Groundwater evolution beneath Hat Yai, a rapidly developing city in Thailand

Abstract Many cities and towns in South and Southeast Asia are unsewered, and urban wastewaters are often discharged either directly to the ground or to surface-water canals and channels. This practice can result in widespread contamination of the shallow groundwater. In Hat Yai, southern Thailand, seepage of urban wastewaters has produced substantial deterioration in the quality of the shallow groundwater directly beneath the city. For this reason, the majority of the potable water supply is obtained from groundwater in deeper semi-confined aquifers 30-50 m below the surface. However, downward leakage of shallow groundwater from beneath the city is a significant component of recharge to the deeper aquifer, which has long-term implications for water quality. Results from cored boreholes and shallow nested peizometers are presented. The combination of high organic content of the urban recharge and the shallow depth to the water table has produced strongly reducing conditions in the upper layer and the mobilisation of arsenic. A simple analytical model has shows that time scales for downward leakage, from the surface through the upper aquitard to the semi-confined aquifer, are of the order of several decades.

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Introduction

The rapid and often unplanned expansion of cities in developing countries means that urban infrastructure and services lag behind population growth. Sewerage cover in particular is usually low in many cities and towns of South and Southeast Asia, and as a consequence urban wastewaters are frequently discharged to the ground or to surface-water courses. Many cities in developing countries use groundwater for urban water supply. However, shallow groundwater beneath these cities is frequently contaminated, largely as a result of the disposal of urban wastes that are rich in organic carbon and nitrogen. As a consequence, shallow aquifers are often abandoned in favour of deeper ones. Yet, pumping from these same deeper aquifers can impose steep vertical hydraulic gradients and induce significant leakage from shallow units. Incipient contamination of deeper aquifers caused by induced downward leakage of shallow groundwater has been observed in Hat Yai, Thailand (Lawrence et al. 1994) and in Leon, Mexico (Chilton et al. 1998).

Hat Yai is the third largest city of Thailand, after Bangkok and Chiang Mai, with a municipal population of 157,062 in 1995, within an area of about 21 km^2. In common with many other cities in the region, it is expanding rapidly. Hat Yai has a strategic location in the southern part of the country near the Malaysian border as shown in *Figure 1*, and serves as a business, industrial, and tourist centre for the surrounding region. The city is situated at an elevation of 5-10 m amsl in a low-lying valley that is bounded by low hills. Two rivers, the Khlong U-Tao Phao and Khlong Toei, flow down the valley and through Hat Yai, where they receive large quantities of urban wastewater.

The area has consistently high temperatures throughout the year (the average annual temperature exceeds 27^{o}C). The total annual average rainfall is 1816 mm, with a distinct rainy season during October to December. Evaporation rates are high; open-pan evaporation exceeds 1850 mm/a. Infiltration to groundwater is about 170 mm/a.

The objectives of this paper are to (1) demonstrate that for Hat Yai, downward leakage from beneath the city provides a significant component of recharge to the semi-confined aquifer; (2) describe the evolution of water quality within the semi-confining unit beneath the city; and (3) confirm that the timescales for this leakage to reach the underlying aquifer are of the order of several decades.

Geology and Hydrogeology

The Hat Yai valley is underlain by a thick sequence of Quaternary and Recent alluvial sediments, which in turn rest upon Permian metasediments. The valley is fault-bounded and the valley sides are composed of the Permian metasediments, which have been faulted up to form low but steep-sided hills. The alluvial sediments within the valley have a thickness that locally exceeds 250 m, and they contain three major aquifer units. These are named the Hat Yai aquifer, the Khu-Tao aquifer and Kho-Hong aquifer; they are at depths of 25-40 m, 45-80 m, and greater than 100 m, respectively. The aquifers consist of sand and/or gravel and are separated by aquitards of poorly permeable fine sand, silt and clay (Ramnarong et al. 1984).

Hat Yai obtains about 50% of its urban water supply from groundwater. Most of the groundwater abstraction is from the semi-confined Hat Yai aquifer. Pumping is mostly from privately owned boreholes used to supply hotels and industry, which are largely concentrated within the city centre. The Hat Yai aquifer is overlain by about 30 m of relatively poorly permeable sand, silt, and clay. In these upper less permeable deposits is a relatively shallow water table, which is maintained by high urban recharge originating from the high rainfall combined with leaking water mains, infiltration from canals and seepage from on-site sanitation systems.

