STATISTICS, OPTIMIZATION AND INFORMATION COMPUTING
Stat., Optim. Inf. Comput., Vol. **16**, October 2026, pp 3294–3307.
Published online in International Academic Press (www.IAPress.org)

Assessment of Groundwater Abstraction Practices and Their Effect on the Surrounding Environment: A Case Study of Tilottama Municipality, Rupandehi, Nepal, 2022

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Abstract Groundwater is the primary source of household supply in many fast-growing towns of the Nepal Terai, yet local data on abstraction practices and on the awareness of the people who depend on these aquifers remain limited. This study examined groundwater abstraction in Tilottama Municipality, in Rupandehi District, and the effects it has on the surrounding environment. A questionnaire survey of 397 randomly selected households across all 17 wards of the municipality was paired with focus group discussions, in-depth interviews, and field observation. Data were collected between January and September 2022. Of the surveyed households, 353 (89 percent) named the piped gravity system as their primary source for household use, while 44 (11 percent) abstracted directly through tube wells; the piped system itself is fed by deep boring, so household supply depends on groundwater throughout. Per capita consumption drawn from groundwater sources averaged roughly 56 litres per day. A change in water table depth over the past decade was reported in 14.3 percent of wells, mostly in the northern wards. About 84 percent of the municipal area remained open, and 99.2 percent of household plots retained some space suitable for recharge. Awareness was the weakest link: 63.1 percent of households did not understand how groundwater recharge works, and 87.2 percent were unaware of the rules and regulations that govern its use. These findings carry direct practical significance for municipal planners in rapidly urbanising Terai towns: the physical capacity for recharge already exists, so the more cost-effective policy lever is building awareness and enforcement capacity now, before the aquifer moves from manageable pressure to the kind of deficit already documented in the Kathmandu Valley. The aquifer appears to be under growing but still manageable pressure, with ample physical capacity for recharge offset by a clear shortfall in awareness and regulation.

Keywords Groundwater Abstraction, Aquifer Depletion, Water Table Decline, Managed Aquifer Recharge, Public Awareness, Household Survey, Nepal Terai

AMS 2010 subject classifications 62P12, 62D05

DOI: 10.19139/soic-2310-5070-4185

1. Introduction

Water sustains life, supports ecosystems, and underpins economic activity. Secure access to it has become one of the defining challenges of this century as populations grow and cities spread outward [18]. Groundwater holds most of the planet's accessible liquid freshwater and supplies a large share of domestic and agricultural demand wherever surface water is scarce or seasonal [6]. Managed aquifer recharge (MAR) – the deliberate replenishment

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ISSN 2310-5070 (online) ISSN 2311-004X (print)

of an aquifer through infiltration ponds, recharge pits, or similar structures, as opposed to the incidental recharge that occurs naturally – is the standard policy response once abstraction begins to outpace natural replenishment, and it is a recurring point of reference throughout this paper. In Nepal, and especially in the towns of the Terai plains, groundwater is often the primary source of drinking water. Rapid urbanisation and rising demand have placed those aquifers under steadily increasing pressure, raising real concerns about both depletion and contamination.

Tilottama Municipality, in Rupandehi District of Lumbini Province, is a clear case in point. The municipality was formed in 2014 from six former Village Development Committees, and it has grown quickly since: its population rose from approximately 102,000 in 2011 to about 124,000 by 2021, a yearly growth rate close to 2 percent and well above the national average [1]. Most of the additional demand has been met through groundwater, either directly through household tube wells or indirectly through a piped system that itself relies on deep boring. None of this is closely monitored. Locally specific information on how much groundwater is being extracted, on the space still available for natural recharge, and on whether residents understand the recharge process or know the rules in force is largely absent. Most Nepali groundwater research has focused on the Kathmandu Valley [11, 14], and Terai towns like Tilottama remain comparatively understudied. This gap has, if anything, become more pressing in the years since data collection: recent assessments of the wider Terai belt describe worsening reports of depletion and contamination between 2022 and 2025, driven by the same combination of over-extraction, weak infrastructure, and policy gaps documented here [24].

This study was designed to fill part of that gap. Its general aim was to assess groundwater abstraction practices in Tilottama Municipality and the effects they have on the surrounding environment. Four specific objectives were set: to estimate the amount of groundwater being abstracted for household use; to assess the open space available for groundwater recharge, at both municipal and plot level; to evaluate public awareness of recharge and abstraction practices, and of the relevant rules and regulations; and to document what households report about the quality of the groundwater they use. The scope was deliberately bounded: only residential households were surveyed, industrial and agricultural wells were not sampled, and no laboratory testing of water was carried out as part of this study. These limits are stated up front so that the findings are read within their proper scope.

2. Literature Review

Groundwater plays a central role in domestic, agricultural, and industrial supply across the world, and reliance on it is especially pronounced in urban areas [6]. Kansakar [9] notes that more than 60 percent of urban water demand globally is met from groundwater. Urbanisation tends to intensify that dependence: impervious surfaces spread, infiltration falls, and demand becomes concentrated in the very places where natural recharge has been reduced. The result, in many cities, is that abstraction begins to exceed replenishment [4]. When the gap persists, water tables drop, future availability is squeezed, and in some settings the ground surface itself subsides as the sediment loses the water that supported it [8]. Falling groundwater levels can also reduce the baseflow that keeps rivers, wetlands, and springs alive [5].

