Journal of Nepal Geological Society, 2002, Vol. 26, pp. 109–119

Geological, geochemical and electrical constraints on the transient flow mechanism of the Dhor Barahi periodic spring in western Nepal

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ABSTRACT

The Dhor Barahi spring in Tanahun district, Western Nepal, is characterised by intermittent periodic flow or unsteady continuous flow, depending on the time of the year. This behaviour can be attributed to a siphon that can be constrained by the local geology and water chemistry data. During periodic discharges, electrical signals are observed with an amplitude proportional to the water flow rate, as predicted by the electrokinetic effect, with a maximum coupling of -1.3 ± 0.3 Vsm^{-3}. The spatial structure of the surface potential leads to a qualitative description of the electrical sources, also compatible with an electrokinetic mechanism, but additional contributions are possible. This study illustrates how combined geochemical and electrical measurements can provide access to the dynamics of groundwater circulation, with possible implications for the monitoring of hydrological, tectonic or volcanic processes.

INTRODUCTION

Groundwater circulation can be detected through electrical fields (or streaming potentials) produced by the electrokinetic effect (EKE) (Ogilvy et al. 1969 ; Bogoslovsky and Ogilvy 1970). As groundwater flow is suspected to occur during the preparation phase of an earthquake (Scholz et al. 1973), precursory variations of the electric potential have been hypothesised (Mizutani et al. 1976) but have not been unambiguously observed so far. Transient groundwater flow occurs in active volcanoes as well, and magnetic and electrical signals have indeed been observed in association with eruptions (Zlotnicki and Le Mouël 1990 ; Malengreau et al. 1994 ; Hashimoto and Tanaka 1995 ; Zlotnicki and Bof 1998 ; Sasai et al. 2001).

Recently, streaming potentials have been the subject of intensive research. In the laboratory, the EKE has been studied with crushed samples and rock samples during deformation (Revil and Leroy 2001 ; Yoshida 2001 ; Jouniaux et al. 2000 ; Lorne et al. 1999a,b ; Jouniaux and Pozzi 1995). In the field, the EKE was first isolated in a geothermal field, in association with the turning on and off of wells (Ishido et al. 1983). Time varying EKE-induced electrical fields have also been measured near reservoir lakes (Trique et al. 1999 ; Perrier et al. 1998), in the soil (Thony et al. 1997 ; Perrier and Morat 2000) or in underground quarries (Gensane et al. 1999). Such signals were associated with groundwater flow which could not, however, be accessed directly. In general, the relationship between measured electric potentials and groundwater circulation remains poorly known.

In order to make progress towards better understanding of the relationship between streaming potentials and groundwater circulation, intermittent springs are potentially interesting natural systems: they have a reasonable size, typically smaller than 100 m, and the water flow can be accessed directly. The Dhor Barahi spring located in Tanahun district in west-central Nepal, which flows during a few minutes with a repetition time of about 30 minutes, is particularly convenient. Clear electrical potential variations have indeed been observed in association with the water discharge (Perrier et al. 1999).

In this paper, we present new electrical measurements performed at the Dhor Barahi spring together with simultaneous water level measurements. Additional constraints on the hydrological mechanism are obtained from a study of the regional and local geology and from a time monitoring of the water geochemistry. We discuss implications of this study for the understanding of the dynamics of groundwater flow, and the relevance of streaming potentials for the monitoring of active tectonic or volcanic processes.

GEOLOGICAL SETTING

The Dhor Barahi spring is located in Tanahun district near the west bank of the Seti river, about 20 km southeast of Pokhara (Fig. 1). Its periodic flow pattern was interpreted by the local people as the manifestation of the Barahi Goddess, and a temple was erected near the spring. The origin of this religious tradition remains obscure and ethnologists have

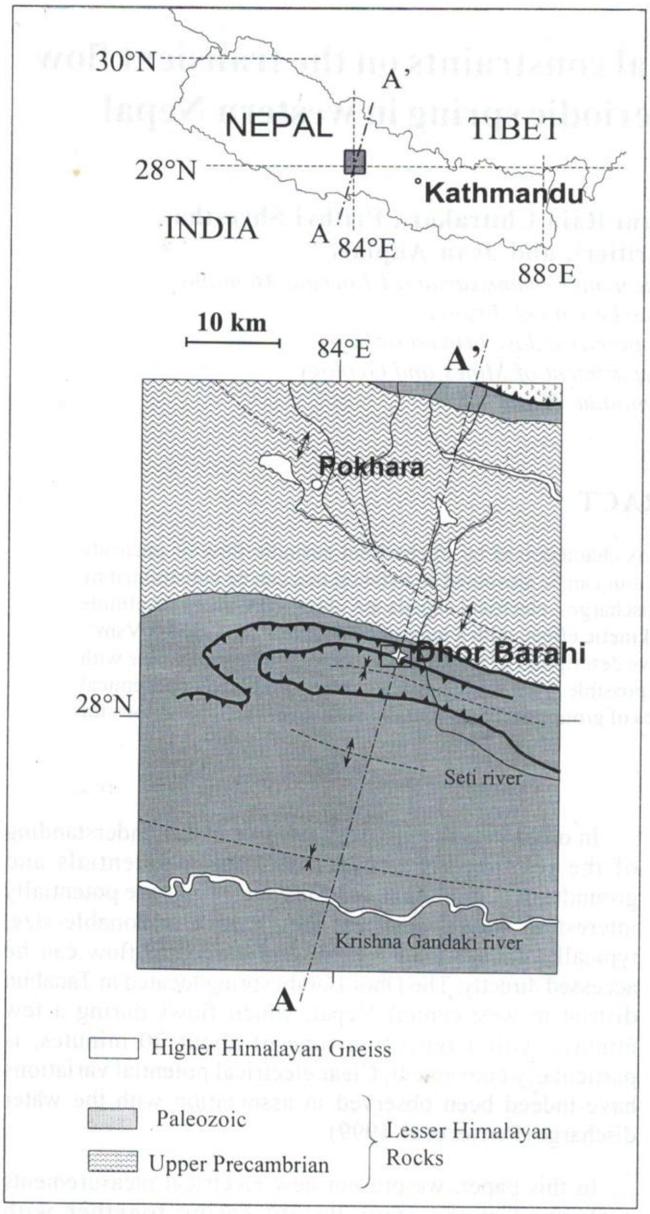

Fig. 1: Localisation of the Dhor Barahi spring and regional geology of the area (adapted from Tater et al. 1983; Paudel and Arita 1998; and Upreti 1999).

suggested a possible connection with Varaha, a form of God Vishnu sometimes associated with earthquakes (Lecomte-Tilouine 1993). The relationship between the Dhor Barahi spring and tectonic processes, however, remains to be investigated.

