over 150 square meters roof surfaces.

Based on the authors' personal experiences (refer to the books Adhikari (1998) and Bhattarai and Conway (2021)), Shrestha's assumption of getting 200 cubic meters of water from a 100 square meters roof could be slightly overestimated because of the natures of roofs and their rain outlets. Thus, our assumptions are that for a theoretical yield of 200 cubic meters of water, at least 175 square meters of roof is essential. However, considering the waste through evaporation, leaks, and other factors for water loss, a roof area of 350 square meters would be necessary to capture 200 cubic meters of water assuming a 50% efficiency rate (30% would be more realistic) of water collection. However, 350 square meters is a large roof area. The typical residential building footprints in Kathmandu are much smaller as they are built on small sites often in the range of 100 square meters lot. Leaving out open spaces, the typical plinth area of the building on such site is just about 60 square meters, and the roof area could be around 75 square meters including overhangs.

- d. Based on these assumptions, we have estimated the possible amount of rainwater that could be harvested each year in the urban areas of the Kathmandu Valley (Figure 8).

Rainwater is not safe for drinking without at least some further treatment. Prof. Ian Cousins and his research team of the Stockholm University from their years of rigorous experiments have concluded that rainwater across the world has never been safe to drink directly because of the contamination of various chemicals. The presence of various byproducts of anthropogenic causes and the presence of forever chemicals in the atmosphere, such as polyform alkaline substances have made rainwater unsafe to drink without further treatments. Prof. Ian Cousins's team has warned that rainwaters even from many pristine geographic areas such as "Antarctica and Tibetan Plateau" are not safe to drink. The most populated places of the world have failed to meet "drinkable water guidelines" (DIW, 2022). "Perfluoroalkyl and Polyfluoroalkyl Substances (PFAS) were the main measuring yardstick used to determine rainwater

pollution levels in this study.” (DIW, 2022) These chemicals do not fragment, they do not combine, have capacities to spread stinks. These chemicals are resulted from packaging, electronics, cosmetics, and detergent washing soaps, which can cause cancerous diseases, including the fecundity problems, inhibit growth in children (DIW, 2022; OnlineKhabar, 2022).

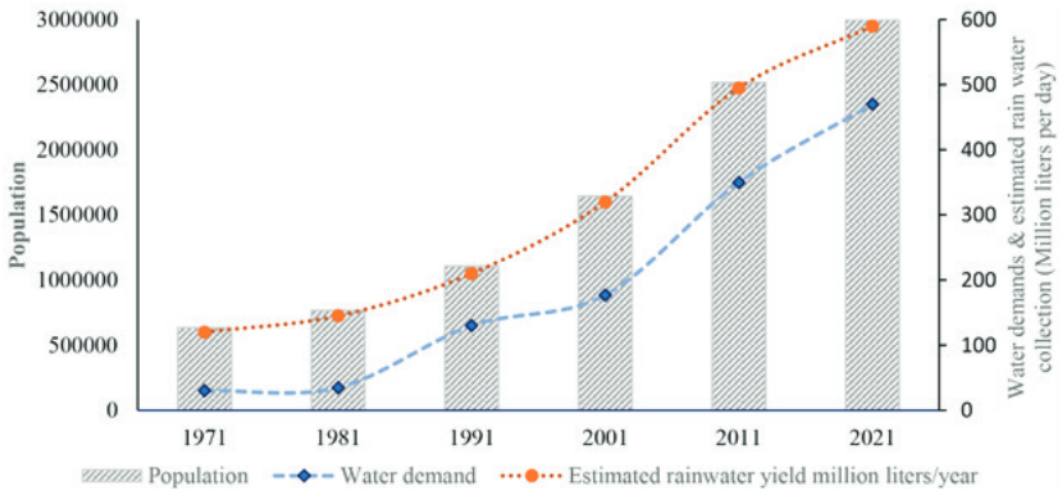


Figure 8. Population growth, daily demand for drinking waters and potential for harvesting rainwaters. Source: Shrestha et. al. (2022), Prajapati et al. (2017), Shrestha (2009) and CBS (2022)

Nonetheless, rainwater when treated properly, is safer to use than the arsenic containing ground water that have been observed in some parts of Dacca, Bangladesh (Shrestha, 2009). Storing and sending rainwater to recharge groundwater, might alleviate pollution problems as contaminants may be retained on soil. Additionally, phyto treatment (planting trees on the watershed), also alleviate such problems to some extent. Nonetheless, while recharging confined aquifers extra precautions are needed following strict guidelines to make water drinkable after ordinary treatment methods as Shrestha (2009) suggests (Figures 9 and 10). The initial rainwater collected on the roof, called “first flush” carries the most dust, dirt, leaves, and contaminants, and is not directed to any active collection system such as in cistern. The first flush is diverted to the ground or nearby bio swales.