Nepal is, in absolute terms, comparatively rich in water. Renewable surface water is estimated at around 225 billion cubic metres a year, and renewable groundwater potential at roughly 12 billion cubic metres, with groundwater concentrated in the Terai plains and in valleys such as the Kathmandu Valley [20]. Shallow and deep tube wells dominate access in the Terai, reflecting the favourable alluvial aquifers of the region. Endowment, however, is not the same as management. Kansakar [9] observes that although water resources are nominally covered by laws and regulations in Nepal, implementation and enforcement are weak, and the shared, fugitive nature of groundwater is poorly addressed in existing law. More recent assessments have reached the same conclusion: despite a sequence of new water and irrigation policies, groundwater in Nepal has largely remained an unregulated resource in practice [12, 19]. This conclusion continues to hold in the most recent literature: reviews published in 2025 still describe groundwater governance in Nepal, and in the Terai in particular, as hampered by unclear institutional roles and weak enforcement rather than by any shortage of formal law [24]. Work on peri-urban water insecurity more broadly makes a related point – that land-use change driven by urbanisation, compounded by increasing climate variability in rainfall timing and intensity, is what converts a physically adequate resource into a locally scarce one, a dynamic documented across peri-urban South Asia and Africa and directly relevant to the rural-to-urban transition under way in Tilottama [26].

The Kathmandu Valley is the most studied and cautionary example. Abstraction there has long exceeded recharge; water tables have fallen and wells have been deepened in response [11, 17]. Index- overlay studies show that much of the valley aquifer is vulnerable to pollution, with the highest risk concentrated in densely built and intensively used parts of the city [14]. The lesson is uncomfortable: urban growth raises demand at the same time as it weakens the capacity of the aquifer to recover. The same tension is now visible in peri-urban parts of the Kathmandu Valley itself, where competing groundwater dependencies among households, small industry, and institutions have intensified even after the 2012 groundwater policy was formulated specifically to manage the problem [25], underscoring how difficult enforcement is even where the regulatory framework already exists. The same pattern, in a less advanced form, is now beginning to appear in Terai towns that draw on the same kind of alluvial aquifer.

The most prominent water-quality concern in the Terai is arsenic, which occurs in shallow alluvial aquifers across the southern plains, released from natural sediments under reducing conditions [16]. Arsenic contamination of Terai groundwater was first reported in the late 1990s, and surveys since have shown that a significant share of tested tube wells exceed the World Health Organization provisional guideline value, with a smaller share above the national standard [13]. The two thresholds need to be distinguished: the WHO guideline value for arsenic is 10 micrograms per litre, while Nepal applies a national standard of 50 micrograms per litre [13, 21]. Long-term exposure to arsenic in drinking water has been linked to skin lesions and to cancers of the skin, lung, and bladder [21], which is why testing and mitigation in affected areas matter for public health. Microbial contamination is a separate problem, mostly anthropogenic, tied to inadequate sanitation and to the exposure of shallow wells to surface runoff and leachate.

Managed aquifer recharge is the standard response to declining water tables. Rainwater harvesting and the construction of recharge ponds and pits can offset some of the loss, though their effectiveness depends on suitable open land, careful siting, and sustained community participation [2]. And because groundwater is a shared resource, durable management depends as much on the awareness and cooperation of its users as on the rules on paper [3, 10]. These ideas frame the present study, which combines estimates of abstraction with an assessment of recharge capacity, water-quality reports, and public awareness in a single Terai municipality.

Site-specific hydrogeological parameters for Tilottama itself have not been published, so the values that follow are drawn from the nearest available district- and zone-level studies and should be read as indicative rather than site-measured. Rupandehi District's aquifers are recharged predominantly through rainfall infiltration in the Bhabar zone at the foot of the Churia (Siwalik) hills, with palaeochannels and present river courses acting as secondary recharge pathways further south [22]. District-wide water-balance work for Rupandehi estimates that, of an average annual rainfall of roughly 2 metres, about 10 percent enters the groundwater system through infiltration [23]. Shallow tube-well yield in the district varies sharply from north to south: discharge exceeds 10 litres per second in the coarse-grained northern (Bhabar/hard-formation) wards, but falls to roughly 6–9 litres per second in the finer-grained southern Marchawar and Lumbini zone, which is the same broad hydrogeological setting in which Tilottama sits [23]. This north-south contrast in aquifer yield is consistent with the ward-level pattern of abstraction reported in Section 4.3 below, where southern wards rely more heavily on direct tube-well abstraction while northern wards draw mainly on the piped supply.

3. Materials and Methods

3.1. Study Area

The study was carried out in Tilottama Municipality, in Rupandehi District of Lumbini Province, in the western Terai of Nepal. The municipality covers about 126 square kilometres at an altitude of roughly 160 to 175 metres above sea level. Formed in 2014 through the merger of six former Village Development Committees, it is divided into 17 wards, and the most recent municipal household survey recorded a population of about 123,836. The climate is sub-tropical monsoonal: hot summers, mild winters, and most of the annual rainfall concentrated between June

Table 1. Comparative Analysis of Selected Groundwater Studies Relevant to This Work