The regional geological setting of the spring area is shown in Fig. 1. The site is located in the Paleozoic metasedimentary sequence thrusted along a shallow south-dipping thrust fault system (Fig. 2). This system of faults possibly results from the building up of a synclinorium in the Upper Precambrian sediments (Upreti, 1999 ; Paudel and Arita 1998 ; Pandey et al. 1995). Currently, the main active fault in the Himalayan convergence is the Main Frontal Thrust (MFT, Lavé and Avouac 2000), and only a little motion is expected to be absorbed by the secondary faults in the Paleozoic series. However, these faults probably have played an important role in establishing the present structure of permeability and groundwater circulation near the spring, as well as the locally steep topography (Fig. 3), which culminates at 1279 m about 2 km west of the spring.

The spring is located at an altitude of about 800 m, in Dhading Dolomite, near one of these secondary faults (Figs. 3 and 4). This blue grey, fine-grained, cherty dolomite (Paudel and Arita 1998) lies above the Nourpul Formation, which is present to the north with grey calcareous slates. The dolomite is overthrust in the south by older Dandagaon Phyllite, which consists mostly of green phyllite with massive thick quartzite beds, as observed in Gurdum, west of the spring (Fig. 3).

Compared to the recently published geological map of the area (Koirala et al. 1998), we refined the contours of local geology by field sampling and measurements. The traces of the faults shown in Fig. 3 were obtained from field investigations and examination of aerial photographs. Near the spring, the strike of the faults change from east-west direction to about a 110° E. The dip of the faults is determined to be about 30° south (Fig. 4). The measured dip angles (Fig. 3) correspond mostly to schistosity and have an average value of about 55° south in all formations.

HYDROLOGICAL REGIME

The spring is located within the temple compound (Fig. 5), at the edge of a thick jungle extending to the West. The water flows from a siphon (Fig. 6) to the first basin, which communicates with the main basin, and from there to a stream flowing from the northern Bhattala ridge (Fig. 3 and 4). In addition to a permanent leakage flow to the stream, a pipe drains the overflowing water from the basin (Fig. 6). The main basin, where animals are sacrificed every morning on two large stones, is surrounded by two small houses(Fig. 5), cemented terraces and stairs.

The most spectacular behaviour of the Dhor Barahi spring is its periodic discharge regime, observed in May 1998 (Perrier et al. 1999), and again in June 1999. In June 1999, the water level in the main basin was monitored by a ruler installed at an angle of about 30° with respect to the horizontal plane. The results are shown in Fig. 7 for one afternoon. Clear water discharges were observed with a repetition time varying from 33 to 62 minutes, with an average value of 42 minutes. The average water flow rate in the overflow pipe is 7.5±1.0 l/s during discharge. The discharges of water are rather irregular (Fig. 7) : sometimes there is no discharge for more than one hour, and sometimes a discharge starts, aborts and restarts, as for example at 3 p.m. in Fig. 7. When a discharge is late, it tends to be larger, and the average water flow probably remains constant. Discharges have a duration varying from 7 to 23 minutes with an average of 11.5 min. In addition to the discharges, a continuous flow of

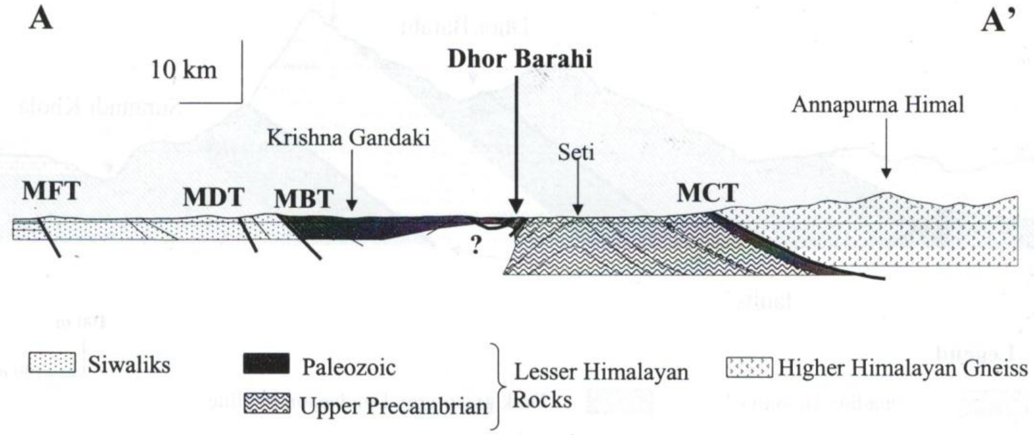

Fig. 2: Cross-section showing the regional geology and main faults (adapted from Tater et al. 1983). The section AA' is defined in Fig. 1.

