



REPORT

Lithological schematization of the Karnali fluvial fan (Nepal's Terai Arc Landscape) using electrical resistivity tomography as a basis for hydrogeological investigations

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Abstract

In the Nepalese and Indian Terai Arc Landscape (TAL), protected nature areas are supported by groundwater systems that have remained largely understudied. This study schematizes the lithology of the Karnali fluvial fan located in the Bardia district (Nepal) as a basis for future hydrogeological investigations. Inversion results of 2D electrical resistivity tomography (ERT) profiles at 21 locations were interpreted by comparing with the local borehole lithology and regional geophysical studies. Multiple lithological cross-sections were prepared to develop a 3D lithological model spanning the fan, and the adjacent Bardia National Park up to the Babai River in the east. Sediment resistivities found were in the range of 8–6000 Ω m. Resistivity less than 40 Ω m was identified as clay, 40–80 Ω m represented silt and fine sand, 80–400 Ω m identified as fine to coarse sand and resistivities higher than 400 Ω m were interpreted as coarse sand, gravel and boulders. A coarse sand-gravelly layer is present at the fan apex and along the foot of the Himalayas in the north that functions as a recharge area and aquifer. The central part of the fan has sandy layers which transition to fine sand and silt layers in the distal south and southeast. Clay layers locally create confining conditions, within the sand and silt dominated areas. These findings on subsurface lithology provide valuable insights for the groundwater systems which sustain ecohydrological processes relevant to the protected ecosystem and fills a critical knowledge gap on regional hydrogeology of the TAL.

Keywords Hydrogeology · Geophysical methods · Nepal · Karnali River · Fluvial fan

Introduction

The Terai Arc Landscape (TAL) located at the southern base of the Himalayas comprises 16 Nepalese and Indian protected nature areas, which provide crucial habitats for the endangered tiger (*Panthera tigris*) (Thapa et al. 2017). It hosts the Terai-Duar Savanna and Grasslands ecoregion which also supports wildlife such as the one-horned rhinoceros (*Rhinoceros unicornis*), Asian elephant (*Elephas maximus*) and leopard (*Panthera pardus*) (Olson and Dinerstein

1998; Wikramanayake et al. 2010). The TAL is densely populated and it has fertile soil suitable for agriculture (Irengbam et al. 2017). To support an increasing population, several infrastructure projects such as highways, irrigation canals, sand and gravel mining have been initiated and are further planned in the region. Between 1930 and 2020, approximately 25% of forest cover loss has been reported in the western TAL (hereafter, refers to TAL in Nepal), along with forest fragmentation and conversion of forested areas to agricultural lands (Ram et al. 2021). Climate projections for Nepal indicate an increase in mean temperature and rainfall across all seasons, except a decrease in rainfall during the pre-monsoon season (MoFE 2019). The TAL is also experiencing an increase in climate variability such as an increasing number of warm days, and high intensity precipitation (Ministry of Forests and Soil Conservation 2015). The increase in heat stress, changes in the timing of seasonal rainfall and human led activities can impact the availability of water for people and the environment. Further, climate change may also induce changes in discharge and water

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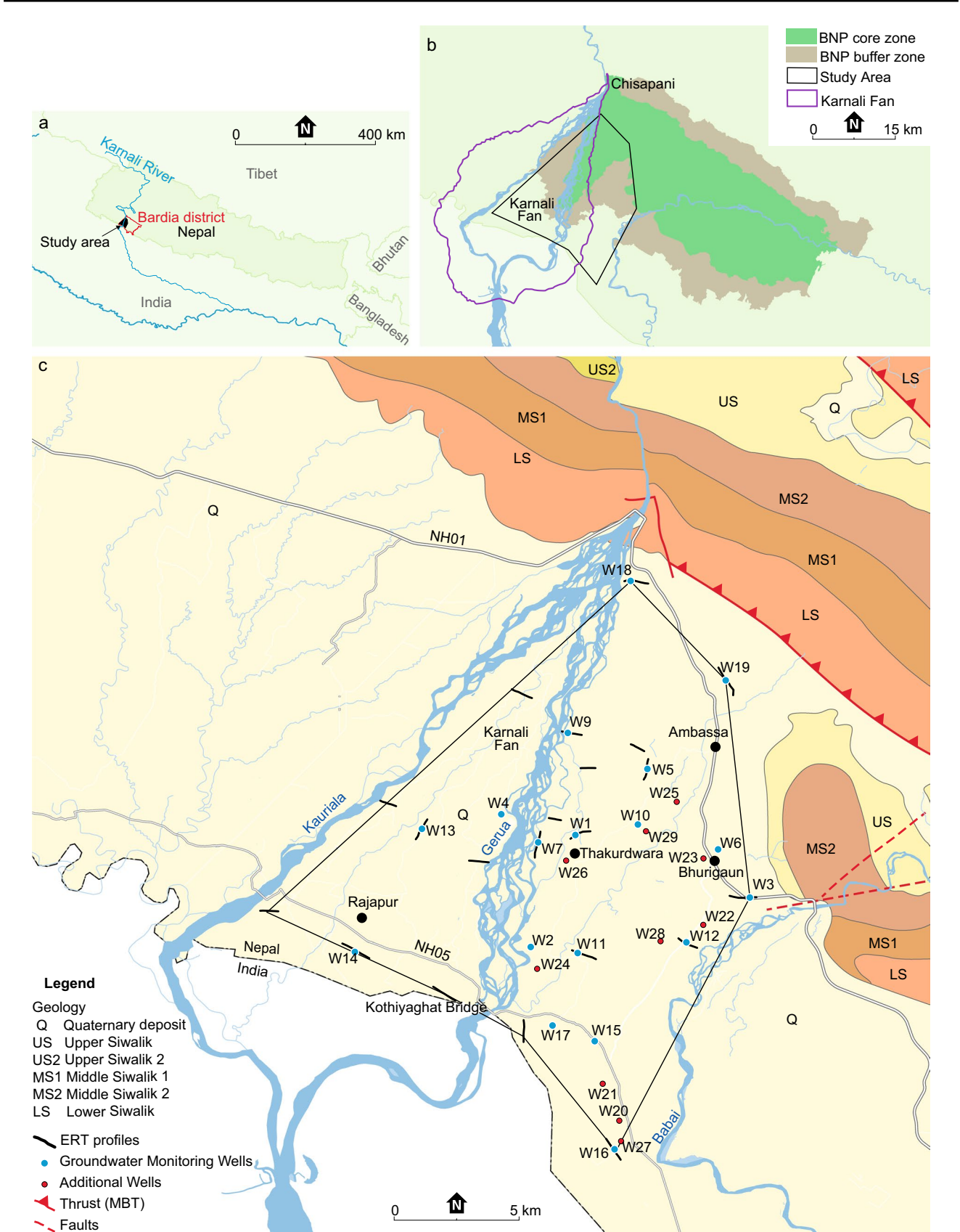


Fig. 1 Location of **a)** study area in Nepal; **b)** Karnali fan and Bardia National Park (BNP) modified after (Rakhal et al. 2021); **c)** Geological units and major physiographic features, ERT profiles and wells (blue: from this project; red: from Shrestha 1992) in the study area modified after (Dhital 2015)

levels of the rivers draining the Himalayas and crossing the TAL. Therefore, nature conservation initiatives in the TAL must consider sustainable management of water resources as a key component.

One of the largest nature reserves in the TAL is Bardia National Park (BNP) (BNP 2022). It is situated partly on the fluvial fan of the Karnali River (Fig. 1), which drains a large part of western Nepal. Fans are cone-shaped sedimentary features formed when rivers exit a steep and narrow mountain front to a flat plain. The width and flatness of the plain accommodates extensive sediment deposition and channel migration processes of the rivers (Leier et al. 2005; Sinha 2014). The formation of these fans is influenced by tectonic events and climatic events which impact sediment flow and deposition cycles (Goswami et al. 2009). On the basis of the length, a fan is classified as a megafan (length > 80 km), a fluvial fan (length 30–100 km) or an alluvial fan (length < 20–30 km) (Hartley et al. 2010; Wilkinson and Currit 2023). As the total length of the Karnali fan is about 44 km, this paper refers to it as the Karnali fluvial fan. In the Gangetic Plains, megafans such as the Kosi, Gandak and the Teesta fans have been well documented. In contrast, the fluvial fans present adjacent to Himalayan foothills have received limited attention. This northernmost part of the Gangetic plain represents a piedmont surface and, hence, some studies have referred to the fans present in this region as piedmont fans (Shukla and Bora 2003).