Author/Study	Setting	Strengths	Limitations
Pandey et al. [11]	Kathmandu Valley, Nepal	Long-term assessment of valley aquifer; documents abstraction exceeding recharge	Confined to one valley; limited applicability to Terai aquifers
Shrestha et al. [14]	Kathmandu Valley, Nepal	Index-overlay vulnerability mapping; spatial risk identification	Vulnerability index approach; does not capture community awareness or behaviour
Pokhrel et al. [13]	Terai region, Nepal	Comprehensive overview of arsenic occurrence and treatment options	Older synthesis; predates more recent district-level surveys
Foster et al. [4]	Multi-country (10 developing cities)	Cross-city comparison of urban self-supply trends and policy issues	Macro-scale review; does not include Nepal-specific data
Raut et al. [24]	Terai region, Nepal (2025)	Recent (2022–2025) comparative status update on Terai groundwater depletion and contamination	Region-wide secondary-data synthesis; not municipality-specific
Vij et al. [26]	Peri-urban South Asia and Africa	Cross-regional framing of climate variability and land-use change in peri-urban water insecurity	Qualitative, cross-country synthesis; not a household survey
This study (2022)	Tilottama Municipality, Terai, Nepal	Ward-level household data on abstraction, recharge capacity, and awareness in a Terai town	Residential households only; no laboratory water testing; single time period

and September. The aquifers are alluvial deposits of the Indo-Gangetic plain, accessed through dug wells, shallow tube wells, and deep tube wells. The Siddhartha Highway passes through the municipality, which has grown rapidly as a trading and education hub. Data collection for the present study ran from January to September 2022, and all 17 wards were included.

3.2. Instrument Design and Content Validation (new subsection)

The questionnaire was developed from the study objectives and from the secondary-data review summarised in Section 2, and was reviewed by the thesis supervisor and by the Department of Disaster Risk Engineering and Management prior to fielding, as part of the institution's thesis approval process described in Section 3.5. This provided a basic check on content coverage and clarity. The instrument was not, however, subjected to formal psychometric validation: no pilot test with a separate sample was conducted, and no reliability coefficient (such as Cronbach's alpha for the multi-item awareness and quality-perception sections) was computed. This is acknowledged here as a limitation of the design rather than glossed over, and it is carried through into Section 3.5 and into the recommendations for future work in Section 5. Studies of comparable household questionnaires elsewhere have typically addressed this through multiple rounds of pre-testing with a small sample before the formal survey [39], and we recommend the same approach for any follow-up round of this study.

3.3. Data Collection

Both primary and secondary data were collected. The primary data came from four sources: a structured questionnaire survey of households, focus group discussions, in-depth interviews, and field observation. Each focus group discussion involved fifteen to twenty community members and followed a structured set of questions. In-depth interviews were held with ward representatives and other knowledgeable persons, and field observation was used to record the physical means of abstraction and the open space present in house plots. For this field

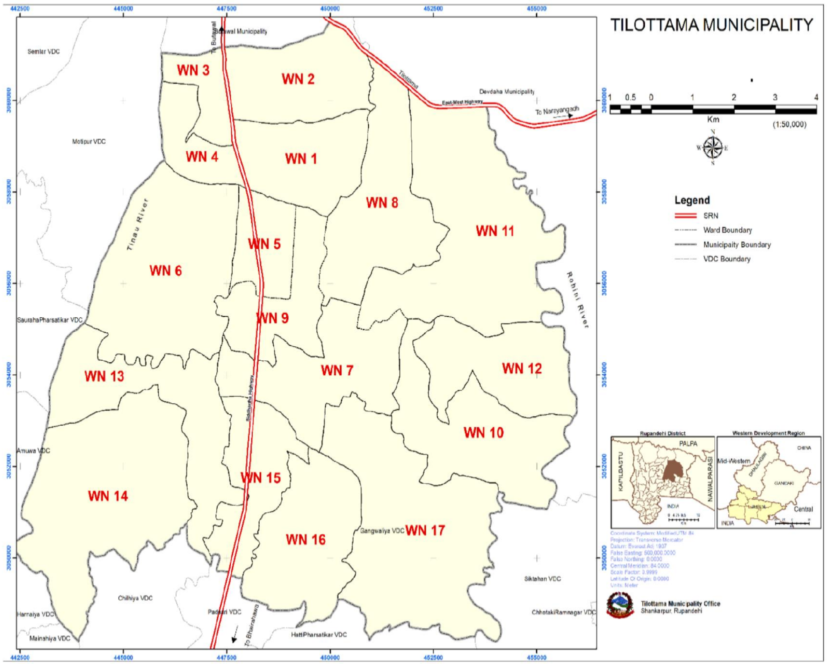

Figure 1. Study Area: Tilottama Municipality, Rupandehi District, Lumbini Province, Nepal.

observation, “open space suitable for recharge” was assessed by visual estimation at the time of the household visit and recorded as present where a plot retained an uncovered, unpaved surface of more than approximately 5 square metres; compacted courtyard soil and vegetated ground were both counted as open in this round, without distinguishing between them. That distinction matters for recharge potential – compacted soil infiltrates far more slowly than vegetated or loosely tilled ground – and its absence from the original protocol is noted as a limitation in Section 3.5; future rounds of this survey should record surface condition alongside the presence/absence of open space. The questionnaire itself asked about the sources of water used, the depth and means of abstraction, the open space available on the plot, household reports on water quality and on any prior water testing, and awareness of recharge and of the rules governing groundwater use. Secondary data were drawn from the municipal and ward offices, the Groundwater Resource Development Board, the local drinking water and sanitation user committees, the Department of Urban Development and Building Construction, and the published literature. The study did not include laboratory analysis of water samples; information on water quality and testing therefore reflects what households reported, not measurements made for this study.

