Investigation of groundwater flow in karst areas using component separation of natural potential measurements

Zhou Wanfang · Barry F. Beck · J. Brad Stephenson

Abstract The natural (electrical) potential (NP) method – also known as self-potential, spontaneous potential and streaming potential (SP) – has been used to locate areas of groundwater flow in karst terrane. NP is the naturally occurring voltage at the ground surface resulting from ambient electrical currents within the earth. The measurement of NP can be used to characterize groundwater flow in karst terrane because electrical potential gradients are generated by the horizontal flow of water along fractures or conduits and the vertical infiltration of water into fractures or shafts. NP data from a site on the Mitchell Plain of southern Indiana, USA, revealed that NP data can be decomposed into three components: topographic effect, residual NP and noise. At this site, NP was inversely proportional to elevation, but the correlation varied with time. The topographic correction factor varied from –2.5 to –1.2 mV/m (NP change per unit elevation increase), with an average linear correlation coefficient (R) of 0.95. Because the site slopes toward an adjacent creek that is the local groundwater discharge zone, one possible explanation for this effect is a streaming-potential mechanism generated by groundwater movement toward the creek. The residual NP data revealed three negative anomalies at the survey area. Two of them coincide with sinkholes. A part of the third anomaly is coincident with a small valley, and concentrated infiltration does occur at this elevation in other valleys at the site, as evidenced by the existence of sinkholes. However, the dispersed, low-magnitude nature of the third anomaly does not prove the existence of concentrated groundwater recharge activity.

Key words Natural potential technique · Topographic effect · Karst terrane · Groundwater recharge

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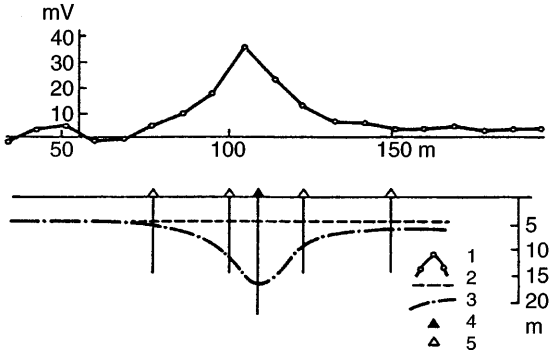
Introduction

The natural (electrical) potential (NP) method – also known as self potential, spontaneous potential and streaming potential (SP) – involves the measurement at the ground surface of the naturally occurring voltage resulting from ambient electrical currents within the earth. Such currents occur everywhere, but they do not arise from random processes. They are caused by a variety of discrete physical phenomena acting underground, including (1) redox reactions around metallic conductors intersecting the saturated zone; (2) fluid diffusion across soil and lithologic contacts; (3) subterranean chemical and temperature gradients; and (4) the streaming potential gradient resulting from water flowing through pores, fractures and caverns in the ground, that is, the electrokinetic effect (Kilty and Lange 1991).

Unlike mining geophysics and well logging where the mineralization potentials and diffusion/membrane potentials are measured, the streaming potential is of primary interest in engineering and hydrogeologic applications (Ernstson and Scherer 1986). Cooper and others (1982) have reported that NP values measured in a similar geologic setting are due mainly to the streaming potential. Corwin and Hoover (1979) have demonstrated that NP anomalies generated by the streaming potential are larger in amplitude than those generated by other mechanisms.

According to the Helmoltz relationship, when water moves through a saturated capillary system by laminar flow, the NP gradient is the product of the water pressure gradient and a coupling constant (Aubert and Atangana 1996). The potential gradient is the result of the electrofiltration process, wherein the natural potential increases positively in the direction of flow. This theory has been proven by laboratory experiments in which the NP generated by the flow of water through porous material is linearly proportional to the Darcian velocity over a broad range of pressure gradients and fluid compositions (Bogoslovsky and Ogilvy 1972). Field measurements have also revealed a positive NP anomaly that mirrored the groundwater cone of depression surrounding a pumping well, as shown in Fig. 1 (Bogoslovsky and Ogilvy 1973).

The proportional relationship between NP and the pressure gradient under fracture flow conditions has been confirmed by laboratory studies conducted by Ahmad (1964) using channel flow models. NP values were found



Source: Adapted from Bogoslovsky and Ogilvy (1973). (1) Measured NP; (2) Initial water table; (3) Water table after pumping; (4) Pumping well; (5) piezometer borehole.