Background water quality in the Hat Yai aquifer is excellent; electrical conductivities are below 50 µS/cm and chloride is less than 10 mg/L. However, monitoring of groundwater quality in the city centre has revealed elevated NH_4 and Cl concentrations indicating incipient contamination as shown in *Figure 2*. The main source of this contamination is believed to be seepage from canals, which receive the bulk of the urban wastewaters (Lawrence et al. 1994). The use of canals for disposal of urban wastewaters is a common practice in low-lying cities of Southeast Asia, where shallow water tables make infiltration from on-site sanitation systems difficult due to surfacing of the effluent during monsoon periods.

Field Study

A simple conceptual model of the groundwater system beneath the city was proposed as displayed in *Figure 3*. The model suggests that downward leakage is greatest beneath the city centre where abstraction is also at a maximum. The shallow groundwater beneath the city centre is assumed to be polluted. The coincidence of maximal leakage with the area where shallow groundwater is assumed to be most contaminated has serious implications for the future water quality in the deeper aquifer.

A field programme was designed to gain more information on the upper aquitard layer, including the lithology, vertical head gradients, and water chemistry in order to test this model. Piezometers were installed in groups of three at five sites across the city to depths of 10, 15, and 24 m. The locations of each of these sites is shown in *Figure 4*. Each piezometer was screened with PVC casing that was slotted over the last two metres and sealed at the bottom with a PVC cap. The piezometers were completed with a gravel pack and sealed at the surface with bentonite. Unfortunately the deepest borehole at site GPH3-4 became contaminated with bentonite during well completion and as a consequence no groundwater data is presented for this piezometer.

During the drilling of the piezometers, an attempt was made to collect cores for pore-water analysis. The local geology is quite variable, with layers of sand interbedded with clay. By a combination of augering through the clay and percussion drilling through the more consolidated sand, reasonable core recovery was obtained. The maximum cored depth was 16 m; the minimum was just 8 m. Once removed from the ground, the core was split longitudinally into two segments, transferred to plastic bags, sealed, and then stored at 4(C. One half of the core was retained for microbial determinations carried out locally, the other was shipped to the UK for pore-water extraction. Pore-waters were extracted by centrifugation (Edmunds and Bath 1976) and the resulting water was analysed for various cations and anions.

On completion of the drilling, water samples were obtained with a small submersible pump from all 15 piezometers. Unstable parameters (pH, redox potential, dissolved oxygen and alkalinity) were determined at the well head. Filtered water samples were returned to the UK for major- and trace- element analysis. In addition, samples were taken at carefully selected sites along the canal and also returned to the UK for the same analytical suite. The analytical chemistry procedures used are described elsewhere in Gooddy et al. (1995).

At three sites, devices for automatic water-level monitoring were installed to observe and record the vertical head differences with depth. Hydraulic testing of the piezometers was carried out at three of the five sites to characterise the upper confining layer. Falling-head tests and short pumping tests were performed on all three piezometers at each of the sites, and the data were recorded using automatic loggers (Gooddy et al. 1997). Data were analysed to obtain the permeability of the confining layer over the depth screened in each piezometer. After the testing, groundwater-level loggers were installed at the three sites as a system for long-term groundwater monitoring; groundwater levels were measured hourly.

Results

Hydrogeology

The results of the drilling broadly confirmed the conceptual model and showed that the aquitard consists of an upper, relatively more permeable, layer of clayey sand overlying a less permeable silty clay. Water levels in the piezometers confirmed the existence of a downward vertical head gradient that approaches 1 in 2 towards the city centre (*Figure 4*). The daily water level response in the piezometers (especially the deeper ones) to pumping from the Hat Yai aquifer is shown in *Figure 5*, and the close correspondence of the responses at the different piezometers confirms the hydraulic connectivity through the aquitard. An estimate of vertical hydraulic conductivity was made from these results, and the value is consistent with the values obtained in the hydraulic tests and that used in modeling. Vertical permeabilities are greater near the top of the aquitard, where drilling indicated that the sediment is more sandy.

Horizontal permeabilities were obtained from falling-head tests and pumping tests. The results indicate that horizontal permeability decreases with depth within the aquitard, and this is in agreement with the lithologies observed while drilling. Values of permeability obtained are very similar for the various sites; permeabilities of 1-5 m/d were measured at a depth of 10 m bgl, 0.4-0.6 m/d at a depth of 15 m bgl, and lower values of 0.01-0.05 m/d at depths of 23 m bgl. The effective vertical permeability of the confining layer, for the purposes of estimating vertical leakage, is dominated by material with the lowest permeability through which water must pass, and vertical permeabilities are usually about an order of magnitude less than horizontal permeabilities. Thus vertical permeabilities probably range from 0.1-0.5 m/d in the upper part of the semi-confining unit and closer to 0.001-0.005 m/d in the less permeable part of the semi-confining unit.