3.4. Sampling

There are roughly 32,000 households in Tilottama Municipality, the large majority of which depend on groundwater for everyday household use. A sampling frame was prepared from municipal household records, and respondents were selected by simple random sampling. In total, 397 households were surveyed, with fifteen to twenty households drawn from each of the 17 wards to ensure proportional representation across the municipality. This sample size was checked against Cochran’s formula for a proportion, $n_0 = Z^2 p(1-p)/e^2$, using a 95 percent confidence level ($Z = 1.96$), the conservative variance assumption $p = 0.5$, and a 5 percent margin of error, which gives a minimum requirement of $n_0 \approx 384$ households. Applying the finite-population correction for the roughly 32,000 households in the municipality, $n = n_0/(1 + (n_0 - 1)/N)$, reduces this minimum only slightly, to approximately 380. The realised sample of 397 households therefore exceeds the minimum required for a 95 percent confidence level and a 5 percent margin of error on a simple proportion, which supports the precision of the percentages reported in Section 4. The mixed-methods design was deliberate: a questionnaire is well suited to estimating the prevalence of practices across a population, but it cannot easily capture the reasons people give for those practices, which the focus group discussions and in-depth interviews were used to bring out. Residents of the selected wards, of any age, sex, marital status, or economic background, were eligible; those living outside the study area were excluded.

3.5. Data Analysis

Quantitative data were entered and processed in Microsoft Excel and analysed using descriptive statistics, namely frequencies, percentages, and means. To give a sense of the precision of the reported percentages, 95 percent confidence intervals were computed for the principal indicators using the Wilson score method, which performs better than the simple normal approximation for proportions close to 0 or 100 percent and is the method used throughout Section 4 wherever a confidence interval is reported. Results are presented through tables, pie charts, and bar diagrams. The study remains descriptive in design: the household-level microdata needed to run cross-tabulations or association tests (for example, between education of the household head and awareness of recharge, or between occupation and primary water source) were not available in disaggregated form at the time of this revision, so no inferential statistics – chi-square tests, regression, or otherwise – are reported here. This is flagged explicitly, rather than left implicit, as a limitation in Section 3.5, and it is the single most direct route for extending this work: Section 4.3 already reports ward-level differences in abstraction method that are suggestive of an association with elevation and affluence, and a chi-square or logistic analysis of the existing respondent-level dataset would let that association be tested formally rather than described narratively. Related survey-based work published in this journal illustrates the kind of inferential extension this points toward [27, 28]. The qualitative information from the focus group discussions and in-depth interviews was grouped thematically and read alongside the quantitative findings, so that the observed prevalences could be interpreted in light of the reasons respondents themselves gave.

3.6. Ethical Considerations and Limitations

The study followed standard ethical principles of respect for persons, beneficence, justice, and respect for communities. Informed consent was obtained orally from every respondent before data collection. Participants were told the purpose of the study, that participation was voluntary, that they could decline or withdraw at any time without consequence, and that no personally identifying information would be recorded or published. The research formed part of the M.Sc. thesis of the first author and was reviewed and approved by the Department of Disaster Risk Engineering and Management at Lumbini International Academy of Science and Technology under the institution's thesis ethics process. Several limitations should be acknowledged. The study examined residential households only and did not sample industrial or agricultural wells, so its findings should not be generalised to those land uses. The questionnaire was reviewed by the thesis supervisor and department but was not formally pilot-tested or psychometrically validated (Section 3.2), and this limits how much confidence can be placed in the internal consistency of the multi-item awareness and quality-perception sections. Without laboratory testing, the information on arsenic and bacteriological quality reflects what households remember about previous testing rather than what was measured for this work, and such self-reported data are subject to recall bias. The same recall-bias caveat applies with equal force to the reported change in water-table depth (Section 4.4): respondents were asked to recall a comparison over the past decade, and residents can and do confuse ordinary seasonal fluctuation in well levels with a genuine long-term decline. Absent piezometric records or repeat physical soundings of well depth, the 14.3 percent figure in Section 4.4 should be read as an indication of where residents perceive change to be occurring, not as a measured rate of decline; this distinction is carried through consistently wherever that figure is discussed below. The study also did not disaggregate the household-level microdata behind the reported percentages, so no formal tests of association between household characteristics (education, occupation, ward) and reported practices could be performed in this round (Section 3.4). Finally, data were collected within a single period of the year and may not capture seasonal variation in abstraction or in water levels. A single cross-sectional round also cannot, by itself, establish a trend: the reported water-table changes and quality perceptions in this paper describe a single point in time, and confirming whether the aquifer is on a genuine declining trajectory would require either repeat cross-sectional rounds at the same households or, preferably, continuous seasonal monitoring of a subset of wells alongside rainfall records.

4. Results and Discussion

4.1. Demographic Profile of Respondents

The 397 respondents included 162 men (41 percent) and 235 women (59 percent). The slight majority of female respondents reflects a familiar pattern in household surveys in Nepal: women, who are typically the primary water users in the home, are more often available and willing to respond. By religion, 360 households (90.7 percent) were Hindu, 30 (7.6 percent) Buddhist, 4 (1.0 percent) of other faiths, 2 (0.5 percent) Christian, and 1 (0.3 percent) Muslim. Brahmins formed the largest ethnic group (133, or 33.5 percent), followed by Magar (106, 26.7 percent) and Chhetri (49, 12.3 percent), with smaller numbers of Tharu, Gurung, Dalit, Madhesi, Newar, and other groups. Agriculture and salaried work were the two most common occupations, at 90 respondents each (22.67 percent), followed by housewives (69, 17.38 percent); 11 respondents (2.77 percent) were unemployed. For education, 186 household heads (46.85 percent) had studied below secondary level, 133 (33.50 percent) to higher secondary level, and 78 (19.65 percent) to bachelor's or above. Taken together, the mix of agricultural and salaried occupations and the spread of educational attainment point to a community in transition between agrarian livelihoods and a more urban service economy, which is relevant for interpreting both the water-use patterns and the awareness levels that follow.