Fig. 1
NP response caused by pumping of groundwater

to decrease with the opening of fissures, but introduction of sand into the fractures can considerably increase the NP values. In a field investigation, Ogilvy and others (1969) observed an NP gradient corresponding to groundwater flow through fractures. In a study of the application of the NP technique to karst aquifers, Erchul and Slifer (1987) demonstrated that NP anomalies associated with sinkholes appear to indicate areas of preferential groundwater movement. The magnitudes of NP anomalies and the NP change were related to groundwater flow rates into the sinkhole. Field evidence has been given for NP anomalies associated with groundwater infiltration into cave systems and groundwater flow in karst conduits (Lange and Kilty 1991; Stewart and Parker 1992; Lange and Barner 1995).

Understanding the basic relationship between NP and groundwater flow through fractures and conduits is critical for distinguishing groundwater flow regimes in karst systems. There is a basic distinction between the lateral flow of groundwater in bedrock fractures and the vertical flow of water through the epikarst zone. With respect to lateral flow, a potential gradient can develop along the flowpath from a recharge area to a discharge area. The upgradient end of the channel can become negatively charged relative to the downgradient end. The typical potential distribution over a discharge point, such as a spring, is a positive anomaly transverse to the flow path. The typical potential distribution over a recharge point, such as a sinkhole, is a negative expression. Positive potential anomalies are expected over zones of groundwater discharge, whereas negative anomalies may indicate buried sinkholes or shafts where water is entering the bedrock. Ogilvy (1967) states that the most significant NP results could be obtained in karst areas where considerable quantities of water flow into sinkholes (Erchul and Slifer 1987).

The primary factor responsible for land-surface collapse in karst regions is the infiltration and vertical percolation of groundwater through shafts into the underlying limestone (Beck, 1988). Because NP anomalies are associated with groundwater flow rather than the mere presence of groundwater, this technique is a very useful tool for evaluating the risk of potential collapses in karst areas. Identification of vertical recharge zones is essential in construction, waste disposal and other activities in karst terrane.

Field investigation

NP data were collected on the Mitchell Plain of southern Indiana, USA. The site is underlain by approximately 9.15 m of unconsolidated clay, which is underlain by the St. Louis and Salem Limestones. At the site, the limestone and the land surface dip approximately 5.68 m per km toward the west. There are six sinkholes immediately surrounding the site. A series of springs and seeps discharge groundwater to a local creek along the base of the slope. The springs emerge from joints in the limestone. Voltage measurements were made on the ground surface using the voltage averaging mode of a multimeter with an input impedance of 10 MΩ. The reference and roving probes (3 and 1.5 in., respectively) were non-polarizing, copper/copper-sulfate, porous-ceramic electrodes. The multimeter was connected to the probes by 549-m-long, 18-gauge military communication wire. Forty-seven data lines 7.6 m apart were measured within an area of approximately 0.076 km^2). NP readings were taken every 7.6 m along each line except for minor spacing changes near obstacles. The length of the lines varies from 83.8 m to 243.9 m. Three base stations were established because of the limited length of the wire and the large, partially wooded area to be measured. Several of the NP lines crossed two sinkholes.

At each base station, the reference electrode was buried in a shaded location to minimize temperature and polarization effects. At each data-collection station, vegetation was cleared, and the roving electrode was set approximately 4 in. deep into the soil with the aid of a garden-variety bulb planter to ensure a good contact. After the multimeter reading became stabilized, the voltage averaging mode was activated. A duplicate reading was taken at each station to ensure that the measurement was representative of that location. If the difference between the two readings was less than 5 mV, the readings were accepted and their average value was used to represent the NP reading at that station (Corwin and Hoover 1979). If the difference between the two readings was more than 5 mV, additional measurements were made until two successive readings differed by less than 5 mV. Readings were made at the base station (near the reference electrode) approximately every hour to record the temporal drift. In addition, base station readings were recorded before and after measuring each line.

