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Water Management in Hariwan Municipality of Nepal: Groundwater Harvesting from Riverbeds and Aquifers

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ABSTRACT

Most of the regions of the Siwalik and Northern Terai (Bhabar) have a scarcity of water due to the water level beyond the suction limit of ordinary centrifugal pumping. In the present study, the Lakhandehi River section in the Sarlahi district is selected for shallow aquifer prospecting. The objective of this study was to assess potential zones of shallow aquifers including riverbeds. It was also aimed to assess the status of the existing subsurface water conditions, and distribution system, and find out suitable locations for groundwater harvesting and uses. The methodological part of the present study covers the field data collection and finding the appropriate shallow aquifer for groundwater extraction. In the field study, both the geological as well as hydrogeological maps were prepared on a 1:25,000 scale to assess the aquifer condition. A social survey was also carried out to find the most water scarcity areas and water availability conditions in the region. The main water scarcity area is found in the Hariwan Municipality, around the northern part of Bhabar and the southernmost region of the Chure region. The water insufficiency area for the present study was found in the places like Hariyon Khola section (Dumrighari), Sano Dume and Dume Khola sections (Samari Bhanjyang), Kothi Khola section (Kothikholagaun), and Attrauli Khola section (Atrauli village) of Hariwan Municipality due to the presence of impermeable layers in shallow depth. The concept of the development of swamp wells by retaining the groundwater flow from the shallow depth of the river channel is proposed in areas like the Samari Bhanjyang and Atrauli villages. Similarly, the development of shallow wells is proposed for the other two regions. To ensure a cost-effective water supply to the communities, it is advisable to implement a water lifting system to elevate the reservoir, followed by gravity-flow distribution.

Keywords: Shallow aquifer, Dug wells, Sump wells, Lakhandehi River

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INTRODUCTION

Many places in the Siwalik region have water scarcity due to the rapid drainage of rainwater which reduces the availability of groundwater. Similarly, the Babhar zone of the region has water unavailability due to highly porous gravelly mass with greater thickness. As a result, the rivers that flow through this zone lose a significant amount of their discharge, which gradually infiltrates the subsurface, recharging the southern part of the region. Typically, the water that percolates through the Bhabar zone emerges at the junction of the Bhabar and Middle Terai or further south of the region. In the present study, the watershed of the Lakhandehi River is chosen for groundwater resource prospecting and utilization. This river is the largest in the district, spanning approximately 25 kilometers. This river is a perennial river and a tributary of the Bagmati River. Its major tributaries include Mathe Khola, Madar Khola, Dayani Khola, Narayan Khola, Hattibanda Kholsi, Baune Khola, and Chapani Khola, which merge with the Lakhandehi Khola to form a single river system. The Lakhandehi River originates from the northern hills of the Chure region. The streams of the river originate from the fractures in the sandstones or at the geological contact between the permeable sandstone and impermeable mudstone. The dendritic pattern of this river is controlled by the regional joints. In the well inventory survey, the SWL of the dug well found varies from 12 m in some places to 20-24 m in others. As per the hydrogeological classification, the southern part of the present study belongs to the Babar zone which is the northernmost flank of the Indo-Ganga Plain. It extends from the piedmont of the Siwalik southward to a maximum width of 8-10 km. This region in the study area is extremely poor in surface water availability. The rainwater in this region either seeps underground immediately or runs as overland flow resulting the flash floods. The Bhabar Zone is the major recharge zone for the Terai region of the country. Rivers crossing these areas lose their water content.

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Geologically, the study area encompasses the Siwalik range to the north, the Bhabar zone in the middle, and the southern Terai region to the south. Within the Lakhandehi watershed, the water scarcity areas of the Hariwan and the Lalbandi municipalities were targeted areas facing water scarcity. However, the northern part of the Hariwan was found to have the most severe water scarcity, making it the focal point of this study. The main objective was to prospect the shallow aquifer either from the terraces or from the riverbed materials and recommend an appropriate water distribution system for the communities. The dendritic pattern of this river seems to be influenced by regional joints (Neupane and Paudyal, 2021). The study area is located administratively in the Sarlahi district of the Madhesh Province of Nepal (Fig. 1). The climate of the region falls within the mild tropical region.

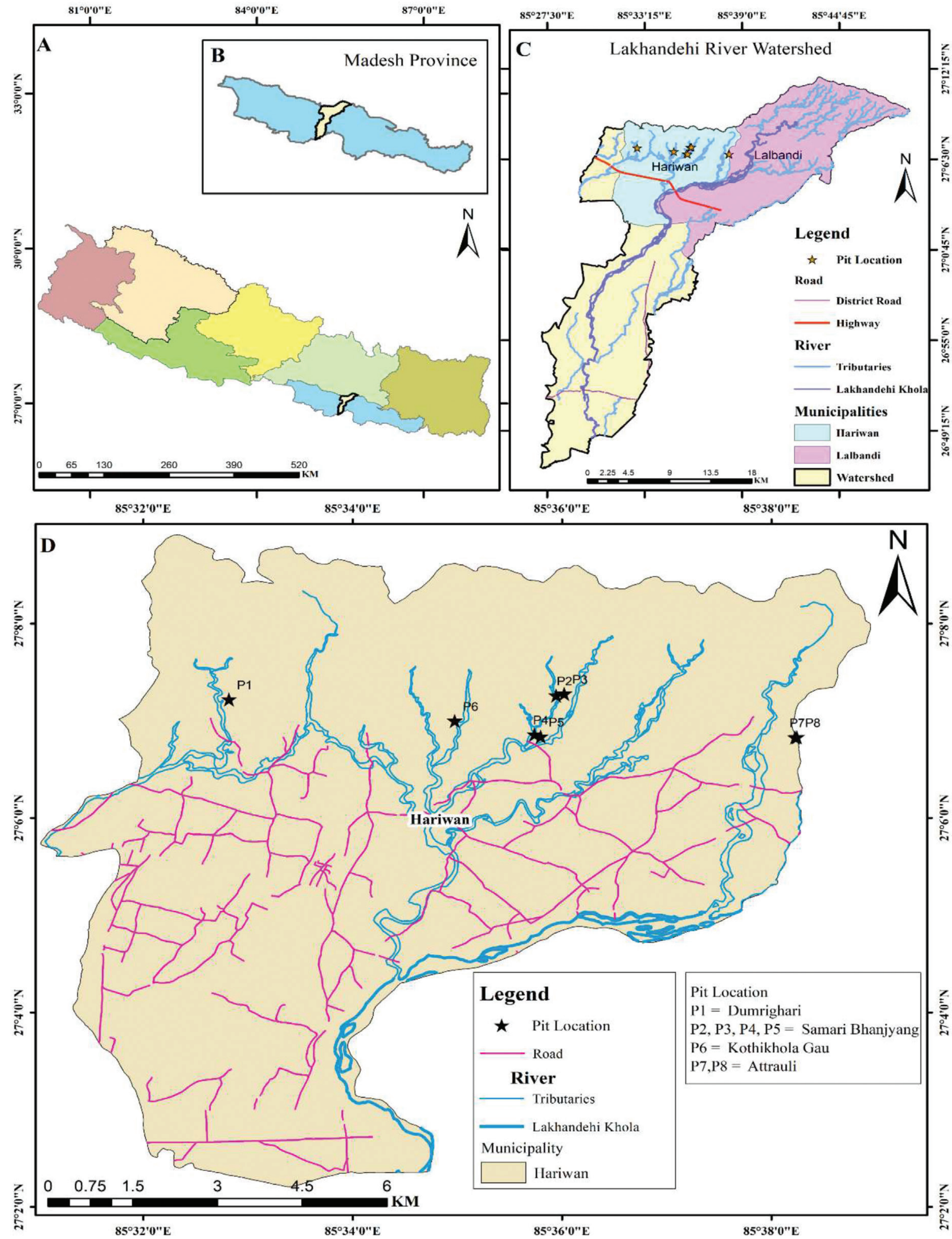

Fig. 1: Location map of the Lakhandehi watershed showing the Hariwan municipality and some adjacent regions (study area). A. Map of Nepal. B. Madesh Province. C. Lakhandehi River Watershed. D. Present study area.

