NATIONAL COMMITTEE FOR SUB-NATIONAL DEMOCRATIC DEVELOPMENT
RURAL POVERTY REDUCTION PROJECT

STRATEGIC STUDY OF GROUNDWATER RESOURCES IN PREY VENG AND SVAY RIENG (PHASE 2)

FINAL REPORT

25 September 2009

Prepared by

INTERNATIONAL DEVELOPMENT ENTERPRISES

International Development Enterprises Cambodia
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In association with

CADTIS Consultants, Co. Ltd.,
Phnom Penh, Cambodia

and

S. S. Papadopulos & Associates, Inc.,
Waterloo, Canada

INTERNATIONAL DEVELOPMENT ENTERPRISES

Phnom Penh
25 September 2009

H.E. Chhieng Yanara
Director, Programme Support Team
National Committee for Sub-National Democratic Development
General Department of Local Administration
Ministry of Interior, P.O. Box 877
Norodom Blvd, Khan Chamcar Morn, Phnom Penh

ATTN: Mr. Ny Kimsan, Chief, Contract Administration and Project Coordination Unit

Dear Sirs:

We, the undersigned, are pleased to submit the Final Report for the **Strategic Study of Groundwater Resources in Prey Veng and Svay Rieng (Phase 2).**

This report presents the results of our investigations into the potential for sustainable development of groundwater in Prey Veng and Svay Rieng provinces. The report provides a concise summary of the hydrogeology of the study area; a review of existing groundwater monitoring data; a description of the groundwater model developed during the study and its use to estimate sustainable groundwater withdrawals; a review of the capacity building and information dissemination activities that accompanied the study; and a summary of conclusions and recommendations.

We trust that this fulfills your requirements at this time and we would be pleased to respond to any questions or comments you may have.

Yours sincerely,

Michael Roberts
Country Director
International Development Enterprises Cambodia

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Executive Summary

Prey Veng and Svay Rieng provinces have groundwater resources that can be accessed through relatively inexpensive boreholes. Since the early 1990s, rapid growth in the use of groundwater for irrigation has led to increased yields and incomes for farmers but has also raised concerns about whether such withdrawals are sustainable. Monthly records of groundwater levels gathered from 49 wells from 1996 through 2008 indicate an average annual decline of 0.14 m/year. If water levels drop more than 6 m below the ground surface, some 130,000 hand pumps used for domestic water supplies in the two provinces may become unusable.

The objective of this study was to estimate sustainable rates of groundwater withdrawal for irrigation in Prey Veng and Svay Rieng provinces. To achieve this, a three-dimensional numerical groundwater flow model was constructed using the MODFLOW software package and calibrated to ensure a close match with observed water levels.

The calibrated model was used to determine the sustainable groundwater withdrawal, which is defined as "the maximum amount of water that can be withdrawn from the aquifer when water levels across Prey Veng and Svay Rieng are drawn down to a specified depth". In total, seven predictive scenarios were analyzed, each scenario corresponding to a different maximum water level depth. For the "6 m below ground surface" scenario, the sustainable groundwater withdrawal is estimated to be 2.3 million m^3/day, which is equivalent to 0.29 mm/day over the area of the two study provinces. Rough estimates of groundwater use for domestic and agricultural purposes in 2005 suggest that 53% of the sustainable withdrawal was being used at that time. Also, if the total sustainable withdrawal amount were devoted entirely to irrigating dry-season rice, the total area that could be irrigated would be about 45,000 ha.

Another objective of the study was to develop Cambodian technical capacity. This was addressed by providing "hands-on" training for four local technical assistants, developing extensive training materials, and conducting three stakeholder workshops.

Key conclusions and recommendations from the study include:

By the Numbers

13 years

Period of record for monthly water level data from a network of 49 observation wells established in Prey Veng and Svay Rieng provinces in 1996

0.14 m/year

Mean annual decline of groundwater levels over the period of record

6 m

Maximum depth below ground level from which most domestic hand pumps can withdraw water

130,000

Number of domestic hand pumps in the study area that would be put out of service if water levels drop more than 6 m below the ground surface

2.3 million m^3/day

Sustainable groundwater withdrawal: maximum amount of water that can be withdrawn from the aquifer when water levels across Prey Veng and Svay Rieng are drawn down to 6 m below ground level. Averaged over a year-long period.