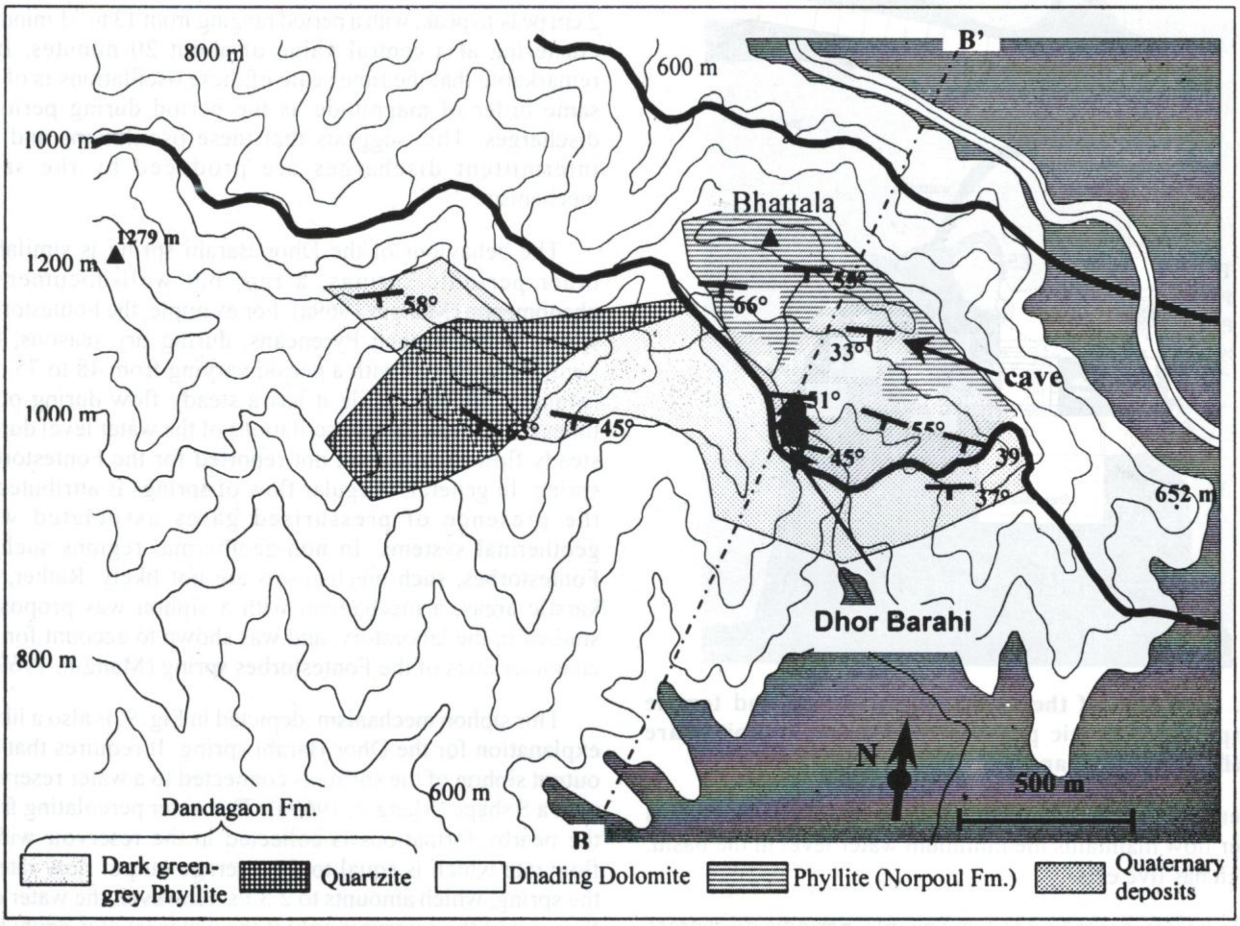

Fig. 3: Map of the site of the Dhor Barahi spring, with local geology. The trace of the faults has been obtained assuming a plane with a dip angle of 30°, compatible with observed contours of the formations in the field, and examination of aerial pictures. The strike of the fault is assumed to be east-west in the left half and 110° in the right half of the map.

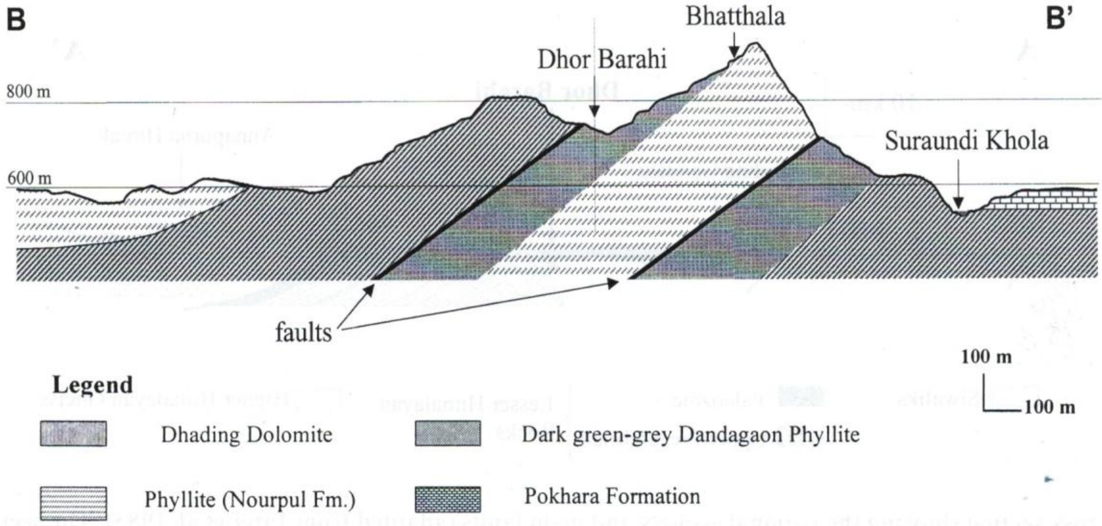

Fig. 4: Cross section showing the local geology. The section BB' is defined in Fig. 3.

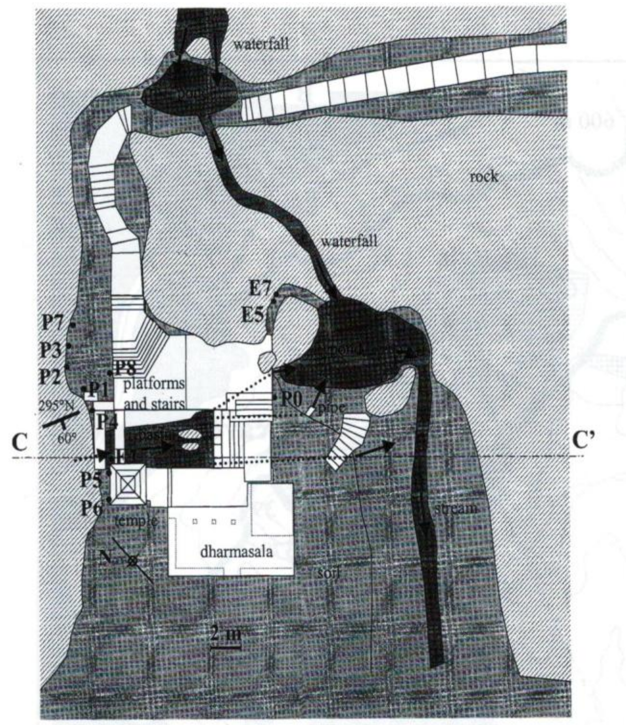

Fig. 5: Sketch of the Dhor Barahi spring and temple compound. Electric potential measurement points are labelled E1, E5, E7 and P0 to P9 (see text).

water was observed with a rate of about 0.4±0.06 l/s. This water flow maintains the minimum water level in the basin, which has live eels.