Component separation of NP data

Components of NP data

It is well recognized that NP measurements are subject to temporal drift, and drift-corrected NP data have been interpreted for karst hydrogeological applications (Lange and Kilty 1991). The temporal drift can be corrected by assuming a linear drift between successive base station readings using the following equation:

$$V_{cj}=V_j-[V_{pi}+(T_j-T_{pi})(V_{ni}-V_{pi})/(T_{ni}-T_{pi})+V_0],$$

where V_{cj} is the drift-corrected NP value for the measured voltage V_j at time T_j on line j; V_0 is the reference NP value, which is the first reading at the first base station; V_{pi} and V_{ni} are the previous and subsequent readings at base station i at times T_{pi} and T_{ni}, respectively. Many previous investigations of NP have measured an electric field characterized by increasing potential in the downhill direction. This phenomenon is known as a topographic effect (Birch 1993; Aubert and Atangana 1996) and has been recognized by geophysicists for more than 70 years. The time dependence of the topographic effect has been well demonstrated in controlled field experiments (Ernstson and Scherer 1986). Based on their experiments, the drift-corrected NP was decomposed into three contributing components: (1) topographic effect (V_j^{te}); (2) residual NP (V_{cj}^{rs}); and (3) noise (a), that is,

$$V_{cj}=V_{cj}^{rs}+V_j^{te}+a.$$

This component separation concept is schematically demonstrated in Fig. 2. As with other geophysical potential field methods, an unambiguous separation is impossible. This decomposition must be considered a gross simplification. Noise exists in all field measurements, and it can hardly be separated from the data. Proper field procedures must be followed to minimize the noise level. In Fig. 2, the NP gradient of the topographic effect is constant along the profile, and the topographic effect can be calculated by computing a regression line of NP versus distance. The linear regression method is often employed to remove the topographic effect, but it is only valid for "linear topography", that is, topography with a constant slope with respect to the station numbers. In irregular terrane, the topographic effect is not linear versus distance, and a topographic correction factor (K) must be calculated. K is defined as the NP change per unit elevation increase. The field data showed that K varied from day to day but is reasonably consistent for adjacent lines measured on the same day. The topographic effect for each NP data is calculated by the following equation:

$$V_j^{te}=K_j(h_j-h_{0j}),$$

where K_j is the topographic correction factor for line j; h_j is the elevation of the station where V_j is measured; h_{0j} is the elevation of the first measurement in line j.

While the topographic effect is more significant on a site-wide scale, the residual NP is the component most relevant for evaluating localized hydrogeologic conditions. In contrast with porous-medium aquifers, karst aquifers are characterized by highly localized flow conditions. Groundwater tends to flow preferentially through conduits or enlarged fractures, and groundwater recharge occurs through discrete sinkholes or shafts. Residual NP signals may provide useful information on such features.

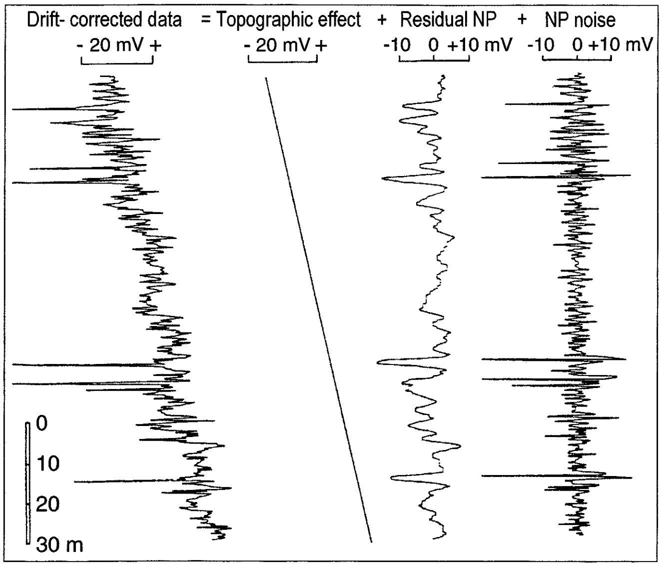


Fig. 2
Decomposition of NP record into three components

Noise component

NP surveys may be impacted by various sources of interference. Telluric currents generated by temporary variations in the earth's magnetic field may sometimes affect NP measurements. Disregarding rare magnetic storms, the electric field may vary several millivolts per mile. However, closely spaced measurements and short profiles may prevent significant influence from such currents (Ernstson and Scherer 1986).

