Alluvial aquifer indicators for small-scale irrigation in northeast Brazil

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Abstract The Brazilian northeast is a semiarid area beset by drought and rural poverty. Irrigated agriculture exploits groundwater in the shallow alluvial aquifers in the base of the ribbon valleys. Uncontrolled exploitation and over-irrigation are leading to soil salinization and to degradation of the ground-water. Efforts have been made to promote efficient irrigation methods and to involve the farmers in reducing wastage. However, farm level water resource assessments are not yet undertaken to complement this activity. Farm and community level approaches to monitor and interpret groundwater level and salinity have been proposed. Interpretation has required physical studies to be undertaken in three typical groundwater systems in the region. The studies identify important links between hillslope runoff, groundwater use, subsurface controls and the annual and longer-term variations in water availability and water quality that have important impacts on sustainable groundwater use. Community level management is seen to be essential for sustainability.

Keywords drought alleviation; groundwater management; hillslope processes; monitoring; northeast Brazil; semiarid; small-scale irrigation; sustainability

INTRODUCTION

This paper describes one element of a United Kingdom Department for International Development (DfID) supported research project that currently is being undertaken in northeast Brazil. The project's overall aim is to demonstrate methods that will build the capacity of local communities in semiarid areas to achieve the sustainable use of groundwater resources for agricultural production and domestic needs. The demonstration is being carried out in three study areas in the semiarid area of northeast Brazil: Mimoso/Rosário, Campo Alegre and Mutuca (Fig. 1). It is anticipated that long-term sustainable use of the groundwater resource, through local management of the resource by the end-users, will lead to:

(a) Improved social standing of the local community (empowerment and participation in the management process).
(b) Reduced vulnerability and better livelihood outcomes through more secure water supply for domestic and agricultural purposes and food production (particularly during severe drought periods).