Anthropogenic activities as observed across the TAL are also occurring in the lower Karnali region. Studies have established the significance of fans as important groundwater reservoirs due to the favourable storage and recharge capacity of their sedimentary deposits (Zhu et al. 2017; Blackburn et al. 2021). Decreasing water levels in rivers, population growth and irrigation requirements increase pressure on groundwater resources notably during the dry period before monsoon. Water scarcity during the dry period causes drying of waterholes and wetlands present in the nature reserve, which in turn necessitates construction of artificial waterholes pumped with groundwater for use by wildlife (BNP 2022; Thapa et al. 2023). It also causes wildlife to venture out of the National Park in search of water and thus increasing risk of human–wildlife conflict. When groundwater levels fall deep in the dry pre-monsoon period, shallow rooted vegetation such as the grasslands in the park may undergo drought stress (BNP 2022; Bijlmakers et al. 2023). Thus, the hydrogeological characteristics of the Karnali fluvial fan steers the

ecohydrological conditions of the BNP. It also supports domestic and irrigation requirements of people. There is increasing dependency on the groundwater to meet human and ecological demands.

Sedimentological studies conducted on the Karnali fluvial fan have investigated key processes such as channel migration, sediment deposition patterns and sand-gravel transitions (Baral et al. 2017; Dingle et al. 2020; Rakhal et al. 2021), contributing to the current knowledge of the fan. However, the subsurface architecture of the fan is unknown. Hence, there is a need to fill in this knowledge gap to support water planning and management.

This study uses electrical resistivity tomography (ERT) to develop a 3D lithological model, as a basis for future hydrogeological investigations of the Karnali fan. The resistivity of a subsurface layer is a function of pore connectivity and pore water resistivity (Endres 1978). Coarser sediments such as sand and gravel exhibit higher resistivity compared to fine grained sediments like clays. Resistivity of clay is low due to high surface conductivity and cation exchange capacity of clay minerals and associated sedimentary organic matter (Kirsch 2009). This resistivity contrast between sediments can be used to identify distinct lithologies which impact groundwater flow due to their different hydraulic conductivities (De Clercq et al. 2020). The spatial variation in electrical resistivity combined with knowledge of subsurface lithology can be used to design a lithological schematization that provides insight to the presence of aquifers and aquitards. The advantage of ERT lies in being minimally invasive, faster than drilling and providing spatially continuous information about resistivity variation in the subsurface (Slater 2007; Benoit et al. 2019). This proves to be particularly useful in poorly studied regions with insufficient hydrogeological data availability. ERT has been successfully used to identify lithology of aquifers based on resistivity variations in previous studies (Galazoulas et al. 2015; Thapa et al. 2019; Pedrazas et al. 2021; Hussein et al. 2023; Kumar et al. 2024). In the Himalayan foothills, ERT has been integrated with surface nuclear magnetic resonance to study seasonal changes in water content of aquifers (Singh and Sharma 2022a). Another study used resistivity imagery with magnetotelluric survey to build a 3D lithology model and characterised groundwater potential in a sub-Himalayan region (Khan et al. 2024a). Integration of resistivity survey with geospatial techniques have been used to delineate water bearing lithology and to understand aquifer vulnerability based on landcover (Khan et al. 2024b). Lithological and hydrogeological schematization of fans has been done previously for the Salado-Juramento fluvial megafan in Argentina (Thalmeier et al. 2024), the Ehen alluvial fan in England (Blackburn et al. 2021), the Punata alluvial fan in Bolivia (Amaya et al. 2016) and the Cubango megafan in Namibia (Lindenmaier et al. 2014).

This research aims to build a lithological model of the Karnali fluvial fan and adjacent parts of the BNP to inform future hydrogeological investigations. An overview of the TAL hydrogeology and groundwater systems is found in (Dhital 2015; Shrestha et al. 2018). The geophysical studies conducted in the TAL (Yadav et al. 2010; Shrestha et al. 2013; Sinha et al. 2014; Thapa et al. 2019) were used to interpret findings in this study. These studies establish the highly heterogeneous composition of the subsurface of the Indo-Gangetic Basin (IGB), which features sedimentary deposits reaching a thickness of 1500 m. The study by (Bonsor et al. 2017) where the IGB aquifer was schematized using seven hydrogeological typologies was used to synthesize the findings of the study.

Materials and methods

Study area

The study area is in the Bardia district of the western TAL in Nepal and is shown in Fig. 1a. The Karnali fluvial fan has its tip (apex) at Chisapani near the bifurcation point of the Karnali River to Kauriala (west) and Gerua (east) River, after it exits from the Siwalik hills (Fig. 1b and c).

The northern boundary of the study area is from the fan apex along the Siwalik foothills, through BNP. The fan continues up to India, where the two branches remerge, and the river joins the Ganges River more downstream. It has a total area of 789 km² (522 km² in Nepal) and a slope of 0–3° (Rakhal et al. 2021). The western part of the BNP partly lies on the fan, on the Gerua River floodplain. A stretch of the smaller but perennial Babai River flows at the eastern border of the study area. The southern extent of the study area is close to the Nepal–India border.

The Karnali fan lies at the piedmont surface at the edge of the Indo-Gangetic Basin (IGB). The Siwalik hill formations, geologically denoted as Lower Siwalik (LS), Middle Siwalik (MS) and Upper Siwalik (US) are present in the north and northeast of the study area (Fig. 1c). The Main Boundary Thrust (MBT) separates the Siwalik hills from the study area. The study area is covered by Quaternary sediments (Q) deposited during the Pleistocene and Holocene Epochs (Singh 1996; Bonsor et al. 2017). Villages such as Thakurdwara where the park entrance is located, Rajapur in the fan area, Ambassa and Bhurigaon are important settlements with public bus stops and market areas. Two National Highways, NH01 in the north and NH05 in the south are the major transport routes in the study area (Fig. 2).

The study area largely consists of croplands and forest ((FRTC 2022); Fig. 3). Extensive agriculture is practised on the fan between Gerua and Kauriala rivers and elsewhere south of the park boundary. Forest areas are dominated by

Sal (*Shorea robusta*) trees outside active floodplains in the core zone of the park and along a stretch of community forest that extends from the buffer zone up to the border in the south between Gerua and Babai rivers. Mixed riverine forests are present along the active floodplains (Thapa et al. 2021). Two types of grasslands are present: alluvial tall grasslands near the rivers, and short mixed grasslands further away from rivers (Bijlmakers et al. 2023). Besides the three major rivers, there are several local, ephemeral rivers which flow during monsoon (Shah et al. 2025).

The climate of the region is subtropical, with four seasons: post-monsoon (October–November), winter (December–February), dry pre-monsoon (March–May) and monsoon (June–September). The average annual rainfall is about 2286 mm, 80% of which occurs during the monsoon (Thapa et al. 2021; BNP 2022).

The hydrogeology of the piedmont and its groundwater behaviour has been described at the IGB scale by Bonsor et al. (2017). Its two geomorphic divisions are (a) the Bhabar belt immediately south of Siwalik hills and (b) the Terai which is comparatively flat (Singh 1996). One of the major differences in the two belts lies in the lithology of subsurface sediments and, hence, the effect on water bearing capacity. The Bhabar sediments consist of coarser sediments, including cobbles, gravels and boulders, while Terai sediments consist mainly of fine sand, silt and clay (Dhital 2015).