The primary aim of this study is to investigate the shallow aquifer including riverbeds to provide drinking water in water scarcity areas of the Hariwan Municipality of Sarlahi district. The specific objectives are as follows:

i. To evaluate the status of the groundwater and find the water insufficiency regions,

ii. To propose the necessary infrastructures for groundwater harvesting and recommend an appropriate system for distributing the harvested water.

PREVIOUS STUDIES AND RESEARCH GAPS

The history of hydrogeological studies in the Terai Plain of Nepal dates to the early 1960s. The initial exploration of groundwater resources in Nepal was executed by the Department of Mines and Geology (DMG) during the 1959/1960 A.D. period, with the support of the Indian government. Duba (1982) was the first to investigate the groundwater resources in the Terai region of Nepal. Sharma (1995) compiled and presented a plethora of data concerning the hydrogeological characteristics, description of shallow and deep aquifers in Terai, tube well yield, and distribution in different parts of the Terai at that time of the Sarlahi district. Pradhan et al. (2002) conducted a comprehensive study on the Siwalik region of the Lakhandehi area, wherein they categorized the Middle Siwalik into two distinct geological sub-units based on the presence of pebbly sandstone beds. Sah (1998) proposed a unified lithological unit from different sections of the Siwalik of Nepal. The units in ascending order are the Bhorlegaon, Bankas, Jungali Khola, Chor Khola, Surai Khola, Dobata, Dudhaura Khola, Dhan Khola, and Deurali Formations. In a separate investigation, Sah et al. (2002) constructed a geological cross-section of the Terai zone specifically in the Sarlahi district. They have shown the distribution of aquifer zones in this region. Neupane and Paudyal (2021) prepared a detailed geological map of the Lakhandehi watershed area in 1:25,000 scales. More recently, Neupane and Paudyal (2021) have carried out some hydrogeological works in Lalbandi Municipality which lies in the Lakhandehi watershed area. They have focused on the hydrogeological condition of the Bhabar zone in this investigation. Their investigation revealed significant insights, including the variation in dug well depth ranging from 12 meters to 24 meters within this region. In this watershed, the region experiencing water scarcity is relatively smaller, and no prior local geological investigations have been undertaken by researchers or institutions. Additionally, tapping water from the riverbed materials is new for the Terai region of Nepal. Both the collection and distribution systems of groundwater are also discussed in this work. Under the UNDP/GWRDP/Shallow Aquifer Investigation program, altogether 20 STWs were installed for groundwater monitoring (average depth 31.4 m) in Sarlahi and established the subdivision of the shallow aquifer (DoI 1994). The actual situation of the availability of water in some of the Terai region is that there is flooding during the monsoon and drought in the rest of the year (Pokhrel, 2019). The same case exists in the present study. The proposed study area consists of the Himalayan Frontal Thrust in its northern part. Pathak (2016) has described the role of the HFT in hydrogeological significance in Terai. He suggests making use of a hard rock aquifer in Siwalik, installing a deep tube well within the Bhabar zone tapping groundwater in the Marshy zone, and supplying to the Bhabar zone to solve the water scarcity problems.

Extraction of groundwater is usually done through shallow tube wells, deep tube wells, and dug wells in the Terai region. In the study area, there is an adequate number of tube wells and dug wells in the Bhabar and Middle Terai (Marshy land) region. There are several artificial as well as natural ponds. The water scarcity problem that the Bhabar zone has been facing since a long time ago has been reduced after the construction of deep tube wells in different places. Recently, Lalbandi municipality has started distributing drinking water through the pipeline for 11 wards among 17 wards in the whole municipality. The water is supplied from a deep tube well developed at five different places. A similar case can be seen in Harion municipality too where water supplied from a deep tube well has fulfilled the water demand. There is not much problem of drinking water and irrigation water around this area now. They depend fully upon the deep tube well water for drinking and household work so negligence of the sources such as dug wells has led to dryness of the well. However, the people residing in Siwalik and the foothills of Siwalik have a major problem with drinking water and irrigation water, especially in the pre-monsoon. During these months most of the sources of water level either decrease or completely dry out. This has significantly affected domestic and wild animals around the region.

METHODOLOGY

A methodological flow chart to carry out the present work is shown in Fig. 2.

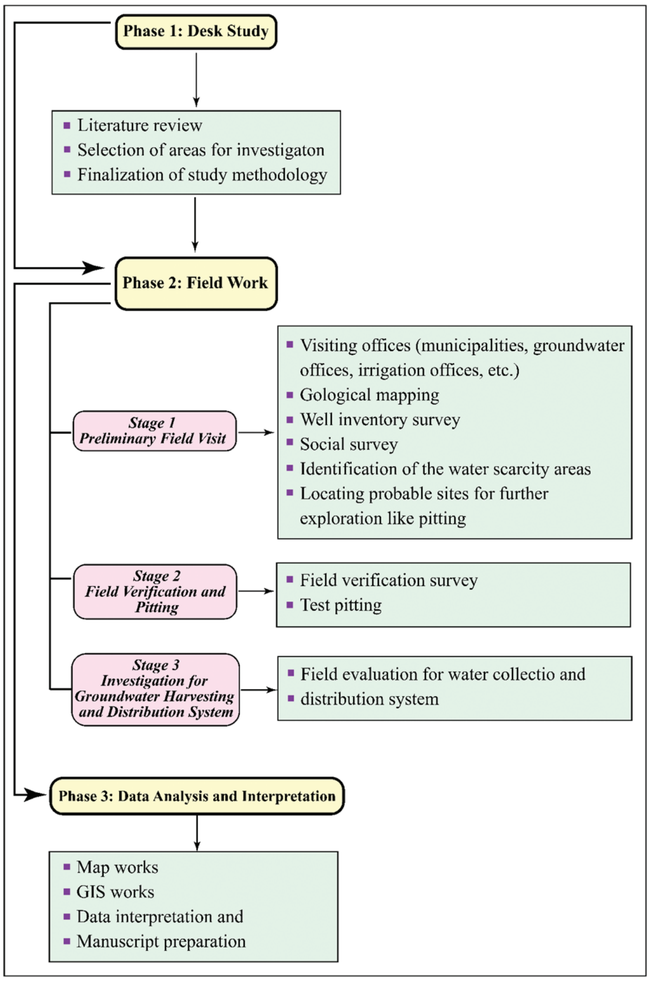

Fig. 2: Flow chart of the methodological framework.

RESULTS

Geology of the Hariwan area

The whole area of the present investigation lies within two geological zones: the Siwalik and Terai (Fig. 3). Within the rock successions of the Lower Siwalik, two geological units have been identified (Fig. 7): the Jangali Khola Formation and the Chor Khola Formation (Sah 1998). The typical lithology of the Jangali Khola Formation is variegated mudstone with thin sub-ordinate beds of loosely cemented, medium-grained grey sandstone. Similarly, the Chor Khola Formation compromises medium-to thick-beds of grey, medium-grained, laminated salt-and-pepper type sandstone. The channel of the Hariwan Khola flows from the axis of an antiformal structure. Many areas of the Siwalik region especially at and around the Main Himalayan Thrust (MFT), have been covered by the alluvial and colluvial admixtures in the form of different levels of terraces. The description of such terraces is made based on their stratigraphic position, geomorphic position, and elevation. Two levels of terraces, designated as T1 and T2 for older and younger respectively, and one active floodplain are distinguished in this area. Based on the grain size of the sediments and topographic breakage, the Terai zone in the present study can be divided into the Bhabar land, Middle Terai (Marshy land), and Southern Terai.