Table 2. Demographic Profile of Survey Respondents

Characteristic	Category	Number	Percentage
Sex	Male	162	40.81
	Female	235	59.19
Religion	Hindu	360	90.68
	Buddhist	30	7.56
	Other	4	1.01
	Christian	2	0.50
	Muslim	1	0.25
Main occupation	Agriculture	90	22.67
	Job (salaried)	90	22.67
	Others	77	19.40
	Housewife	69	17.38
	Business	38	9.57
	Social worker	21	5.29
	Unemployed	11	2.77
	Student	1	0.25
Education of household head	Below secondary	186	46.85
	Higher secondary	133	33.50
	Bachelor's and above	78	19.65

4.2. Sources of Water and Consumption

Of the 397 surveyed households, 353 (89 percent) named the piped gravity system as their primary source for household use (95% CI: 85.4–91.6%), while 44 (11 percent) abstracted directly through tube wells (95% CI: 8.4–14.6%). Because the piped system is itself fed by deep boring, household supply in Tilottama depends on groundwater throughout. Per capita consumption from groundwater sources averaged roughly 56 litres per day.

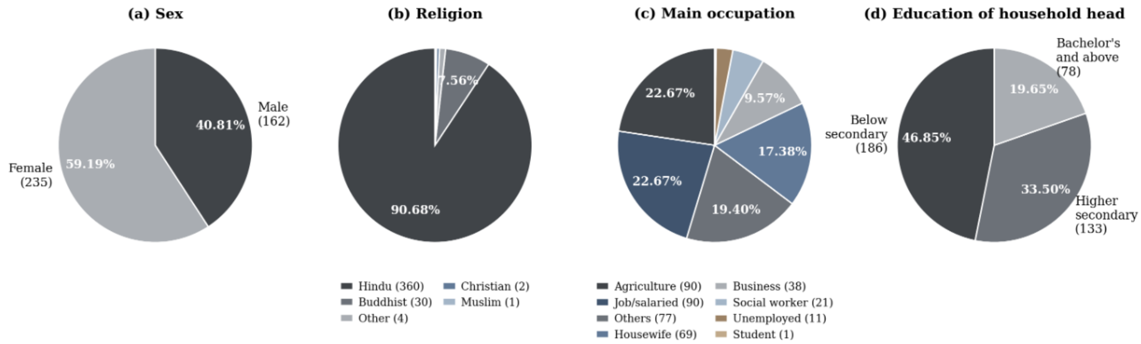

Figure 2. Demographic Profile of Respondents ($n = 397$): (a) Sex, (b) Religion, (c) Main occupation, (d) Education of household head.

4.3. Means and Depth of Abstraction

Households in Tilottama abstract groundwater through dug wells, shallow tube wells, and deep tube wells, and the pattern varies sharply from ward to ward. In the northern wards, most households take their water from the piped supply and abstract very little directly; in Ward 1, for instance, about 99.8 percent of households were on the piped supply. The southern wards are different. In Ward 14, around 98 percent of households abstracted through shallow tube wells, and in Wards 15 and 16 a large share relied on shallow and deep tube wells. The contrast reflects a combination of elevation and economic conditions: direct tube well use is more common in the lower-lying, less affluent southern wards. Where depths were recorded, shallow tube wells generally fell in the range of about 10 to 25 metres, and deep tube wells were deeper than 25 metres. This ward-level contrast is broadly consistent with the independently reported north-south difference in shallow aquifer yield across Rupandehi District as a whole, where coarser sediment in the north supports higher-yielding wells feeding the piped system's source boreholes, while the finer sediment of the southern Marchawar/Lumbini zone, in which Tilottama's southern wards sit, is associated with lower yields and a correspondingly greater reliance on direct household abstraction [23] (see Section 2). This parallel is offered as context, not as a formal test of association – establishing it statistically would require the ward-level cross-tabulation discussed as a limitation in Section 3.4.

4.4. Change in Water Table Depth

Respondents were asked whether they had noticed any change in the depth of water in their well or tube well over the past decade. A change was reported for 14.3 percent of wells (95% CI: 11.2–18.1%), while 85.7 percent showed no observed change (95% CI: 81.9–88.8%). The reported changes were concentrated in the northern wards, namely Wards 1 to 5. Respondents and key informants linked the change to population growth and urban expansion over the past ten years, both of which have pushed abstraction in some areas beyond the rate at which the aquifer can naturally replenish itself. Because this assessment rests on what households observed rather than on monitored water-level records, it points to where decline is being noticed; it does not give a measured rate of decline. As noted in Section 3.5, this figure is a recall-based perception rather than a physical measurement, and residents can confuse normal seasonal drawdown with a genuine multi-year trend; establishing a measured rate of decline would require systematic monitoring across seasons.