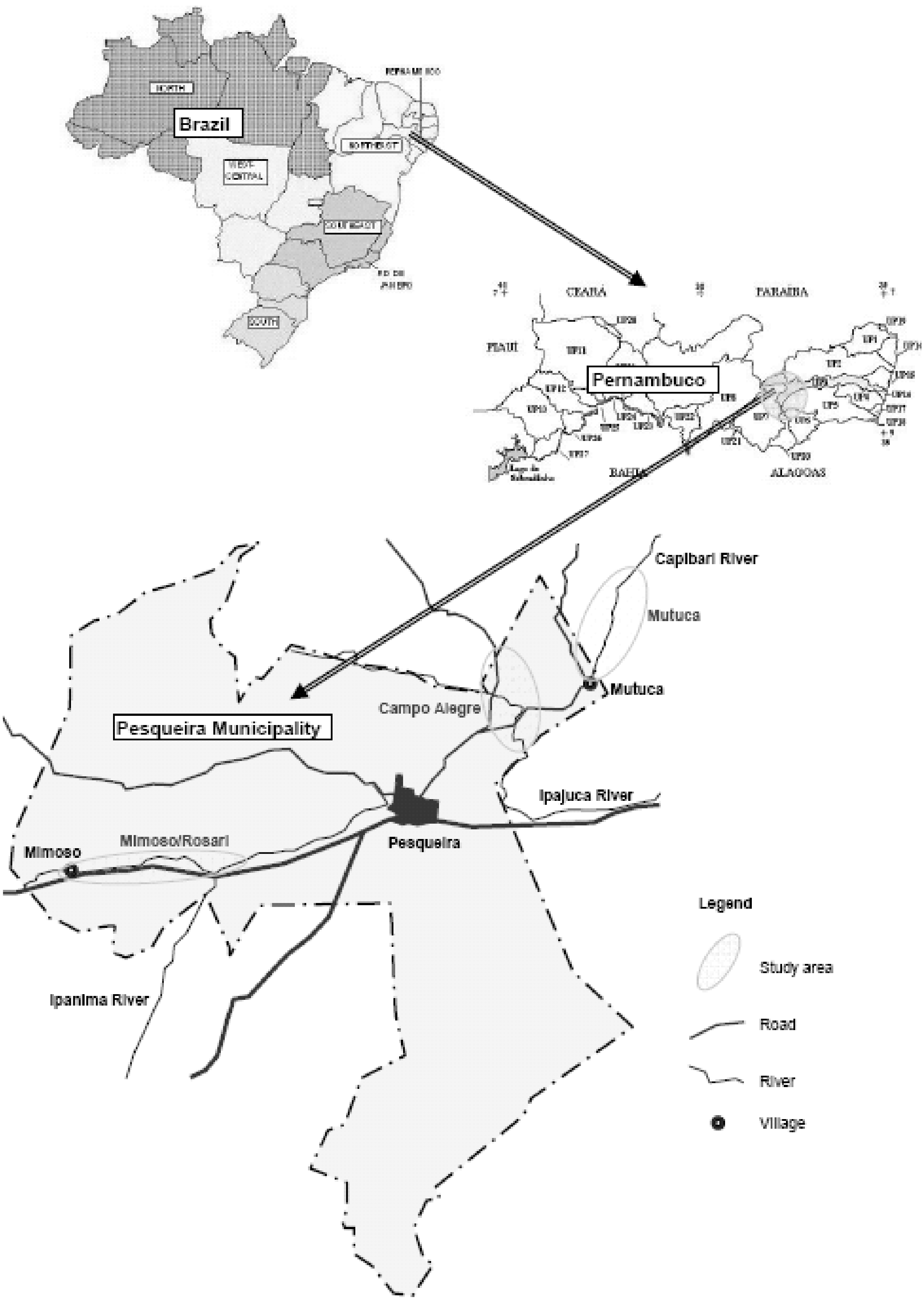

Fig. 1 Location of the study areas showing the three aquifer systems: Rosario, Mutuca and Campo Alegre.

(c) Reduction of harmful environmental impacts of over-exploitation of the groundwater resource (soil and water salinization and stress on natural vegetation imposed by groundwater level decline).

A significant aspect of the project is the demonstration of methods for monitoring the condition of the groundwater resource and their adoption by the communities to minimize wastage and to optimize the use of the groundwater resource during periods of water scarcity caused by frequent drought conditions.

Sustainability of the groundwater system is not simply about the control of groundwater exploitation to ensure availability at all times. It is much more about the establishment of decision rules that guide water consumption and water use depending on the risks of non-replenishment at different stages during the annual cycle of depletion of the resource and adverse water quality variations. If such decision rules are to be usable they must be based on sound interpretations of the behaviour of the groundwater resource under different climatic and operational conditions. For this reason, a programme of study has been undertaken to investigate the physical systems in each catchment and to determine the main water balance components and their impact on groundwater occurrence and water quality. Using the early data from these studies, a range of monitoring options has been proposed for farm and community level adoption. Participatory approaches are seen to be essential to the realization of long-term use of the monitoring systems and work is ongoing within the community through community led workshops and field trials. Initial results are encouraging but much work has still to be completed.

THE STUDY AREAS

The state of Pernambuco provides the setting for the study. Pernambuco State is characterized by three distinct sub-regions: the humid coastal area, known as the *Zona da Mata*, the transitional area, known as the *Agreste*, and the semiarid hinterlands, known as the *Sertão.* The humid *Zona da Mata* covers 11% of the area, whereas the transitional *Agreste* occupies 19% of the state and the dry *Sertão* covers 70% of the state land. The study areas are all located in the municipality of Pesqueira in the transition zone between *agreste* and *sertão*, in the semiarid region. The study areas are located in three different watersheds: Mutuca valley is located in the Capibaribe River basin; Mimoso valley is located in the Ipanema River basin; and Campo Alegre is located in the Ipojuca River basin.