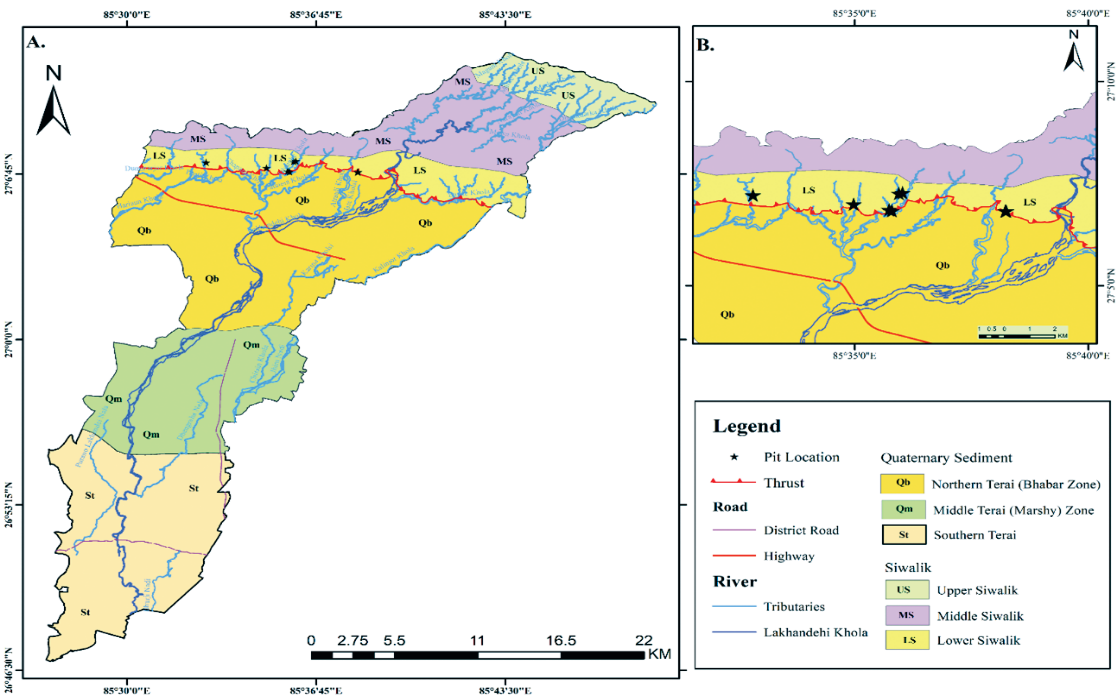

Fig. 3: Regional geological map of the Lakhandehi River watershed (modified after Neupane and Paudyal, 2021, and authors' observation (A) and geological map of the present study (B).

The corridor lying at the base of the south of the Churia hills is the Bhabar zone which is the northernmost flank of the Indo-Gangatic plain. It extends from the piedmont of the Siwalik southward to a maximum width of 8-10 km. This region in the study area is extremely poor in surface water availability.

The rainwater in this region either seeps underground immediately or runs as overland flow resulting the flash floods. Rivers crossing the Bhabar areas lose their water content. It is mainly composed of boulders, pebbles, cobbles, and coarse sand derived from the immediate northern vicinity of the Chure and the Mahabharat Range. In the study area, the Bhabar zone was observed around the Hirapur, Nawalpur, Patharkot, Atrauli, Sasapur, Daubari, Setibhir, Jiyajor, etc. The middle Terai consists of flat land of marshy nature and there exists artesian conditions. This zone is characterized by the dominance of clay, mud, sand silt, pebbles, and cobble at the surface. This is an extremely flood-affected area (Fig 4).

Water Insufficiency Areas

Water scarcity is described as a condition where water demand exceeds over available water supply. In the present study, the scarcity was evaluated based on the water availability vs demand by users. Local governmental bodies and water management authorities in the region were contacted to gather information about the watershed and any water scarcity issues during the data collection. Discussions were held with local body authorities of the Lalbandi municipality, Hariwan municipality, and their ward offices to obtain information about the water sources and distribution system within the study area and assess the major sites of water scarcity. The local people of the respective places were consulted to determine the locations of wells, natural ponds, and springs. The condition of water supply facilities to the local people was also assessed during the field survey. Public interaction played a crucial role in identifying the problems in the area, as connecting with people familiar with the region provided more specific insights.

The hydrogeological well inventory survey (Fig. 5) and social survey covered the Siwalik, Bhabar, and Middle Terai regions of the study area. The results showed that a few settlements in the Siwalik region and villages near the boundary of the Bhabar and Siwalik zone at Hariwan municipality lacked water supply and were still facing water scarcity. In these rural areas, accessing clean water is a challenge, particularly during dry seasons.

Many households rely on springs in the Siwalik region, shallow wells (dug wells) in Bhabar, and rivers in the Terai region for their water supply, but these sources do not provide sufficient water throughout the year, resulting in water-deficient conditions. From the field survey, it was found that the northern part of the study area, including Dumrighari, Kothikholagau, Samari Bhanjyang, and Attrauli villages in Hariwan municipality, experienced a high scarcity of water (Fig. 6). Detail geological and hydrogeological survey was carried

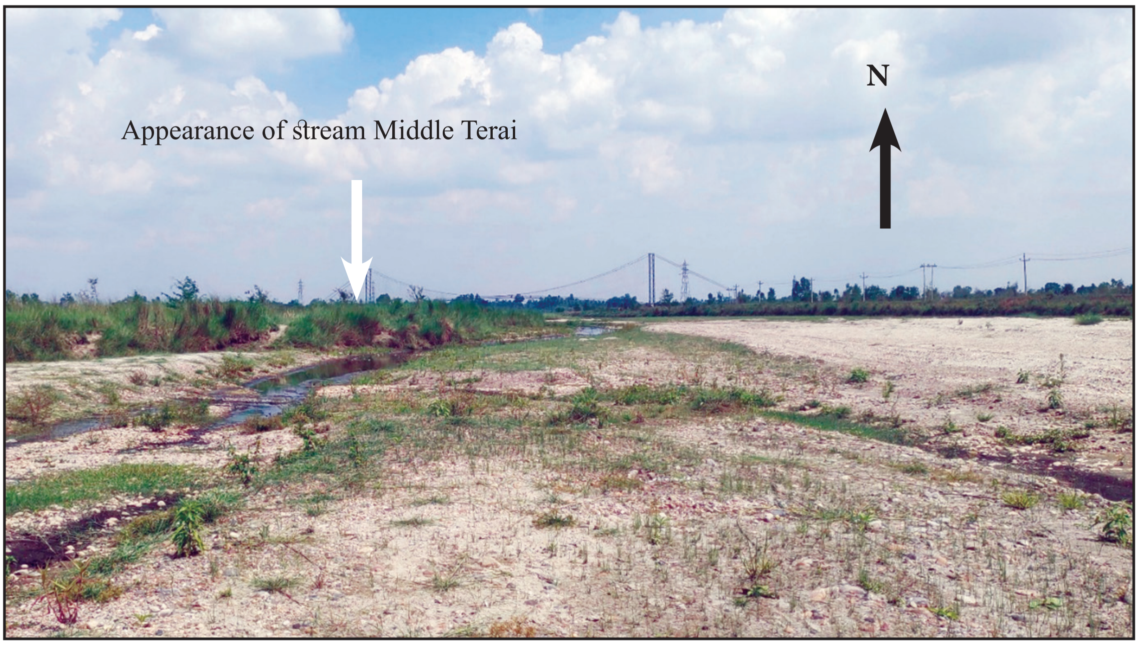

Fig. 4: The geomorphic view showing the Bhabar (recharge zone) and Middle Terai (discharge zone).