Hydrochemistry

A summary of results from the pumped groundwaters from the peizometers is shown in *Table 1*. These data show that beneath the city groundwaters are contaminated with elevated concentrations of ammonia (nearly 20 mg/L as N), chloride (more than 60 mg/L), and dissolved organic carbon (3.7 mg/L). Only in the deeper piezometers located near the edge of the city do groundwater concentrations approach background values (*Figure 6*) with the chloride concentration falling to below 3 mg/L and sodium and potassium following a similar pattern. Bicarbonate concentrations are highest beneath the city centre and decrease with increasing depth and increasing distance from the centre ranging from more than 200 mg/L at the most contaminated sites to less than 10 mg/L at the least contaminated. Similarly iron and manganese show very high concentrations (up to 28 mg/L and 1.9 mg/L respectively) beneath the city centre but decrease by two orders of magnitude in the deepest borehole at the city limits. Concentrations of dissolved organic carbon are relatively enhanced in the canals (*Table 1*) ranging from 4.5 – 16.7 mg/L and are high in the pore-waters as shown in *Figure 7*, with a maximum concentration of 47 mg/L near the surface and a peak of 35 mg/L at 8 metres below the surface. These values are high, although not as high as those in more arid climates (Ronen and Margaritz 1985). These findings are consistent with the concept that the canal water in Hat Yai contains domestic wastewater and is recharging the shallow aquitard.

Hydrochemical Evolution

In contaminated groundwater bodies, abiotic or biologically mediated chemical transformations of organic compounds are closely linked with the local geochemical environment. The overall favorability of specific degradation pathways depends upon prevailing redox conditions in terms of the availability of electron acceptors/donors and the presence of suitable microorganisms. In turn, the transformation of significant quantities of organic compounds may feed back to impact groundwater chemistry in terms of aqueous speciation (particularly redox-active species), pH, and the saturation states of various mineral phases (Lee and Bennett 1998). The results are discussed in the framework of groundwater quality deteriorating as urbanisation occurs rapidly, and relate to the different locations within the aquitard and the principal chemical processes controlling the water quality. With a highly complex and variable contaminant source such as a wastewater canal and changes in the local geology many geochemical reactions are occurring in the shallow subsurface environment and the equations presented are merely to represent the type of reactions that are taking place and are certainly not definitive.

In the unconfined phreatic aquifer, which has a very shallow water table, the data show that dissolved oxygen is largely absent. Because virtually no unsaturated zone exists, the little oxygen that was available (especially compared with many unconfined aquifers) is consumed during the oxidation of the organic matter (1):

$$CH_2O + O_2 \; (\; CO_2 + H_2O \tag{1}$$

When oxygen is the electron acceptor, carbon dioxide is produced resulting in the formation of carbonic acid that reacts with carbonate minerals. That is, when oxygen is in the system the geochemistry is controlled primarily by carbonate equilibrium (2-4):

$$H_2O + CO_2 \; (\; H_2CO_3 \tag{2}$$

$$H_2CO_3 \; (\; H^+ + HCO_3^- \tag{3}$$

$$HCO_3^- \; (\; H^+ + CO_3^{2-} \tag{4}$$

Base cation concentrations (primarily calcium and magnesium) in the groundwater are very low (typically less than 20 mg/L for calcium and 2 mg/L for magnesium). This condition probably reflects the evolution of groundwater beneath the city. During initial stages of urbanisation, leakage from septic tanks and the canals may have occurred, but sufficient oxygen was still present to enable nitrification (5):

$$NH_4^+ + 2O_2 \; (\; NO_3^- + 2H^+ + H_2O \tag{5}$$

In poorly buffered sediments, the addition of protons is buffered primarily by the alkalinity of the matrix. Where concentrations of aqueous base cations are low either little nitrification is taking place or the source of base cations has already been depleted. Pore-water profiles for most sites show high calcium concentrations (up to 250 mg/L) for the upper few metres of the profile, suggesting that some nitrification is taking place in the very shallow unsaturated zone where oxygen should still be available. In contrast, at depth the calcium source, together with oxygen, has been largely removed during the earlier evolution of the system. An example is given in *Figure 7*. Therefore, beneath the water table, dissolved oxygen is rapidly depleted and other ions take over as terminal electron acceptors and include nitrate, manganese, iron, and sulphate. When these electron acceptors are used bicarbonate is produced without generating acidity, and without significant carbonate dissolution (6-8):