Rainwater can usually be used for several other purposes with simple filtration. These uses include irrigation for landscaping and agriculture, flushing toilets, and for washing many household items including cars. In Arizona, some municipalities encourage and some even mandate on-site rainwater harvesting for use as irrigation water for plants and trees on site. For example, the City of Tucson, Arizona in 2008

passed an ordinance requiring commercial developments to meet 50% of landscape irrigation water using on-site rainwater harvesting (City of Tucson, 2008). As rainfall is low and water demand is high in Arizona, many cities are crafting and implementing regulations and guidelines to encourage water harvesting and use the water for irrigating landscaping and urban agriculture on site, and for other gray water uses such as for creating ponds and fountains on-site, and to use the stored rainwater for aesthetic reasons and for acceptable household uses. Many cities in the US require or advise the creation of rain gardens (which are irrigated by rainwater) for landscaping the site and prohibit the use of potable water to irrigate landscaping except when they are being established. The International Green Construction Code (IgCC), (IgCC 2018) generally prohibits the use of potable water to irrigate urban gardens, turfs, and landscapes except during the plant establishment period. An example of redirecting rainwater collected through the building roof to irrigate on-site landscaping is provided in figure 9.

At a time when many of the stone waterspouts in the Valley have died, and the Valley water supply has been unreliable, the Kathmandu Valley might benefit from harvesting rainwaters for two objectives: recharging the depleting water to avoid land subsidence (Figure 5 and 7), and supplementing the water needs of the Kathmandu Valley's residents (Figure 8).

Shrestha (2009) along with local communities of Patan at the initiation of the UN-HABITAT have devised a scheme (Figure 10) to recharge groundwater. This scheme may be helpful in mitigating the issues of ground subsidence which has been observed in the Kathmandu Valley caused by



Figure 9. Redirecting rainwater to landscape irrigation in Tempe, AZ, USA. Photo by the authors.

the excessive pumping of groundwaters (Bhattarai et. al., 2017; Hu et al. 2009). When excess of water is pumped, the soil and rocks naturally compact (Figure 7) (USGS, 2018, 2022). As land subsides due to the movement of gravels, sands, and boulders to occupy the vacant spaces created due to the extraction of water, it not only reduces and lowers the water levels, but also a shift in the topographic gradients occurs on the surface (Yamaguchi, 1969), which also leads to the damages to the structures on the ground. Evidence of ground subsidence have been reported from Brazil (Chaves and Lorena, 2019); Red River Basin, USA (Sabzi et al. 2019); Tokyo, Japan (Yamaguchi, 1969); Mexico (Ortega-Guerrero et. al., 1999); Saudi Arabia (Ghanim, 2019); Ravenna, Italy (Teatini et al., 2005); Bangkok, Thailand (Bergado et al., 1987); Pingtung Plain, Taiwan (Ting et. al. 2020); and China (Xu et al., 2008). These studies have revealed that land subsidence occurs due to multiple causes, of which, the diminishing of the amount of underground water and displacement of materials to replace the water have been the major causes. Bhattarai et al. (2017) from their observations between 2007 and 2010 have reported such incidences in the Kathmandu Valley. Extreme precautions are warranted to avoid further irreversible incidences of ground subsidence in the Kathmandu Valley.

The Kathmandu Valley needs aggressive groundwater recharge programs to avoid land subsidence. High volume of water has already been extracted by industries, hospitals, and more specifically by multistorey apartment buildings. The forceful withdrawal of water has led to the collapses of soil, surface collapses, compacts, and eventually dropping of the subsurface layers (USGS, 2018) which eventually leads to structural damage on the surface. Land subsidence is most often caused by human activities, mainly by the removal of

