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GROUNDWATER FLOW SECTION MODELLING OF SALINISATION PROCESSES IN THE CHAMPHONE CATCHMENT, SAVANNAKHET PROVINCE, LAO PDR

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ABSTRACT

A steady state, two-dimensional vertical section groundwater flow model has been developed for a salinised area of the Xe Champhone catchment in Savannakhet province, Southern Lao PDR. The area is underlain by evaporite beds and clastic sedimentary rocks of the Khorat Group that are the source of salt found in groundwater and surface soils. The Xe Champhone catchment is of interest because of plans for construction of several new reservoirs and extensive expansion of irrigated areas. This study provides an example of how a relatively sparse and limited data set has been used to construct and successfully calibrate a numerical flow model to investigate groundwater flow patterns and potential impacts of increased groundwater recharge on land salinisation. Results show the predominance of local flow systems and that deeper flow systems in contact with the rock salt layer operate over much longer time scales in the order of millions of years.

1 INTRODUCTION

In the early 1980s, salt affected soils covered 2.9 million hectares of land in Northeast Thailand or 17.5 per cent of the total land area (Arunin 1984). More recently, saline soils have been identified in neighbouring parts of the Lao Peoples Democratic Republic (Lao PDR). These include areas in Vientiane province, a narrow corridor along the Mekong River near the town of Tha Khek in Khammuane province and the Xe Champhone[1] catchment in western Savannakhet province.

Impacts of salinity include reduced crop yields, widescale loss of arable land and adverse effects on freshwater fisheries and forest resources. Increasing salt loads in surface water and shallow groundwater also threaten access to irrigation water and safe domestic water supplies. The accumulation of salts in surface soils and groundwater in a geological setting characterised by evaporate deposits is a natural phenomenon and is referred to as primary salinity. Secondary salinity is a human-induced circumstance whereby certain activities alter the hydrological balance and lead to increased severity and rate of salinisation (Ghassemi *et al*. 1995). In Northeast Thailand, secondary salinity has been associated with deforestation, irrigation and reservoir construction (Rimwanich and Suebsiri 1983; Arunin 1984; and Arunin *et al*. 1988) as these activities often lead to increased accessions of water to shallow and deep aquifers.

In Savannahket province, the Lao Department of Irrigation (DOI) has developed plans for construction of numerous new storage reservoirs and a major expansion to the current irrigated area. Savannakhet province is one of the most important rice producing areas in Laos owing to its low lying topography and wide flat floodplains that are suitable for lowland paddy cultivation. Given the presence of saline soils and underground evaporite deposits there is concern that these new developments may exacerbate existing salinity problems. This modelling project builds on research carried out under Australian Centre for Agriculture Research (ACIAR) project no. LWR1/97/150: *Salin-*

[1] *Xe* is the Lao term for 'river'

ity Management in South-Eastern Australia, North-Eastern Thailand and Lao PRD (ACIAR 2000).

This project utilised information collected for the Lao component of the ACIAR project to develop a relatively simple, steady state groundwater flow model to investigate groundwater flow and salt transport mechanisms. Such a model will provide useful information with which potential impacts of planned expansion of reservoir and irrigated areas can begin to be evaluated. The specific aims of the project were to:

- Investigate major patterns of groundwater flow;
- Identify and quantify the relative proportion of various recharge and discharge mechanisms;
- Assess which aquifer parameters and hydrological stresses have the largest influence on groundwater levels at various points of the aquifer system;
- Gain information about rates of groundwater flow and solute transport to surface soils.

2 STUDY AREA

2.1 Location, Topography and Drainage

The focus of the ACIAR project research and this modelling work is the Kengkok study area located in Champhone and Outhoumphone districts in western Savannakhet province, Southern Lao PDR (Figure 1). It covers the lower portion of the Xe Champhone catchment where the river is characterised by large meanders and cutoffs and where saline soils are found on the wide adjacent floodplain. The Xe Champhone is a tributary of the Xe Bang Hiang which drains into the Mekong River south of Savannakhet and has a catchment area of just under 2 million ha covering the entire eastern part of Savannakhet province. The study area is bounded in the west, southwest and north by a ridge of low lying hills and high terraces (160-200 mASL). A number of small streams (*huay*) drain the mid-slope areas towards the gentle undulating wide floodplain (130-140 mASL) characterised by numerous natural and seasonally flooded lakes, marshes and wetlands. The primary land-use on the floodplain and mid-slope areas is rain fed or irrigated rice paddy cultivation. Small-scale solution mining and refining of rock salt occurs near the district centre of Kengkok. The hills surrounding the study area are covered by deciduous dry dipterocarp forest and shrubland with some rice and cash-crop cultivation.