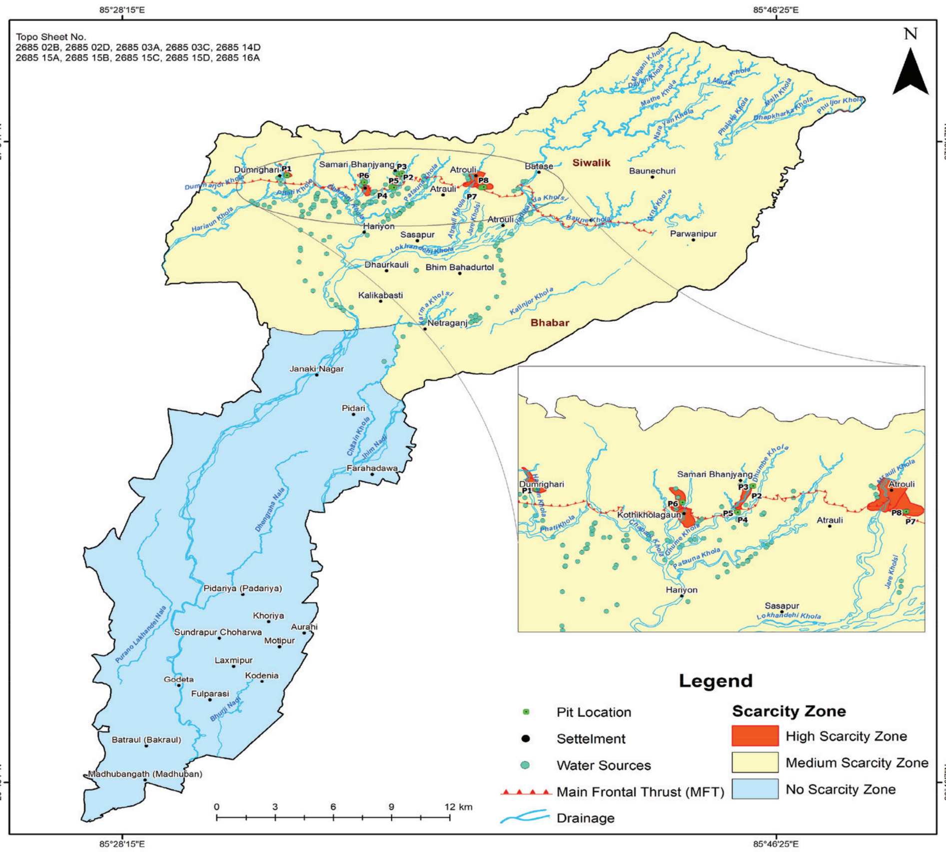

Fig. 5: Water scarcity mapping in the Bhabar-Siwalik section of the Lakhandehi Khola.

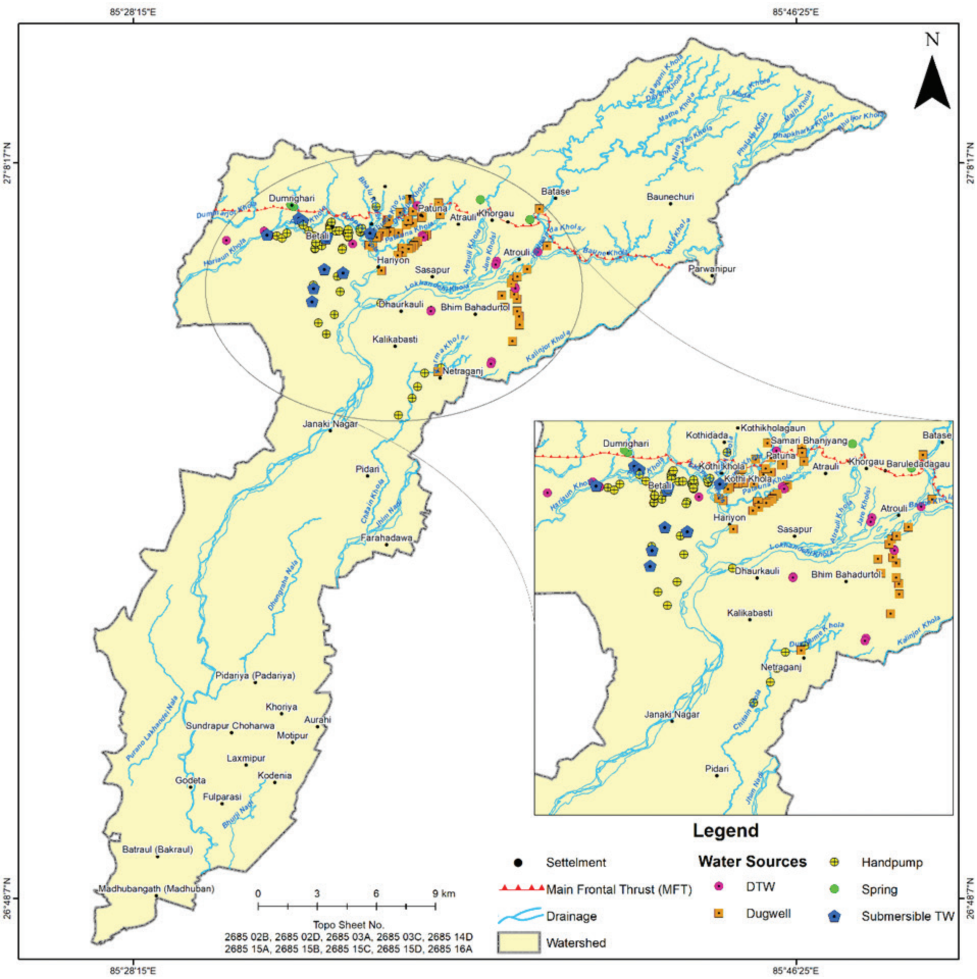

Fig. 6: Inventory mapping of water resources in water scarcity areas (shallow tube wells with single phase pump operated submersible pump).

