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# Correlation of electrical resistivity and groundwater arsenic concentration, Nawalparasi, Nepal

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## ABSTRACT

The Asian Arsenic Crisis has expanded into the headwaters of the Ganges River, now including the plains (Terai) of Nepal. This study seeks a non-invasive predictive tool to estimate groundwater arsenic concentration prior to drilling, enabling "arsenic avoidance" in contaminated areas. Detailed chemical studies indicate that in Himalayan-sourced aquifers arsenic is released by microbially-mediated redox reactions. Likely hydrogeological settings for oxidising chemical conditions (immobile arsenic) should be more porous (higher infiltration rate for oxygenated waters) and contain fewer fine organic sediments (oxygen-consuming material). Both conditions should yield higher electrical resistivity, and such aquifer heterogeneity effects should be most prominent in headwater regions such as Nepal. To test this approach, a series of vertical electrical resistivity soundings were made near Parasi, Nepal, constituting a profile extending 2 km across a known high-arsenic area. Correlation of the horizontal and vertical distribution of measured resistivity and ENPHO groundwater arsenic measurements demonstrated a distinct inverse relationship between these variables. Out of 240 arsenic sample points, 75% of those extracted from high resistivity zones (>100 ohm-m, inferred lower clay content) exhibited arsenic <150 ppb. Conversely, 75% of samples from low resistivity zones exhibited arsenic >150 ppb. Given these preliminary results, the resistivity technique appears to hold great promise as a predictive tool for finding low-arsenic groundwater zones within contaminated areas, thereby allowing "well-switching" from highly toxic to new safe or more readily treatable wells. The method should be applicable in most circum-Himalayan high-arsenic areas.

## INTRODUCTION

Preliminary results of surface electrical resistivity surveys in the subtropical plains of Nepal (Terai) provide strong encouragement that this method can be used to predict in three-dimensions the location of low-arsenic groundwater within contaminated zones. Such surveys could be used to develop safer drinking water sources, thereby reducing the incidence of arsenicosis in Nepal and perhaps much of South Asia. In the late 1990s, toxic levels of natural arsenic in groundwater were discovered in Nepal after similar occurrences were uncovered in much of South Asia. The affected areas have much in common, including dense population, leading to widespread contamination of surface water, forcing a dependence on shallow groundwater extracted from aquifers of Himalayan origin. Under tropical conditions, these Himalayan-sourced sediments yield mobile groundwater arsenic, often in concentrations far in excess of world health standards. The geological conditions allowing arsenic to be mobilised in groundwater in these cases are beginning to be understood, and may be detectable using surface geophysical techniques. In particular, zones with high clay and organic content would be expected to contain more soluble arsenic and to release it into groundwater more readily because of chemically reducing conditions. Conversely, coarser-grained zones should have lower soluble arsenic content, and are more likely to have oxidising conditions that limit arsenic dissolution. A surface technique that can estimate subsurface clay and/or organic content would be of tremendous value in predicting arsenic content prior to well drilling. Such an approach is likely to have the greatest chance of success near aquifer material source regions, such as Nepal's Terai, where aquifer heterogeneity can be expected to be maximum.

## BACKGROUND

Nepal may provide an ideal natural laboratory for characterising aquifer controls on arsenic distribution, the results of which may be applicable throughout the Asian Arsenic Crisis region. For this reason it is important to keep in mind the geological commonality between arsenic occurrences in this region. Since the late 1970s, evidence of this growing environmental crisis has emerged from many South-Asian countries. Incidence of arsenicosis led to the discovery of extremely high natural levels of arsenic in groundwater, first in West Bengal (Garai et al. 1984; Saha 1984), then Bangladesh (van Geen et al. 2003; McArthur et al. 2001), India (Chakraborti et al. 2003; Acharyya et al. 2000), Cambodia (Bou and Fredericks, 2004), Myanmar–Bhutan (Smedley 2003), Vietnam (Berg et al. 2001), Pakistan (Shahbaz

