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Threatened groundwater resources in rural India : an example of monitoring

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Abstract In the absence of available surface water in semi-arid areas, groundwater has become the main water resource for various purposes. In many places in southern India, groundwater even is the only source of drinking water in rural areas. Therefore, quality and quantity aspects of groundwater management constitute acute issues for the well-being of Indian rural populations. This study proposes to use borewells drilled by farmers for irrigation purposes in order to assess the quality and quantity of available groundwater. A very accurate map of the water table and its variations was drawn and zones of water table depletion were compared to water pumping locations. Overexploitation is quantified at the watershed scale. Quantity is associated with quality. A groundwater electrical conductivity map reveals highly mineralized groundwater near the villages, and pollution plumes downgradient of the main inhabited areas. The absence of sewage or solid waste collection and treatment facilities threatens groundwater quality by increasing its chloride content, even in such small rural villages. The overall analyses indicate increasing risk for sustainability of groundwater resources. At the regional scale, salinisation of groundwater due to irrigation practices is suspected.

Keywords: *Groundwater, Water table, Overexploitation, Electrical conductivity, Chloride, Irrigation*

1. Introduction

Groundwater now irrigates a larger total area of farmland in India (27 million hectares) than surface water (21 million hectares), and now therefore sustains almost 60% of the country's irrigated land (Roy and Shah 2002). On a local level, an increasing number of districts now have more irrigated land under groundwater irrigation than under surface-water irrigation. This change has been extremely rapid since the 1970s. Between 1970 and 1994, the amount of farmland irrigated with groundwater in India increased by 105%, while the areas of land irrigated with surface-water increased by only 28%. The rapid increase in groundwater irrigation is also illustrated by the soaring number of mechanised and tube wells over the last 40 years, from less

than 1 million in 1960 to more than 19 million in 2000, making India the country with the most pumpsets. Because groundwater is a limited resource, this enormous development of borewells threatens aquifers and cases of declining water tables have been widely reported, particularly in densely populated areas (Narain 1998).

In coastal areas, water table depletion induces saline intrusion, which degrades groundwater quality (Radharkrishna and others 1998). In industrial areas, the presence of heavy metals (Sharma et al. 2003) and high contents of various elements (Subrahmanyam and Yadaiah 2001) have been reported. In agricultural areas, the use of fertilizers and pesticides threatens groundwater quality (Pimentel 1996). Groundwater salinisation and water logging jeopardize the sustainability of the Green revolution in several states such as in Haryana (Datta and de Jong 2002). Uncontrolled anthropogenic activities such as metal ore smelting, and the use of arsenic pesticides and wood preservatives may release arsenic directly into the environment (Bhattacharya and others 1995). The origin of As can also be natural and the occurrence of high As concentrations (0.2–2.0 mg/l) in groundwater used for the drinking water supply have been measured in the Indo-Gangetic delta plains of West Bengal (Chakraborty and others 1987). In 1993, 15 of India's 32 states were identified as endemic for fluorosis (Rajiv Gandhi National Drinking Water Mission 1993) due to high concentrations (> 1.5 mg/l) of fluoride in groundwater.

It is usually not easy to monitor groundwater quality and quantity problems due to the difficult access to groundwater and relevant information. The existence of many abandoned borewells in rural India provides a rare opportunity to monitor groundwater with a dense observation network. It was used to draw very accurate water table and water electrical conductivity maps at the watershed scale. Both maps were analyzed and enabled us to quantify the severity of the problems and understand their origins. Based on this work, we discuss here the effects of human activities on groundwater quality and availability and show how groundwater is strongly threatened in rural areas. Given the representativeness of the study area and the importance of rural regions in India, this is the sign of a major issue at the scale of the entire country which necessitates an accurate spatial monitoring in order to assess the state of groundwater resources and identify the exact magnitude of the problem.