In winter, according to local people, periodic discharges of the spring are not observed. Indeed, in January 1999, the level in the basin at first sight looked constant, with an average flow of about 3.6±0.4 l/s. The water level was, however, monitored with a ruler installed at an angle of 13°, and this revealed unambiguous time variations (Fig. 8). These variations are oscillations with an amplitude of about 1.5 to 2 cm peak to peak, with a period ranging from 13 to 31 minutes, clustering at a central value of about 20 minutes. It is remarkable that the time scale of these oscillations is of the same order of magnitude as the period during periodic discharges. This suggests that these oscillations and the intermittent discharges are produced by the same mechanism.

The behaviour of the Dhor Barahi spring is similar to other periodic springs, a rare but well-documented phenomenon (Mangin 1969a). For example, the Fontestorbes spring in the French Pyreneans, during dry seasons, has regular discharges with a period varying from 48 to 75 min (Mangin, 1969b), while it has a steady flow during other times of the year. Small oscillations of the water level during steady flow is, however, not reported for the Fontestorbes spring. In general, irregular flow of springs is attributed to the presence of pressurised gases associated with geothermal systems. In non-geothermal regions such as Fontestorbes, such mechanisms are not likely. Rather, for karstic areas, a mechanism with a siphon was proposed, studied in the laboratory, and was shown to account for the characteristics of the Fontestorbes spring (Mangin, 1969a).

This siphon mechanism, depicted in Fig. 9, is also a likely explanation for the Dhor Barahi spring. It requires that the output siphon of the spring is connected to a water reservoir with a S shape (Mangin, 1969a). The water percolating from the nearby formations is collected in the reservoir with a flow rate which is equal to the average output flow rate of the spring, which amounts to 2.3 l/s. However, the water can flow out of the reservoir only if the water level is equal to a maximum level L_{max}. As the output flow rate of the siphon (7.1 l/s) is larger than the input flow rate of the reservoir, the water level in the reservoir decreases till a minimum value L_{min}, where the siphon stops. Following this, the level in the reservoir slowly increases again, till the maximum level is

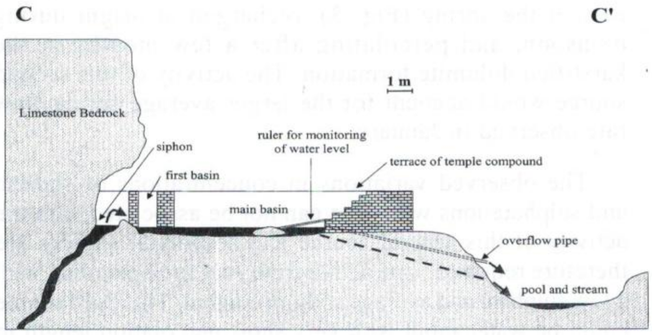

Fig. 6: Cross section of the Dhor Barahi spring with first and main basins. The section CC' is defined in Fig. 5.

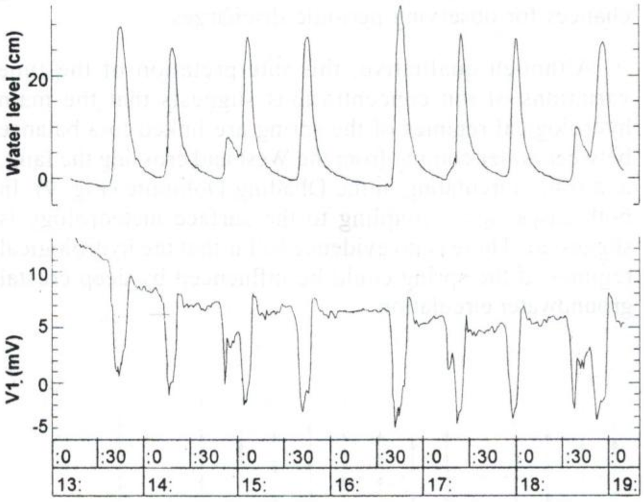

Fig. 7: Water level in the main basin and potential of electrode E1 with respect to E5 (Fig. 5) recorded on June 8, 1999. The data are recorded with a sampling time varying between 30 seconds to 1 minute.

reached and the siphon is restarted. Such a S-shape siphon is rather likely in the vicinity of Dhor Barahi and the end of this siphon is actually observed behind the first reservoir (Fig. 6). Other siphons are also observed in the Dhading Dolomite in a cave near the Bhattala ridge (Fig. 3). The volume of the reservoir between the levels L_{min} and L_{max} can be estimated as the product of the maximum discharge rate times the discharge duration and it amounts to 5 m^3. A reservoir with such a small volume possibly occurs to the west of the spring (Fig. 3), near the fault. Given the close distance to the fault suggested on geological basis, the reservoir can actually be assumed to be directly associated with the fault, as depicted in Fig. 9.

If the water flow rate into the reservoir is increased, then at some point, a dynamic equilibrium between input and output in the siphon is reached. Then, both the water level in the reservoir and the output flow remain roughly constant, and the spring is no more periodic. This was the case in January 1999 when an average steady flow of 3.6 l/s was observed, indeed larger than the average flow rate of 2.3 l/s observed in June 1999. Further constraints on the hydrogeology of this system can be obtained from water chemistry data.

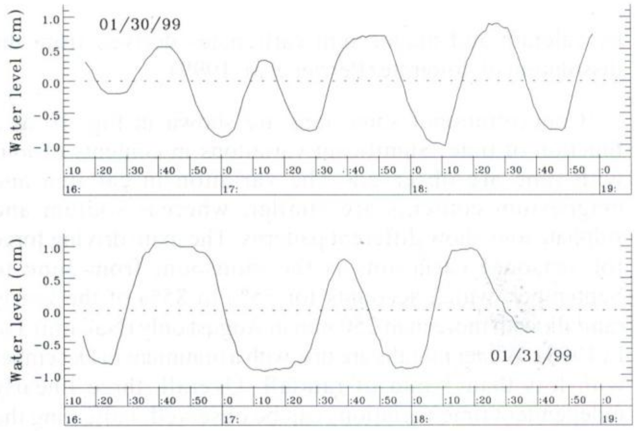

Fig. 8: Water level in the main basin recorded on January 30 and 31, 1999. The data are recorded with a sampling time of 1 minute.