The electrical resistivity of the ground is another important factor affecting NP measurements. Field data have indicated that variations in topography and vegetation may distort the patterns of current flow. Figure 3 compares the noise levels between the wooded and grassy areas. The noise level is apparently higher in the wooded area than in the grassy area. The maximum error (difference between duplicate measurements at a station) in the wooded area is 3.4 mV with 90% of the errors less than 1.6 mV. The maximum error in the grassy area is only 2.2 mV with 90% of the errors less than 1 mV. Figure 3 also shows the cumulative error distribution for all of the NP measurements. The maximum error is only 3.4 mV with 90% of the measurements having an error less than 1.3 mV. The small errors indicate that the collected NP data are reliable.

Temperature changes in the electrode and temperature, moisture, and chemical fluctuations in the soil can also affect NP measurements. These factors are the main causes of temporal drift. Temporal drift was corrected by

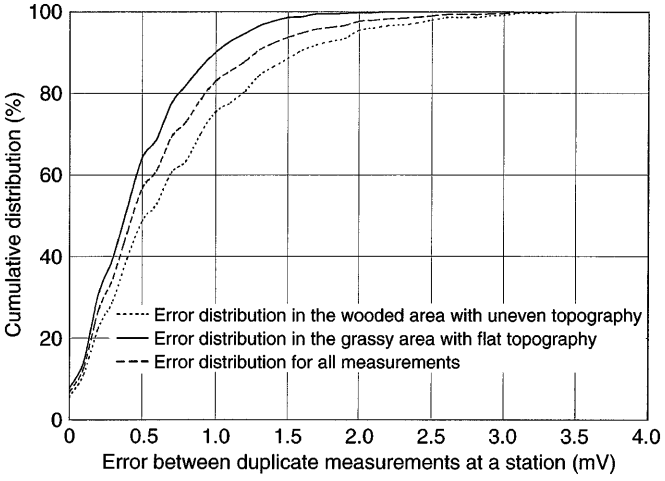


Fig. 3
Noise distribution in field data

assuming the temperature was constant at the buried reference electrode and that the temporal drift at the base station was representative of the whole site. Stray currents generated by the metallic debris within the survey area may contribute noise to the NP readings. Careful field observations were made regarding the location of possible sources of stray currents to attempt to avoid their interference.