2. Study area

The Maheshwaram watershed is located around the village of Maheshwaram, 30 kilometres from Hyderabad (Andhra Pradesh, India). It has a surface area of around 55 km² (Figure 1). With an annual potential evapotranspiration close to 2,000 mm and an annual rainfall of 700 mm over a 4- to 5-month period, the climate of the region can be classified as semi-arid. This is a typical rural basin of southern India, with a total population of about 15,000 living in five villages, listed by decreasing population: Maheshwaram, Tummaluru, Sirigiripuram, Gangaram and Mohabatnagar. The principal occupation of local inhabitants is agriculture: rice, vegetables and flowers being the main crops. Archean granite constitutes the aquifer formation in the Maheshwaram watershed. The weathering profile, easily observable in many dugwells previously used by farmers for irrigation, is generally truncated by erosion. Below several decimetres of red soil, the weathered mantle has a rather homogeneous thickness of less than three meters in the entire watershed (Dewandel and others 2004). A high density of subhorizontal fractures is observed in the underlying fractured-weathered layer, inducing a vertical anisotropy of permeability (Maréchal and others 2003b). The thickness of this layer is estimated from borewell observations to be

between 20 and 40 meters (Maréchal and others 2003a). Groundwater is withdrawn from this part of the geological profile (Maréchal and others 2004).

Except for two factories in the northeastern part of the basin (located downstream the aquifer), there is no industrial activity in the watershed. Consequently, the main sources of pollution are agriculture (including breeding in poultry farms) and the villages.

The borewells were mapped using portable GPS between June and July 2002. A total of 929 wells have been reported, of which 707 are pumped. The high number of borewells in this study area provides a dense observation network for measuring the water table and water quality.

3. Results

3.1 Groundwater overexploitation

Spatial analysis

The pumping trend in the Maheshwaram watershed is similar to what is observed at the national scale, with a huge increase in the number of borewells during the 90s. The water is used mainly to irrigate paddies that produce 2 crops a year.

In order to determine the undisturbed 'static' level of the aquifer, the water table was measured both in observation wells drilled for this research project and in abandoned wells, in June and July 2002, at the beginning of the monsoon. Temporal monitoring of 10 wells shows that water level does not fluctuate during this period due to balancing of pumping by small recharge at the beginning of the monsoon. Therefore, the data can be considered as simultaneous and compared for water level mapping. There are 99 water table measurement points for an area of 55 km², thus providing a very dense observation network of about two measurement points per km². This is much greater than the density of hydrograph stations usually maintained by the Central Ground Water Board.

The data were interpolated on the watershed area using the universal kriging technique on a 100 × 100 m grid. The map was then criticised. It is observed that automatic interpolation technique gives satisfying results thanks to the high density of observation network and to the fact that there is no surface water capable to locally modify the water table by any relationship. Regional flow (hydraulic gradient) is to the north, reflecting regional topography (Figure 1). The water table is globally affected by groundwater abstraction and totally disconnected from ground surface: the correlation between the location of pumping wells and zones of water table depletion is obvious. The decline in the water table is observed mainly in alluvial plains at the bottom of the valleys, low-lying areas where cultivated fields, paddies in particular, are concentrated. The largest water table depletion area (zone 1) is located along the basin's western stream, north-west of the village of Maheshwaram where flow stagnates in several areas before being pumped. There is a marked decline in the groundwater level near the village of Mohabatnagar (zone 2) where there are many pumping wells. A third depletion area (zone 3) is located along the eastern river downstream of the village of Tummaluru. These depletion areas globally modify the groundwater flows and tend to create endoreic conditions reducing regional flow outgoing the watershed towards the north. A

mathematical model has shown that initial natural conditions before pumping development were drastically different with water table globally following topography and groundwater outflowing in rivers.

Temporal analysis

All of the shallow dugwells in the watershed are now dry and have been abandoned, and farmers must drill deeper borewells to reach water. The water table decline is therefore regional, affecting the entire watershed, as confirmed by periodic water table measurements (Figure 2) in an open well located in an apparently non-depleted area (Figure 1). The depth of the water table has increased over the last fifteen years from 7 to 11 meters, which suggests that the depletion due to increased pumping in recent years is not limited only to the areas identified above (zones 1 to 3), but is widespread.

The water table depletion is also aggravated by dry years like 1992 and 1993 during which there was only 469 and 466 mm of annual rainfall, respectively (Figure 2). The water table was not able to recover after these two dry years due to high water abstraction. It is now crucial to refute the idea occasionally accepted by policy makers, that widespread groundwater depletion is caused only by climate change.