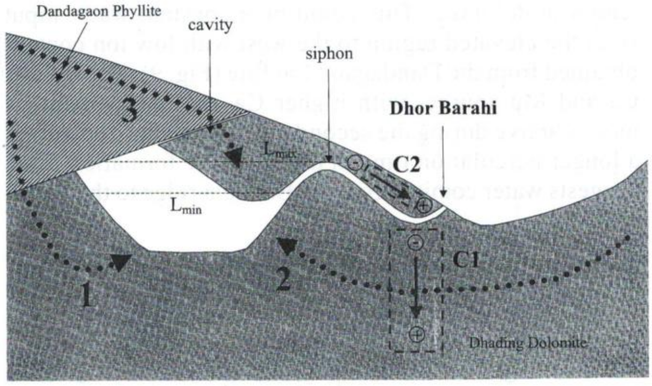

Fig. 9: Model for the Dhor Barahi spring. The siphon is responsible for the periodic discharge during the dry season. Three main water sources are proposed. Source 1 comes from the west, constant over the year, has a low dolomite content. Source 2 is active after monsoon and has high dolomite content. Source 3 has the same dolomite content as source 1 but lower sulphate content and is active during monsoon (June to September).

MONITORING OF WATER CHEMISTRY

Water samples were collected from the main basin every two weeks. The water conductivity was measured in the basin with an average value of 285 μS/cm, which is comparable with water conductivity values obtained in the Pokhara valley (Gautam et al. 2000) or waters from carbonate formations in the Jhikhu Khola region (Nakarmi and Li 1998). Main ion content was measured with electrophoresis in the laboratory. The spring and stream waters are both dominated by calcium and magnesium carbonates derived from the dissolution of dolomite (Perrier et al. 1999).

Concentrationof some ions are shown in Fig. 10 as a function of time. Significant variaitons in contents of ions with time are observed. The variaiton in calcium and magnesium contents are similar, whereas sodium and sulphate ions show different patterns. The main driving force for seasonal variations is the monsoon, from June to September, which accounts for 75% to 85% of the yearly rainfall, with more than 250 mm in August only (Nakarmi and Li 1998). Winter months are dry, with a minimum in December with less than 5 mm of rainfall. Overall, three linearly independent time variations can be observed, indicating the presence of mixing between at least three independent time-varying sources.

Two sources are indeed necessary to explain the time variation of the calcium and magnesium ions. One source has a low Ca and Mg content, indicating a short percolation length in dolomite. This could be a constant water input from the elevated region to the west with low ion content obtained from the Dandagaon Phyllite (Fig. 9). The second Ca and Mg source, with higher Ca and Mg content, is mostly active during the second part of the year, indicating a longer percolation time in the dolomite formation. This suggests water coming from the Bhattala ridge to the north-east of the spring (Fig. 3), recharged at origin during monsoon, and percolating after a few months in the karstified dolomite formation. The activity of this second source would account for the larger average spring flow rate observed in January.

The observed variations in concentrations of sodium and sulphate ions with time can not be associated with the activity of this second source and additional sources are therefore required : one active from July to September, with a low sulphate and average sodium content. This third source could be water input with very short percolation length in the unsaturated zone (Fig. 9). The variations of sodium content from March to May could be associated with a lower percolation rate of source 2, inducing a significant decrease in the overall spring flow rate, and therefore increasing chances for observing periodic discharges.

Although qualitative, this interpretation of the time variations of ion concentrations suggests that the main hydrological regimes of the spring are linked to a balance between water coming from the West and crossing the fault, and water circulating in the Dhading Dolomite (Fig. 9). In both cases, some coupling to the surface meteorology is suggested. There is no evidence so far that the hydrological regimes of the spring could be influenced by deep crustal groundwater circulation.