2.2 Climate

Southern Laos is subject to a monsoonal climate comprised of distinct wet (May-September) and dry (October-April) seasons. At Xeno, average annual temperature is 25.6ºC and pan evaporation is 1390 mm. Average annual rainfall at Xeno and Kengkok is 1318 and 1510 mm respectively (record period: 1988-2002). Highest rainfall occurs during July and August (240-330 mm/mth) and lowest between November and January (<10 mm/mth). Over the available record period from 1988 to 2002, annual rainfall at Kengkok ranged between 908 and 2054 mm and at Xeno between 894 and 1928 mm.

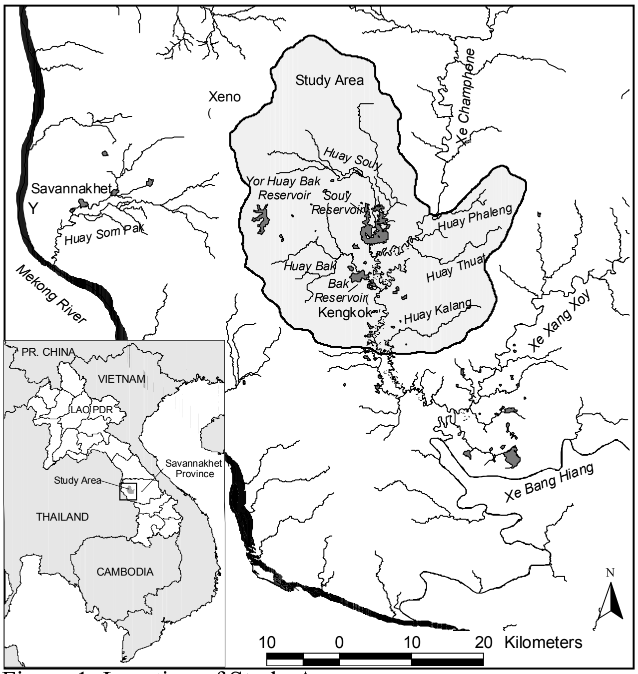

Figure 1: Location of Study Area

2.3 Irrigation and reservoir storage

There are currently three storage reservoirs used for irrigation purposes in the Kengkok study area: Yor Huay Bak (362 ha), located at the headwaters of Huay Bak near the western catchment boundary; Souy (1021 ha), in the centre of the study area; and Bak (237 ha), at the downstream end of Huay Bak. Together these storage bodies irrigate an area of 8314 ha or 7.6 per cent of the study area. Within the larger Xe Bang Hiang catchment, 22 535 ha or 3.5 per cent of the land area is currently irrigated and in the remainder of the province along the Mekong River, a further 4 636 ha is irrigated.

Within the Kengkok study area there are three new reservoirs planned for the upstream reaches of the Huay Phaleng, Huay Thuat and Huay Muang. The total potential irrigated area in the study area is 58 606 ha or 53.8 per cent of the total land area. This translates to a seven fold increase on the current area of irrigated land. Within the Xe Bang Hiang and Huay Som Pak catchments, these plans include the construction of several new reservoirs covering an additional area of 70 469 ha and a 17 fold increase in the total irrigated area to 461 418 ha or 20.5 per cent of the total catchment area.

2.4 Geology

The geology of eastern Savannakhet province, further north around the town of Tha Khek and also Vientiane province in central Laos is similar to that of Northeast Thailand as these areas lie within the Khorat Plateau, a large saucer-shaped basin tilted to the east. The Plateau consists of a sequence of Mesozoic and Tertiary aged sedimentary rocks known as the Khorat Group, which lie on a basement complex of Carboniferous metamorphic and igneous rocks and the Ratburi Limestone Formation (Bunopas 1992 and Piyasin 1995). The upper Khorat Group includes the Maha Sarakham Formation of evaporite beds and clastic sediments that were deposited in the late Cretaceous period. The three rock salt layers vary in thickness with reported averages of 20, 70 and 134 m for upper, mid and lower layers respectively, however the lower layer has been found to be over 1 000m thick in some parts of Northeast Thailand (Supajanya *et al.* 1992). The upper and mid salt beds are most often missing as a result of dissolution by groundwater percolation (Suwanich 1986), yet salt veins are readily found in and along bedding plains of the upper and mid clastic layers (Löffer and Kubiniok 1988).

Overlying the Maha Sarakham is the Phu Tok Formation of fluvial and aeolian origin, the younger red beds deposited between the late Tertiary and early Quaternary, and clays, silts, sands and gravels of the Quaternary alluvium (Lertsirivorakul 1999).