Only mathematical models can simulate the water table fluctuations caused by increased water abstraction and various recharge conditions (Bredehoeft 2002). We used the global hydrologic model GARDENIA (Thiery 1988), which calculates water table fluctuations in aquifers recharged by rainfall, to model the water table fluctuations observed in the open well. Using rainfall data from the Maheshwaram station and evapotranspiration data measured at the Patancheru meteorological station (40 km away), we simulated the water cycle in the watershed (ground- and surface water). The water cycle is represented by a system made up of three reservoirs:

- evaporation in the first centimetres of soil,
- quickflow,
- baseflow to the aquifer.

The model was calibrated with a series of water level measurements from 1987-1992 (Engerrand 2002). The first two years of data were used to start the model, after which there is good agreement between observations and simulated results. This indicates that the model is reasonably well calibrated and able to simulate the water table. The validity of the water budget (evapotranspiration, runoff, percolation) was also verified by comparing the results to reference values from a similar hydrogeological context (Rajagopalan and others 1998). The model was then run with measured evapotranspiration and rainfall as input to simulate the water cycle for 1993 to 2000. The simulated water level declines during both dry years (1992 and 1993), as observed in the well. Simulations show that rainfall in 1994 (767 mm), heavy late in the season when the soil was humid, should have increased the water table, and the above-normal and normal annual rainfall in 1995 and 1996 (873 and 792 mm, respectively) should have brought the water table back to its initial level of the end of the 1980s. This was not observed in the open well where the lower water table indicates that the well was dry for much of the observation period. A cause 'external' to the constraints applied to the model must be found to explain the observed behaviour of the water table. In view of the increased number of borewells around the open well, the increase in groundwater abstraction is naturally the most probable cause of the difference between observed and simulated levels. This model shows that climatic conditions alone cannot explain observed water table decline: increased pumping is mining the groundwater

resources. Sustainable pumping rates must be assessed over the long-term, taking into consideration all of the components of the water budget, including irrigation return flow (Kendy 2003), which is very great given the fact that paddy crops are common in the area.

3.2. Groundwater quality

Electrical conductivity

Electrical conductivity (EC) is a physico-chemical parameter that is easy and fast to measure in order to assess the general quality of water and therefore constitutes a useful tool for repetitive measurements on an extensive scale. EC was measured in the watershed along with the groundwater level (i.e., before the 2002 monsoon) and corrected to a reference temperature of 20°C.

Five hundred and fifty measurements were done, giving an average density of 10 observations per km². This enabled to draw a very accurate and detailed map at the watershed scale. The universal kriging technique was used to interpolate the data at a 100 × 100 m cell size (Figure 3). The map and the histogram (Figure 4) of EC values provide information on groundwater mineralization and its correlation with land-use and the location of villages. The natural EC of groundwater appears to be between 500 and 1000 µS/cm. EC is low in the southern area where there are no villages and three water tanks recharge the aquifer with fresh water. This recharge zone is characterized by the lowest measured EC value (< 400 µS/cm). Groundwater with high EC is always located close to or downgradient of the villages, suggesting an influence of wastewater from inhabited areas. Indeed, there are no sewer systems in the villages and rainwater percolates through solid waste before infiltrating into the aquifer. The high EC values (> 1,000 µS/cm) are probably caused by anthropogenic influence. The geostatistical variography analysis of EC shows that this parameter generally has an isotropic variability but the directional variograms show that the range of influence of EC is greater in the direction of flow than in the perpendicular direction.

The range of EC values shows that the anthropogenic influence is variable (Table 1). The village of Mohabatnagar has the least influence (medium) with a maximum EC of less than 1,500 µS/cm north of the village. It is also the smallest of the five villages and the highly mineralized water can be easily evacuated by the groundwater flow towards the north. The same is true of Gangaram with flow towards the south and a low population. The influence here is medium to high. Maheshwaram is the largest village but does not have the highest influence due to the high flow towards the northwest. The high population, however, causes a high influence. Tummaluru is located in an area where there is only a very weak hydraulic gradient towards the north. Highly mineralized infiltrating water cannot, therefore, exit and groundwater mineralization is as high as in Maheshwaram despite the lower population. The most highly-influenced area is located near Sirigiripuram where there is no hydraulic gradient. Highly mineralized water accumulates and EC becomes very high. Although they are not the most populated villages, Tummaluru and Sirigiripuram have the greatest influence on groundwater due to the absence of groundwater flow that would carry away highly mineralized water. The correlation between maximum EC and the low hydraulic gradient near some of the villages is very marked (Table 1).