Aquifers in Nepal's TAL are classified as shallow (0–46 m depth) and deep (>46 m) (Pandey et al. 2021). The upper part of the aquifer (up to 50–60 m depth) is considered a productive zone which is extensively tapped for domestic water use through the installation of private handpumps and borewells, while deeper aquifers are exploited for community-scale irrigation water supply (Shrestha et al. 2018). Most of the groundwater extraction for domestic use is through shallow wells while a limited number of deeper well is present for irrigation. The aquifers present within 100 m depth serve as principal sources to meet domestic water and irrigation requirements in the study area as well as influences the ecohydrology of the BNP.

Methods

General approach

To schematize the lithology of the Karnali fluvial fan and surroundings, the following methodological steps (workflow shown in Fig. 3) were taken:

- Electrical resistivity tomography (ERT) survey at 21 locations to collect data on subsurface apparent resistivities (Fig. 2). They are referred to as line A (A = 1–18) pertaining to locations with a monitoring well lying on

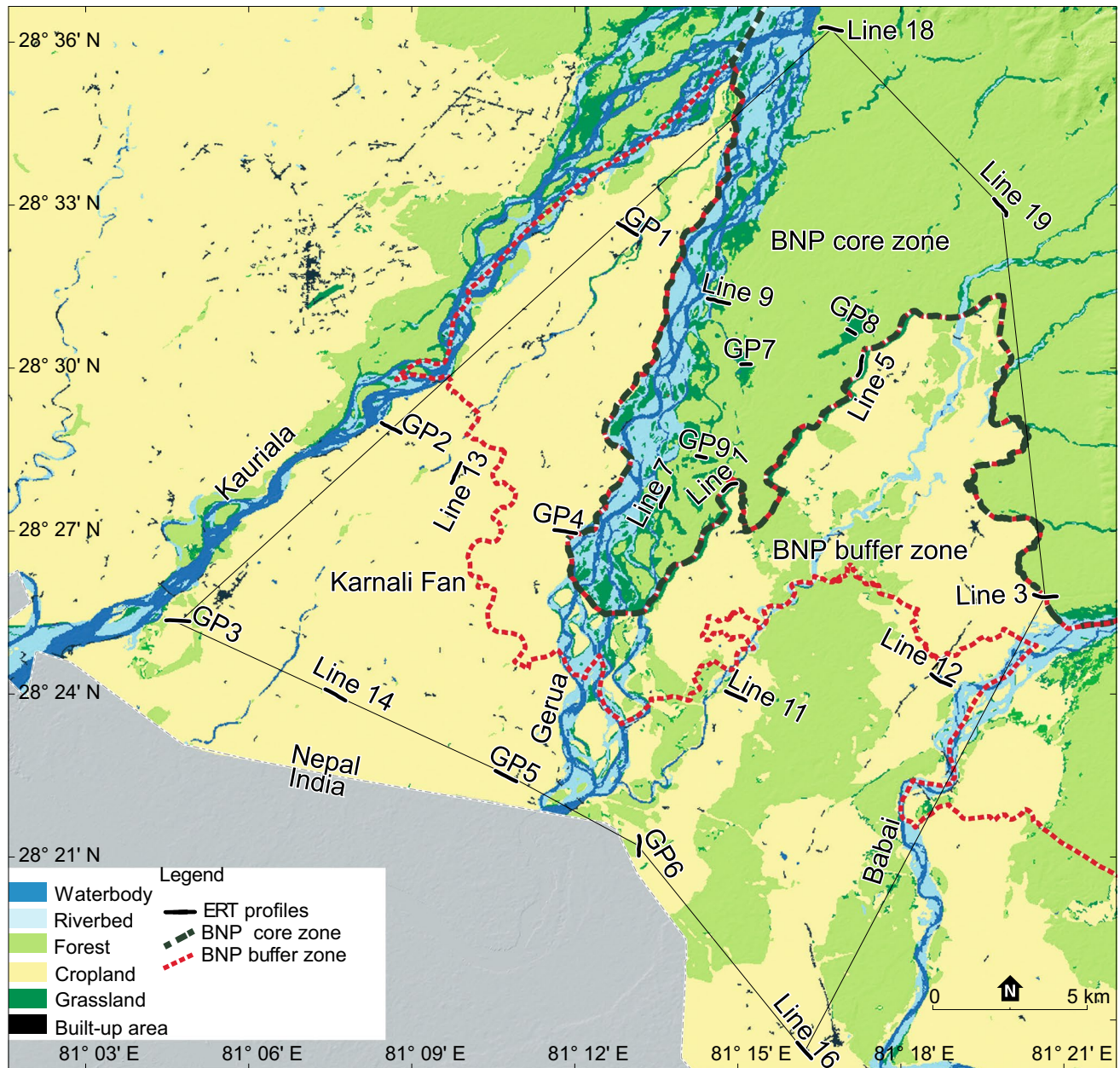


Fig. 2 Location of ERT profiles in the study area on a landcover map of 2019 (FRTC 2022)

the profile (e.g. line 18 for survey near W18) and GP B ($B = 1$ to 9), for locations without a well on the profile)

- Data processing (inversion) was done using Res2DInv software (version 2024.1) to generate 2D ERT models. These show subsurface resistivity variation whose response is similar to the measured apparent resistivity values along the field survey lines.
- Classifying resistivities in the ERT profiles into five lithological classes based on comparison with nearby lithologies and with data from geoelectrical studies conducted in the wider vicinity of the study area in Nepal

and India, generating lithological cross-sections for each 2D ERT model.

- Transforming the cross-sections into a 3D lithological model using RockWorks software (version 20), from which a fence diagram was developed with seven east–west and three north–south cross-sections.
- Translating lithological information to hydrogeological relevance for the study area.

Eighteen wells (coded W1 to W19, except W8 which became dry and could not be used further in the research)

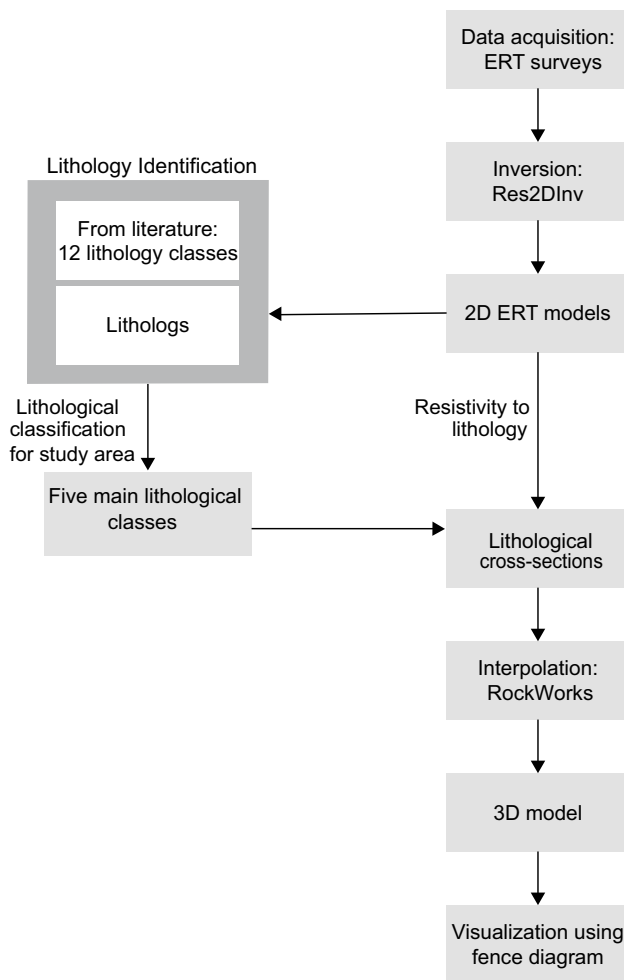


Fig. 3 Workflow used in the study

were installed in the study area within the framework of this project. The additional 10 wells (coded W20 to W29) present in the study area were installed from 1980–1990 (Shrestha 1992; Brikowski et al. 2018) during projects conducted by the United Nations and the Ground Water Resources Development Board of Nepal (Fig. 1c). Lithologs of these 28 wells are given in Fig. 7 in Appendix 1. The lithologs showed the presence of clay, sandy clay, sand-silt, sand and mixtures of gravel, pebbles, and cobbles with sand. There are mostly shallow lithologs with maximum borehole depths in the study area being 101 m. Groundwater monitoring at 18 wells for 2 years during 2023 and 2024, revealed groundwater levels between 187 m above sea level (asl) in the north and 143 m asl in the south. Its flow follows the decreasing surface elevations from north to south and drainage by the ephemeral rivers at least outside monsoon season.