4.5. Open Space Available for Recharge

Land cover data for the municipality indicate that about 84 percent of the total area remained open and roughly 16 percent was built up. That represents a substantial physical capacity for natural recharge. At the household level, 99.2 percent of surveyed plots retained some open space suitable for recharge (95% CI: 97.8–99.7%), and only 0.8 percent did not (95% CI: 0.3–2.2%). As clarified in Section 3.2, "open space" here means an uncovered, unpaved surface exceeding approximately 5 square metres, identified by the surveyor's visual estimation at the time of the household visit; the criterion does not distinguish compacted courtyard soil, which infiltrates poorly, from vegetated or loosely tilled ground, which infiltrates well, and this is an important qualification when reading the recharge-capacity claim below. Open space was most constrained in densely built core areas such as Manigram, Drivertol, and Bhalwari, where high land values and small plots leave little ground uncovered. Across the rest of the municipality, the availability of open land is itself an opportunity: recharge interventions such as recharge pits are physically feasible for almost every household, provided they are supported by awareness and regulation , and provided the surface itself is suitable for infiltration or can be prepared to be, which is why the compacted-versus-vegetated distinction noted above matters for implementation.

4.6. Household Reports on Water Quality and Testing

Households were asked both about the quality of the groundwater they use and about any testing that had been carried out previously. The great majority, 93.5 percent, reported no observed change in water quality over recent years (95% CI: 90.6–95.5%), with the remaining 6.5 percent reporting some change (95% CI: 4.5–9.4%). Where the appearance of water was described, most was reported as clean and clear, with smaller shares mentioning a foul smell or muddiness. On testing, 77.1 percent of households reported that their water had previously been tested for arsenic (95% CI: 72.7–80.9%); among these, the great majority reported a result within the national limit, with only a very small number reporting a result above it. A previous presence/absence vial test for bacteriological quality was reported by 63 percent of households (95% CI: 58.1–67.6%), generally with an absence result. These figures need to be read carefully. They are household reports of testing done previously, and they were not verified by laboratory analysis in this study. They should be taken as an indication of testing history and perceived quality rather than as a direct measurement of contamination. The distinction between what a household perceives and what a laboratory would measure is not a minor caveat here – it is the central limitation of this section, and it is worth stating plainly: a household's judgement that its water "looks clean" carries no diagnostic information about arsenic or bacteriological contamination, both of which are frequently undetectable by appearance, taste, or smell. That distinction matters, because arsenic of geogenic origin is a documented problem in shallow Terai aquifers and cannot be detected by appearance, taste, or smell [13, 16]. The reassurance that residents draw from clear-looking water is, therefore, not a reliable guide to its safety. And the share of households that had never tested their water at all, more than a fifth for arsenic and more than a third for the vial test, represents a real coverage gap. No official municipal or Groundwater Resource Development Board laboratory dataset for Tilottama specifically was identified during this revision to cross-check against the reported testing history; this remains an avenue for a follow-up study, ideally in direct collaboration with the Board's Butwal branch office, which holds district-level well records for Rupandehi [23].

Table 3. Household Reports on Previous Water Testing ($n = 397$)

Test reported	Result reported	Number	Percentage
Arsenic test	Reported tested, within national limit	306	77.1
	Reported tested, above national limit	2	0.5
	Not tested	89	22.4
Presence/absence vial test	Reported tested, absence result	250	63.0
	Not tested	147	37.0

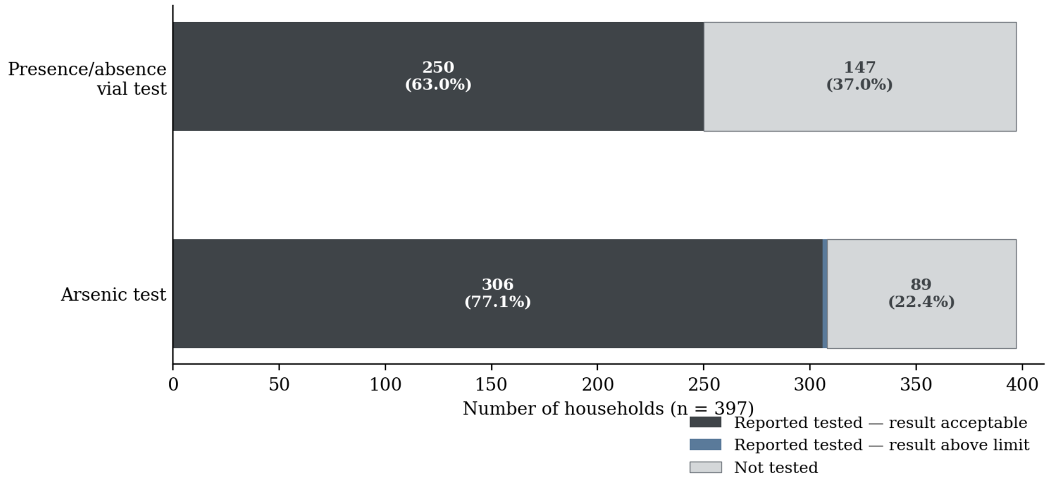

Figure 3. Household Reports on Previous Water Testing ($n = 397$).