Moreover, due to the high level of groundwater irrigation, a possible salinisation of groundwater in the cultivated areas cannot be excluded. This point is discussed in the next chapter.

Major elements

The results of analyses for major elements of 17 water samples collected in August 2001 show that the groundwater quality meets WHO drinking water standards (WHO, 1984). The groundwater samples vary from a sodium-bicarbonate type water to a calcium-bicarbonate type water. The dominant anions are bicarbonate (50 to 92%), chloride and nitrate (8 to 50%) and sulphate (0 to 10%). The dominant cations are calcium (15 to 60%), sodium and potassium (10 to 70%), and magnesium (18 to 42%).

Chloride is a well-known tracer of anthropogenic influence and its behaviour in this type of granite aquifer, which is naturally free of chloride, is of interest. The positive correlation between chloride content and EC (Figure 5a) confirms the anthropogenic origin of EC in the watershed. The main sources of chloride are the villages and the large poultry farms, each of which houses up to 10,000 chickens. The correlation between chloride content and distance from the sampling point to the nearest source of chloride (village or poultry farm) is noteworthy, with chloride content decreasing with increasing distance (Figure 5b). The highest chloride contents (samples 2 and 12) are observed downgradient of Tummaluru and Maheshwaram, the villages previously identified as being located in highly influenced areas. Areas of low to medium influence with chloride contents between 100 and 150 mg/l (samples 13, 14, 15 and 17) are located a few hundred meters from chloride sources (< 500 meters). Although sample 9 is located very close to a poultry farm near Mohabatnagar (Figure 3), it has a low chloride content because it is upgradient of the farm, where the groundwater contains no chloride. Except for one sample (8), the decrease in chloride content with distance is very marked 500 meters downgradient. The quality of groundwater more than 500 meters from any source of chloride does not seem to be directly affected by human activity. Anyway, non negligible contents in chloride (up to 50 mg/l, Figure 5a) and high electrical conductivity values (up to 1000 $\mu\text{S}/\text{cm}$, Figure 4) of natural waters suggest an increasing groundwater salinity. It appears to be the result of endoreic flow conditions and of concentration in irrigation return waters by crops evapotranspiration (rather than rising water-table and phreatic evapotranspiration, the water table being 10-20 meters depth), although there could also have been a component of mobilising salts from the soil and vadose zone when the area was first brought under irrigation. This trend, probably initiated by the development of extensive irrigation, threatens the quality of groundwater at a regional scale and has to be monitored in order to take control it by suitable measures (see example in Argentina, Foster & Garduño 2002).

4. Discussion

Extensive measurements of water table levels and EC enable us to make a preliminary assessment of water quantity and quality problems at the catchment scale in a rural basin in India. There is widespread water table depletion that cannot be explained solely by climate changes (low rainfall during consecutive dry years or high evapotranspiration during consecutive hot years). Overexploitation of groundwater by farmers threatens the resource, mainly close to cultivated areas. A change in cropping patterns or alternative solutions such as rainwater

harvesting (both in order to reduce global evapotranspiration) are necessary in order to improve the groundwater balance and reverse the present trend.

The intensive irrigation practices and endoreic flow conditions contribute to increase the “natural” salinity of groundwater at the regional scale. At a local scale, the groundwater quality is influenced by infiltration of waste water and/or water that has percolated through solid municipal waste in the villages, which increases the mineralization of groundwater, in particular its chloride content downgradient of chloride sources (villages and poultry farms). Even small villages in rural area are shown to have an impact on the groundwater quality due to the absence of sewage collection and treatment facilities. At the present time, the level of chloride content is still acceptable but its accumulation in soil and groundwater must be monitored and controlled in order to avoid health problems for the local population for whom groundwater is the only source of drinking water.

This study shows that understanding pollution plume propagation requires an accurate piezometric map. By comparing both types of information (water table and EC maps) natural processes can be correctly identified.