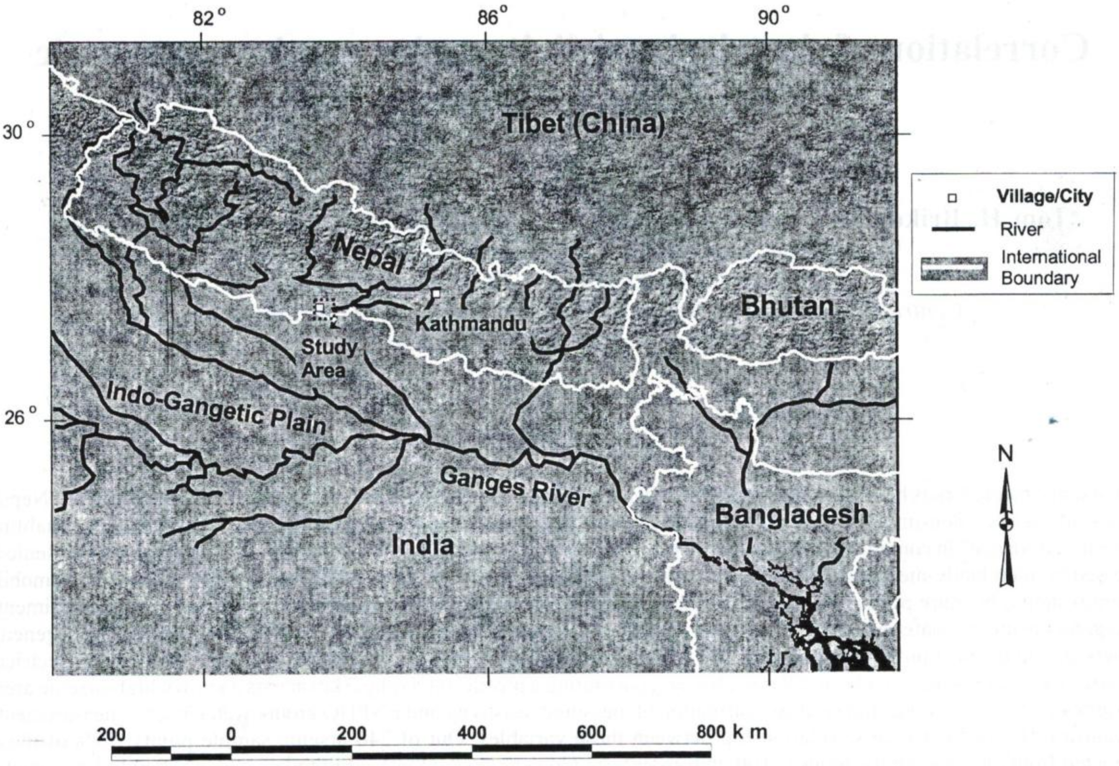

**Fig. 1: Regional shaded topographic relief showing country boundaries, and Ganges-Brahmaputra River (Indo-Gangetic) plain, of which the Terai in Nepal is a part. Dashed square in south-central Nepal shows boundary of study area in Nawalparasi district. Municipality of Parasi within study area is indicated by white square (not labelled).**

et al. 2004), China (Yinlong 2004; Smedley et al. 2003), and Nepal (Shrestha et al. 2004a; Neku and Tandukar 2003). All of these sites share the geological setting of large Quaternary sedimentary basins, primarily supplied by erosion from the mountain belts (Fig. 1), and a tropical climate that enhances weathering and subsurface mobilisation of arsenic. The arsenic problem is particularly acute in this region because the distribution of natural toxic levels of groundwater arsenic coincides with some of the highest human population densities on Earth (Chakraborti et al. 2004).