Climate

The climate of all three study areas is similar to that monitored at the Pesqueira Meteorological Station, located between 15 and 20 km from the study areas. In Table 1, the main climate variables compiled from a 30-year period are presented. Rainfall is unevenly distributed, with 75% of the annual precipitation falling in 6 months (from January to July). The dry season—from September to January—accounts for about 47% of the annual evaporation. The temperature distribution is typical of a semiarid zone, with high temperatures and little variation. The annual maximum temperature is about 29°C and the minimum is just less than 18°C. The annual average relative humidity is 75%, with the highest values after the rainy period (May–July) and the

Table 1 Pesqueira Station main climate parameters (averages over the 30 year period from 1974 to 2003).

Parameters	J	F	M	A	M	J	J	A	S	O	N	D	Total/Average
PREC (mm)	51	91	86	121	101	81	72	37	23	19	18	29	730
TEMP (^{o}C)	25	24	24	23	22	21	20	20	22	23	24	24	23
PE (mm)	164	147	153	133	122	106	110	125	140	159	160	163	1683

lowest values in the dry period (September–November). Insolation reaches a value close to 2400 h year^{-1}, which means a daily solar incidence of about 5 h uniformly distributed throughout the year. About 19% of the annual insolation occurs from May to July. Winds are predominantly southwestern with moderate wind velocities of less than 4.4 m s^{-1}: the greatest wind speeds occur in the dry period.

Groundwater occurrence and exploitation

Characterization of the Mimoso valley has been previously developed through the long term development of a communal irrigation project located at "Nossa Senhora do Rosário" *assentamento* and monitoring activities, described in Montenegro *et al.* (2003a). The *assentamento* lies in a gently sloping watershed. The average altitude is 630 m above sea level, with an average natural slope of 0.3% in the line of the valley. The flat topography controls the natural drainage of the system. The watershed stream network comprises the "Mimoso", "Ipaneminha" and "Jatoba" tributaries. The "Mimoso" is the main tributary of the watershed and is connected to the aquifer along its length. These tributaries are ephemeral, flooding the area during wet rainy seasons, and becoming dry for several months in the dry season. The use of the surface water resources, which are regulated by means of small dams, has been restricted to domestic supply of the nearby cities. Thus, the groundwater is the only suitable source of water for irrigation. The underlying alluvial aquifer is relatively shallow, about 10 m deep, 300 m wide and 15 km long. The aquifer is a fine to medium sand deposit, with some clay lenses. The water table in the area is relatively shallow, with depths ranging from 1.2 to 5 m. Previous hydrological studies have indicated values between 160 000 and 300 000 m^3 as the annual exploitable water resource in the aquifer (CONESP, 1988; Montenegro, 1997). The average hydraulic conductivity has been found to be about 5–6 m day^{-1} and the specific yield is about 6% (CONESP, 1988). The relatively high hydraulic conductivity has allowed aquifer exploitation by open wells, connected to lateral multilevel drain tubes (radial collectors). Pedological investigations have been carried out in the "Nossa Senhora do Rosário" *assentamento* area in order to adequately identify those soils with potential to be irrigated, mainly from the point of view of drainage and water transmission. The total area of the survey constitutes 173.6 ha. The soils were classified into five groups: alluvial, yellow red podzol, regosol, litholic and gleyed. More regionally, the upstream area is characterized by sandy soils with little clay, but the clays increase significantly downstream. The upstream area has good drainage caused by natural soil units while downstream the soil drainage is more restricted. The link between geology and pedology is apparent in this simple