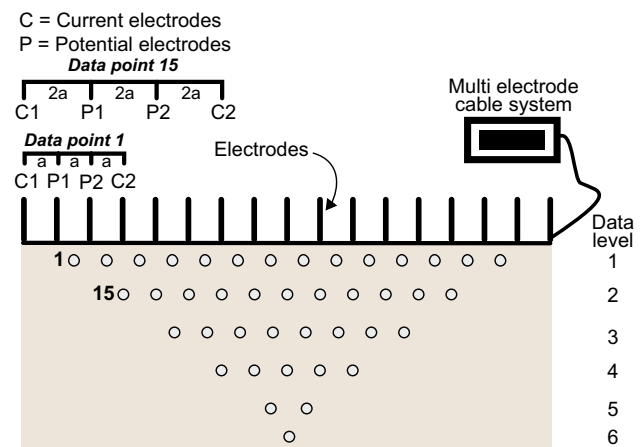


Fig. 4 Schematic diagram of ERT using Wenner configuration

Electrical resistivity tomography

Electrical resistivity tomography (ERT) was used to obtain information about changes in subsurface resistivity both laterally (x direction) and vertically (z direction) along the survey lines (Loke 2022). An electric current penetrates the ground, while the resulting potential difference is measured, using electrodes installed along the length of the survey line. The electrodes were arranged in Wenner configuration where the space between electrodes remained constant (Fig. 4). In a comparative study with different ERT electrode combinations, Wenner showed the highest signal strength and its geometric factor decreased with depth making it least sensitive to background noise (Singh and Sharma 2022b). It also has the ability to demarcate horizontally extensive and stacked lithologic layers (Oyeyemi et al. 2022; Bienibuor et al. 2025) making it suitable for the purpose of lithologic schematization.

The resistance to current flow through the subsurface depends on properties such as conductance and porosity of the sediments, the degree of water saturation, and pore water quality (Pedrazas et al. 2021). The apparent resistivity (ρ_a) is obtained using the relation $\rho_a = 2\pi aR$ where a is the electrode spacing, R is the total resistance encountered by the current. ρ_a is equivalent to the resistivity over the total path traversed by the current through heterogeneous soil layers (Uwiringiyimana 2019).

Data collection and processing

2D ERT surveys were conducted at 21 locations across the study area (Fig. 2) during April 2023. A multi-electrode cable system (GD-10 Supreme 2D+) was used, which

worked with a maximum transmitting power of 3200 W, voltage of 800 V and a current of 4 A (Geomative 2020). Electrode spacing of 5–12 m and a survey line length of 510–710 m was used. Groundwater levels were obtained from the nearest monitoring well to identify the depth of the water table.

For data processing, the Res2DInv software (version 2024.1) was used (Loke 2022). The raw data was loaded into the software and examined for noisy data which showed up as excessively deviated values which were then removed (Hussein et al. 2023). Two modelling subroutines, i.e. forward and inverse modelling, were executed using the software. In forward modelling, the potential difference that will be produced as a response to the apparent resistivity was calculated. In inverse modelling, the resistivity values that will generate the same potential difference as calculated in the previous step were determined (Loke and Dahlin 2002). The robust constraint optimization method was used to reduce the differences between the apparent (measured) and calculated resistivities through an iterative process. This method was used as it creates models with sharp boundaries between geological layers of varying resistivity (Loke 2022). This study assumed that discrete boundaries exist between coarse grained and fine-grained lithology with different resistivity values in the cross-section. This helped delineate the presence of distinct lithological layers with resistivity contrast (Pedrazas et al. 2021). The convergence limit was set at 5%, i.e. inversions continued until the relative change in root mean square error (RMSE) between two iterations were less than 5% (Seequent 2023). The absolute resistivity misfit between measured and modelled resistivities is

used to measure the goodness of fit for the ERT models (Geotomo 2017; Uhlemann et al. 2017; Uwiringiyimana 2019).

Interpretation of 2D ERT models

Table 1 presents typical resistivity values for 12 lithological classes compiled from the geoelectrical studies conducted in the wider vicinity of the study area. On the basis of these classes, five simplified lithological classes were determined for schematising the Karnali fan subsurface architecture. Each of these lithological classes consists of a combination of lithologies that cannot be differentiated owing to low contrast in resistivities. The 2D ERT models were compared to lithologs present near the ERT location and sediments in the cross-section were identified. For locations with sparse and shallow well, lithology of sediments were assigned using resistivity values present in Table 1. Lithologs not directly present on the ERT profile but within the surrounding area were used to validate the spatial continuity of the identified lithology. Then the lithologic classification using the five main classes was applied to convert the ERT models into lithological cross-sections. Four ERT models with their lithological cross-sections are discussed in the “Results” section along with their hydrogeological relevance and the remaining models are presented in the electronic supplementary material (ESM).

Development of 3D lithological model

RockWorks software version 20 (RockWare 2024) was used to build a 3D lithological model. The 2D ERT models were

Table 1 Resistivity values of sediments as obtained from (Shrestha et al. 2013; Thapa et al. 2019; Yadav et al. 2010; Sinha et al. 2014;) in columns 1–3, 4, 5 and 6, respectively; and 5 main simplified lithological classes for the study area in columns 7–8

Typical resistivity values of sediments outside the study area in Nepal and India							Lithological classification for the study area	
Lithology	Resistivity values (Ω m)						Lithology classes	Resistivity (Ω m)
	1	2	3	4	5	6	7	8
Clay	-	< 20		- < 20	1–15	< 20	Clay	0–40
Clay and silt	< 15	< 50	13–1793	20–50	10–25	20–50		
Sandy clay	15–50	-		- -		-		
Silt and fine sand	-	50–100		- 50–100	25–35	-	Silt to fine sand	40–80
Clayey sand	50–100	-		- -		- -	Fine to coarse sand	80–400
Fine sand	-	-		- -		- 50–100		
Fine to coarse sand	-	100–200		- 100–200	30–220	100–500		
(Coarse) sand and gravel	100–500	250–1000		- 250–1000		- 500–900	Coarse sand with gravel	400–1100
Gravel with fine materials	-	-	495–8728	-		- -		
Gravel	-	-		- -		- > 2000	Gravel and boulders	1100–6000
Boulders/cobbles	-	~ 2000		- -		- -		
Boulder and cobbles in sand	-	-	2131–25,000	1000–5000		- -		

exported to a single database in ASCII format, containing longitude, latitude, elevation and resistivity values (X , Y , Z , and R , respectively). This database was imported into the Utilities module of RockWorks. The model domain extended from $X = 507,300$ to $534,060$ m, $Y = 3,129,150$ to $3,164,220$ m, $Z = 220$ to 10 m (UTM Zone 44N, WGS 84 datum). The grid was constructed with node spacing of $X = 30$ m, $Y = 30$ m and $Z = 10$ m, and resistivity values were assigned to the grid nodes, resulting in a total of 22,985,820 nodes, out of which 14,726,396 have non-interpolated values. The lithological classification (Table 1; columns 7–8) was applied to translate the resistivity values to the five main lithology classes. The inverse distance weighted (IDW)-anisotropic method was used for interpolation. This method assigns the lithology of an unknown point as per the weighted average of nearby lithologies within an octant. The anisotropy component ensures that the interpolation conforms to the spatial distribution of neighbouring data points (Mei 2014; Babak 2014; Yasrebi et al. 2019; Ongarbayev and Madani 2022). This method was preferred as it does not exaggerate the lithology of a point in the model beyond the area of influence of nearby lithologies, thus enhancing the sedimentological plausibility. The resulting 3D model was sliced into three north–south, and seven east–west cross-sections to create a fence diagram from which the five main lithological units were identified.