Tectonism during the early-Tertiary period led to the uplift of several ranges including the Phu Phan Range and division of the Khorat Plateau into a number of smaller sub-basins. The salt beds underwent extensive folding and deformation resulting in a variety of salt structures such as domes, ridges, anticlines and synclines (Suwanich 1986). Piyasin (1995) identified five distinct sub-basins, however most other authors (Workman 1975; Suwanich 1986; and Dheeradilok 1992) identify only three major sub-basins: Khorat, located in the lower central part of Northeast Thailand; Sakon Nakhon in the north, separated from the Khorat Basin by the Phu Phan Range and extending into Laos at Vientiane province and the western part of Khammuane province at Tha Khek; and Savannakhet, located wholly within Laos on an east-west axis, extending from the Mekong River east to Xepone near the Vietnamese border.

2.5 Geology and Hydrogeology of Study Area

Geological and hydrogeological information for the study area has been acquired from a variety of sources:

- 1:250 000 scale geological map of Laos;
- drilling activities conducted by ACIAR project;
- drilling logs of water supply wells and mineral exploration bores;
- field observation by ACIAR project staff.

Figure 2 shows the geology of the Champhone area. Formations have been reclassified according to major geological formations in Northeast Thailand and field observations. Well logs of Vietnamese exploration drill holes near Kengkok indicate the presence of rock salt at depths ranging between 72 and 94 m below ground, and at an ACIAR drill hole in the mid-slope areas at Ban Phailom, rock salt was found at a depth of 85 m. The thickness of the rock salt at Kengkok ranges between 66 and 110 m and is capped by a thin layer (3-7 m) of anhydrite. The top of the rock salt is relatively flat with some deformation in the vicinity of Kengkok. It is overlain by approximately 80 m of stiff to plastic clay. A pumping/recovery test carried out on the ACIAR bore at Ban Phailom indicates that the hydraulic conductivity of fractured clay zone above the rock salt is 1.78×10^{-7} m/s.

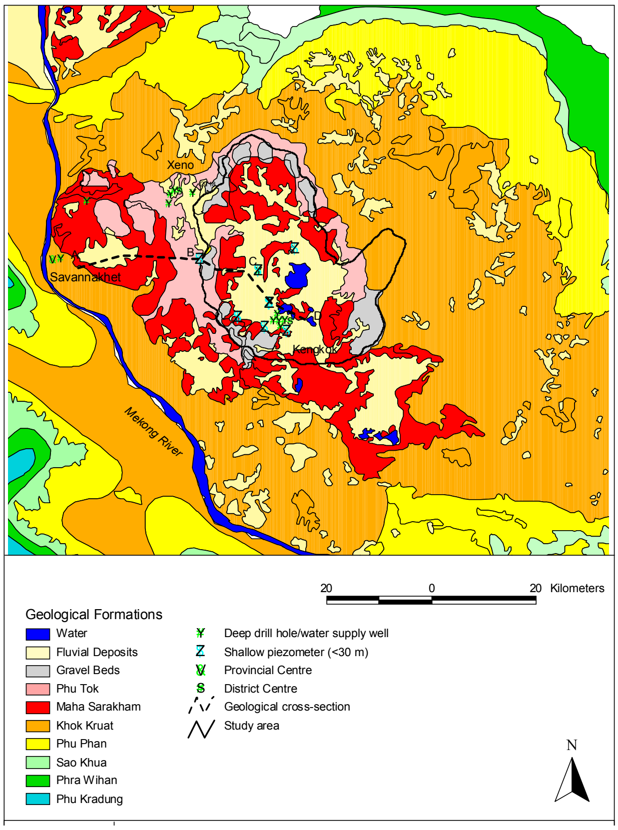

Figure 2: Geology of the study area

In 2002, the ACIAR salinity project completed construction of nine piezometers within the Kengkok study area: two shallow screened at a depth of 15 m, six intermediate screened at 30 m, and one deep screened at approximately 80 m. In addition to several field surveys where static water level and water quality measurements were collected from piezometers and 32 village wells, automatic water level loggers were installed in all nine piezometers during July/August 2002 to collect daily water level measurements. The average static water level in the shallow alluvial aquifer during 2002 was 1.5 m below ground level in the wet season and 3 m in the dry season, with respective ranges of 0-8 m and 0-9.5 m.