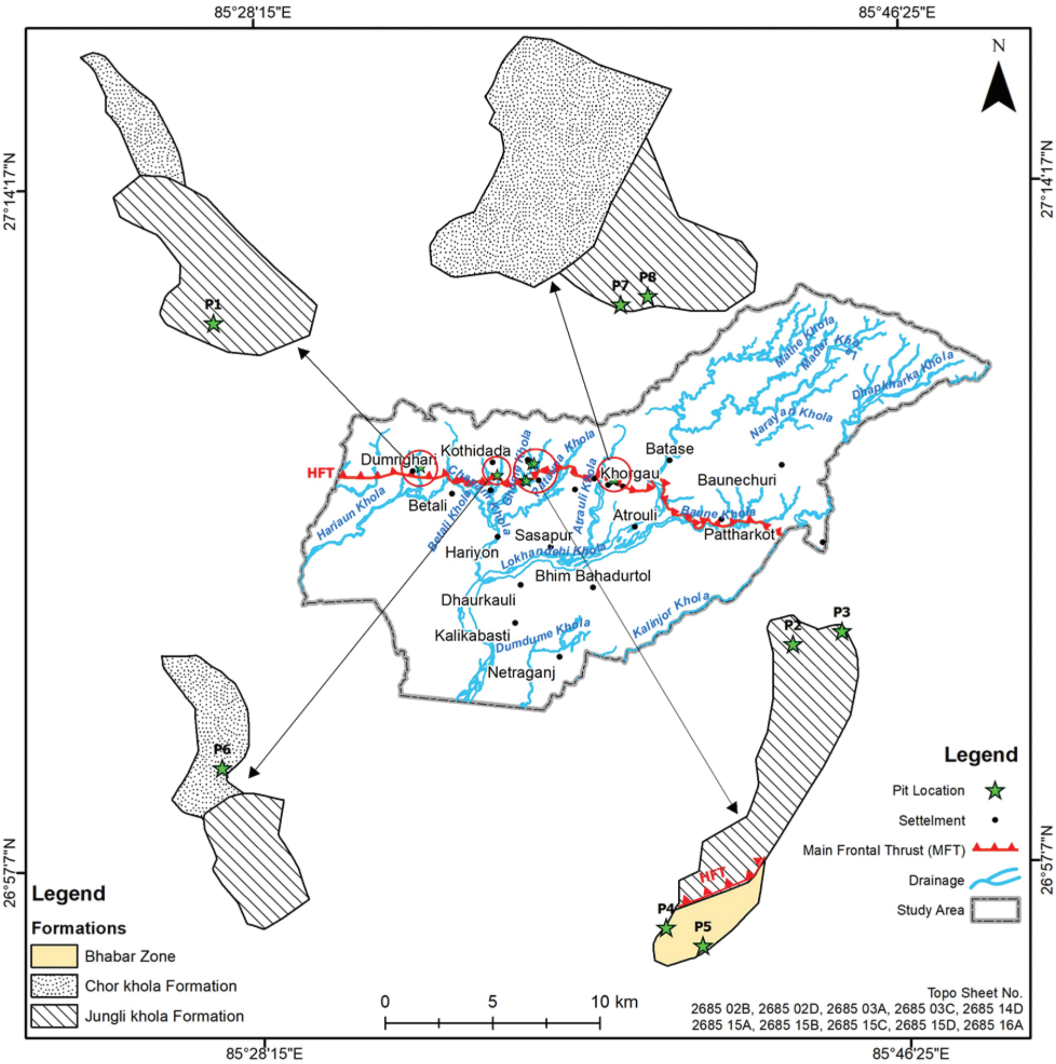

Fig. 7: Map depicting the site geology and location of investigation pits within the water-deficient region.

out in water scarcity areas (Fig. 7). Possible shallow aquifer sites including riverbeds were investigated for pitting in those areas to determine water availability at shallow depths.

The depth of pervious and impervious layers was determined directly through newly prepared pits of dimensions ~ 3 m x 2 m (length and breadth) with the depth varying from 2 m to 4 m. The depth of size was determined based on site conditions for water tapping, storing, and distribution. The local geological, and hydrogeological conditions and the subsurface litho-log details from each of the pits of each scarcity region are described in the following sections.

Geological and Hydrogeological Condition of Dumrighari Area

The Hariwan Khola section, located in the water scarcity region of Dumrighari areas, is characterized by rocks belonging to the Siwalik Group. In this vicinity, the rocks can be classified into two geological units: the Jangali Khola Formation and the Chor Khola Formation. The former unit primarily consists of variegated mudstone, with a smaller proportion of loosely cemented, medium-grained grey sandstone. On the other hand, the latter unit comprises medium-to-thick beds of medium-grained grey laminated salt-and-pepper type sandstone. Within the vicinity, there are two levels of river terraces along the Hariwan Khola, as well as a recent floodplain representing Quaternary deposits. The groundwater water indications in the area include seepages and springs that originate from the contact between the older terraces and Siwalik rocks (Fig. 8).

The existence of water-bearing layers at shallow depths in this region is indicated by both the contact springs and seepages. The alluvial cover is mainly composed of loosely held sand and gravels, with a finer matrix. The Dumrighari area consists of a few types of aquifers along the Hariwan Khola section and its adjacent regions.

Fig. 8: a) Field photographs of the contact spring with discharge 4 liters/minute (left) (GPS: 355890E, 3000949N) and b) seepage with discharge 2 liters/minute (right) (GPS: 355772E, 3001065N) on the older terrace and younger terrace respectively at Dumrighari.

Test Pitting (P1)

The site is located at latitude 27.118732 and longitude 85.543326. It is situated on the younger terrace (Fig. 9). The shallow aquifer discovered after digging is made up of gravelly sand, with a thickness of 2 meters. The discharge is about 6 liters per minute on average as a continuous flow. This aquifer level corresponds to the riverbed channel. The water extracted from this aquifer is suitable for the establishment of drinking water resources as a point source.

Geological and Hydrogeological Condition of Samari Bhanjyang Area

The geological condition of this site closely resembles that of the Hariwan Khola. The rock sequence consists mainly of variegated mudstone with a smaller proportion of loosely cemented, medium-grained grey sandstone. Many surface areas are covered by the terraces of the Sano Dume and Dume Khola. The MFT is located immediately south of this region. An indication of groundwater on the surface is evident from a dug well present there. The presence of a shallow aquifer can be inferred from the water available at a depth of about 4.0 meters in the existing dug well, situated in a flood plain. The aquifer is developed within the younger alluvial deposits. Geological observation reveals that water is flowing from the contact between the alluvial deposits and the mudstone and claystone of the Jangali Khola Formation. Four pits, one at the older terrace, another at the younger terrace of the Sano Dume Khola, and two in the Bhabar zone near Dume Khola, were excavated to determine the water table in this region.

Test Pitting

Test pits designated as P2, P3, P4, and P5 were excavated in this area. The pit site P2 is situated on the left bank of the Sano Dume Khola, on the older terrace (Terrace 1), at latitude 27.122785 and longitude 85.597321. The site of the pit construction lies slightly in depressed topography (Fig. 10).

Although the surface appears moist, no shallow

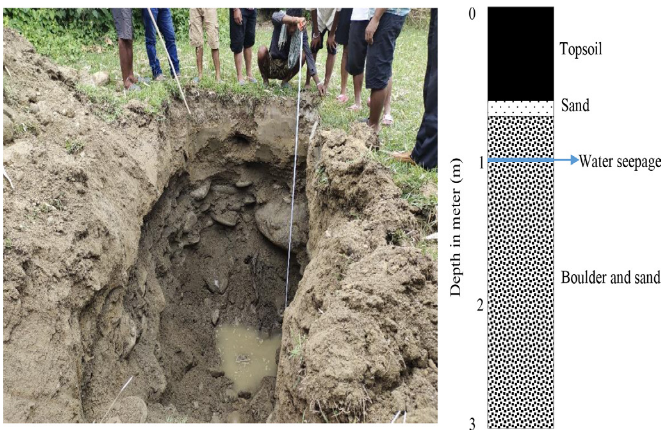

Fig. 9: Excavation of Pit (P1) at Dumrighari (left) and detail lithology of the pit (right) (GPS: 27.118732N, 85.543326E)

Fig. 10: Excavation of pit P2 (left) and lithology (right) at Samari Bhanjyang (GPS: 27.122785N, 85.597321E).

aquifer was found within the pit up to a depth of 3.5 meters. The topsoil and silty soil (B horizon of soil) were moist. However, the moisture gradually diminished in the underlying layers and became dry upon reaching the claystone and mudstone layers of the Siwalik rock. No shallow aquifer was identified at P2, and it is abandoned for water collection purposes.