Results

This section presents the five main lithological classes defined for sediments in the study area as based on resistivity values. Next, the translation of 2D ERT models to lithological cross-sections presented for four locations. Thirdly, the 3D lithological architecture of the Karnali fluvial fan and surroundings is summarized and related to its hydrogeological relevance using the fence diagram.

Lithological classes of sediments from resistivity values

Columns 1–6 of Table 1 present typical resistivity values for 12 lithological classes as compiled from regional studies in the wider vicinity of the TAL. Columns 7–8 show the five simplified lithological classes assigned to resistivity values found in the study area. Out of these five classes, one class represents an aquitard unit consisting of clay. The remaining four classes represents aquifer units comprising, respectively, silt to fine sand; fine to coarse sand; coarse sand with gravel; gravel and boulders.

Lithological interpretation of ERT data

The 2D ERT models obtained using inversion modelling show resistivity variation in cross-section with a depth of investigation (DOI) of about 85–120 m below the surface. The absolute resistivity misfit for the models is shown at the bottom of each model. Overall, the resistivity values of sediments in the study area have a range of 8–6000 Ω m. Figure 5 shows four examples of 2D ERT models and their translation to cross-sections of lithologic classes.

Line 18 is located at the northernmost point of the study area in a Sal forest. The lithology of nearby well W18 shows 6 m of sand followed by sand with gravel down to a depth of 33 m. The groundwater level was at 187 m above sea level (asl) at W1 on 11 April 2023, i.e. 18 m below surface. In the ERT model, resistivities of 40–370 Ω m are present from near the surface up to 200 m asl, i.e. up to a depth of 10 m. These sediments are identified as silty to sandy deposits. Higher resistivities of 400–1136 Ω m are present below 200 m asl. These resistive sediments are identified as coarse sand with gravel. Three highly resistive zones (> 800 Ω m) are present between 30 and 70 m depth, which may indicate the presence of buried boulders and cobbles. The lithological cross-section shows the subsurface with 10 m deep fine to coarse sand deposits overlaying a 90 m thick sequence of sand mixed with gravel. The subsurface can be interpreted as an unconfined aquifer with high permeability and relatively deeper groundwater level.

Line 5 is located at the border of the BNP core zone. The nearby well W5 is 9 m deep with a lithology of sand up to 4 m depth, followed by a thin clay layer of 1 m and sand with gravel between 5 to 9 m depth. The groundwater level was at 170 m asl at W5 on 19 April 2023 which means 5 m below surface. In the ERT model, a thin layer of low resistivity (< 100 Ω m) is present near the surface which increases in thickness to 40 m in the northern part. This layer is identified as finer sediments such as clay and silt. Resistivities of 100–500 Ω m are present from near the surface up to 100 m depth in the southern and central part of the profile, indicating fine to coarse grained sandy sediments. A high resistivity section (> 1500 Ω m) is present in the north at a depth between 40 and 100 m from the surface. This section has an abrupt transition to higher resistivity compared to the nearby sediments indicating a distinct change in lithology to coarse grained sediments. The lithological cross-section of line 5 reveals predominantly sandy layers with a silty layer near the surface which increases in thickness in northern direction. Groundwater is present in shallow depth in this area. Another silt pocket is present in the centre of the profile. A gravel dominated section is present at 20–100 m depth surrounded

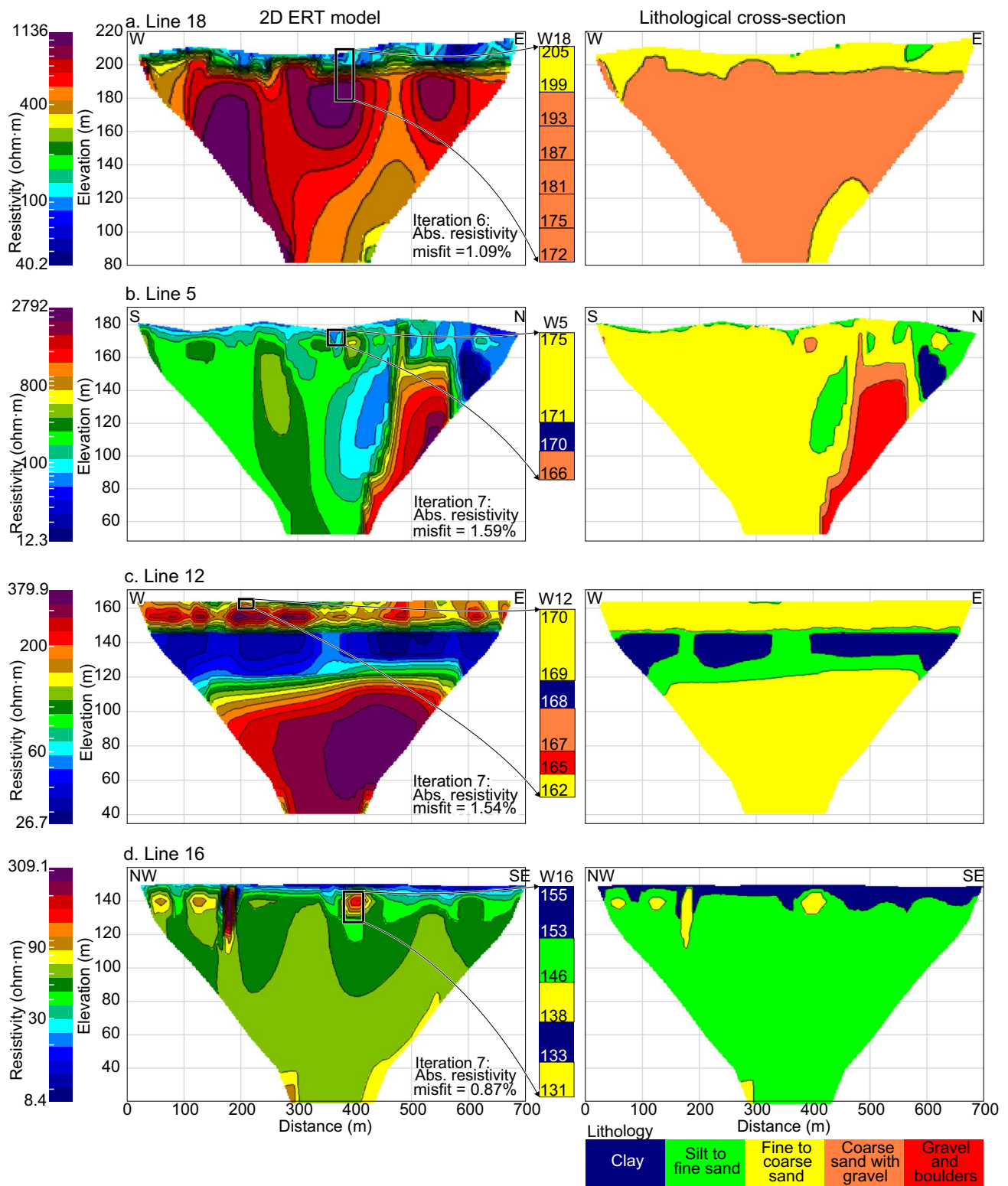


Fig. 5 Four 2D ERT models of subsurface resistivities (left), litholog of nearby well (centre) and interpreted lithological cross-sections (right) for line 18 (a), line 5 (b), line 12 (c) and line 16 (d). ERT locations (indicated by line numbers) are in Fig. 2. (Abs.= Absolute)

by finer sediments. Similar coarse sand and gravel dominated subsurfaces have also been delineated for locations in the northern part of the fan at GP1 (Fig. S9a and S9b of the ESM) and nearer to the Gerua River at line 1, line 7, line 9 and GP4 (Fig. S1a and S1b; Fig. S3a and S3b; Fig. S4a and S4b; Fig. S12a and S12b of the ESM, respectively).