3 METHODS

The first stage of the modeling task was to develop a conceptual model of local geology and groundwater flow. This required compilation and interpretation of all available geological and hydrogeological data. Since geological data was sparse, development of the conceptual model relied heavily upon good understanding of geology and hydrogeological processes in Northeast Thailand. The conceptual model was used to construct the numerical flow model in Processing Modflow for Windows Professional (PMWIN *Pro*) which involved discretising the model domain, specifying boundary conditions and assigning initial estimates of hydraulic parameters and stresses. Discretisation reduces the partial differential equations that describe 2 and 3-dimensional groundwater flow to a series of simultaneous algebraic equations that can be solved with a variety of iterative and direct matrix techniques. The Strongly Implicit Procedure (SIP) was utilised in this modeling project . The MODFLOW set of codes include the main code and a series of packages that handle various sources and sinks of the aquifer system.

The steady state model was calibrated against available hydraulic head observations at five locations. A sensitivity analysis was performed to evaluate model uncertainty and identify those parameters and stresses with the largest influence on hydraulic heads.

3.1 Conceptual Groundwater Flow Model

The conceptual groundwater flow model is illustrated as a vertical cross section spanning from Savannakhet to the Xe Champhone (Figure 3). The transect location is shown in Figure 2. The model domain was selected according to major aquifer boundaries. The western boundary is a groundwater divide along the ridge that separates the Xe Champhone and Xe Som Pak catchments and the eastern boundary corresponds to the groundwater divide below the Xe Champhone. The permeability of rock salt is typically very low (~10^{-12} m/s) so flow within the unit is assumed negligible. The top of the rock salt layer is therefore taken as the base of the model domain.

According to well logs, the lower clastic layer is distinctly different from the upper two. It is saline and plastic and therefore more like clay than claystone, with minor flow occurring through pores rather than fractures as in the claystone of the upper two layers. Flow is also likely to occur along the contact with the rock salt. Essentially however, the clay and claystone layers are considered to be aquitards.

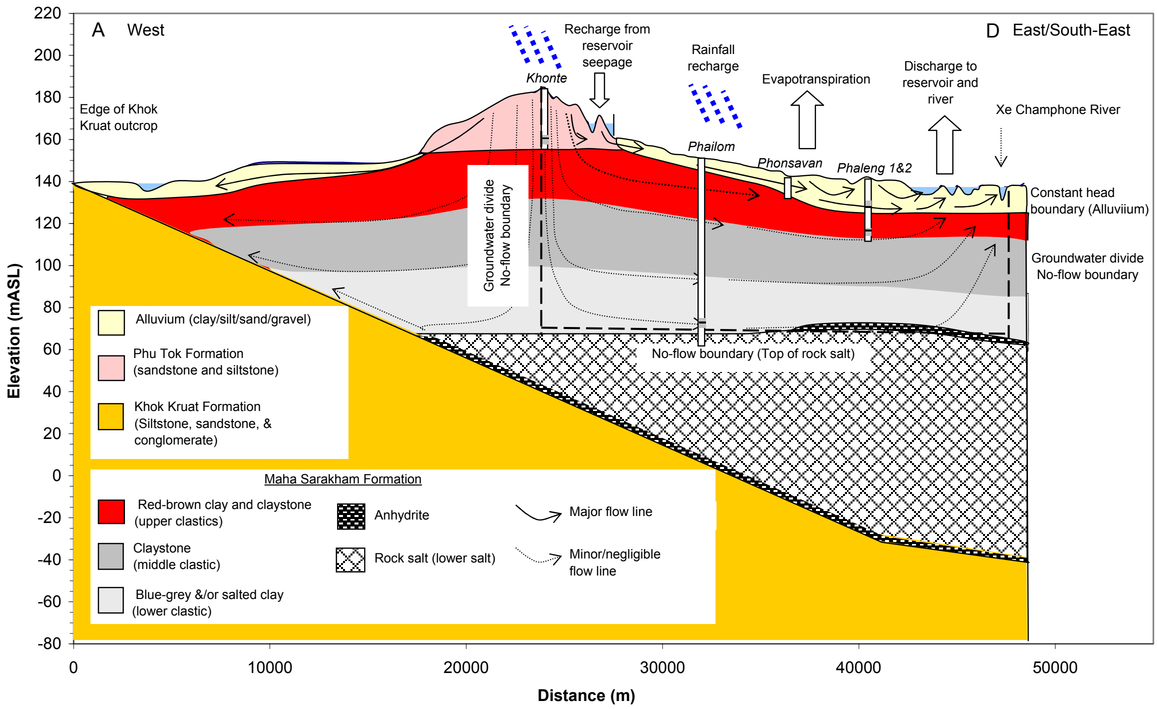

Figure 3: Conceptual groundwater flow model

The major inputs of water to the model are recharge from rainfall, leakage from reservoirs and infiltration of flood waters during the wet season. Land-use is divided between mosaic deciduous forest in the upland areas and rice paddy and remnant forest between Yor Huay Bak Reservoir and the River. The main recharge areas are believed to occur along the ridgeline that surrounds the catchment. Weathered and fractured sandstone and siltstone units and upper terrace gravel beds (not shown) provide preferential pathways for infiltration. Diffuse rainfall recharge also occurs in the mid-slope and lowland areas but is likely to make up a smaller proportion of rainfall than in upland areas.