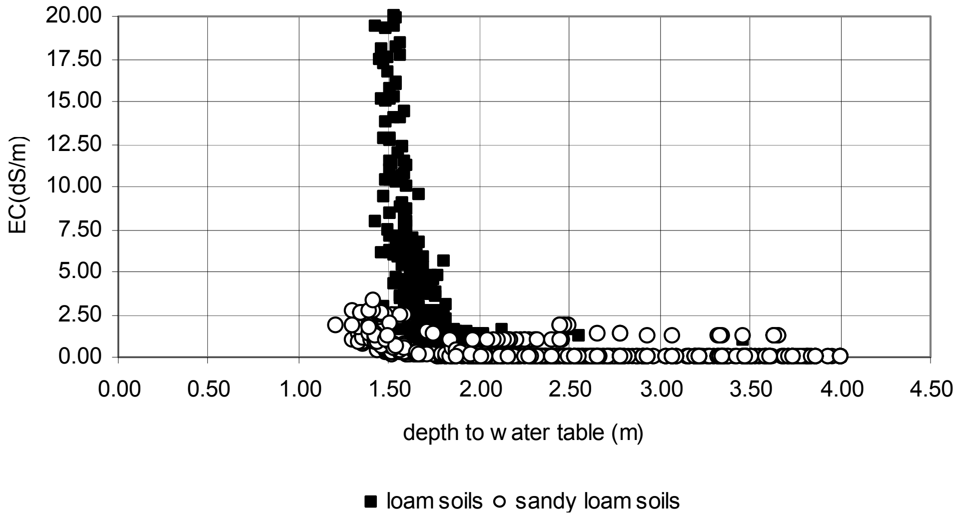

Fig. 2 Soil electrical conductivity as a function of the groundwater depth at Nossa Senhora do Rosario farm, for two soil indicators.

observation (Montenegro *et al.*, 2003a). According to the available soil data, the salinity is also strongly correlated with the geology and soil texture, but it is also partly linked to the inputs of water and salts from the stream tributaries that join the main stream. Numerical modelling using the saturated zone code PARADIGM (Mackay, 1993) coupled to a lumped unsaturated zone model (Montenegro *et al.*, 2002) was undertaken to explore salt concentration in the root zone arising from groundwater-fed irrigation. Results for soil salinity as a function of groundwater depth are shown in Fig. 2. The distribution reflects conditions in the middle of the dry season, just after three months irrigation, using water applications corresponding to a leaching coefficient of 1.20. It is evident from this and other simulations that the loam soils, where groundwater is less than 2 m deep, are at risk, mainly due to secondary salinization from groundwater. This result is being validated within the current project.

The Mutuca valley contains 10 underground dams built along the alluvial valley of the Mimoso rivulet (in the Capibaribe River basin) by the Pernambuco State Government in 1999. The valley is located on the border between Jataúba (to the north) and the Belo Jardim municipality, and is covered by a high percentage of planosols. Although the valley sediments are relatively deep (from 4.0 to 10 m), impermeable layers restrict direct recharge. Groundwater storage is partly controlled by the underground dams and partly by natural barriers to flow along the valley where harder basement rocks occur close to the bed of the river. Irrigation is practiced primarily using the groundwater reserves upstream of each dam. In addition to monitoring along the valley and investigations into recharge mechanisms, a pilot area has been installed with micro-sprinkler irrigation, just upstream from one of the dams. Montenegro *et al.* (2003b) detail the hydrogeological behaviour of this unit, and the irrigation impact on water quality. According to Montenegro *et al.* (2003b), loam and sandy loam soils are also dominant in this valley. Infiltration tests have been conducted across the area, indicating an average infiltration rate of 90 mm day^{-1}. Such low infiltration characteristics require careful irrigation management and low irrigation water depths. Soil electrical conductivity monitoring during the dry season in 2003 indicated that around 35% of the total samples analysed exhibited values greater than 4 dS m^{-1}, which requires salt management.