## THE GEOLOGICAL CONNECTION

Virtually all of these occurrences are in thick sequences of Quaternary sediment in tropical settings. The ongoing uplift of the Himalayan range is the primary source of these sediments in South Asia. The largest accumulation is in the Indo-Gangetic Plain (Ganges–Brahmaputra floodplain, Fig. 1) just to the south of the Himalayan range. The bedrock mineral source of the arsenic is thought by many to be micas shed from the metamorphic and igneous rocks of the Himalaya (Dowling et al. 2002). Prolonged weathering, erosion and redeposition or re-precipitation of these outwash sediments appears to be necessary to finally liberate arsenic. Groundwater arsenic occurrence in the shallow aquifers is highly variable (e.g. Bangladesh, van Geen et al. 2003), evidently depending on strong heterogeneity in local mineralogical arsenic source as well as hydrochemical environment needed for arsenic mobilisation. In Nepal, the Quaternary aquifers are composed of highly heterogeneous braided stream deposits (Nakayama and Ulak 1999). Average grain size generally decreases southwards from the mountains, and east–west away from rivers (Rao and Pathak 1996). These authors report that the most productive wells in Nawalparasi (location of the study area) encounter aquifer zones of gravel with fine to coarse sand, with thicknesses of 6–50 m comprising 10–30% of the shallow sedimentary column. In Nawalparasi, Shrestha et al. (2004b) report southward thinning of the upper fine aquifer facies, concomitant with decreasing arsenic concentrations.

The effects of hydrogeological heterogeneity are magnified by typical well usage in this region. Most well installations are around 20 m deep, and use a hand pump to provide drinking and cooking water for a single family. Production from each well is probably on the order of 100 l/day, compared to production on the order of $10^6$ l/day for a typical municipal well in the United States. These small production rates mean that only a small portion of the aquifer is sampled by each well, thereby emphasising any heterogeneity effects.

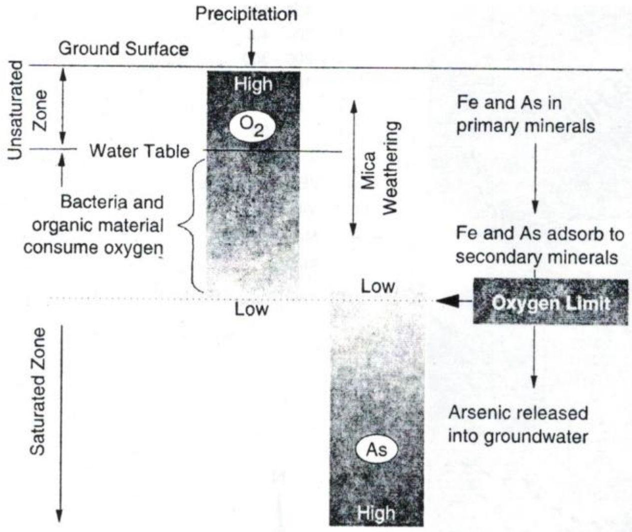

**Fig. 2: Conceptual model for extraction and mobilisation of arsenic from Quaternary sediments of the Indo-Gangetic plain. Breakdown of aquifer minerals in the upper $O_2$-rich saturated zone releases As and Fe to form iron hydroxides. In the lower $O_2$-absent saturated zone arsenic is released from these hydroxides into the groundwater. Bacteria control the redox conditions.**

## CONCEPTUAL MODEL

While considerable debate continues about the mechanisms of arsenic mobilisation in these settings, it seems clear that prolonged weathering of minerals shed from the Himalaya is the ultimate source of arsenic. Arsenic is primarily mobile in its reduced state, and so weathering in the near-surface oxidised zone moves arsenic from its host minerals to be adsorbed onto fine organic-rich sediments and amorphous iron-hydroxides. Final mobilisation from these requires reducing (oxygen-absent) conditions, most probably mediated by bacterial action up to a depth of 150 m (Fig. 2). Arsenic abundance in soil/aquifer materials has been related directly to the abundance of fine and organic-rich sediment (McArthur et al. 2001). These zones are also more likely to exhibit reducing conditions, since groundwater flow rates through them will generally be low. Variability in arsenic content during monsoon season (primarily decreases in concentration) indicates that subsurface flushing is concentrated in the more permeable zones (Yokota et al. 2001), and conversely that low permeability zones are likely to exhibit the highest arsenic content year-round.