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Figure 1

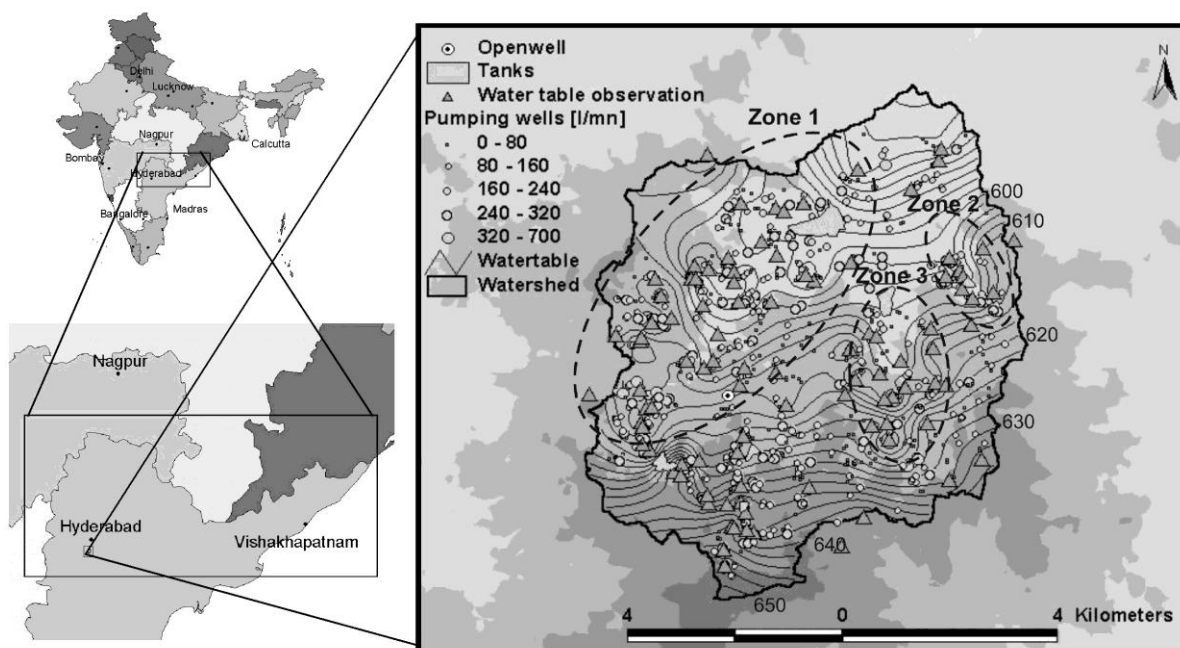


Figure 1 Piezometric map of the Maheshwaram watershed. Water table contours on a background constituted by digital elevation model (DEM). The size of the dots indicating pumping wells are proportional to the pumping rate.