Campo Alegre is the least well characterized of the three study areas. Physically, it is distinctly different to both of the other two study areas in that the alluvial sediments are constrained in a much narrower valley. The Campo Alegre area has an undulating relief, and valleys with relatively steep sides and narrow alluvium bands occur. The morphogenetic forces that created the geomorphological unit of the local Borborema Formation have moulded the relief. The alluvial-colluvial sandy sediments, attributed to the Holocene period, occur predominantly in narrow zones on the edges of the Ipojuca River. All of the irrigation area has already been deforested. Only isolated locations can be found where the original vegetation of the Caatinga remains. Groundwater is highly saline in the dry season, limiting crop production and irrigation. The study area is located in the part of the catchment downstream from the eastern boundary of the Xukurú Indian Reservation. Near the head of the steep sided valley, on Xukuru reservation land, is the Pão de Açucar reservoir. This is the largest reservoir in the region (with a capacity of 45 Mm^3) and has a major controlling influence on the transmission and retention of waters in the river system. Historically, waters were released along the river from the Pão de Açucar reservoir, and these certainly were exploited for irrigation. Since the start of the drought in 1988, the flows in the river have been reduced significantly and groundwater exploitation from the alluvial deposits was expanded to compensate for the reduced surface flows. Most of the wells excavated in the alluvium were destroyed during the recent heavy floods. Several dams/weirs are located along the river corridor, which impede surface and subsurface water flow. The impounded waters upstream of these structures provide surface water for irrigation during the rainy season and groundwater exploitation as the surface waters recede in the dry season. The alluvium cannot sustain groundwater supplies indefinitely during drought periods and the water becomes strongly salinized. Streams contributing to the river have been dammed to construct small water supply reservoirs in some parts of the catchment. Rain-fed agriculture is extensively practised. Rainwater harvesting on these agricultural areas is restricted. Soils in the area are typically thin, overlying regolith, and these have limited moisture-holding capacity. Livestock farming is a major component of the land use of the area. Some rainwater is trapped behind earth embankments for livestock watering.

DATA COLLECTION

The programme of data collection for the current project was initiated at the end of 2003 (although previous projects have been monitoring the area since 1994) and includes direct measurements of groundwater availability and quality and indirect observations obtained through systematic farm level and community level surveys. Direct measurements have included spatial mapping of farm units, well locations and capacities, formations and soils (Milmo, 2004), geophysical measurements of aquifer depth and groundwater flows (Last, 2004), borehole investigations of lithology and hydraulic property measurements (Hardisty, 2004) as well as infiltration capacities and recharge characteristics (Walker, 2004). Salinity measurements have been taken from a majority of the wells on a regular basis, as well as soil salinity measurements and runoff and surface water measurements. Indirect observations have covered historical data on groundwater use, patterns of cultivation, evidence of water stress, water management strategies and community practices at times of water shortage.

INTERPRETATION OF THE CURRENT DATA

A basic conceptual model describing the functioning of the groundwater system in each of the study areas has been established from the available data and is schematically illustrated in Fig. 3. The main features of the conceptual model can be summarized as follows. Recharge of the aquifers is achieved through surface water floods from upstream areas and from adjacent hillslope runoff processes (both surface and subsurface). Minor rainfalls do not lead to significant recharge: recharge is limited to more intense periods of rainfall (>40 mm day^{-1}). The surface water floods are typically of short duration but provide a significant proportion of the total recharge contribution during the rainy season. Overland flows appear to be of relatively low salinity (1 mS cm^{-1}) and therefore the salinity of the groundwater is reduced in the first weeks following a recharge event in the rainy season. Delayed recharge occurs as a result of sub-surface hillslope runoff. The salinity of this water is substantially higher (4 mS cm^{-1}) which leads to a significant increase in salinity that appears after a delay period of up to 3 months in the observations of groundwater salinity in the alluvial formations. Salinities are then controlled by irrigation, which further increases the salinity through evaporation and the leaching of soil-water salts. During periods of drought, salinity reductions due to overland flow and flooding do not arise and salinity progressively increases as the groundwater levels decline and the only recharge contributions arise from slow migration of hillslope waters into the aquifers. Thus, in periods of drought, groundwater exploitation for irrigation is restricted both due to the reduced discharge capacity of the wells and due to the poorer quality of the water. The pattern of salinity variation shown in Fig. 4 for Rosario farm (Montenegro & Montenegro, 2004) provides an illustration of the consistency of this conceptual model.