Line 12 is on agricultural land, close to the Babai River in the east. The nearby well W12 shows alternating layers of sand and gravel with clay in the 8 m deep litholog. The groundwater level was at 167 m asl at W12 on 17 April 2023, i.e. 3 m below surface. A distinctly low resistivity layer (28–80 Ω m) extends across the length of the model between 25 and 50 m deep from the surface. This indicates the presence of conductive and water-saturated sediments such as clay and silt. From near the surface to 25 m deep and below 50 m deep, moderately resistive (80–378 Ω m) sediments are present. These pertain to sandy sediments. Near the surface, the resistivities show greater heterogeneity indicating alternating layers of fine to coarse grained sediments, as also seen in W12. The lithological cross-section shows 25 m thick sand layers on top of a laterally continuous layer of clay enclosed in silt. The clay layer behaves as an aquitard while the sandy layers can be interpreted as aquifers. Below the aquitard, another sandy aquifer can be distinguished up to 120 m deep. Gravel and boulders as seen in W12 litholog are not present in the interpreted lithological cross-section as these thin layers near the surface are not resolved by ERT as separate lithologies. A similar silty-clayey layer buried within sandy deposits is also present in the subsurface of line 3 (Fig. S2a and S2b of ESM) located at the northeastern border of the BNP, also near the Babai River.

Line 16 is also on agricultural land in the most southeast-ern point of the study area. The lithology of the nearby well W16 shows clay overlying fine sand and silt mixed sediments up to 10 m depth and then alternating sand and clay up to 24 m depth. The groundwater level at W16 was at 145 m asl, i.e. 10 m below surface, on 16 April 2023. The low resistivity (9–40 Ω m) layers present in the ERT model from the surface to a depth of 10 m, are interpreted as clay. Some high resistive zones (80–300 Ω m) are present near surface which indicate sandy sediments. From 10 to 100 m depth, sediments with resistivities of 40–80 Ω m are present, which are identified as fine sand mixed with silt. The lithological cross-section shows a confining clay layer overlying silt mixed with fine sand. These sediments indicate the presence of a fine-grained aquifer which may yield poor aquifer properties compared to the predominantly sandy aquifer. The clay layer is present throughout the length of the profile and its thickness varies between 10 and 20 m. The presence of finer sediments with clay pockets acting as locally confining layers is also observed in the southern part of the fan, i.e. near the Kauriala River in the west at GP 3 (Fig. S11a and

S11b of the ESM) and in line 14 closer to the international border (Fig. S7a and S7b of the ESM).

Overall, sediments with higher resistivities are observed at the apex of the fan in the north of the study area and along sites adjacent to the Gerua River which are identified as coarse sand and gravel beds. The lowest resistivities are present at the southern part of the fan and to the eastern side near the Babai River which are interpreted as silt- and clay-rich sediments. The central part of the fan and the remaining locations show moderate resistivities with localized variations, suggesting the presence of sand dominated sediments.

Lithological schematization of the Karnali fan and surrounding areas and its hydrogeological relevance

A 3D lithological model was developed for the study area based on interpolation of the 21 lithological cross-sections. Then a fence diagram (Fig. 6) was created of seven east–west and three north–south cross-sections to visualize the spatial variability of the sediments spanning the Karnali fluvial fan up to the Babai River in the east. The three north–south cross-sections represent the subsurface respectively near the Kauriala (west), Gerua (centre) and Babai (east) rivers. The lithological composition of the study area is summarized and related to its hydrogeological relevance.

At the apex of the Karnali fan in the north at about 200 m asl elevation, the subsurface is characterized by gravels (shown by orange and red) with intervening sand layers. Near the Kauriala and the Gerua rivers, permeable gravel beds with coarse sand are present closer to the surface with variable thickness between 10 and 20 m depth and again between 50 and 100 m. Gravel deposits are present in the lower part of the subsurface up to about 9 km to the east of the Gerua River, as seen along the length of cross-section II. The presence of gravels at shallow depth, specially at cross-sections I and II, reflects recent deposition by the rivers. While the presence of gravels at deeper part indicates high energy flood events in the past (Sinha et al. 2014). In events of flash floods and landslides during monsoon periods, ephemeral rivers can also carry eroded rocks from the Siwalik and deposits in the valleys at the base of the mountains (Shukla and Bora 2003; Bhandari and Dhakal 2020) which could also contribute to the gravel deposits seen in the eastern part of these cross-sections.

A distinct and highly permeable gravel and boulder zone is present at about a depth of 25 m from the surface as observed in cross-section IV. It is located about 15 km southeast of the fan apex, east of the Gerua River. This area can be recognized as another past high energy zone for deposition of Himalayan derived gravels (Singh

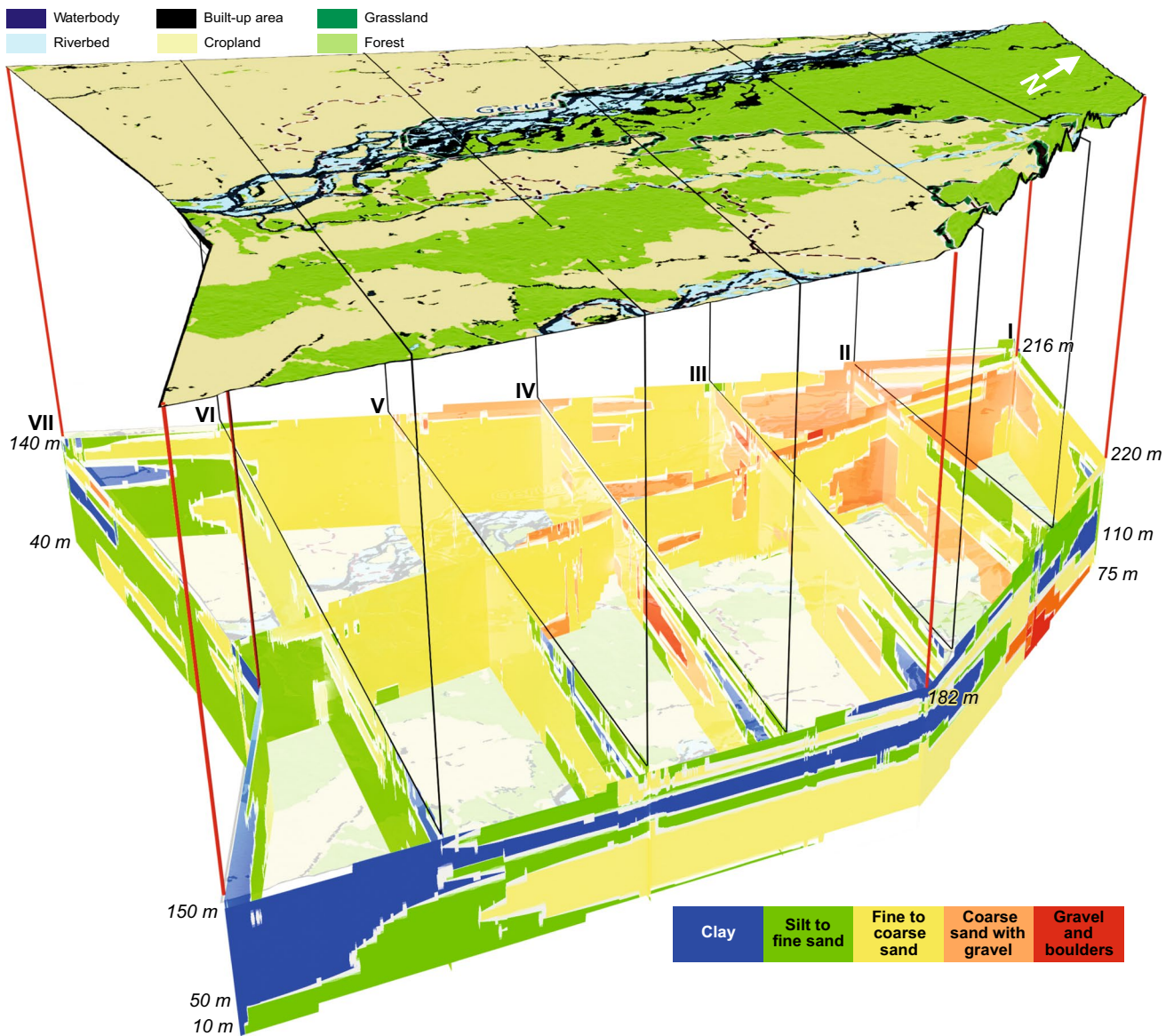


Fig. 6 Fence diagram of the Karnali fan up to the Babai River in the east, showing the subsurface to be composed of five main lithological classes. The model extends 27 km in east–west (X) and 35 km in north–south (Y) direction. Z axis represents elevation (10–220 m asl)