The low hydraulic conductivity of claystone, clay and rock salt layers of the Maha Sarakham Formation means that local flow systems are likely to dominate in the study area. The major flow path is believed to be from the main recharge areas in the weathered and fractured bedrock aquifers along catchment boundaries, down the topographic gradient in the shallow and thin alluvial aquifer and finally to discharge points in natural depressions, reservoirs and the Xe Champhone. Given the shallow depth of the water table (Mean SWL = 3.5 m in the dry season) another major mechanism of groundwater discharge is likely to be evapotranspiration in the mid-slope and lowland areas, particularly in the dry season when there is little cloud cover, high radiation and low humidity levels. Groundwater is evaporated directly from the water table by capillary action and transpiration by plants. This is also the primary mechanism of salinisation of surface soils whereby dissolved salts present in shallow groundwater are transported to the surface via capillary action.

Deeper percolation of rainfall recharge may reach the upper claystone unit, particularly where it is weathered in upland areas. Further flow would be limited to fractures and bedding planes of the three clastic layers from where the upper and mid rock salt layers have been weathered away.

3.2 Model development

The major assumption in modelling groundwater flow along a vertical section of an aquifer is that no flow occurs across the side boundaries of the section (Spitz and Moreno 1996). Potentiometric surface maps show that shallow groundwater flow is driven primarily by topography so the transect was drawn using 1:10 000 scale topographic maps. The transect location and potentiometric surface map is shown in Figure 4. The model domain was divided into six layers, one row (200 m wide) representing the vertical slice and 117 columns, each 200 m long. The layers vary in thickness along the length of the section and correspond to major aquifers and aquitards outlined in the conceptual model. Figure 5 illustrates the spatial discretisation of the model domain along with the location of Yor Huay Bak and Bak reservoirs and head observations points.

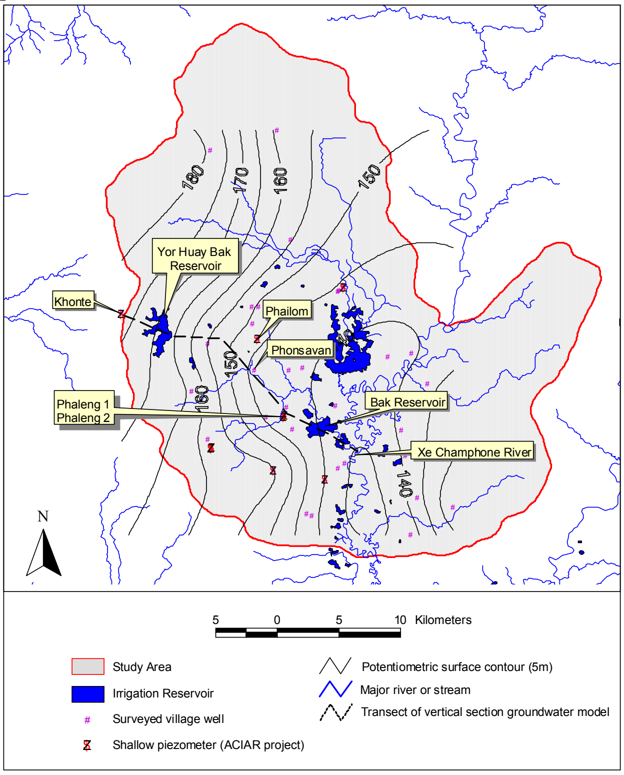

Figure 4: Potentiometric surface for shallow aquifer and location of model transect and all monitoring points.

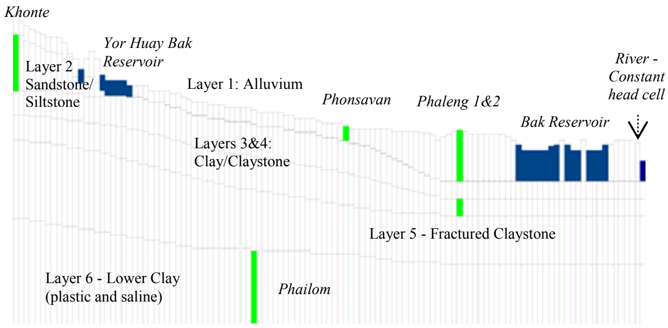

Figure 5: Spatial discretisation of model domain and location of head observation points (green cells), reservoirs and the River (blue cells).