## GROUNDWATER ARSENIC IN NEPAL

Naturally, toxic levels of groundwater arsenic have recently been found in Nepal, along the headwaters of several tributaries of the Ganges River. To date, the central districts within the Terai (Indo-Gangetic plain within Nepal) have shown high levels of groundwater arsenic, while far south-eastern districts have not. As of the beginning of 2003, approximately 36% of the population of the Terai (3.6 million people) has been shown to be drinking above-standard arsenic contaminated water. Results within one of the contaminated districts, Nawalparasi, show similar heterogeneity to that observed in Bangladesh (van Geen et al. 2003). Few deep wells are present in this area, and only a weak correlation between arsenic concentration and depth has been observed.

## GEOPHYSICAL INVESTIGATIONS

A central purpose of this project was to explore the feasibility of using surface geophysical surveys to predict groundwater arsenic. Adopting the conceptual model of arsenic mobilisation illustrated in Fig. 2, zones with lower clay content might be expected to be more oxidising (higher permeability, lower organic content) and to be more remote from presumed fine-grained sedimentary sources of mobilisable arsenic. In principle, such zones can be readily detected in the shallow subsurface using electrical resistivity surveys.

## PARASI SURVEY SITE

Ten VES points were surveyed in an area of extreme variability in arsenic in Nawalparasi District. This area is in the vicinity of the village of Parasi, located at the end of the major southbound highway in the district (white square, Fig. 3). The USGS has conducted a lithological core drilling at this locality (approximately at the VES point 1; Fig. 4), which can allow a direct correlation between lithology and observed resistivity with depth.

## DETERMINATION OF SUBSURFACE LITHOLOGY

Aquifer resistivity is determined by mineralogy, water content and salinity. Accurate determination of lithology from modelled resistivity can be difficult without onsite lithological information, preferably from boreholes. Unofficial lithological information has been provided from a USGS core hole located at the west end of the VES profile. Correlation between modelled resistivity and described lithology (grain size) is relatively good (Fig. 5). Lithology is reported at 5-foot intervals (i.e., ±1 m depth); VES electrode spacing of 6 m implies that modelled resistivity points are located within ± 3 m. Given these constraints, three "sandy" zones can be discerned, separated by relatively clay rich, low resistivity zones. The latter are most clearly correlable between resistivity and lithological description.

Given the calibration indicated in Fig. 6, four resistivity-based lithological classes were defined for use in this study. Resistivity values less than 20 ohm-m were assumed to