1996) by the Gerua River. There is a 100 m deep borehole located between cross-sections III and IV (W29, Fig. 7 in Appendix 1) which also shows a 90 m deep sequence of gravel, cobble and pebble from a depth of 10 m below the surface validating these findings. The upper 10 m of the litholog indicates that clay is present. The upwards fining of lithology is also exhibited towards the east of the cross-sections III and IV. The top gravel layer is present in these two north–south cross-sections to about 19 km south of the apex of the fan. In this area, the upper part of the shallow aquifer changes from gravel to sand which reduces permeability. This hydrogeological transition corresponds to the

gravel sand transition zone reported by (Dingle et al. 2020) along the length of the Karnali River, where bed sediments change abruptly from gravel to sand usually due to lowered energy of the water flow downstream.

In the central part of the fan subsurface (cross-sections III, IV and 528–529 V), sandy layers are present. Fine- to coarse-grained sand forms the principle lithological class in the study area as it is present in all the cross-sections with varying thickness, forming sandy aquifers. Towards the eastern part of all three cross-sections, the sandy aquifers show an increasing presence of fine sand, silt and clay layers indicating reduced permeability.

In the southern part of the Karnali fan (cross-sections V, VI and VII), about 23 km south of the apex, the subsurface gradually becomes less permeable with an increasing presence of silt and fine sand layers as well as clayey horizons interspersed with sand deposits. The easternmost north–south cross-section near the Babai River shows alternating layers of sand, silt and fine sand, and clay layers. The interbedded clay and silt horizons indicates the presence of paleochannels, ephemeral streams and low-lying depressions where fine sediments were deposited during periods of low or absent flow and high evaporation after the monsoon (Sinha et al. 2023). The presence of 5–15 m of clay near the surface underlain by silt and fine sand rich sediments is also observed in the lithologs of wells W21, W20 and W27 which are in the southeast part of the study area (Figs. 1 and 7 in Appendix 1). However, the model does not capture the presence of sand with gravel in the lower part of the aquifer in the southeastern part, as observed between 30 and 50 m depth as seen in the lithologs of W20 and W27 (Fig. 7 in Appendix 1).

Discussion

This study is the first to describe the subsurface lithology at the Karnali fluvial fan and parts of the Bardia National Park in western Nepal. Using ERT, comparison with lithologs and information from regional geoelectrical surveys, a 3D model was developed showing spatial distribution of five main lithological classes. Four of these represents aquifers, and one is an aquitard.

The coarse sand and gravel layers present in the fan apex and along the river floodplains in the northern part of the study area form an unconfined, permeable aquifer. Along the immediate south of the Siwalik hills, this unconfined aquifer shows relatively deeper groundwater (18 m below surface). This aquifer can be identified as a part of the Bhabar zone, where the sediments exhibit variable hydraulic conductivity of 1–50 m/day and high specific yield of 20–30% (Bonsor et al. 2017). These areas serve as groundwater recharge areas, due to infiltrating rainwater as well as seepage from rivers (Shrestha et al. 2018; Wagle et al. 2024).

The sand deposits predominantly present in the central part of the fan extends to 12 km east up to the Babai River. These layers form a highly productive sandy aquifer which is extensively tapped for drinking water and irrigation purposes, with reported well yields in Bardia exceeding 2000 m³/day (Pandey et al. 2021). The hydraulic conductivity of this aquifer was estimated at about 5–30 m/day by (Bonsor et al. 2017). In the fan, the sandy aquifer has gravel beds in the upper part, specially near the rivers. While to the immediate east of the Gerua River, gravel beds are present at depth below 25 m

within the sandy aquifer. The depth to groundwater is shallower and is typically between 3 and 5 m below surface.

Further to the south and the east, the aquifer sediments become finer and dominated by silt and fine sand. Groundwater is relatively deeper than the sandy aquifer (10 m below surface). The intervening clay layers present sparsely in the south of the fan and more prominent to the east in the Babai floodplain zone are characterized by low hydraulic conductivity. These act as aquitards and create locally confining conditions for the underlying sandy and silty aquifers.

The spatial demarcation between coarse Bhabar and finer southern Terai sediments is not defined for the study area in existing studies. However, observations by (Shrestha 1992) reported Bhabar sediments along a cross-section at 195 m asl in the north closer to the Karnali fan apex. The study also indicated the increasing coarseness of the aquifer to the west, a general fining of aquifer sediments north to south along the rivers and noted the presence of clay horizons with silt sediments at around 175–145 m asl in a southern cross-section closer to the international border. The results of this study conform to these earlier observations. A gravelly apex in the north transitions to a sandy central section and a silty-clayey distal section in the south. The progressive fining of sediments towards the east is reflected by the greater presence of silt and clay-rich horizons towards the Babai River, due to its lower hydraulic gradient compared to the Kauriala and Gerua rivers.

The results also align with the subsurface configuration expected from typical sedimentary fans. The transport energy of rivers decreases along the direction of flow while moving from mountains towards the flat basin. This leads to successive fining of sediments from the apex to the distal part of sedimentary fans (Zhu et al. 2017). Such patterns have also been observed in sedimentary fans globally, including the Chaobai fan in China (Zhu et al. 2017), the Kosi megafan in Nepal and India (Sinha 2014), and the Punata alluvial fan in Bolivia (Amaya et al. 2016). In the Chaobai fan, hydraulic conductivity of sediments and its variance also decreased from apex to distal part of the fan indicating an implication of grain size and sediment sorting on hydrogeological properties. The aquifer system of the Punata fan was revealed to be an unconfined aquifer at fan apex composed of coarse sand and gravel transitioning to a confined system overlain by clay in the distal part of the fan. The subsurface of the Kosi megafan, located at the eastern TAL, showed the presence of shallow gravel deposits in the proximal part indicating past high energy of the Kosi River.

The insights on Karnali fan subsurface architecture provides a baseline for informing groundwater management in the study area. The aquifer units composed of coarse sand-gravel (resistivity 400–1100 Ω m) and gravel and boulder zones (> 1100 m) are important for groundwater recharge.

These are present within the BNP core zone, mainly along Siwalik hills and serve as natural drainage pathways for rain and ephemeral streams flowing from the hills. These recharge areas should be protected from polluting sources. Well development in the study area is done mostly by manual digging except in the Bhabar zone in the north where machinery drilling is required to dig through the gravel and boulders. This makes well development more expensive. The sandy aquifer (resistivities 80–400 Ω m) offers favourable conditions for shallow well development. Within the Karnali fan, this aquifer is exploited in conjunction with surface water irrigation channels, stimulating agriculture. In the area between Gerua and Babai rivers, there are only minor irrigation channels and so there is greater dependency on groundwater. The fine-grained aquifer in the south and southeast (resistivities 40–80 Ω m) with clay pockets (resistivity < 40 Ω m) has groundwater hosted in semi-confined aquifers. Deeper wells need to be installed to tap groundwater bearing zones below and away from the clay pockets.