3.3 Model parameters and stresses

Initial estimated values of horizontal and vertical hydraulic conductivity are presented in Table 1 together with calibrated values. Initial estimates are based on values reported for similar rocks in Northeast Thailand (Lertsirivorakul 1999; Srisuk *et al.* 1999; Srisuk *et al.* 2000).

Table 1: Initial and calibrated values of horizontal (HK) and vertical (VK) hydraulic conductivity

Layer	HK (m/s)		VK (m/s)	
	Initial	Calibrated	Initial	Calibrated
1a	$5x10^{-5}$	$1x10^{-4}$	$1x10^{-5}$	$1x10^{-5}$
b	$1x10^{-5}$	$1x10^{-5}$	$1x10^{-6}$	$1x10^{-6}$
c	$1x10^{-5}$	$1x10^{-3}$	$1x10^{-6}$	$1x10^{-4}$
2	$1x10^{-5}$	$8x10^{-5}$	$3.5x10^{-6}$	$3.5x10^{-6}$
3/4a	$5x10^{-8}$	$1 x 10^{-7}$	$1x10^{-9}$	$1 x 10^{-9}$
b		$1 x 10^{-7}$		$1 x 10^{-12}$
5	$5x10^{-8}$	$5 x 10^{-7}$	$1x10^{-9}$	$1 x 10^{-10}$
		$1 x 10^{-7}$		$1 x 10^{-12}$
6	$1x10^{-7}$	$1 x 10^{-8}$	$1x10^{-9}$	$1 x 10^{-9}$

Recharge from rainfall was modeled via the Recharge package in PMWIN Pro. Based on experience from Thailand, recharge was assumed to be 15 per cent of rainfall in upland areas and 10 per cent in lowland discharge areas, and applied to each cell in the top layer with the exception of reservoir and constant head cells. This corresponded to rates of 270 and 180 mm/yr in upland and lowland areas respectively.

Discharge of groundwater by plant transpiration and direct evaporation from the capillary zone was simulated via the Evapotranspiration (ET) package in PMWIN Pro. The package uses head-dependant boundary conditions and requires input of three parameters: Maximum ET rate (LT^{-1}), elevation of the ET surface (land surface) and extinction depth. The maximum ET rates for upland and lowland areas are estimated at 900 and 700 mm/yr respectively. These are based on values reported by Lertisirivorakul (1999) for land-uses of upland crops and paddy rice respectively. Extinction depths were set at 3 m and 2 m for upland and lowland areas respectively.

The constant head cell which represents the Xe Champhone was prescribed a head of 133 mASL, based on average annual stage measurements during 2001/02. Vertical exchange of water between the reservoirs and groundwater was simulated using a head-dependant boundary condition within the Reservoir package in PMWIN Pro. Required input parameters were reservoir stage, elevation of the reservoir bottom, thickness of the reservoir bed and vertical hydraulic conductivity of the reservoir bed. The stage of Yor Huay Bak was based on monthly data obtained from IRD for 2002, while that of Bak Reservoir was estimated from topographic maps since no other data was available.

3.4 Calibration methodology

The steady state model was calibrated by adjusting model parameters and stresses over successive model runs until an adequate match was obtained between simulated and observed hydraulic heads. Heads were compared at five observation points along the vertical section as indicated in Figure 5. MODFLOW assumes unit density and therefore calculates fresh-water heads. The hypersaline nature of deep confined groundwater at the contact of the clay and rock salt units meant that head observations at Phailom needed to be corrected for density differences. This was achieved by converting measured point-water heads into equivalent fresh water heads (Fetter 2001).

4 RESULTS

4.1 Steady state head distribution

Simulated heads for the calibrated steady state model are presented in Figure 6. The residual error between modelled and observed heads ranged between 0.04 and 0.33 m. Overall, a good fit between observed and modeled heads was achieved. Flow (as interpreted from the hydraulic head contours) in the shallow aquifers is primarily horizontal and follows the topographic gradient from the upland recharge areas to Bak Reservoir and the Xe Champhone. Hydraulic gradients are greatest in the upland areas, especially immediately upstream and downstream of Yor Huay Bak Reservoir.

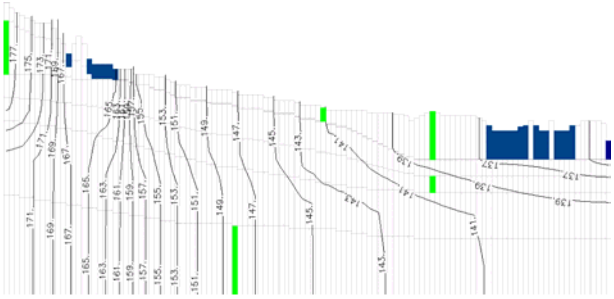

Figure 6: Steady state model simulation results: distribution of hydraulic head (mASL) (observation points marked in green).