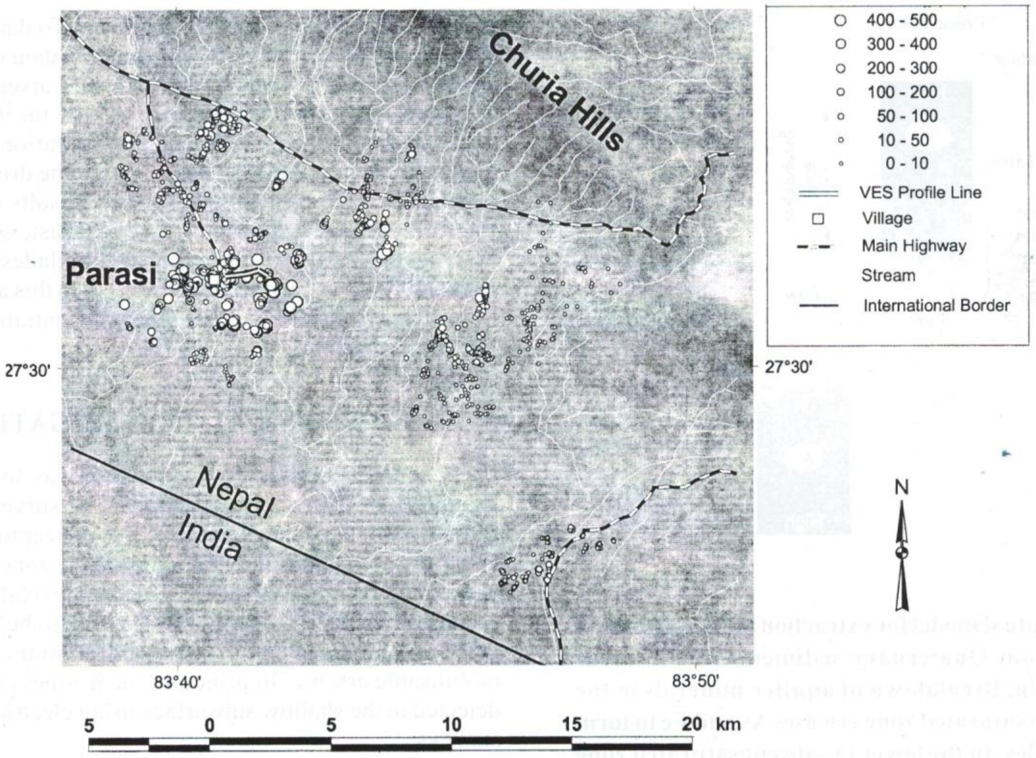

**Fig. 3: Results of groundwater arsenic sampling in Nawalparasi. Location of VES profile (Fig. 4) shown extending eastward from Parasi, study area location indicated in Fig. 1. Shaded relief shows Churia Hills to the northeast, forming the headwaters of the local streams.**

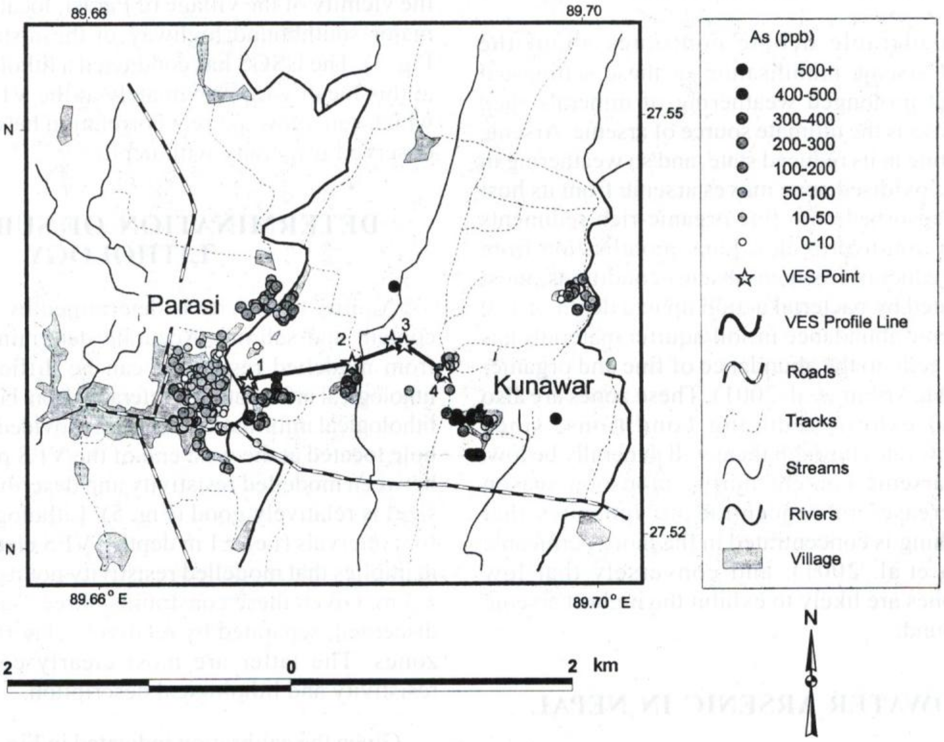

**Fig. 4: Close-up view of VES profile (solid line and numbered stars extending eastward from town of Parasi) and 241 arsenic samples within 500 m of profile.**