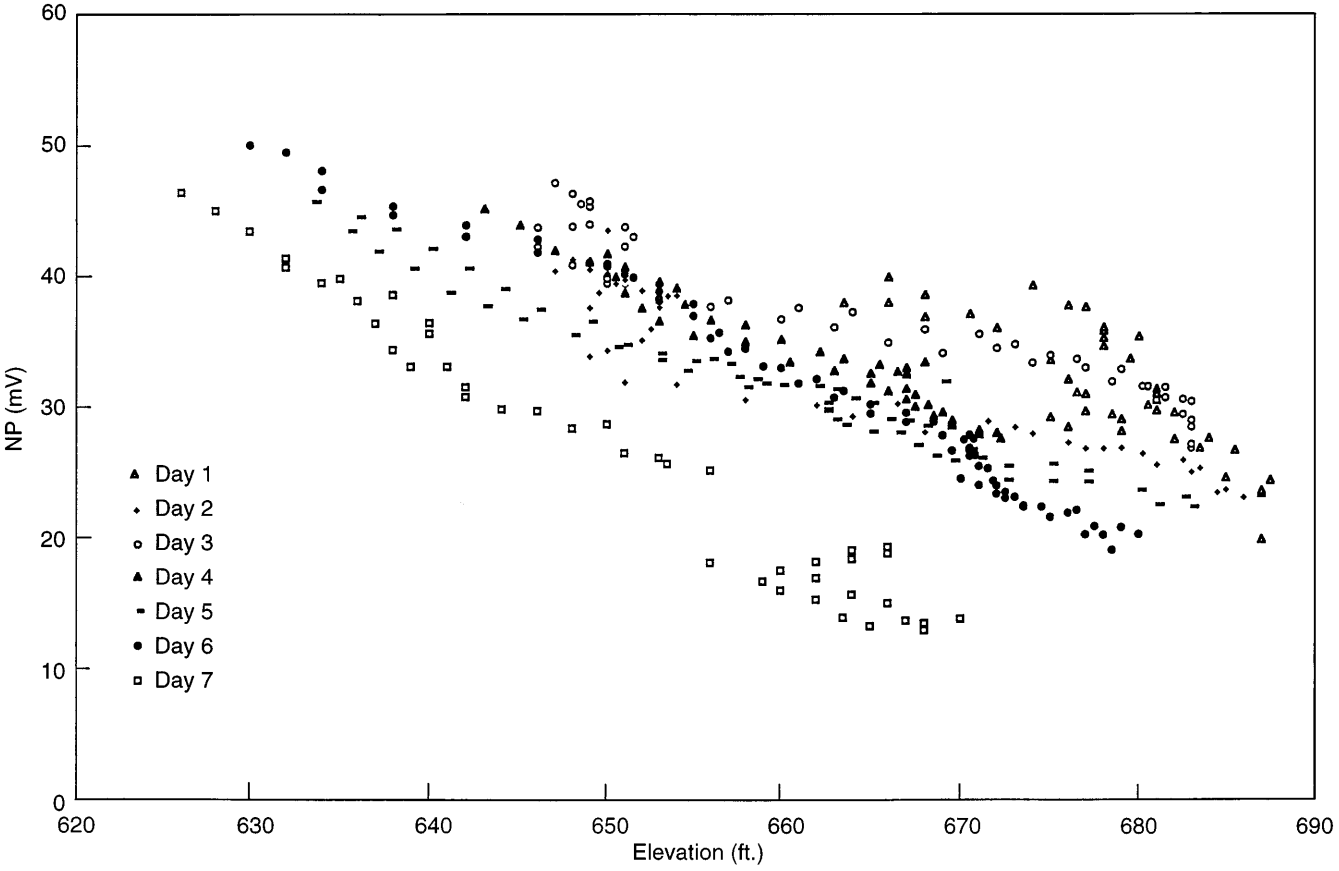
Topographic component

The survey lines were grouped by date, assuming that the ground conditions at the site did not change significantly during the course of a single day. For each daily group, two lines with no apparent anomalies were selected to determine the topographic effect. The drift-corrected NP values were plotted against their corresponding elevations, as shown in Fig. 4. The trend line for each group indicates that the relationship between NP and elevation is approximately linear. A linear correlation coefficient (*R*) was calculated for each trend line. NP is inversely proportional to elevation at this site. A correction factor was obtained for each daily group (Fig. 5). The linear correlation coefficient ranges from 0.83 to 0.99 and averages 0.95. K varies from –0.38 to –0.75 mV/foot and averages –0.55. These correction factors are within the range reported by other investigators (Aubert and Atangana 1996; Ernstson and Scherer 1986).

Residual NP component

The residual NP signal was obtained by removing the topographic effect from the drift-corrected NP data and assuming that the data noise was negligible. For profiles with a relatively constant slope, the separation of the re-

Fig. 4
Drift-corrected NP versus elevation



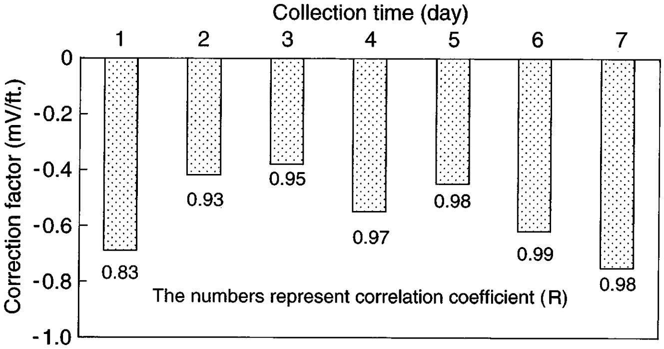


Fig. 5
Topographic correction factors versus time

sidual NP and the topographic effect are similar to correcting the data with a regression on distance (Fig. 6), because the elevation is mostly proportional to distance.

However, for profiles measured over varying topography, use of the topographic correction factor produces a much superior result to a simple regression on distance (Fig. 7). The residual NP component is initially overshadowed by the topographic effect in localized recharge areas, such as sinkholes. However, removing the topographic effect leaves the residual NP component showing prominent anomalies over the recharge areas.

Figure 8 shows the residual NP, plotted based on the average topographic correction factor and a reference elevation (the first station of line 1). Three negative NP anomalies (labeled I, II and III) are delineated. Anomalies I and II are related to sinkholes B and C. Their magnitudes are greater than 5 mV. The anomalies are not exactly centered on the respective sinkholes, but they are within 15 m). Anomaly III is enclosed only by the 15-mV contour line and the magnitude is less than 5 mV. Several positive anomalies enclosed by only one contour line were also observed at the site.