4.7. Public Awareness of Recharge and Regulations

Awareness of groundwater management was low on both of the items the survey examined. Awareness of the recharge process and of the need for balanced abstraction was reported by 36.9 percent of households (95% CI: 32.4–41.9%), while 63.1 percent reported no such understanding (95% CI: 58.1–67.6%). Awareness of the rules and regulations governing groundwater use was lower still: 12.8 percent of respondents knew of them (95% CI: 9.9–16.5%), and 87.2 percent did not (95% CI: 83.5–90.1%). The two items measure different things, and the lower figure for regulations indicates the gap is sharpest on the rules side. This is a central finding of the study. The municipality has ample open land for recharge, but physical capacity alone does not produce recharge. With nearly two-thirds of households unaware of how recharge works and almost nine in ten unaware of the relevant rules, the practical barrier to sustainable management is knowledge and enforcement, not space. These findings align with broader literature, which has long identified weak public engagement and limited enforcement as the central obstacles to groundwater sustainability in Nepal [3, 9], and with the broader principle that a shared resource is managed durably only when its users understand and cooperate with the rules in place [10].

4.8. Effects on the Surrounding Environment

The study points to several effects on the surrounding environment, which should be read in the light of its residential scope. The reported change in water table depth in the northern wards is consistent with abstraction outpacing recharge in those areas, a pattern documented in a much more advanced form in the Kathmandu Valley [11]. Sustained over-abstraction has been associated elsewhere with land subsidence and with reduced baseflow to ponds and rivers [7, 8]. These are recognised consequences of declining groundwater levels and represent plausible risks for Tilottama if current trends continue, although confirming them locally would require direct measurement of land levels and surface water that lay beyond the scope of this study. The conversion of open land to built-up area, which respondents themselves noted as a feature of the past decade, reduces the surface available for infiltration and so works against natural recharge. The picture as a whole is one of an aquifer still in manageable condition, but under growing pressure, and protected by an asset, open land for recharge, that is currently going unused. Two further pressures sit outside the scope of the household survey but are worth naming explicitly. First, increasing variability in monsoon timing and intensity is an emerging driver of peri-urban water insecurity across South Asia, distinct from and additional to the urbanisation pressure this study measures directly [26]; if rainfall becomes more erratic, the roughly 10 percent infiltration fraction estimated for the district as a whole (Section 2) should not be assumed to hold steady. Second, this study did not attempt to quantify actual abstraction volumes against measured recharge, so the “over-abstraction” label used in Figure 4 below describes an inference from observed decline, not a measured water balance; this is clarified in the figure caption.

Modelling work in the Kathmandu Valley has shown that aquifer recovery is sensitive to both abstraction rates and climate scenarios, and that resiliency varies markedly across the valley [15]. The parallel for Terai municipalities such as Tilottama is useful. The rural-to-urban transition is at an earlier stage here than in the Kathmandu Valley, which means there is still time to act before stress becomes severe. Establishing routine monitoring of water levels and abstraction now, while only about one in seven wells shows observed change, would be a far less costly intervention than the management response required once decline becomes widespread.

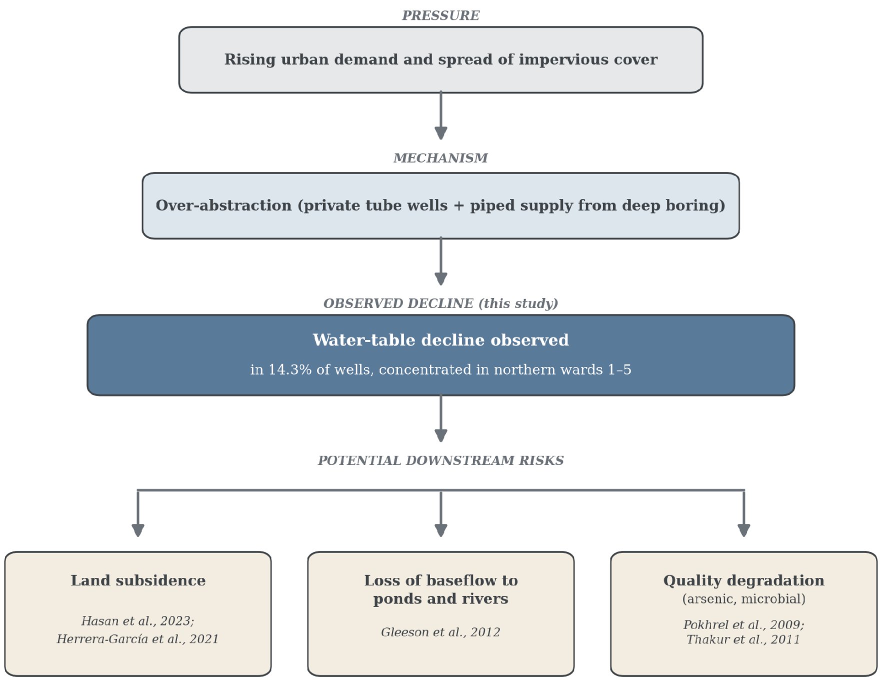

Figure 4. Pressure-Decline-Risk Pathway for Groundwater in Tilottama Municipality. Caption clarified in this revision: the box labelled “Over-abstraction” represents an inference drawn from the reported water-table decline described in Section 4.4, not a directly measured imbalance between abstraction and recharge volumes; this study did not measure abstraction volume with sufficient precision to establish the imbalance directly.