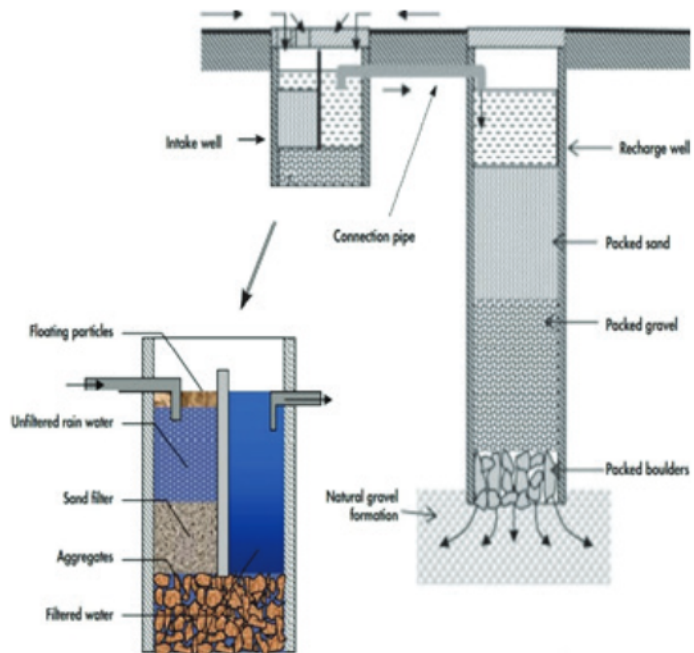


Figure 10. Cross-section of recharge pit for shallow ground water. Modified and adapted from Shrestha (2009).

subsurface water (USGS, 2018), and the Kathmandu Valley has already experienced a similar incidence in 1974, these incidences must have alarmed the Nepali politicians, scholars, planners, and policy makers. The findings by Bhattarai et al. (2017) using Differential Synthetic Aperture Radar Interferometry (DinSAR) are evidence that the subsidence in the dense settlement areas of Kathmandu Valley in the range of 1 cm to 17 cm have already occurred between 2007 and 2010 perhaps mainly due to the extraction of groundwaters. They have observed such subsidence in areas with unconsolidated fine-grained sediments (silica, sand, silt, clay, and silty sandy gravel) in dense settlement areas. As more water was extracted, terrestrial materials moved to occupy the space previously occupied by water (USGS, 2018) (Figure 7). As land subsidence occurs, not only does it change the topographic gradients but also causes “infrastructural damages” with the reduction in the volume of aquifer waters (Figure 7 and 10). The bowl shaped valley of Kathmandu with two principal landforms— alluvial and flood plains makes it even more prone to subsidence if actions are not taken soon. Similar issues have been resolved in many parts of Italy, Brazil, Mexico, Indonesia, and Thailand by tapping rainwater and injecting the collected water into the confined aquifers. In areas where lands are less disturbed /compact, water was allowed to seep below ground through wells and through horizontal conduits. The examples from various parts of the world shows that utilizing modern techniques of rainwater harvesting will help to full the unmet water demand and recharge groundwaters in the Kathmandu Valley.

7. Regulating water recharge system:

Groundwater recharge helps to seep back out into stream flow and improve water quality for various uses. Landscape that is impacted by drought can be improved through groundwater recharge. Such a recharge of groundwater will help plant growth and urban forestry to sequester carbon. In 2014, the State of California, USA passed a Sustainable Groundwater Management Act (SGMA), which puts restrictions on unregulated recharging and groundwater pumping. In biologically active soil, there is always a possibility of microbial intrusion in the drinking water, so regulations are needed to maintain groundwater quality while recharging groundwater. The SGMA aims to avoid undesirable results for both water quality and quantity while recharging underground water. The SGMA dictates that households not maintaining pre-defined levels of water quality may lose credit for pumping out groundwater but may be required to recharge groundwater. The financial incentives contribute to groundwater replenishment and quality. In gravelly grounds, recharging become affordable (Figures 9 and 10). However, in heavy soils with deep profile, groundwater recharge becomes problematic (Han et al. 2017) such as in the southern region of the Kathmandu Valley

where “Kalimati” presents challenges in recharging groundwater through unconfined aquifers. Additionally, great attention is needed to avoid nutrients in waters that are washed out not only from the root zone but also from the subsurface while deep injecting waters in confined aquifers.

Some countries use environmental defense funds (Hall, 2022) to allow households to buy and sell their groundwater sustainability plans. In the State of Arizona, USA, mechanisms have been developed to monitor and track recharge credits for the actual trading or selling of those credits using specific software (Hall, 2022). In the context of global climate change and with the increasing number of “the heat waves”, the Kathmandu Valley does not have the luxury to delay recharging of groundwater using available opportunities; otherwise, water-rich Nepal may be adversely impacted by water but shortages just like the countries in the developed world that were once water-rich are now facing water crises due to increasing incidences of heat waves.