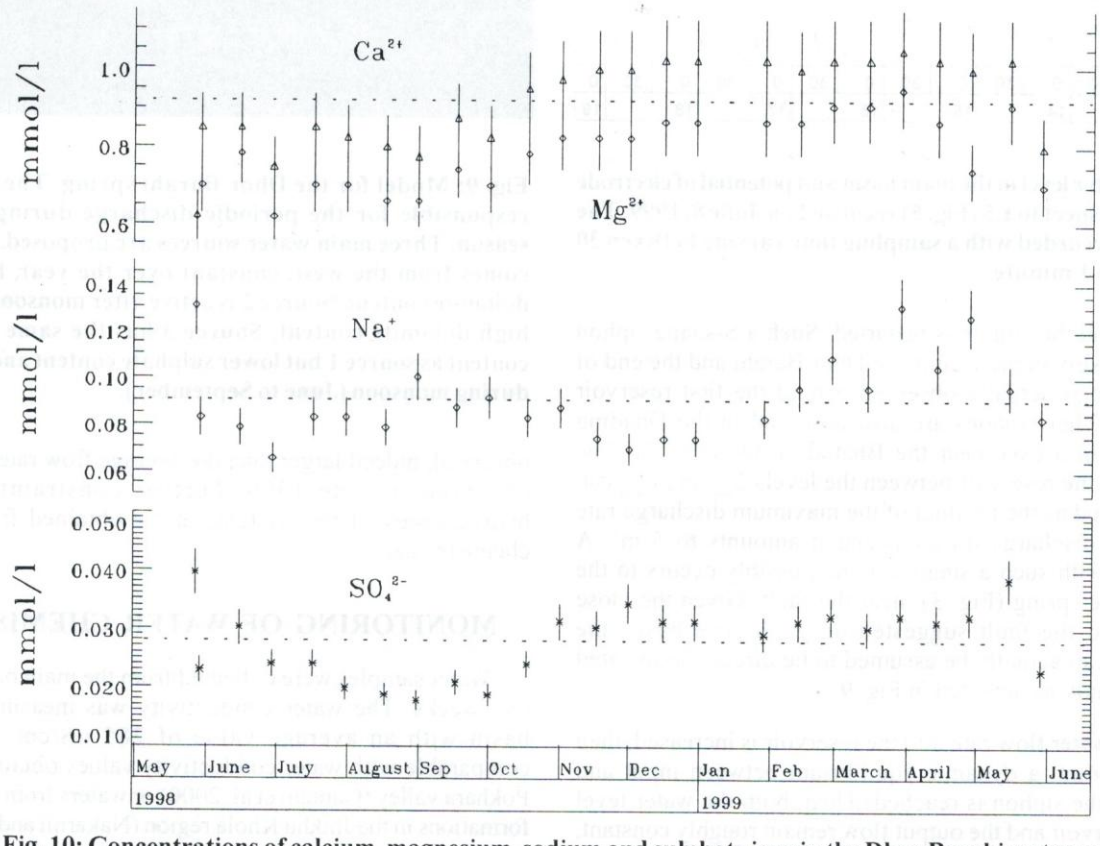

Fig. 10: Concentrations of calcium, magnesium, sodium and sulphate ions in the Dhor Barahi water as a function of time. Concentrations are measured with electrophoresis with an accuracy of 10%.

OBSERVATIONS OF ELECTRIC POTENTIAL VARIATIONS

When the spring is periodic, clear electrical signals are associated with the water flow (Fig. 7), confirming the earlier measurements (Perrier et al. 1999). Electric potentials were measured using Pb/PbCl$_2$ electrodes (Petiau 2000) following the same methodology as before (Perrier et al. 1999). During the water flow, the electric potential V_1 of electrode E1 in the first basin with respect to a remote reference electrode E5 (Fig. 5), is decreased by about 10 mV. The electric potential is correlated to the water flow rate, and this is especially remarkable during the aborted water discharges (Fig. 5).

Fig. 11 shows the electric potential V_1 as a function of the time derivative of the water level during the rising part of the level pulse. At the beginning of the water discharge, indeed, the water loss from the main basin can be neglected and the derivative directly reflects the input water flow into the basin. The fact that the electric potential is proportional to the water flow supports the hypothesis of an electrokinetic source.

When an electrolyte is circulating through an electrically isolated sample of porous material, an electric potential difference ΔV is created (e.g. Mizutani et al. 1976; Lorne et al. 1999a)

$$\Delta V = C_s \Delta p \qquad (1)$$

where, Δp is the pressure drop across the sample and C_s is a parameter describing the interaction between the material and the electrolyte, referred to as the streaming potential coefficient (SPC). Equation (1) has been checked in the laboratory (e.g. Jouniaux and Pozzi 1995; Lorne et al. 1999a, b). In the field, the data obtained in Dhor Barahi are to our knowledge the first direct observation of a linear correlation between a measured electric potential and a measured water flow rate. In this case, the ratio of potential in the flow channel to the water flow rate amounts to -1.3±0.3 Vsm^{-3}.

In January 1999, when no periodic flow was observed, no clear correlation between the electrical potential V_1 and the water level in the first basin was observed. A water level variation of 2 cm peak to peak (Fig. 8) corresponds to a fluctuation of flow rate of about 5%, which would produce an expected potential variation in the flow channel of 0.23 mV, which is at the noise level for oscillations with a period of about 20 minutes.

Together with the electric potential of the electrode E1, the electric potential of a travelling (mobile) electrode is measured with respect to the same reference point (E7). With the travelling electrode, the electric potential of 9 points (P0 to P8 in Fig. 5) is monitored in turn during at least two water discharges of the spring. Typical results are shown in Fig. 12 as a function of time. As observed before (Perrier et al. 1999), on the surface near the spring, positive electric potential pulses are associated with the water discharge. When the electric potential is corrected for electrode drift (Fig. 12), the time variation of the electric potential on the surface is proportional to the time variation of the potential in the first basin.

In Fig. 12, the time variation of both electric potentials V_1 and V_2 is starting about 30 seconds before the water level in the basin is affected. This precursory effect is likely to be due to the fact that the siphon edge is slightly higher than

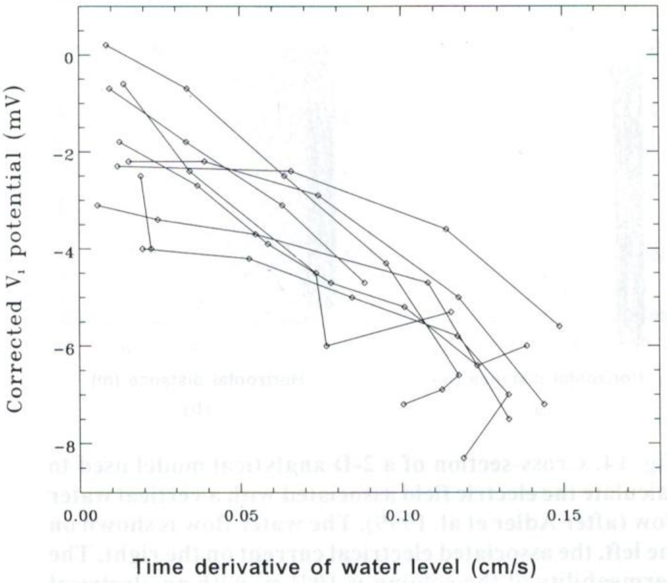

Fig. 11: The electric potential difference V_1=E_1-E_5 corrected for drift versus the time derivative of the water level measured in the main basin. Only time sections during the first few minutes of the discharges are retained.