$$5CH_2O + 4NO_3^- \; (\; 2N_2 + 2HCO_3^- + CO_2 + 3H_2O \tag{6}$$

$$CH_2O + 3Fe(OH)_3 \; (\; HCO_3^- + 3Fe^{2+} + 4OH^- + 3H_2O \tag{7}$$

$$2CH_2O + SO_4^{2-} \; (\; H_2S + 2HCO_3^- \tag{8}$$

Beneath the city centre, concentrations of ammonia and iron in the shallow groundwater are greatest, and redox potential is at its lowest, all consistent with iron and sulphate as the electron acceptors. Reaction 7 results in an increase in dissolved ferrous iron and bicarbonate but also results in the production of hydroxide; hence, the pH increases. This condition is observed in the most contaminated sites beneath the city centre; these sites have much greater concentrations of iron and bicarbonate and a higher pH than the least contaminated site. Farther away from the city centre, the redox potential is higher and manganese and nitrate dominate as electron acceptors.

The upper 2-3 m of the porewater profiles represents the unsaturated zone and, below this in the saturated zone, pore-water iron concentrations begin to increase as conditions become more reducing. The relatively low concentrations of iron and nitrate in the upper few metres and the presence of ammonia (*Figure 7*) could indicate pyrite oxidation (to reduce the oxidation state of iron) (9), followed by nitrate reduction (10):

$$\mathrm{5FeS_2 + 14NO_3^- + 4H^+ \ (\ 7N_2 + 5Fe^{2+} + 10SO_4 + 2H_2O} \tag{9}$$

$$\mathrm{10Fe^{2+} + 2NO_3^- + 14H_2O \ (\ 10FeOOH + N_2 + 18H^+} \tag{10}$$

This reaction generates a large number of protons that would require buffering.

Alternatively the high concentration of ammonia and low concentrations of nitrate may indicate another possible way of denitrification (11):

$$\mathrm{NO_3^- + H_2O + 2CH_2O \ (\ NH_4^+ + 2HCO_3^-} \tag{11}$$

The profile also contains high concentrations of manganese, although iron reduction is the dominant electron acceptor process in the upper 10 m. Below this depth, sulphate concentrations decline rapidly as sulphate reduction commences. Iron concentrations also decrease as iron sulphides are formed and precipitated. At the most contaminated sites, evidence for sulphate reduction from the depleted sulphate concentrations exists is the form of black sulphide deposits on the interior of the piezometer casing and an odour of hydrogen sulphide. These zones have yielded groundwater with arsenic concentrations up to 1 mg/L (one hundred times the value of the WHO recommended limit, WHO (1995)). Arsenic is likely to be naturally present in the rock matrix as arsenopyrite or adsorbed to ferric hydroxides.

Criteria for redox parameters that could be used for assigning redox status to groundwater samples affected by landfill leachate based on redox-sensitive compounds have previously been developed by Lyngkilde and Christensen (1992). They recognised that although electrochemical determination of redox potentials is mechanically very simple, it often yields results which are difficult to interpret or in some cases misleading. Identifying redox zones is very important in terms of understanding pollutant fate in a contaminant plume (Gooddy et al. 1998). The criteria used for the groundwater beneath Hat Yai., which are similar to those used by Lyngkilde and Christensen are presented in *Table 2*.

Microbially mediated methane generation in groundwater in general proceeds by either reduction of carbon dioxide or fermentation of organic carbon (Appelo and Postma 1993). Methane formation involving organic sources may be approximated by (12):

$$\mathrm{2CH_2O \ (\ CH_4 + CO_2} \tag{12}$$

Although no direct measurements were made for methane the presence of a methanogenic zone has been inferred from the redox criteria used.

Figure 8 shows a cross section across the city form South to North with the redox zones indicated. The large range observed for most of the parameters within each redox status shows the wide span of groundwater samples belonging to the same group. Average values reveal that the redox status is closely correlated to the pollution level. Conditions are most reducing beneath the city centre, where methanogenic/sulphidogenic conditions extend to a depth of at least 24 m. A slight skew exists in the redox conditions toward the northern end of the city, possibly due to limited lateral movement from the canal. The environment becomes less reducing both with distance from the city centre along the canal and with distance from the canal. The highest DOC concentrations occur at the most contaminated sites, implying that a build-up of organic carbon occurs as terminal electron acceptors are sequentially consumed.