8. The heat waves

The world is getting hotter due to global warming. For example, China, Europe, and many other Western countries have faced unprecedented hot climate in summer of 2022. England recorded 40.2°C in July of 2022. In 2019, Paris experienced a record 42.6°C temperature, which is one of the highest records within the past 7.5 decades. Paris’ temperatures of 42.6°C is considered exceptionally higher. China experienced a 62-day long heatwave in 2013 which is the longest since 1961. Many unimaginable incidences have been reported from Po River of Italy where the water level has dropped by up to 4 meters. Likewise, the water level in the 1,233 kilometers long Rhine River of Germany has dropped beyond the navigable limit reducing impacted 0.2 percent of the total Gross Domestic Product (GDP) of Germany. This has caused a decrease of 30-40 percent in agricultural production and increased the cost of ground transportation by over 40 percent. In 2018, a decrease in water level due to dryness in six months resulted in the losses of €5 billion in the German economy. In 2022, the water level has dropped by 50 percent in the Yangtze River of China that has resulted in the scarcity of drinking water for 400 million people in addition to depriving 246 million people from farming of 2.2 million hectares of land in the Xingjian Province of China (Pokharel, 2022). In July 2022 alone, in the European countries, 5.5 million people were impacted by dry conditions. The dryness has led to a decrease in 25 percent of electricity production in Europe (Pokharel, 2022). Scientists are arguing that they have not seen records of such a climatic situation in the past five centuries. In 2021, Paris experienced 40 millimeters of rain in 90 minutes, an amount of rainfall that used to happen in a month’s time. This is 70 percent higher than the normal rainfall. According to the Global Forest Watch, in 2021, fire

has been destroying a football ground size area in every minute due to rise in temperature (Pokharel, 2022). In India, if the weather system records an increase in temperature by 3-4°C higher than an average for over three days, the government declares such incidence as heatwave and provides some form of protection to its citizens. However, the government of Nepal has not paid any attention to the impact of heat waves on people (Pokharel, 2022). The government must take several measures to help its citizens, and also utilize the available technology to ameliorate the impacts of climate change and other environmental disasters.

Global warming increases pressure on water use, creates increasing drought events and cycles, and makes the management of groundwater even more important and urgent.

9. Concluding remarks:

In this paper, we reviewed literature on how the water supply system in the Kathmandu Valley has advanced from stone waterspouts, well, deep tube well to Melamchi-based project, but still how the Valley faces several environmental and geomorphic concerns. We also reviewed the published records about how the demand for water has increased from 35 million liters per day in the 1990s to 500+ million liters per day in the Kathmandu Valley. Our focus was on the ground water levels, its changes led by increase in extraction and decrease in recharging. We discussed how the lowering of the water table is causing land subsidence resulting in damages to various overground structures such as buildings, bridges, and pavements. We explained the process of how land subsidence occurs and what needs to be done to control this irreversible damage by timely interfering in the water uses by harvesting rainwater and recharging groundwater through confined and unconfined aquifers based on the types of the geology of areas.

We used geographic information systems (GIS) to identify how and where the problem started in sustaining the traditional methods of water supplies through stone waterspouts, wells, and Rajkulos, and what can be done to alleviate these problems. Our study was mainly a literature review and analysis supplemented by personal experience. However, we have supplemented the study with our firsthand experience in Nepal and the US. This paper is intended to contribute towards the study of systematization of the water supply in the Kathmandu Valley, Nepal through ground water recharging processes. Eventually, socio-economic, demographic and the lessons can be utilized by other parts of the world having similar circumstances.

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Authors Bio

Keshav Bhattarai,

Keshav Bhattarai is a Professor of Geography at the University of Central Missouri. Keshav has 22+ years of teaching experience in the US, and 15+ years of job experiences in forestry sector of Nepal. He was also a visiting faculty at the Forestry Institute in Hetauda. He served as Department Chair at the Department of Geography at the University of Central Missouri. He obtained his Doctor of Philosophy (Ph.D.) in Geography from Indiana University, Bloomington, Indiana; and a Masters in Natural Resource Management degree from The University of Edinburgh, Scotland, UK. Prior to that he received AIFC degree from Indian Forest College, Dehradun, India. Dr. Bhattarai has published three books and numerous book chapters and journal articles.

Ambika P. Adhikari

Ambika P. Adhikari is a Principal Planner with the City of Tempe, Arizona, USA, where he heads its Long Range Planning Division. He has more than 35 years of experience in urban and environmental planning and international development including in the US, Canada, Nepal, India, Mexico, Fiji, and Kenya. In Nepal, he was the Country Representative for International Union for Conservation of Nature (IUCN), and earlier an Associate Professor at the Institute of Engineering, Tribhuvan University. He is a Senior Global Futures Scientist (an honorary position) at JAW Global Futures Laboratory, Arizona State University, where he also taught for many years as an associated faculty. He is a Distinguished Adjunct Fellow at the Institute of Integrated Development Studies (IIDS), Nepal. He obtained his Doctor of Design (DDes) degree from Harvard University and Master of Architecture from University of Hawaii. He has authored one and coedited six books, and published widely in journals and newspapers.