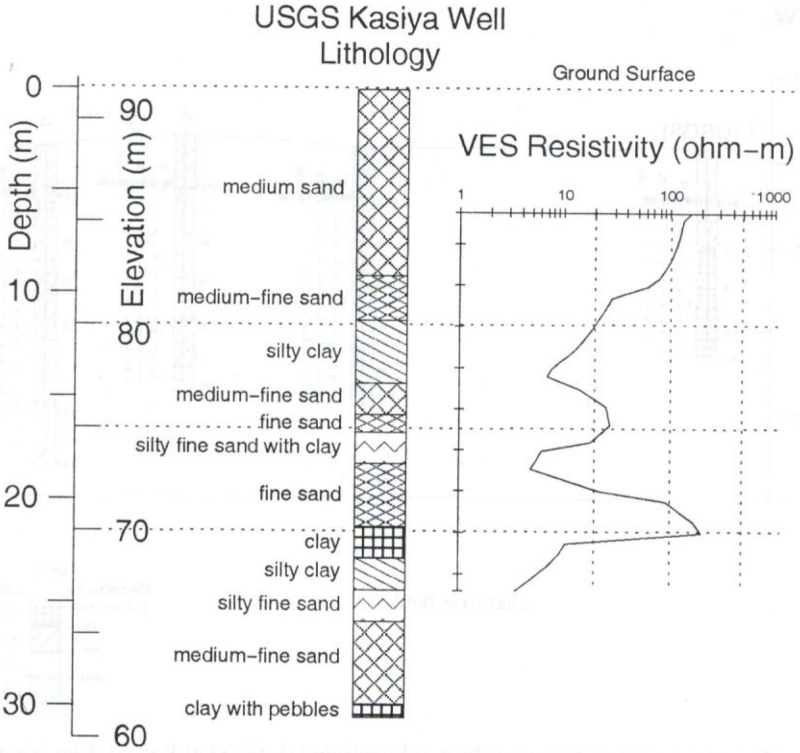

**Fig. 5: Correlation of modelled resistivity and observed corehole lithology, Parasi. Borehole lithology provided by USGS (unofficial). Horizontal dashed lines at 5 m elevation intervals, borehole collar at 91.15 m elevation (based on GTOPO30 DEM), VES results begin at 6 m depth. Vertical dashed lines on resistivity plot show lithology distinctions used in later figures (clay: <20 ohm-m, silt: 20–100 ohm-m, silty sand: 100–500 ohm-m, sand >500 ohm-m).**

represent clays, 20–100 silt, 100–500 sand, and >500 ohm-m coarse sand. The lithology names are meant only to express relative grain size (and presumed permeability) differences. Though the soundings were limited in number, a clear indication of decreasing resistivity (and presumably increasing clay content, as confirmed by the corehole lithology log) with depth is apparent near Parasi at the west end of the VES profile (site 1, Fig. 6). Conversely, clay content appears to decrease with depth at the eastern end of the profile, in the vicinity of site 4. While the specific lithological interpretations are uncertain, the indicated trends with depth should be reliable.

The small-scale variation details observable in the VES logs (Fig. 6) are likely to be somewhat less accurate. Sedimentological studies (Rao and Pathak 1996) and field observations (L. Smith, unpublished mapping) indicate that sandy bodies within the Quaternary aquifers are typically on the order of 1–10 m thick, extending at most several hundred meters laterally. While the fine variation presented in Fig. 6 is of similar spatial scale, it is also at least partly an artifact of model and/or data noise. Consequently sandy zones, such as that indicated below 70 m elevation at site 4 probably reflect stacks of 3–5 m thick sandy zones interspersed with finer material.

## CORRELATION BETWEEN RESISTIVITY AND ARSENIC CONTENT

A distinct inverse correlation is evident between modelled resistivity ("sandiness") and groundwater arsenic values in the study area (Fig. 7). Both in the shallow sandy (resistive) zone in the vicinity of Parasi (site 1, west side of profile) and deeper resistive zone near Kunawar (site 4, east side of profile) relatively low arsenic values are measured in the groundwater. Very high values of arsenic (ppb) are found only in zones of high clay content, or low resistivity ("Silt-Clay" in Fig. 7, arsenic content shown in Fig. 8). Observations indicate a higher proportion of silt in produced water east of Parasi (i.e. at sites 3,4), consistent with the resistivity observations.