Discussion

Groundwater abstraction from the semi-confined Hat Yai aquifer has produced steep vertical head gradients within the aquitard. Substantial downward leakage is possible, even though the permeability determined for the aquitard is relatively low. A simple analytical model was developed to describe vertical leakage beneath Hat Yai city (Barker and Lawrence 1994). The model results indicate that the vertical permeability of the aquitard is about 0.002 m/d. The model and field values are therefore in reasonable agreement.

The water-quality data presented provide strong evidence for the significant reduction in redox potential of the groundwater in the aquitard as a result of the seepage of water high in organic carbon from the canals. This appears to be an evolving process, with the most reducing groundwaters occurring beneath the city centre close to where seepage is greatest. These strongly reducing groundwaters will probably spread outward with time. The change in redox potential is significant, because it produces changes in the quality of groundwater in the aquitard by mobilising redox-sensitive elements. Evidence already exists that these shallow groundwaters in the aquitard are producing changes to water quality in the underlying Hat Yai aquifer as a direct result of pumping induced leakage (Lawrence et al. 1994).

The front of polluted groundwater within the aquitard has ’broken through’ into the aquifer within a radial distance of less than 1 km of the city centre. From *Figure 6* it can be seen that a comparison of the front position with modeled travel-time fronts suggests that the front originated from recharge 30-35 years ago. Since Hat Yai expanded rapidly in the 1960s and 1970s this timeframe is quite reasonable and provides validation of the model. These time scales of 30-35 years to migrate through the aquitard have important implications, because whereas monitoring of groundwater in the semi-confined aquifers shows no pollution, this result may simply be because the pollution front has not migrated through the aquitard. Once the front has broken through, pollution would spread out radially through the aquifer unless vertical gradients can be reversed, which would be extremely difficult to achieve in practice. Likewise, whereas removal of organic loading at the surface would have beneficial effects in the longer term, it would take decades for the better quality shallow water to flush through to the aquifer.

A special concern is the very high concentrations of arsenic in the shallow groundwater; the arsenic could originate from oxidation of sulphide minerals or desorption from iron oxides. The relationship between arsenic and sulphate is shown in *Figure 9*. The presence of reducing conditions and sulphide precipitation on the borehole casing implies that active sulphide oxidation is not occurring. Therefore arsenic mobility is probably controlled by desorption from iron oxide phases followed by some reprecipitation of sulphides as redox moves from oxidizing to reducing conditions. In the most reducing environments dissolution of arsenic occurs at a greater rate than its removal from solution by sulphide precipitation, hence, very high concentrations are observed in the groundwater.

The addition of organic materials has not only facilitated some chemical reactions but greatly accelerated others. Previous studies have noted that under certain conditions, organo-metallic complexes have enhanced mobility in aquifer systems (Christensen et al. 1996). This has not been observed in the study area, possibly due to the moderate organic carbon concentrations in the groundwater. However, a potential problem would develop if DOC concentrations start to rise. Pore-water profiles reveal considerable depletion in base cations, reflecting the geochemical evolution of the unsaturated zone as conditions became more reducing. Any future addition of protons could have a serious impact on the pH of the environment. Toxic metals such as copper, zinc, and aluminium, which may be present in the aquifer matrix or in wastewater, are more soluble at a lower pH and may therefore compound the contamination problem.

Conclusions

Rapid urbanisation can and often does lead to widespread contamination of shallow groundwater and to its abandonment for potable supply in favour of deeper more protected aquifers. Rapid urban growth has led to a parallel expansion of groundwater abstraction and to significant changes to the groundwater flow system. Such changes in flow patterns can have important consequences on both the quality and sustainability of the resource. Although semi-confined aquifers are less susceptible to contamination from activities at the surface, heavy abstraction can produce large vertical gradients in the semi-confining (or leaky) layer and induce substantial downward leakage from the shallow layers. In the longer term, this condition can produce significant changes to water quality.

In Hat Yai, the combination of high organic content of the urban recharge and the shallow depth to the water table has produced strongly reducing conditions in the upper layer. These conditions have led to elevated concentrations of ammonium (but low nitrate) and bicarbonate together with the mobilisation of iron, manganese, and arsenic. These redox-induced changes to water quality appear to be of greater significance than the contamination that has been introduced. The timescales for downward leakage, from the surface through the upper aquitard to the semi-confined aquifer, are of the order of several decades, and incipient contamination of the semi-confined aquifer has only recently become apparent. This conclusion has important implications for groundwater monitoring and demonstrates the need, in semi-confined aquifers, to monitor within the upper leaky layer, especially where early warnings of future changes in water quality are required.

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