The P3 site is situated on cultivable depressed land adjacent to the ridge on the right bank of Sano Dume Khola at Latitude 27.121266 and Longitude 85.597892, on the younger terrace (Terrace II). The selection of this site was based on recommendations from residents, as it remains consistently moist throughout the year. The lithology of the pit reveals a 1.9-meter-thick layer of moist topsoil overlaying mudstone (Fig. 11).

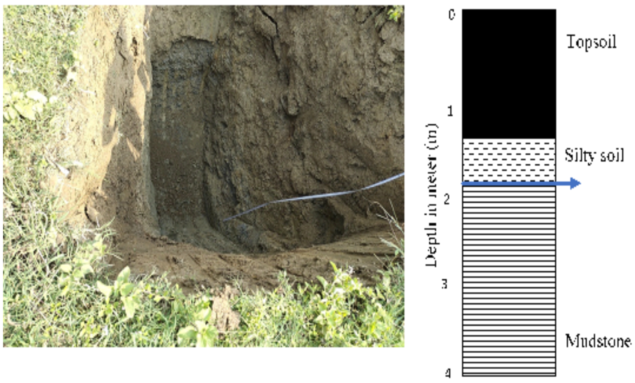

Fig. 11: Excavation of Pit (P3) (left) and litho-log (right) at Samari Bhanjyang (GPS: 27.121266N, 85.597892E).

Indications of groundwater couldn't find in this pit as mudstone is found at the bottom. Site P4 is located on cultivable land near the Dume Khola at latitude 27.115343 and longitude 85.595407. The area falls under the Bhabar zone. No shallow aquifer was found since the area acts as a recharge zone (Fig. 12). Pit P5 is located on the right bank of the Dume Khola on the river channel at latitude 27.114024 and longitude 85.59488 (Photograph 30). It lies in the Bhabar zone. The shallow aquifer was not found as the digging was made up to 4.1 m depth in the riverbed (Fig. 13).

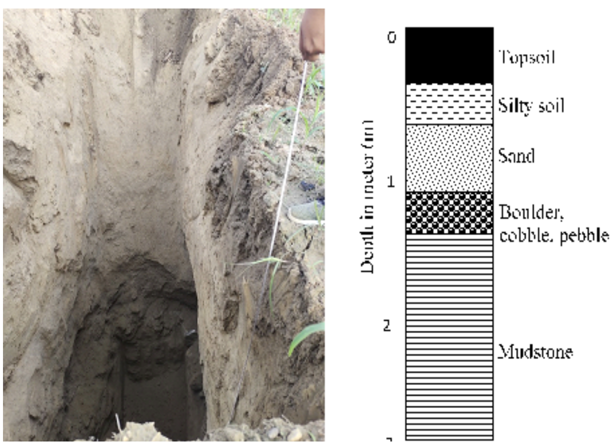

Fig. 12: Excavation of Pit (P4) (left) and lithology (right) at Samari Bhanjyang (GPS: 27.115343N, 85.595407E).

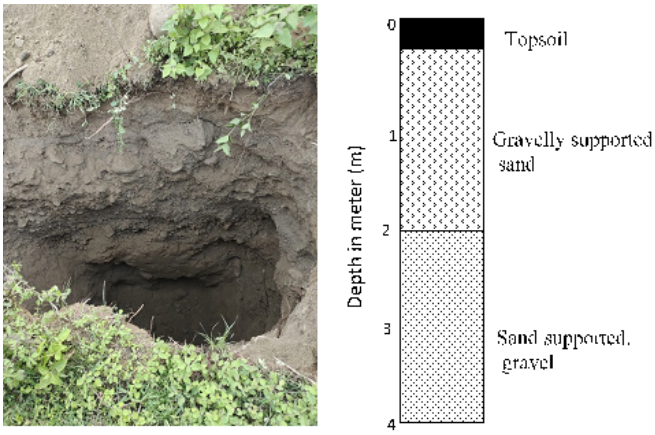

Fig. 13: Excavation of Pit (P5) (left) and corresponding lithology (right) at Samari Bhanjyang (GPS: 27.114024N, 85.59488E).

Geological and hydrogeological condition of the Kothi Khola Section

The area comprises Siwalik rock succession with alluvial deposits over it. The major geological units of the section area are the Jangali Khola Formation and the Chor Khola Formation. Water availability in the form of spring and seepage is found in three places in the area in older terrace (Terrace II), the younger terrace (Terrace I), and the riverbed channel. There are contact springs developed from the contact of the alluvial cover and the Siwalik rock.

The pit designated as P6 is located on the right bank of Kothi Khola on the wide ground of the old school at the younger terrace. The pit is at latitude 27.118175 and longitude 85.581944. The location is in Terrace II at around 2 m in height from the riverbed channel. The shallow aquifer was observed at a depth of 1.8 m in a gravelly sand layer (Fig. 14).

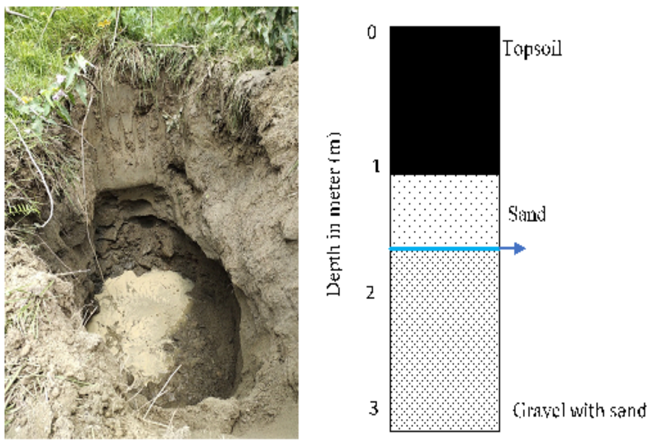

Fig. 14: Excavation of Pit (P6) (left) and lithology (right) at Kothikhholagau (GPS: 27.118175N, 85.581944E).

The discharge from observation at P6 is around 10 liters per minute as measured by the bucket method.

Geological and hydrogeological condition of the Atrauli Khola Section (Atrauli)

The rock successions of this area can be mapped under the Jungli Khola Formation, and the Chor Khola Formation of the Siwalik Group in the northern section while there is the Bhabar zone in the south. The attitude of beds is different from other sections. In this section, beds are dipping locally towards the south. Many places in this region are covered by alluvial and colluvial deposits. Some seepage and wetlands are also observed on the floodplain of the Atrauli Khola and its tributaries. Along the Atrauli Khola section towards the western side of Chisapani Village, there is a wetland. The seepage is likely to be the contact springs as signs of water flowing from the contact between soil and calcareous sandstone. Within the colluvium, a well is developed, and local people are using the groundwater available in the well (Fig. 15). Test Pit P7 was developed on the right bank of the Atrauli Khola on the river terrace at longitude 85.630264 and latitude 27.116205.

Fig. 15: a) Field photograph showing the seepage at the left bank of the Atrauli Khola (GPS: 364490E, 3000967N) and b) wetland in the western hill of Chisapani village (right) (GPS: 363910E, 3001039N).

Within the range of 2 m depth, a mudstone layer (bedrock) is found which was completely dry in field condition (Fig. 16). Pit (P8) was located on the existing channel of the Atrauli Khola. Seepages were found at about 0.9 m depth at the contact of upper river deposits (topsoil) and lower mudstone layers (Fig. 17).

Groundwater Harvesting and Distribution System

The present study area has identified the development of shallow wells as a suitable method for initial water collection at the source (Fig. 18).