4.9. Practical Implications for Municipal Planners and Policymakers

The findings above translate into a small number of practical points for the bodies most directly responsible for groundwater management in Tilottama. Because the constraint is knowledge and enforcement rather than physical space (Section 4.7), the highest-return intervention available to the municipality is probably the cheapest one: ward-level awareness programmes and consolidated by-laws, both of which require no capital investment in infrastructure. Because open space is already available on almost every plot (Section 4.5), making a recharge pit a condition of building-permit approval is administratively straightforward to implement through an approval process the municipality already runs, though its effectiveness will depend on distinguishing plots with genuinely infiltration-suitable ground from those with compacted surfaces, per the qualification in Section 4.5. Because the reported signal of water-table decline is concentrated in five specific wards (Wards 1 to 5), routine monitoring resources are most efficiently targeted there first rather than spread evenly across all 17 wards. And because household testing coverage for arsenic and bacteriological quality is incomplete (Section 4.6), and because appearance is not a reliable proxy for either contaminant, extending the existing municipal and Groundwater Resource Development Board testing programmes to reach the untested share of households would close a real information gap at comparatively low cost per household reached.

5. Conclusion

This study examined groundwater abstraction in Tilottama Municipality through a household survey of 397 respondents across all 17 wards, supported by focus group discussions, in-depth interviews, and field observation. Four findings stand out, and each maps onto one of the four objectives set out in Section 1. On abstraction, household supply in the municipality depends on groundwater throughout, whether abstracted privately through tube wells or delivered through a piped system fed by deep boring. The same evidence also speaks to the environmental-effects objective: a change in water table depth over the past decade was reported in 14.3 percent of wells, concentrated in the northern wards , though, as discussed in Section 3.5, this is a recalled perception rather than a measured rate. On recharge capacity, the municipality retains substantial open land for recharge, with 99.2 percent of household plots holding suitable space , with the caveat on surface quality noted in Section 4.5. And on public awareness, awareness is the weakest link: 63.1 percent of households did not understand the recharge process, and 87.2 percent were unaware of the rules governing groundwater use. Taken together, these findings describe a municipality whose groundwater is not yet in crisis but is under steadily increasing pressure, and which still has the physical means to protect itself if regulation, monitoring, and public awareness can be put in place in time. Because groundwater recharge also depends on rainfall that recent regional literature suggests is becoming less predictable under climate variability [26], the margin for delay is arguably narrower than a reading of the abstraction and awareness findings alone would suggest.

5.1. Recommendations

On the basis of these findings, six recommendations follow. Each is tied directly to the result that motivates it.

(i) *Quantification of abstraction and recharge.* Because a change in water table depth was reported in 14.3 percent of wells in the northern wards, abstraction and recharge should be quantified at regular intervals so that the aquifer's condition is known and timely action is possible.

(ii) *Compulsory recharge pits in new construction.* Because 99.2 percent of surveyed plots retain open space suitable for recharge, the construction of a recharge pit should be made a compulsory condition for the approval of new residential and other buildings, so that recharge capacity is preserved as the built-up area grows.

(iii) *Clearer regulation and enforcement.* Because 87.2 percent of respondents were unaware of the rules governing groundwater use, federal, provincial, and local authorities should prepare clear and consistent rules for abstraction and recharge and enforce them through municipal building approval and water user committees.

(iv) *Sustainable and resilient supply planning.* Because both the piped system and direct abstraction depend on groundwater, responsible authorities should identify and plan supplementary sources to reduce pressure on the aquifer over the long term.

(v) *Sustained public awareness.* Because 63.1 percent of households did not understand the recharge process, sustained awareness programmes should be conducted at ward level so that residents understand recharge, the consequences of unbalanced abstraction, and the rules in force.

(vi) *Repeat the survey with disaggregated microdata retained.* Because the present round could not support cross-tabulation or inferential testing (Section 3.4), any follow-up survey should retain the respondent-level dataset in a form that permits chi-square or regression analysis of the associations between household characteristics and abstraction, awareness, and quality-perception outcomes.

Table 4. Summary of Findings, Recommended Actions, and Responsible Parties

Finding	Recommended action	Responsible party
Water table change reported in 14.3% of wells, concentrated in Wards 1–5	Establish ward-level monitoring of water levels and abstraction; report annually	Tilottama Municipality; Groundwater Resources Development Board
99.2% of plots retain open space suitable for recharge	Make recharge pits a compulsory condition for building permit approval	Tilottama Municipality (Building Permit Section)
87.2% of respondents unaware of rules governing groundwater use	Issue consolidated municipal byelaws on groundwater abstraction and recharge, and enforce through permit and user-committee mechanisms	Federal Ministry of Water Supply; Province; Tilottama Municipality
89% of households on piped supply, itself fed by deep boring	Identify supplementary surface and conjunctive sources to reduce sole dependence on groundwater	Department of Water Supply and Sewerage Management; Tilottama Drinking Water and Sanitation User Committees
63.1% of households do not understand the recharge process	Conduct ward-level awareness programmes through schools, FCHVs, and user committees	Tilottama Municipality (Education and Health Sections); local NGOs
Present round could not support cross-tabulation (new)	Retain respondent-level micro-data in any follow-up survey	Study research team / Policy and Strategy Unit for any follow-up

Acknowledgements

This article is derived from the M.Sc. thesis of the first author in Disaster Risk Engineering and Management, submitted to Lumbini International Academy of Science and Technology and awarded by Lumbini Buddhist University. The authors thank the supervisor and faculty of the Department of Disaster Risk Engineering and Management, the residents and ward representatives of Tilottama Municipality, and all respondents and key informants who made the fieldwork possible.

Conflict of Interest

The authors declare no conflict of interest.

Ethical Statement

This study is based on original research. Informed consent was obtained from all participants prior to data collection, and the work has not been published or submitted for publication elsewhere.

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