Figure 2

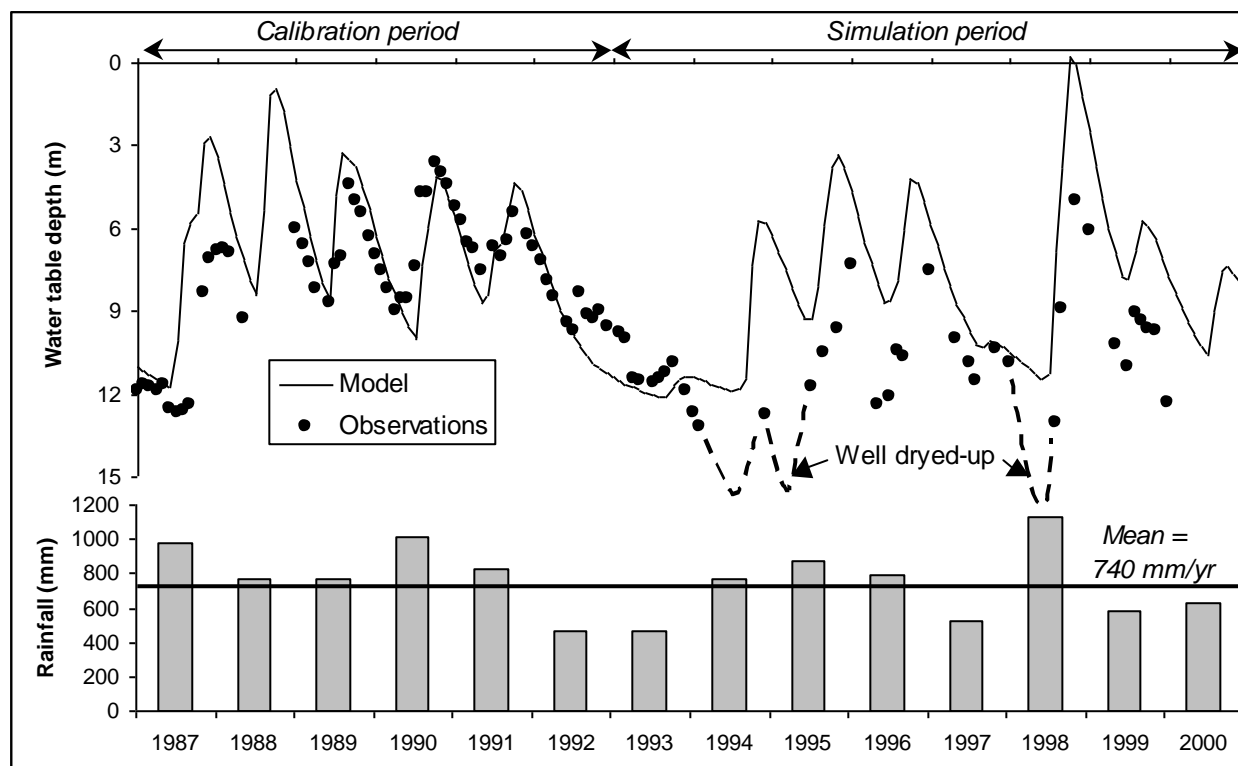


Figure 2 Annual rainfall at the Maheshwaram station, water table fluctuations observed in an open well and results of their simulation using a global hydrologic model