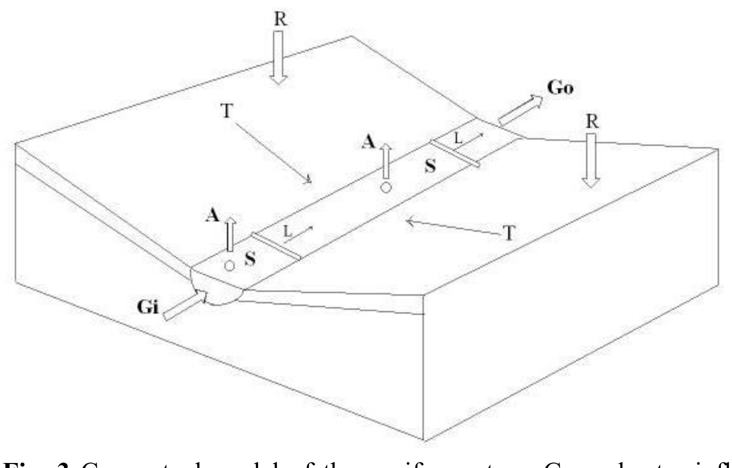

Fig. 3 Conceptual model of the aquifer system. Groundwater inflows (Gi) feed the system along with effective rainfall on the hillslopes (R), which reaches the aquifer as recharge in throughflow in the basement granite (T). Upstream of each dam is a store (S), and downstream of each dam is a component of dam leakage (L)

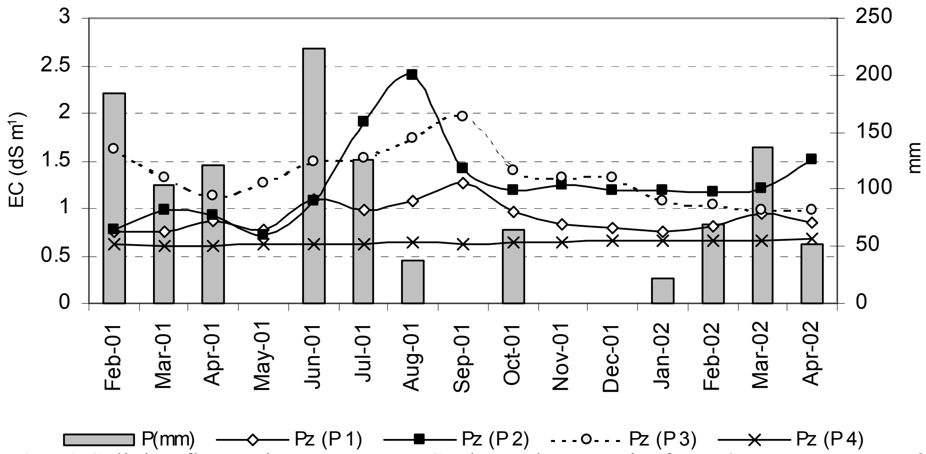

Fig. 4 Salinity fluctuations at Nossa Senhora do Rosario farm (Montenegro *et al.*, 2004)

The pattern of annual groundwater recharge and salinity variations depicted by this conceptual model imply that groundwater-fed irrigation should adopt a pattern that reflects the recharge patterns. Production of salt intolerant crops should immediately follow flood recharge periods with salt tolerant plants being cropped during second or third irrigation periods. The risks of crop failure increase substantially due to high salinities and low water availability when groundwater recharge is not maintained by flooding. In this case, salinity level indicators are needed that can be applied by the farmers. One possibility is to provide salinity meters but these are expensive when compared to the typical incomes of the farmers. The second option is to use a combination of groundwater level data combined with records of flood timings. These indicators can be easily measured and recorded, although they have a level of uncertainty associated with them that will depend on the pattern of irrigation and the scale of recharge from the different sources in any one year. In addition, soil types influence this uncertainty, suggesting groundwater depth management may be practised more easily beneath loamy soils.

Excess irrigation during drought periods can render the groundwater unsuitable for drinking water. Since drinking water is essential to the population during periods of drought and because a loss of income from irrigation can be offset by alternative income sources (such as lace making), restrictions on groundwater irrigation are also needed to maintain drinking water supplies. The use of salinity level indicators must therefore be implemented to determine the stage at which groundwater irrigation should cease until a flood recharge event. The maintenance of records of recharge conditions and groundwater levels can provide this information in the same manner as that proposed to determine crop type. Maintenance of records is most effectively achieved at the community level and a water users association might potentially be forged to facilitate such record keeping. Work is currently ongoing to extend the ideas and concepts presented in this paper.

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