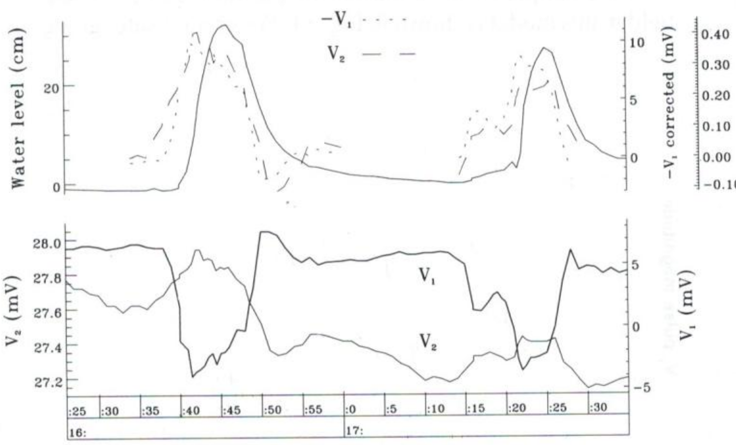

Fig. 12: Comparison of the electric potential differences V_2=P_5-E_7 and V_1=E_1-E_5 as a function of time during two discharges of the Dhor Barahi spring. Raw data are shown in the lower plot. The electric potential data superimposed on the water level data are corrected for linear electrode drift. The respective scales of V_1 and V_2 are indicated in the right side of the upper plot.

the input of the first basin (Fig. 6). The electrical signal seems to be directly related to the rising water level in the siphon, and proportional to the flow rate in this siphon. So the potential of electrode E1, which is electrically connected to the siphon, is changing before the water level is actually rising in this basin.

The amplitude of the signal on the surface depends on the position and varies from about 0.6 mV to 0.2 mV at 4 meters distance from the spring (Fig. 13). The amplitude of the signal decreases with distance, but not very fast. The electrical source associated with the positive pulses, therefore, must have a size of the order of one meter, much larger than the size of the siphon itself, which has an average diameter of about 15 cm in its visible part before the first basin.

INTERPRETATION OF THE ELECTRIC POTENTIAL VARIATIONS

Although the data unambiguously point to an electrokinetic mechanism for the generation of the electric potential associated with water discharge, understanding the spatial structure of the observed electric potential variations is not straightforward, even at the qualitative level. The solution of the coupled electrical and water flow problem is in general complex because of flow and current leakage in the medium imbedding the circulating groundwater. For the purpose of our discussion, we shall use a simplified 2 dimensional analytical model (Adler et al. 1999). In this model, a vertical flow is forced from above in a vertical column of fractured material imbedded in a porous medium, and reasonable boundary conditions are imposed for the flow and the electrical potential at depth.

An example of the solution for the flow and electrical field in this model is shown in Fig. 14. For groundwater going

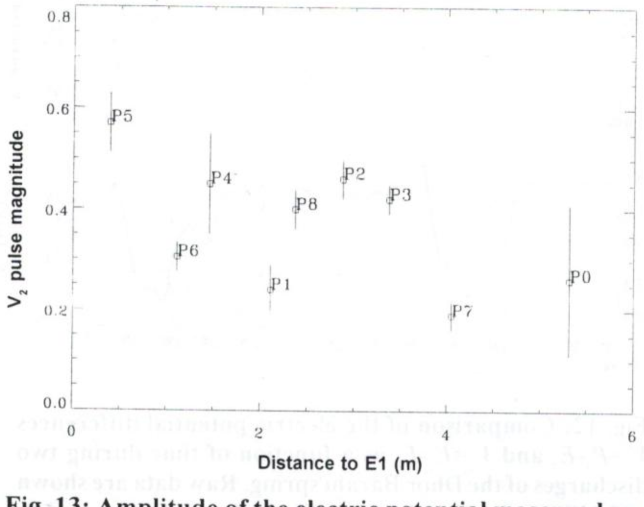

Fig. 13: Amplitude of the electric potential measured on the surface near the spring versus the distance to the E1 electrode. The positions of the measurement points are shown in Fig. 5.

downwards, a negative electrical signal is observed on the surface, and the potential extends to the imbedding medium (Fig. 15). Assuming gravitational flow over a height of 20 m and taking reasonable values of the resistivity of the medium (Gautam et al. 2000) and values of the SPC obtained in the laboratory (Perrier et al. 1999; Lorne et al. 1999a), a maximum amplitude of about –25 mV is expected above the flow column. This value is compatible with the measured amplitude range of V_1. Conversely, for a water flow going up, a positive potential would be created at the exit on the surface.

With this picture in mind, two independent columns of percolating water have to be imagined to account for the negative signal observed in the flow channel and the positive signal observed on the surface (Fig. 9). The negative potential in the flow channel in the first basin would be created by a column C1 activated by water pressure in the siphon, with an intensity proportional to the water level in the exit branch of the siphon. The positive potential on the surface near the spring would be associated with another column C2 activated by water pressure at the upper branch of the siphon, after the reservoir cavity. This column would be of a size of the order of 1 meter, with a leakage tail decreasing with distance as in Fig. 15. The water pressure at the input of C2 would be smaller than the pressure above C1, producing a smaller intensity of this source according to Eq. (1).

One may object that these two sources are not compatible. Indeed, the negative electrical potential of column C1 is expected to have, as shown by the model of Fig. 15, a negative leakage tail in the imbedding medium, which would create a negative tail on surface larger than the observed positive signal. One explanation is that the leakage of negative potential does occur on the surface, but it is cancelled by the whole positive signal on surface from

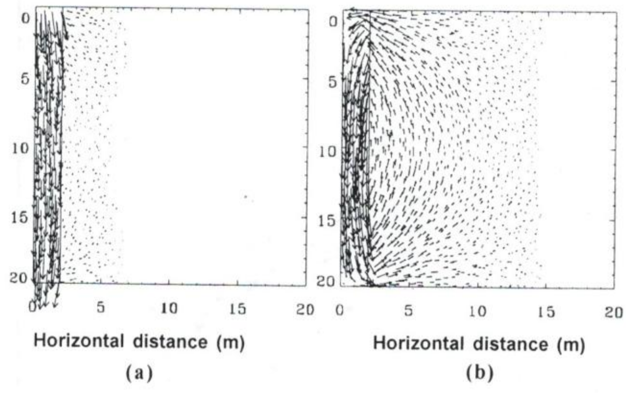

Fig. 14: Cross-section of a 2-D analytical model used to calculate the electric field associated with a vertical water flow (after Adler et al. 1999). The water flow is shown on the left, the associated electrical current on the right. The permeability of the column is 10^{-13} m² with an electrical resistivity of 10 Ωm and a SPC of 30 mV/0.1MPa. The permeability of the imbedding medium is 10^{-15} m² with an electrical resistivity of 3000 Ωm and a SPC of 3 mV/0.1MPa.

column C2. This would require a close matching of the intensities of the two sources C1 and C2, and furthermore a slightly larger intensity for C2. This explanation is not likely.