Figure 3

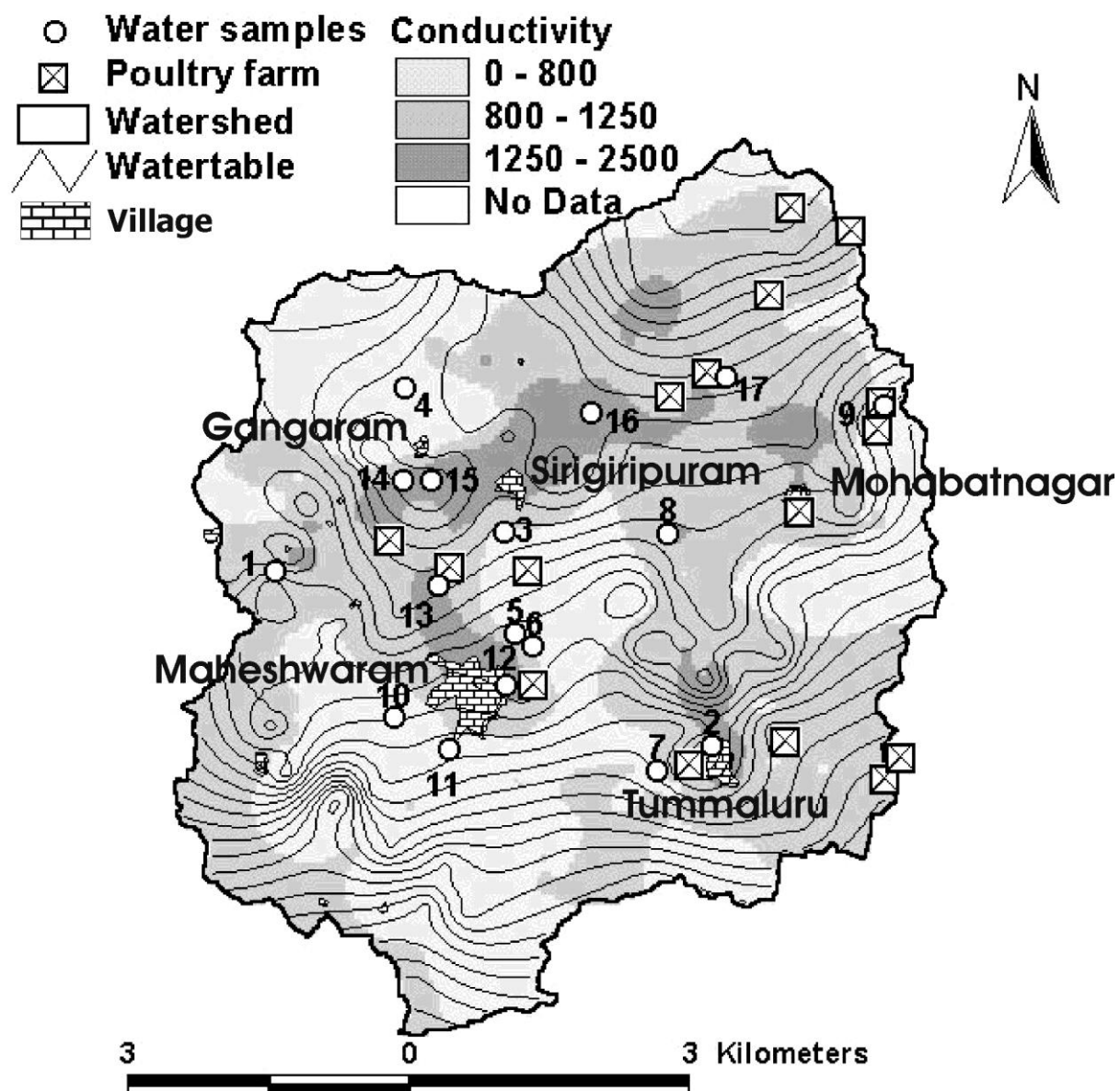


Figure 3 Groundwater electrical conductivity (EC) map, showing water table iso-levels. Circles indicate sites where samples were collected for major element determination.