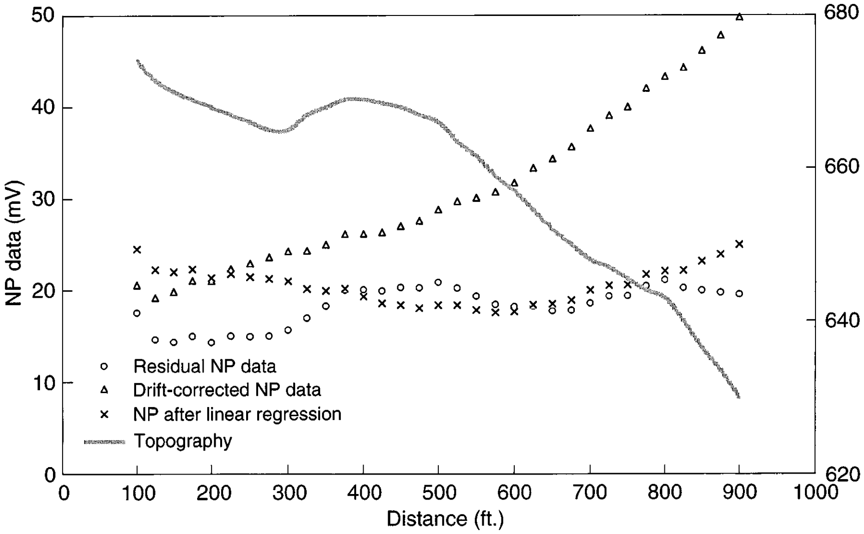


Fig. 6
Separation of residual NP for constant slope profiles

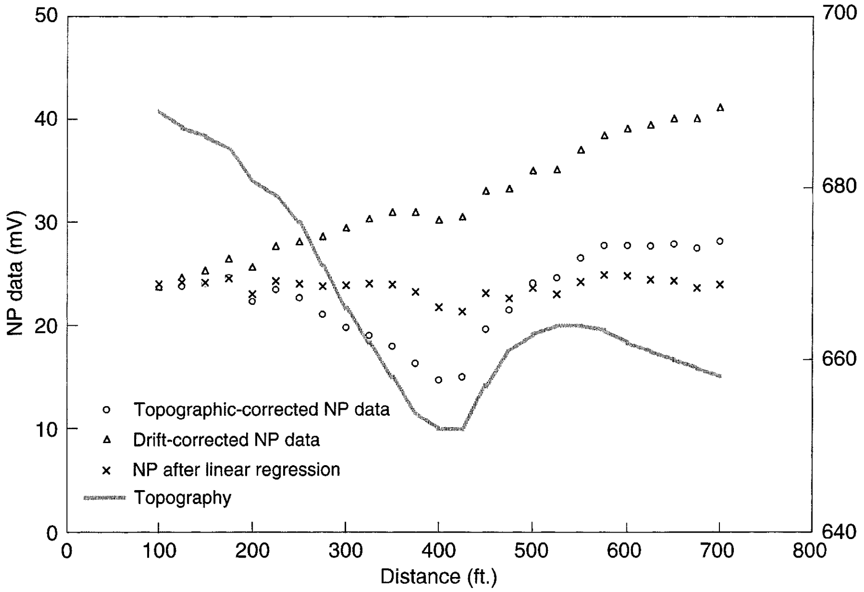


Fig. 7
Separation of residual NP for varying slope profiles

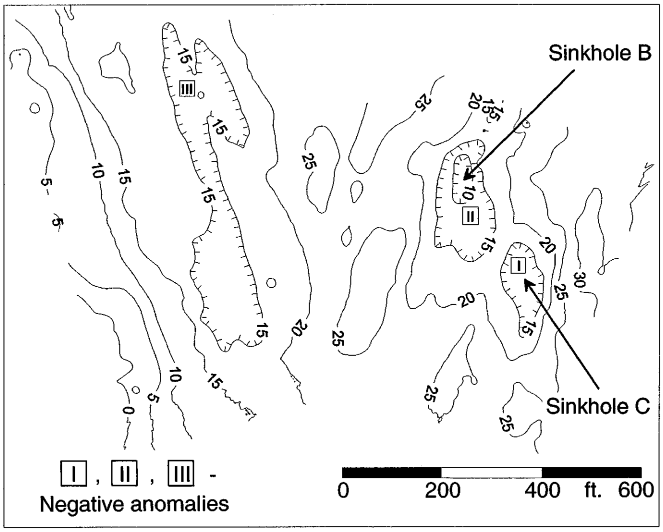


Fig. 8
Residual NP map

Interpretation and discussion

Topographic effect: streaming potential from lateral groundwater flow

Many previous investigations have demonstrated the existence of the linear topographic effect (Corwin and Hoover 1979), but observations of constant electric fields with increasingly positive potential in the downhill direction have not been explained clearly. The role of thermoelectric effects and a hypothetical "vertical telluric current" have been heavily debated. In recent years, however, it has become widely accepted that the observed phenomenon results from streaming potential induced by groundwater flow. Controlled field experiments have clearly demonstrated a correlation between precipitation and NP, although there was a 1-month delay in the NP response (Ernstson and Scherer 1986). This 1-month time lag excludes surface runoff as a possible cause.

The streaming potential mechanism also provides a reasonable explanation for the correlation of NP with elevation observed during this study. Exploratory boreholes and groundwater traces indicated that groundwater at this site receives recharge through sinkholes and discharges at the springs. Topographically, it flows from high surface elevations to low surface elevations. Therefore, the observed linear correlation between NP and elevation is to be expected. The time-dependence of the topographic effect results from the dynamic characteristics of groundwater flow conditions.

Residual NP: streaming potential from vertical groundwater recharge

The residual NP data represent the effect of local streaming potential. According to Ernstson and Scherer (1986), groundwater infiltration in carbonate rocks can cause NP anomalies, and their polarity is dependent on the pH of the groundwater. They suggest that infiltration of neutral water (pH of 7) causes a negative anomaly, although they did not confirm this. Negative anomalies have been documented in the field in areas with active infiltration (Ishido and Mizutani 1981; Lange and Kilty 1991). Because groundwater in uncontaminated limestone aquifers has a pH of approximately 7, it is possible that the negative anomalies at the site are caused by vertical groundwater infiltration.