A more reasonable explanation is that the negative potential remains confined above the water column. This is possible. This situation for example occurs when some water is driven from a column into a very permeable imbedding medium, as illustrated in Fig. 16. In such a case, the leakage of water flow into the imbedding medium cancels the leakage of electrical current. The negative potential leaking on the surface near the spring is then very small, making the positive source with smaller intensity visible.

One may also notice that, for some potential pulses in Fig. 7, a small positive pulse is observed after the maximum level, when the water discharge stops. This may be an indication for a strong induced polarisation of the medium. Beyond the pure electrokinetic sources, other contributions therefore may be necessary to account for the observed signals. This study demonstrates that a detailed modelling of electric potential associated with water flow is rather difficult in practise, even in a simple case such as the Dhor Barahi spring.

IMPLICATIONS

The Dhor Barahi spring exhibits a peculiar behaviour over its yearly cycle, with periods of periodic discharges during the dry season, and periods of fluctuating steady flow. Whether the instabilities of the flow and the periodic discharge are related remains an open question. The monitoring of the water chemistry as a function of time suggests mixing of several water sources, probably all of superficial nature. Although this hydrological system is interesting *per se*, it is unlikely that it has any connection to deep crustal groundwater and the seismogenic zones. As this system has strong non-linear features, it may, however, exhibit enhanced response to changes of remote stress. Such effects could only be assessed after several years of monitoring.

Other hydrological systems similar to Dhor Barahi may exist in Nepal, with a better connection to the zone of stress accumulation located in the Higher Himalayas (Pandey et al., 1999), and less connection to the surface meteorology and hydrology. Taking the features of the site of the Dhor Barahi spring as a hint, it would be interesting to investigate springs near active faults in dolomite formations where karsts may have appeared as a result of neotectonics, with drastic consequences on the flow rate, such as periodic discharges. Such springs may respond to precursory stress changes, which could affect groundwater circulation. Indeed, magneto-telluric data suggest that the seismogenic MFT zone, associated in the Higher Himalayas with stress accumulation and microseismicity, is pervaded by fluids (Lemonnier et al. 1999).

The measurements performed in Dhor Barahi do raise some reservations on the effectiveness of using electric potential variations to monitor time variations of groundwater flow. Although the electrical signals in Dhor Barahi are clear, and provide a beautiful illustration of the EKE in a natural setting, the potential applications appear limited. The amplitudes are decreasing with distance, and are small anyway, and consequently the electrical measurements have to be performed basically on the electrical sources. In addition, even in a natural system of a few meters size, a qualitative understanding of the measured potential variations associated with the water flow remains difficult unless a quantitative modelling is done.

However, electric potential variations have an important feature that can not be underestimated : they are transported quasi-instantly, which is not the case for the water flow. For

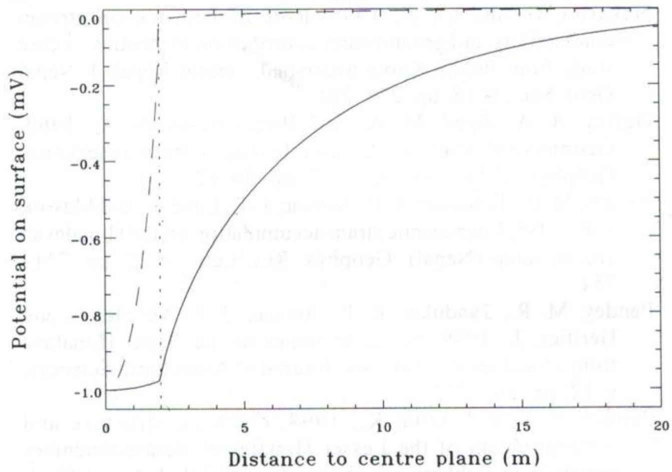

Fig. 15: Electric potential on the surface as a function of distance for the 2D analytical model depicted in Fig. 14 (full line), normalised to the maximum potential (after Adler et al. 1999). The dashed line corresponds to the parameters of the calculation of Fig. 16, also normalised to the maximum potential.

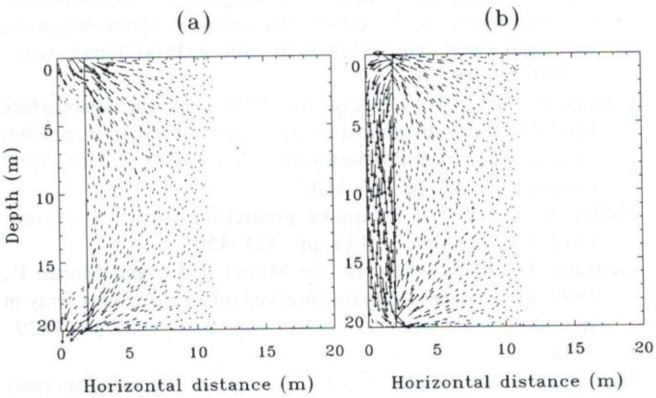

Fig. 16: Cross-section of a 2-D analytical model used to calculate the electric field associated with a vertical water flow (after Adler et al. 1999). The water flow is shown on the left, the associated electrical current on the right. The values of the parameters are the same as in Fig. 14, except the permeability of the imbedding medium, which is here 10^{-11} m^2.

example, in Dhor Barahi, the geometry of the siphon and the basin caused fortuitously the water flow to be about 30 seconds late compared with the change of the electric potential. Studying the time variations of the electric potential may lead to discover features of groundwater flow which are not known or otherwise accessible. Since electric potential variations can also be produced by meteorological artefacts (Perrier et al. 1997), at least one other geophysical parameter would be needed to confirm the tectonic origin, such as tilt or radon emanation (Trique et al. 1999). Even if the chances appear slim at the current level of understanding, precursory electrical signals, which are observed repeatedly in various settings, such as the controversial VAN signals in Greece (e.g. Eftaxias et al. 2000; Geller 1997), still remain a path to be investigated with an open mind.

ACKNOWLEDGEMENTS

The authors are grateful to N. R. Sthapit and M. R. Pandey of the Department of Mines and Geology for support and encouragement. DASE/LDG is thanked for support and DASE/RCE is thanked for the analysis of the water samples. Laurent Bollinger is thanked for sharing his insight on the geology of Western Nepal. R. P. Tandukar and one anonymous reviewer are thanked for their careful reading of the manuscript.

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