The methodology used in this study draws from previous studies that have consolidated geological, sedimentological and hydrogeological data to reconstruct subsurface composition using simplified hydrogeological units, such as by Thalmeyer et al. (2024) for the Salado-Juramento fluvial megafan and Lindenmaier et al., (2014) for Cubango megafan, and studies which produced 3D hydrogeological models from 2D geophysical data (Di Maio et al. 2014; Uwiringiyimana 2019). This study has been constrained by sparse and shallow lithologies, absence of deeper lithologies in the fan and the lack of published data on aquifer characteristics for the study area. The number of ERT survey locations is limited compared to the size of the studied area. Lithologies with low resistivity contrast cannot be distinguished by ERT, introducing uncertainty in differentiating between sediments with overlapping resistivities. The electrode spacing of 12 m limits the vertical resolution of thin lithologic layers, leading to some discrepancies seen specially in the upper shallow layers of the lithologic cross-sections compared to the lithologies. Nonetheless, referencing to published resistivity values helped in defining the representative lithological classes for the Karnali fan (Table 1). The reliability of the 3D lithological model is inherently linked to the quality of inversion of the geophysical data. The absolute resistivity misfit of the 2D ERT models varied between 0.8 and 7.96% which indicates good quality of fit between measured and modelled data (Galazoulas et al. 2015). The 3D model is produced using cell size of $30 \times 30 \times 10$ m covering a model area of 938 km². The model resolution reflects an appropriate compromise to maintain consistency with the spatial resolution of the ERT data set while ensuring computational efficiency. Deeper borewells located further from the profile were used to validate the spatial extent of lithological classes in the 3D model. The model provides valuable understanding of the lithological structure

of the Karnali fan. However, it is unable to capture finer layers and localized heterogeneities. Therefore, the mode should only be interpreted as a first indication of the lithology of the Karnali fan and surroundings. The main trends in the subsurface architecture (north–south and east–west variability) seem plausible considering general configuration of sedimentary fans. The decreasing energy of rivers away from the fan apex and the difference of hydraulic gradient between the Karnali River system and the smaller Babai River also causes the difference in sediment grain size. The 3D lithological model behaves as a conceptual framework for schematizing the Karnali fan hydrogeology, which will serve as a basis for future groundwater investigations in the study area.

Conclusions

This study schematized the lithology of the Karnali fluvial fan from the bifurcation of the Karnali River near Chisapani to the Nepal–India border with the rain-fed Babai River as the eastern boundary. Resistivities between 8 and 6000 Ω m were present in the study area. Sediments with low resistivities (0–40 Ω m and 40–80 Ω m) were classified as clay and silt with fine sand. Resistivities higher than 80 Ω m were correlated to coarser sediments such as sand, gravel and boulders. The 3D lithological model based on 21 ERT profiles enabled visualization of the spatial heterogeneity of the subsurface, which was then interpreted in terms of hydrogeology. An unconfined coarse sand and gravel dominated aquifer with comparatively deeper groundwater is present in fan apex which extends along the Siwalik foothills in the north. A sandy aquifer with shallow groundwater is present in the centre which is exploited for domestic and ecological requirements. A fine-grained aquifer composed of silt and fine sand is present in the distal south and east with clay acting as locally confining units. Limitation in the study includes the presence of sparse and shallow lithologies. Localised heterogeneities due to low resistivity contrast between sediments and thin lithologic layers are not resolved by ERT. However, the 3D lithologic model shows plausible regional trends consistent with dissipation of fluvial energy and conform to general buildup of sedimentary fans elsewhere. The findings of this study enhance our understanding of the Karnali fan subsurface architecture. This provides insight into the groundwater system that sustains the ecohydrological regimes of the Bardia National Park as well as domestic and agricultural needs of the local population. As the hydrogeology of the Terai Arc Landscape is underexplored, these findings fill a critical knowledge gap on the piedmont of the Nepalese and Indian Himalayas, as well as contribute to broader understanding of fluvial fans.

Appendix 1

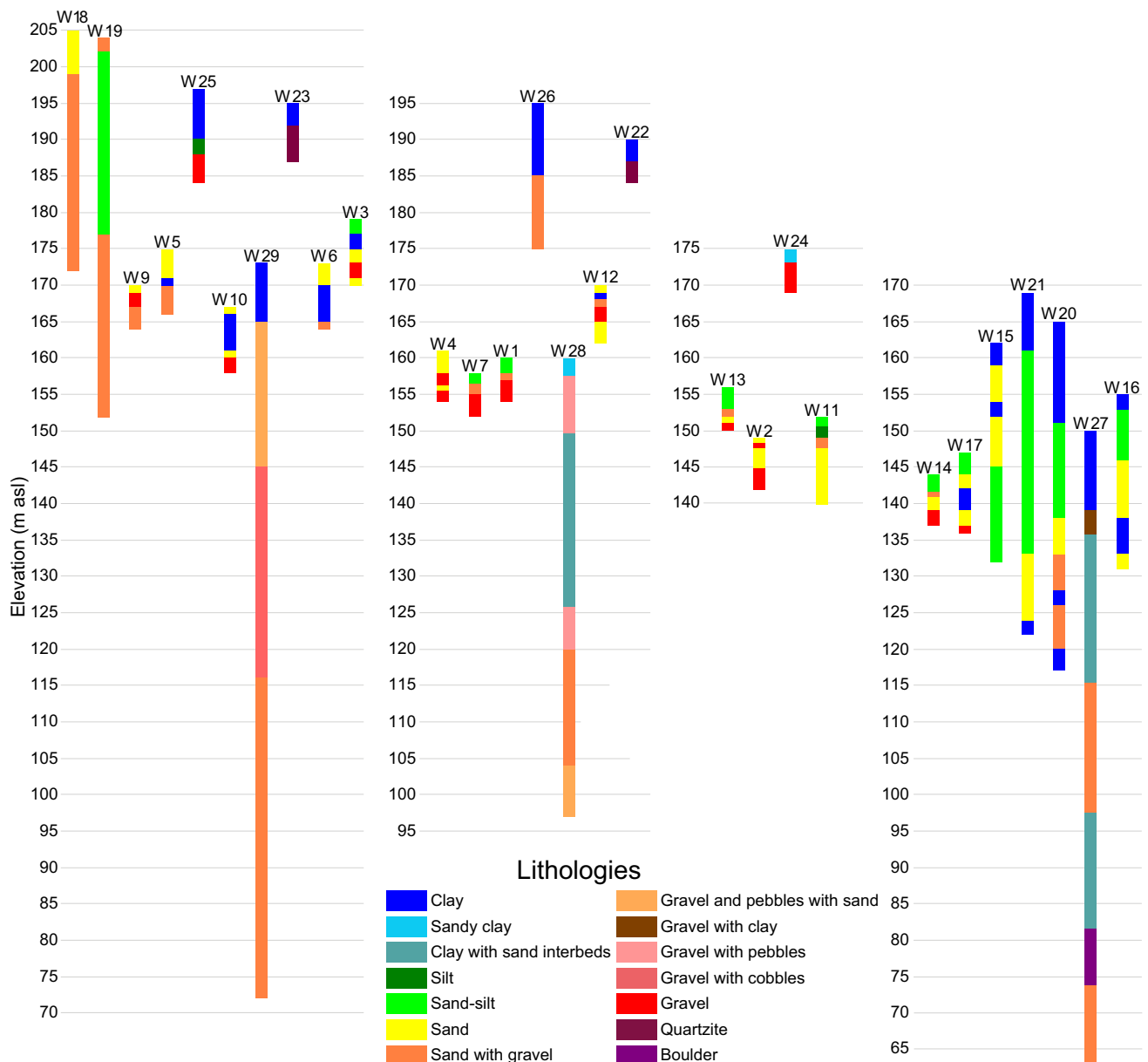


Fig. 7 Lithologs of wells in the study area. Wells W1–W19 have been installed as part of this project. W20–W29 were adapted from (Shrestha 1992)

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Methodology, data collection, review and editing: Moti Lal Rijal.

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All authors read and approved the final manuscript.

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Data availability The 2D ERT models generated in this study are provided as electronic supplementary material (ESM). The input data and the 3D model are available in Yoda Portal.

Declarations

Conflicts of interest The authors declare that they have no conflict of interest.

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