4.2 Water budget

The water budget calculated for the steady state model shows that the primary accession of water to the groundwater system is from rainfall recharge (74 per cent of all inputs) and the main discharge mechanism is by ET (65 per cent of all outflow). Leakage from reservoirs accounts for 26 per cent of total inputs, while discharge of groundwater to reservoirs accounts for 16 per cent of all outflow. The water budget also shows that under equilibrium conditions, the river is primarily a point of discharge; accounting for 19 per cent of all outflow.

4.3 Sensitivity Analysis

A sensitivity analysis was carried out on the steady state model and allowed model parameters and stresses to be ranked in order of influence on simulated hydraulic head at five observations points in the model domain. Heads in the shallow unconfined layers were most sensitive to annual rainfall, infiltration factor, hydraulic conductivity of Layer 1, maximum ET rate and reservoir stage. Heads in the deeper confined aquifers were sensitive to horizontal and vertical hydraulic conductivities at various depth and regions of the model domain as well as model stresses.

4.4 Particle Tracking

Particle tracking was carried out using the advective transport model PMPATH. This model calculates groundwater paths and travel times based on the simulated steady state head distribution. Particles were placed in each cell of layers 1, 4, 5 and 6 and run forward and backward over 100, 10 000 and 1 million year time periods (Figure 7).

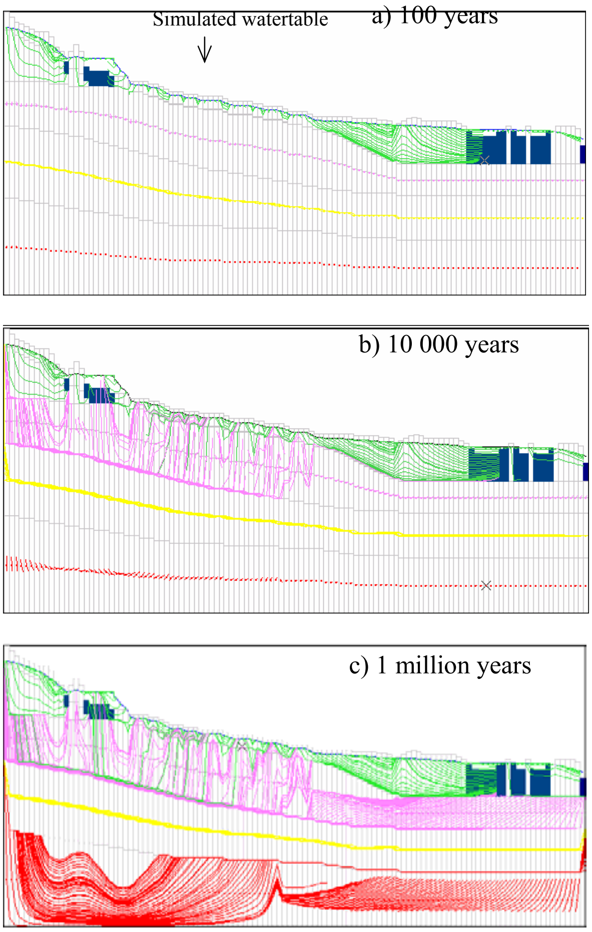

Figure 7: Forward and backward particle tracking for steady state simulation over a) 100, b) 10 000 and c) 1 million year periods. Coloured lines correspond to simulated flow paths of particles placed in Layer 1 (green), Layer 4 (pink), Layer 5 (yellow) and Layer 6 (red).

5 DISCUSSION & CONCLUSIONS

The results of the particle tracking show the time scales over which local, intermediate and deep groundwater flow systems operate. Over short time scales (~100 years), recharge entering the groundwater system remains in the shallow model layers and local flow systems are characterised by localised recharge and discharge zones. Over longer time scales (~10 000 years) particles originating from the water table begin to circulate through the upper claystone unit while flow in the lower claystone and clay units remains negligible. Recharge from Yor Huay Bak reservoir can be seen to enter the claystone unit.

Figure 6(c) shows that deeper flow systems operate at time scales of millions of years. After one million years, recharge to Layer 6 can be seen to occur from the overlying layers in the upstream part of the model and discharge to the surface at the downstream end of the model. Flow in Layer 5, where vertical hydraulic conductivity ranges between $1x10^{-10}$ and $1x10^{-12}$ m/s, remains negligible even after one million years.