Because the magnitudes of the negative anomalies are directly proportional to the infiltration rate (Erchul and Slifer 1987), the greatest groundwater infiltration appears to coincide with the sinkholes. This is logical since sinkholes generally function as discrete groundwater recharge sites in karst areas. However, this association verifies the applicability of the NP technique for identifying vertical recharge zones. It should be noted that the term "vertical flow" is an oversimplification of the actual flow patterns in the epikarst zone. In this context, vertical flow refers to flow that is dominated by the vertical component.

The third anomaly (III) covers a broad area of some 6038 m^2). Because the anomaly magnitude is less than 5 mV, the interpretation is uncertain. It may be the effect of noise (Corwin and Hoover 1979), or it may be related to groundwater recharge in the epikarst zone. It is much less concentrated than the anomalies over the sinkholes, so the infiltration rate should be smaller. Although this dispersed, low-magnitude anomaly does not prove the existence of concentrated recharge activity, its western portion coincides approximately with a small valley. Concentrated infiltration does occur at this elevation in other valleys at the site, as evidenced by the existence of several sinkholes.

Conclusions

This investigation has confirmed that NP data can be decomposed into three components: a topographic effect, a residual NP value and noise. The topographic effect may be generated by lateral groundwater flow; it varies with time. The topographic effect may overshadow any anomaly caused by vertical groundwater infiltration, especially in areas with irregular terrane. A methodology to remove the topographic effect has been developed and applied at the investigation site. Vertical groundwater recharge produces negative NP anomalies in an uncontaminated karst aquifer, as shown in the residual NP map. Three recharge zones (negative anomalies) were delineated. Two of them coincide with sinkholes. The association of vertical recharge with existing sinkholes confirms the applicability of the NP technique for identifying groundwater recharge zones in karst areas. Part of the third anomaly is coincident with a surface valley. Because sinkholes exist at approximately the same elevation within valleys elsewhere at the site, this anomaly could indicate the presence of a zone of infiltration without surface expression. However, the dispersed nature and small magnitude (less than 5 mV) of the anomaly do not provide conclusive evidence for concentrated groundwater recharge at that location.

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