Figure 4

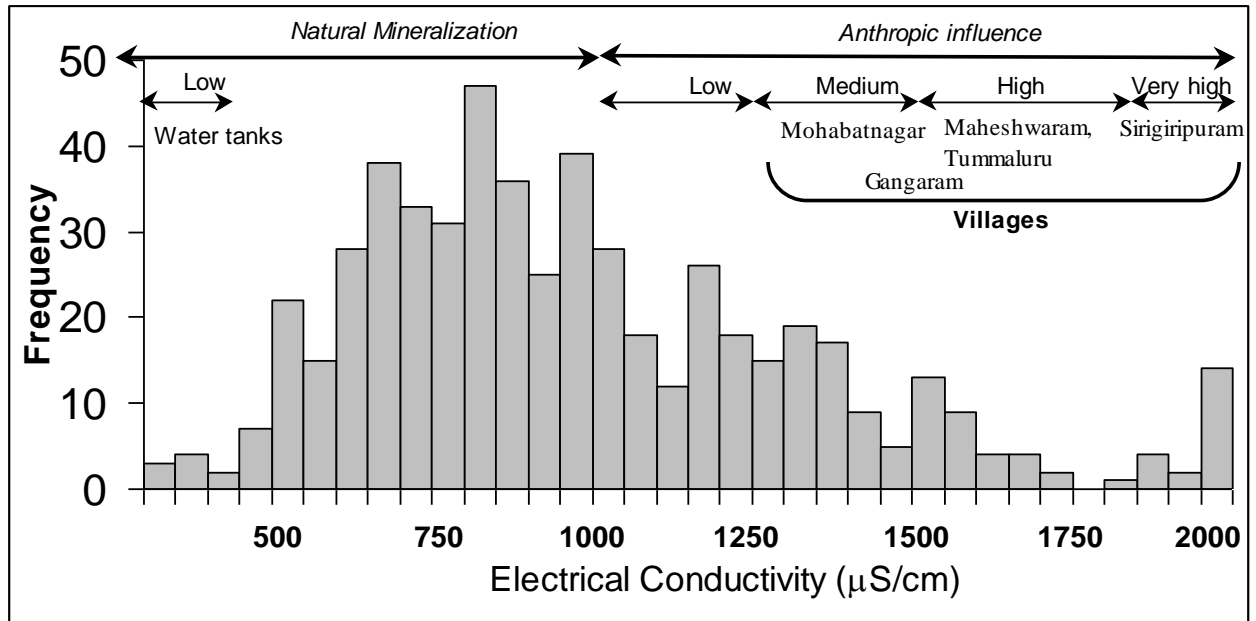


Figure 4 Histogram of groundwater electrical conductivity

Figure 5

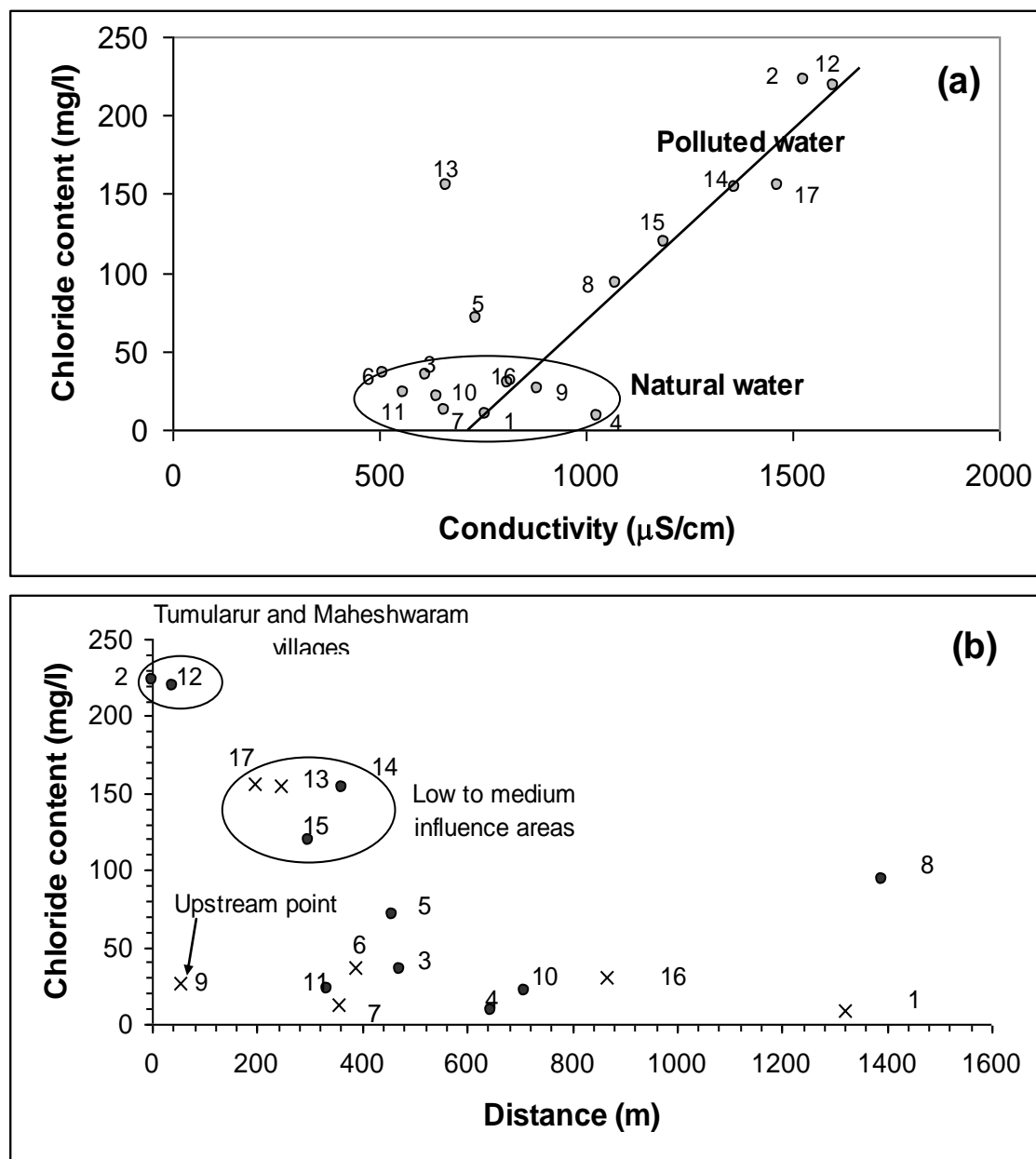


Figure 5 (a) Water chloride content vs. electrical conductivity (EC) in water samples from 17 wells (b) Chloride content in groundwater vs. the distance to the nearest possible chloride source ('x' village, '•' poultry farm)

Table 1

Village	Population (inhabitants)	Range of EC ($\mu\text{S}/\text{cm}$)	Influence rate	Hydraulic gradient (-)
Mohabatnagar	637	1250-1470	Medium	0.0091
Gangaram	764	1450-1600	Medium-High	0.0114
Maheshwaram	6611	1530-1720	High	0.0057
Tummaluru	2363	1520-1850	High	Very weak
Sirigiripuram	1150	> 2000	Very High	0

Table 1 Electrical conductivity (EC) measured down-gradient of the villages, village populations and local hydraulic gradients