The implications of these results are that the rate of supply of salt to surface soils from the lower rock salt layer is likely to be extremely slow, with solute transport operating at time scales of millions of years. This means that changes to the hydrological regime that increase groundwater recharge are unlikely to affect the current rate at which deep rock salt is transported to the surface within the foreseeable future. They probably will on the other hand, affect groundwater flow times at shallow and intermediate depths and therefore may increase the rate at which more shallow salt stores are transported to the surface. Potential shallow stores include remnants of top and middle rock salt layers and salt stored in clay soils. The critical issue for evaluating the impact of increased recharge then becomes the mechanism of salinisation.

Two main hypotheses on the process of salinisation have been proposed in Northeast Thailand. The first suggests that salts are derived from deep confined groundwater in contact with rock salt of the Maha Sarakham Formation and flows upward through fractures of consolidated rock to contaminate shallow groundwater in the upper sediments (Haworth *et al.* 1966; McGowan Int. Pty Ltd. 1983; Williamson *et al.* 1989; and Imaizumi *et al.*1996).

The second hypothesis proposed by Sinanuwong and Takaya (1974) (as cited in Tuckson *et al.* 1982) is that salt is derived from the weathered zones of shales and siltstones of the Maha Sarakham Formation in upland areas and is redistributed to lowland areas by interflow. Both hypotheses suggest that once in the shallow aquifer, salt is transported to the surface by capillary action.

Tuckson *et al.* (1982) and Löffer and Kubiniok (1988) propose that both hypotheses are valid and provide several field studies that illustrate the influence of one or both mechanisms depending on the hydrogeological setting. The occurrence of salt seeps at the break of slope surrounding low lying hills and ridges provide evidence of the upland weathered zone/interflow mechanism. Löffer and Kubiniok (1988) explain that this is particularly the case when the salt seep has emerged or increased in severity following land clearing in upland areas where the Maha Sarakham Formation is present.

In lowland areas underlain by saline groundwater such as the large alluvial plains of the Tung Kula Ronghai, Tuckson *et al.* (1982) and Löffer and Kubiniok (1988) attribute soil salinity to deep groundwater circulation in contact with evaporites. In this situation, the distribution of saline soils is irregular and both authors suggest that the volume of salt in groundwater is too large to be derived solely from adjacent upland areas.

There is evidence to suggest that both mechanisms are operating in the Xe Champhone catchment. The absence of deep alluvial deposits, suspected presence of shallow salt sources and occurrence of salinity at the break of slope all point towards the upland weathered zone/interflow mechanism. However, from a larger regional scale perspective, the area of salt-affected land and shallow groundwater is highly localised and corresponds closely with the spatial distribution of rock salt deposits.

It should also be emphasised that the interpretations of very slow groundwater flow rates in the deeper aquifer layers are based on the very small values of vertical hydraulic conductivity for the clastic layers that were obtained through the calibration process. Vertical fractures that allow transport of deep brines to shallow aquifers may exist in other parts of the catchment. Accordingly, the interpretation that changes to the hydrological regime are not likely to increase rates of salt transport from deep aquifers in contact with the rock salt layer may not be valid for the whole study area. While groundwater flow velocities in the clastic units are low, changes in hydraulic pressure are transferred rapidly through confined aquifers and therefore if an increase to recharge occurs and preferential pathways for groundwater discharge such as vertical fractures and faults exist, then rates of salt transport may increase over shorter time periods. This uncertainty could be resolved by developing a three-dimensional groundwater flow and solute transport model covering the whole catchment, dating deep brine waters with Carbon-14 and Tritium methods and measuring stable isotope compositions of groundwater at various depths and aquifer units. Analysis of groundwater age and stable isotope composition could also assist in determining recharge rates and sources of salt in surface soils and groundwater.

The sensitivity analysis highlights how uncertainties in recharge and hydraulic conductivity of the shallow unconfined layer create the most concern for model confidence and salinity management. Variation of these parameters within their expected ranges results in large fluctuations (1-3m) in calculated water-table depth in lowland areas with potentially large impacts on the rate of transport to salt to surface soils by capillary action. In order to increase confidence in the calibrated model and its ability to predict the impacts of planned land-use changes including irrigation development, future field investigations should focus on obtaining estimates of hydraulic conductivity of the shallow alluvium and infiltration capacities of soils and underlying sediments and rocks in various parts of the catchment.

While development of this model has increased our understanding of the groundwater system and allowed us to make certain hypotheses regarding the effect of increased recharge to the system, much more detailed data, interpretation and modeling is required for the impacts of reservoir and irrigation development to be properly assessed.

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