Resistivity, as reflected in the lithological assignments of Fig. 7–8, appears to be a clear discriminant between zones with high probability of high arsenic, and those with low probability. While the precise reasons for this discrimination

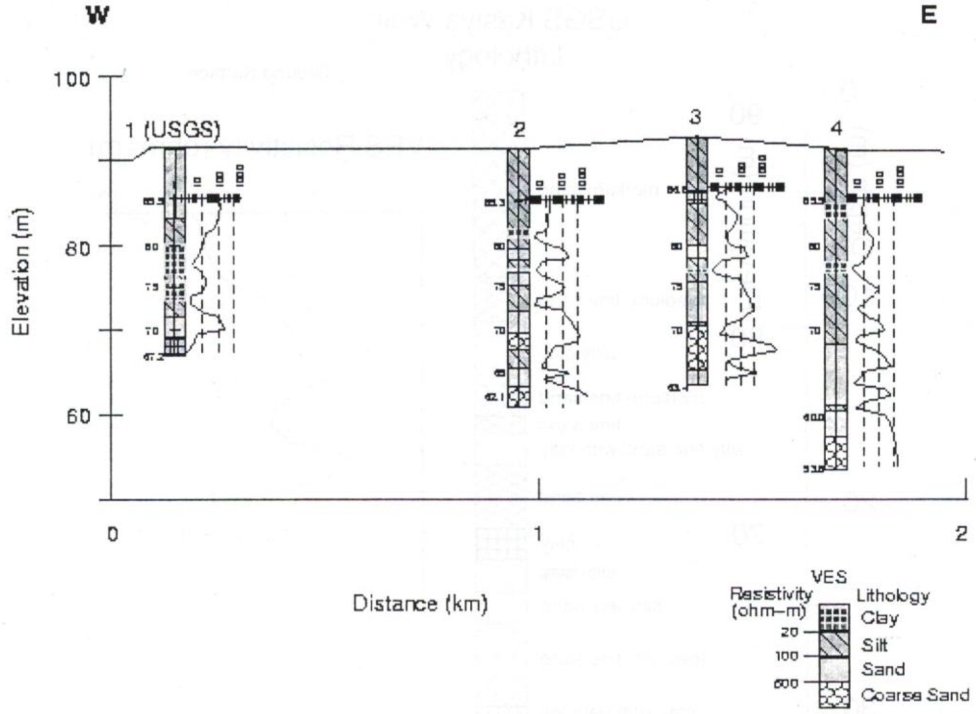

**Fig. 6: Geological section based on parametric sounding at borehole 1(USGS) at Parasi. Electrical resistivity (ohm-m) and modelled lithology at locations 2, 3, and 4 are also displayed. Vertical dashed lines show values of inferred lithology transitions; resistivity–lithology conversion scale is shown at bottom right.**