Both dug wells and sump wells are recommended for this area. Shallow wells especially dug wells, are considered the most appropriate water source in groundwater supply systems due to their cost-effectiveness and shorter construction periods. The relatively low yield of shallow wells makes them ideal for rural areas with minimal water consumption,

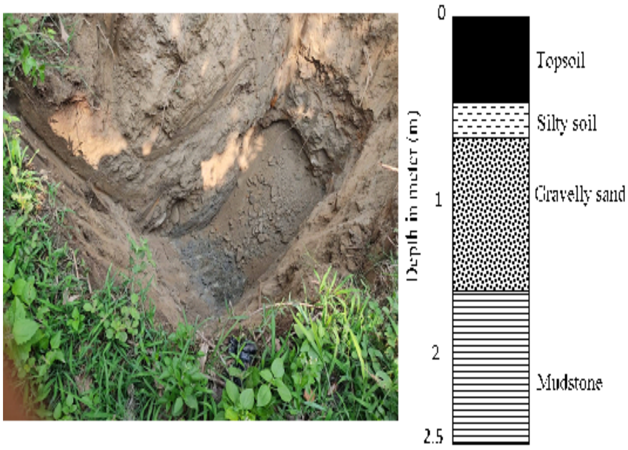

Fig. 16: Excavation of Pit (P7) (left) and litho-log (right) at Atrauli (GPS: 85.630264E, 27.116205N).

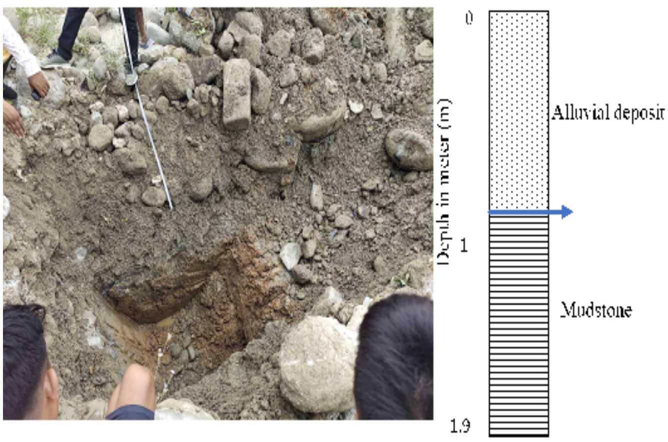

Fig. 17: Excavation of pit (P8) (left) and litho-log (right) at Atrauli (GPS: 85.630474 and latitude 27.115989).

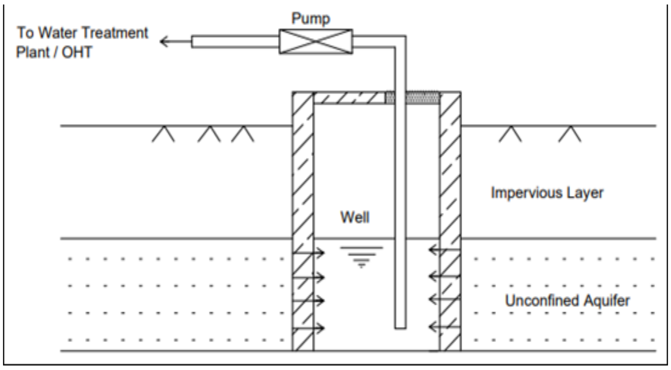

Fig. 18: Idealized schematic diagram of the shallow well as recommendation (Not to scale).

primarily for domestic purposes (Sharma, 1981). In the Atrauli area, it is recommended to utilize sump wells to tap the groundwater as an improved version of a shallow aquifer.

These sump wells are shallow wells constructed along the riverbed or directly at the river channel to collect water seeping through their bottoms (Fig. 19). The water collected in the shallow wells like dug wells and sump wells can initially be pumped to a water treatment plant for physical and chemical treatment before being distributed to the community across all groundwater sources under study. The treated water will then be pumped to a water storage tank before being supplied to the community.

A water reservoir tank (RVT) is another essential component of the water supply system, required to store water to meet the hourly fluctuation of consumers' water demand and ensure peak flow in the distribution network. RVTs are constructed at ground level on hilltops higher than the service area. In areas with flat topography, the tanks may be elevated above the ground on towers to provide adequate water pressure, known as overhead tanks (OHT). For all sources in the study area, an overhead tank (OHT) is recommended to store the water. Water can be pumped from the source (dug well or sump well for this case) and stored in the OHT, from where it can be distributed to consumers through the distribution system. Distribution lines are another crucial component of the water supply system, responsible for carrying water from the storage tank to its end-use points, such as household taps, yard connection taps, or public stand posts. The distribution pipelines should consist of a main pipeline connected to the RVT, sub-main pipes connected to the main pipeline, and service/branch pipes connected to the sub-main pipes for distribution to households. Based on the available discharge and water demand, yard connections and public stand posts are recommended for the present investigated area. Efficient distribution requires water to reach its end-use points with the required flow rate and adequate pressure in the piping system. There are three main types of distribution systems commonly adopted these days.

(a) Gravity-Fed Distribution: Water flows in the distribution pipeline due to gravity, eliminating the need for pumping. This system is highly reliable and cost-effective.

(b) Pumping System: Water is supplied through continuous pumping in this type of system.

(c) Dual or Combined System: This system utilizes both gravity and pumping systems for water distribution.

In the case of all our study areas, a Dual system, i.e., pumping (from shallow well to water treatment plant and then to OHT) and gravity-fed distribution (OHT to stand post through distribution pipelines) is necessary as per the topography of the source location and service area. The recommended groundwater supply system is shown in Fig. 20.

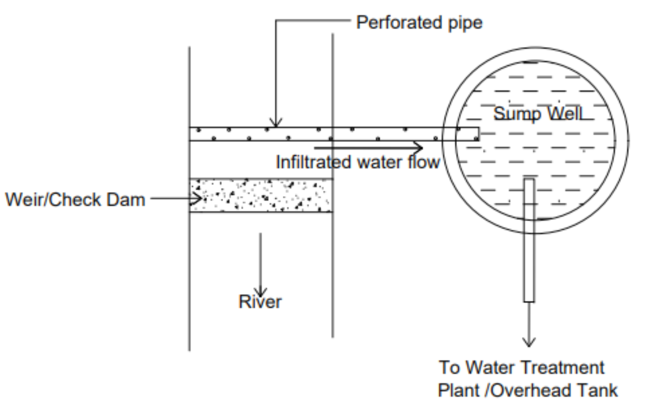

Fig. 19: A typical schematic diagram showing the plan for a sump well development (Not to scale).

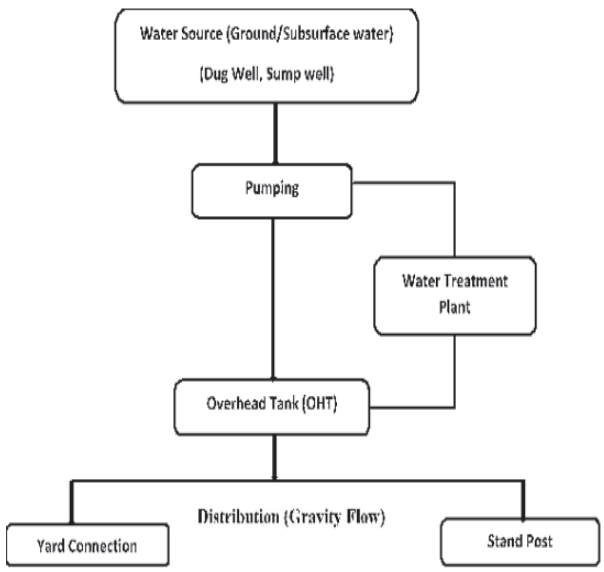

Fig.20: Recommended groundwater supply system components in the study area.