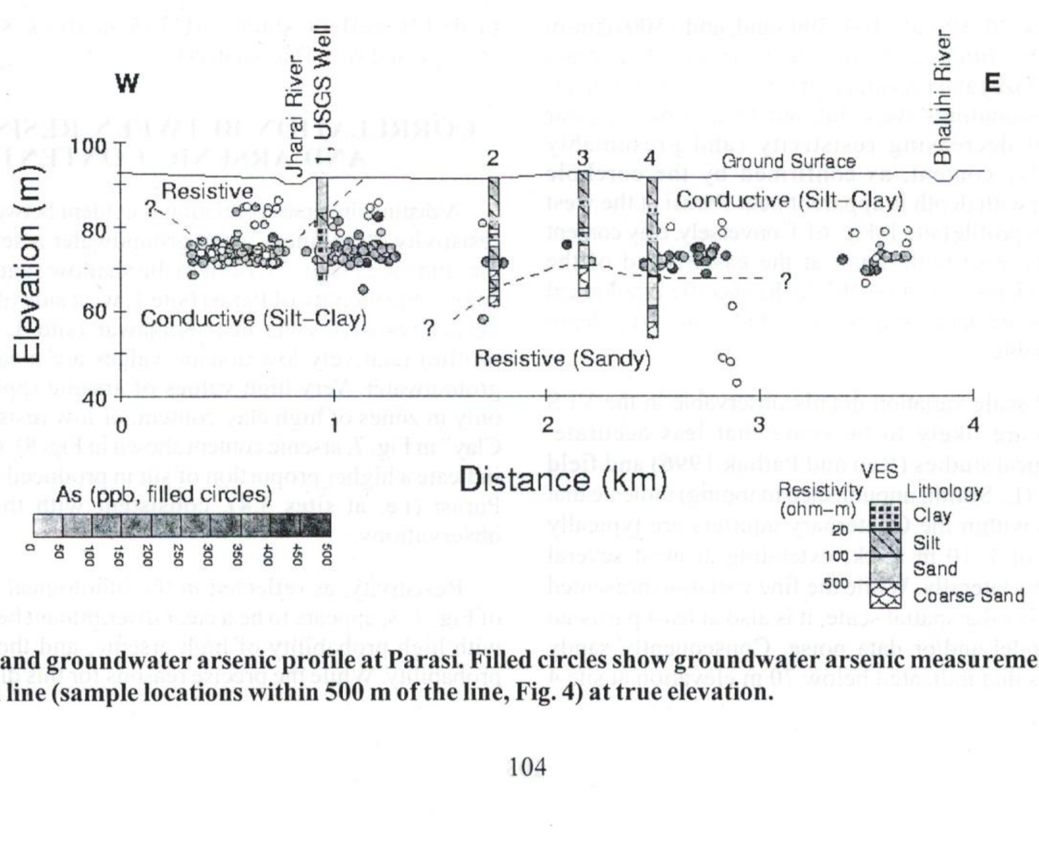

**Fig. 7: VES and groundwater arsenic profile at Parasi. Filled circles show groundwater arsenic measurements projected onto section line (sample locations within 500 m of the line, Fig. 4) at true elevation.**

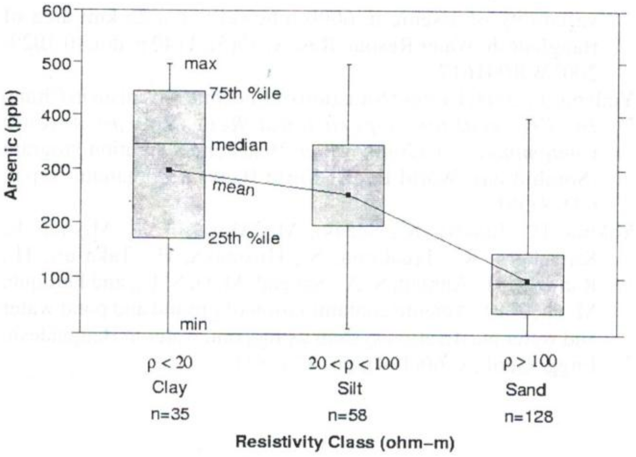

**Fig. 8: Box-and-whisker plot of groundwater As for VES-inferred lithology classes. Gray box shows distribution of central 50% of samples in each resistivity class. High resistivity (>100 ohm-m) zones typically exhibit distinctly lower arsenic content.**

were not explored in this preliminary study, it is consistent with current conceptual models (McArthur et al. 2001; Harvey et al. 2002; Dowling et al. 2002).

## CONCLUSIONS

Preliminary data collection in the Terai of Nepal suggest that surface resistivity surveys may be useful in identifying high-arsenic groundwater areas. This identification could then be used to guide future drinking water well drilling to sites expected to have lower arsenic content. Confirmation of these results will require additional detailed surveys near existing wells, coupled with groundwater chemical analyses of arsenic and oxidation-reduction state. Similar correlations are expected throughout the Indo-Gangetic Plain, at least away from coastal-swamp dominated river deltas.

## ACKNOWLEDGMENTS

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