DISCUSSIONS AND CONCLUSIONS

The present study is targeted to assess the source of water from the shallow depth in the Hariwan municipality. Both geological as well as hydrogeological investigation was carried out on the paleo-river channels, active river channels as well areas near the riverbanks. The areas of water scarcity were identified based on well-inventory mapping followed by the questionnaire surveys on the communities. The possible sources of groundwater were investigated based on the geological as well as hydrogeological knowledge of the experts. It is a preliminary type of study to assess the location of groundwater, especially the shallow aquifer.

Detail aerial mapping, geophysical investigation for sub-surface information, and deep drillings are not applied in this study. In the present work, four water scarcity areas were selected for the detailed study to prospect shallow-level groundwater. For direct observation of groundwater location and its discharge, several pits were constructed using an excavator that could dig to make a pit of desirable size up to a depth of five meters. After determining the depth to water level, type of aquifer, and discharge of water to the pits, an appropriate water distribution system was suggested based on site conditions and the location of settlements. The use of Single-phase submersible pumps (cost-effective for STWs) is considered the best for extracting water from the wells.

Altogether, four places were found as the main water scarcity region within the Hariwan Municipality. Geologically, all the studied areas lie in the immediate north of the Bhabar region, however, some parts of the study location lie in the boundary between the Bhabar and the Chure region. There is a distinct geological boundary to separate the Bhabar and the Chure region which is called the Main Frontal Thrust (MFT). The presence of such boundary was demarcated based on the topographical breakage, the appearance of inclined bed rocks, and fault breccias and slickensides. In a regional geological map, the concept of Lower, Middle, and Upper Siwalik is used in this study (Fig. 3). However, in the water scarcity region, further classification is made locally to understand the aquifer condition of the region. Two units like the Jungali Khola and Chor Khola Formations are distinguished by comparing the lithological similarity from different sections (Fig. 7).

As the first location of the study, the Dumrighari area of Hariwan-9 lies about 2 km north of the Bhabar zone. It is located immediately north of the MFT region. Geological units like the Jungli Khola Formation and the Chor Khola Formation are found in this region as hard rocks while the two levels of terraces are found as the Quaternary deposits in addition to recent deposits of rivers. The Jungli Khola Formation is composed of dominantly mudstone and shale with a minor proportion of sandstone and siltstone while the Chor Khola Formation consists of a dominantly salt-and-pepper type of sandstone with a lesser proportion of mudstone and shale. The source of water is found in two locations: one at the paleo-flood plain of the Hariwan Khola while the other at the up-hill section of the same river. The water in the first case is found about 3 m depth from the surface as an unconfined aquifer composed of gavel-rich porous material while in the second case, it is found at the interface between the colluvium soil and bed rocks of the Siwalik Group lying below it. There are other possibilities for finding such types of water sources based on the geological criteria and judgment of experts.

The second water scarcity zone was assessed in the Samari Bhanjyang area of Hariwan Municipality- It also lies at the foot of the Chure hills, immediately north of the Bhabar region crossing the MFT region. Locally, the region consists of the Jangli Khola unit from a geological perspective. In general, there is no groundwater till 4 m depth from the surface. Two pits developed in this area revealed that there are mudstone beds of the Chure region below the 4 m without any water seeps. This shows that there is no water horizon above the bed rocks and to get the water level, the depth of hard rock aquifer should be reached. However, there is one well near the Sano Dume Khola, where there is a water level about 3.5 m depth from the surface. This well lies at the paleo river channel of the Sano Dume Khola. Therefore, the region around this well (especially at the right bank of this river as the settlement is on this side) is proposed as a suitable site for groundwater tapping and harvesting. Similarly, an investigation was made around the Dume Khola section of the Samari Bhanjyang village. The groundwater level couldn’t find till 4 m depth from the existing dry channel of this Dume Khola. It shows that deep borings are necessary for such regions. The third water scarcity zone was found in the Kothi Khola village of Hariwan Municipality-1. It geologically lies in the foothills of the Siwalik region and the rocks found in this area can be mapped under the Jangli Khola Formation and the Chor Khola Formation. In the paleo-flood plain of Kothi Khola, at the right bank side, groundwater is found at a depth of 2.5 m from the surface. The discharge of water is satisfactory in this region. Water bearing horizon is composed of poorly graded gravel with admixtures of silt and sand in various proportions and the aquifer is unconfined in nature. Therefore, this area is proposed as the groundwater harvesting site after detailed studies and investigation. The fourth site reported for water scarcity lies in Atrauli village of Hariwan Municipality-2. Geologically, this area also lies at the foothill of the Siwalik. The rock in this region dominantly consists of sandstone with a minor proportion of mudstone and shale. Two pits were developed at the banks of the Atrauli Khola where mudstone beds are found at a depth of 2 m from the surface. Further, another pit was constructed at the present channel of the Atrauli River, and the layer of mudstone (an impervious layer) is found at a depth of 2 m from the surface. Then the concept of water collection by blocking the running groundwater through the riverbed and the development of a sump well at the riverbank is proposed to fulfill the water demand in this area. It is considered one of the best conjunctive uses of groundwater (Sharma 1997).

Lifting of groundwater from the wells in a reservoir located at a certain height and distribution of water through gravity flow is proposed as the distribution system of the water to the communities. However, the tapping and harvesting of groundwater varies from site to site depending upon the site condition.

Previous studies show that there is a decreasing trend in the overall groundwater table in the Bhabar zone of Nepal. In the Siwalik region, most of the natural sources of water such as streams, sloughs, arroyos, rivers, etc. are either completely dried up or the water level decreases significantly during the winter season. This may be due to several reasons as many landslides lying immediately north of the Bhabar region due to activity of the Main Frontal Thrust which has diverted the water sources, high rate of deforestation, newly constructed roads through the region, and unscientific mining of construction materials without considering even the basic principles of mining and its severity on the environment. Therefore, the status of soil erosion and mass movement should be studied thoroughly to assess the stability condition of the hills and ultimately to conserve the water sources of the region. In this region under consideration, the water demand encompasses domestic usage along with various other applications like gardening and small-scale irrigation purposes. Abundance prevails during the monsoon season and persists for approximately two to three months thereafter. However, water scarcity becomes apparent during the remaining months, primarily attributed to natural factors, specifically the subsurface geology and the presence of unconsolidated materials i.e., the Bhabar region at the foothills of the Siwalik range. It is noteworthy that the present study was carried out during the pre-monsoon peak dry season and immediately after the monsoon season. The pit development and observation were carried out during the peak dry season. The following conclusions are made from the present study:

1. There is no water scarcity problem in the southern part of the Lakhandehi River watershed. The demand for water is easily fulfilled by tube wells, dug wells, and deep tube wells.
2. The major water-scarce areas are found in the northern part of the Lakhandehi Khola watershed. These areas are Dumrighari, Kothi Khola Gau, Samari Bhanjyang, and Atrauli of Hariwan Municipality. The main cause of water scarcity is the unavailability of groundwater at shallow depths. Deep tube wells might be the alternative source for water supply system in the area, however detail hydro-geological study should be carried out to ensure the sustainable and adequate discharge.
3. In Dumrighari, Samaribhanjyang, and Kothi Kholagau, new possible sites for shallow groundwater harvesting are found. Similarly, for the Atrauli areas, a source of groundwater from the adjacent riverbeds is recommended.
4. In the Atrauli area, the concept of developing sump wells by retaining the groundwater flow from the relatively shallow sections of the river channel is proposed.
5. Water lifting system to the elevated reservoir and distribution of water to the communities through gravity flow is proposed as the use of water in the region.

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