53%

Percentage of the sustainable groundwater withdrawal that is already being used for agricultural and domestic purposes in Prey Veng and Svay Rieng

45,000 ha

Area of dry-season rice crops that could be irrigated if the sustainable groundwater withdrawal were used solely for this purpose

- The data collected from the 49 monitoring wells is a major achievement of significant value to Cambodia. It is recommended that collection of monthly water levels should continue and that the measurement procedure should be clearly documented.
- It is recommended that the government investigate strategies to protect against further groundwater drawdown and/or ways to mitigate the potential negative impacts resulting from excessive drawdown.
- It is recommended that a detailed inventory of current groundwater usage be undertaken to determine how much of the sustainable withdrawal is currently being utilized.
- The Prey Veng - Svay Rieng groundwater model developed during this study represents an accomplishment of lasting value for Cambodia. In the current study, only a small portion of the model's ultimate value and potential has been realized. The groundwater model can and should be used by other researchers to assess additional development scenarios and to extend the understanding of the groundwater system.
- In order to develop a critical mass of local experience in groundwater modeling, resources should be concentrated to create centralized expertise within an appropriate institution at the national level.
- In order to ensure that groundwater modeling projects provide practical answers to relevant questions, it is important to have meaningful and frequent interaction between modelers, development planners, and other stakeholders. It is recommended that future modeling projects, including future applications of this groundwater model, be designed and budgeted to ensure that this integration of modeling and development planning occurs.

1 Introduction

1.1 Overview

In 2006, the Seila Task Force Secretariat (STFS), in cooperation with the Ministry of Water Resources and Meteorology (MoWRAM), received funding from the International Fund for Agricultural Development (IFAD) under the Rural Poverty Reduction Project (RPRP) for a ***Strategic Study of Groundwater Resources in Prey Veng and Svay Rieng***. In January 2008, upon the dissolution of the STFS, responsibility for this Study was transferred to the National Committee for Management of Decentralization and Deconcentration (NCDD) and subsequently the National Committee for Sub-National Democratic Development (still abbreviated as NCDD), took responsibility for this Study in 2009. Throughout this report, the STFS and the NCDD are referred to jointly as "the Client."

The study was divided into two phases, both of which have been conducted by International Development Enterprises Cambodia (IDE) in collaboration with CADTIS Consultants, Co. Ltd., in Cambodia, and S.S. Papadopulos & Associates, Inc. (SSP&A), a Canadian firm with expertise in groundwater modeling.

Phase 1 of the study was completed in December 2005 and comprised the following activities:

- Investigating and collecting existing geologic and hydrogeologic information,
- Provincial stakeholders' workshops in Prey Veng and Svay Rieng,
- A survey of current groundwater usage, and
- Recommendations and work plan for groundwater modeling in Phase 2.

The current phase of the study, Phase 2, builds on the information gathered and the recommendations made in Phase 1.

1.2 Problem Statement

Prey Veng and Svay Rieng provinces are located in southeastern Cambodia and are among the country's poorest and most densely populated provinces. Most of the land area of these provinces is used for rice cultivation; however, irrigation systems are limited in extent and in most places only a single annual crop, watered by rain or by flood recession, is possible. Both provinces suffer from unpredictable rainfall so that there is a high risk of failure of the annual rice crop. Prey Veng province is also liable to flooding. Therefore, there is an urgent need to improve irrigation and water management practices to improve crop reliability and food security, to alleviate poverty, and to encourage growth of agriculture and related sectors of the rural economy. Increased availability and reliability of irrigation would allow increased rice production and diversification to higher value crops.

Prey Veng and Svay Rieng provinces have groundwater resources that can be accessed relatively easily and inexpensively through borehole wells. In the past, wells have been used mainly for domestic water supplies; the rate of extraction was not sufficient to endanger the resource. However, there appears to be a rapid and unregulated growth of groundwater irrigation in districts where groundwater is most accessible with simple flush-bored wells and diesel pumps. Farmers using these techniques have reported encouraging results on crop yields and income.[1] Farmers are able to exercise local control over the time of application and rates of pumping, and over operation and maintenance of these irrigation systems.

[1] The growth of groundwater irrigation and encouraging yield and income results were reported in Roberts (1998) and have been confirmed in recent years through personal communication with NGO personnel, well drillers, and farmers.

Large increases in rice production on the irrigated fields, and diversification into other crops, have been achieved. It is not known what the long-term consequence of continued unregulated growth of groundwater irrigation will be. There have already been reports of domestic water supply wells becoming dry as a result of nearby irrigation pumping activities.[2] The official policy of MoWRAM is to exercise caution and to discourage expansion of groundwater exploitation for irrigation; however, MoWRAM and its Provincial Departments do not have the capacity to enforce effective regulation at present. The potential benefits of expanding groundwater irrigation are clear, but these must be weighed against risks that have, until now, not been quantified.

1.3 Study Objectives

The General Objective of this groundwater study is "to estimate the potential for development of sustainable groundwater irrigation in Prey Veng and Svay Rieng provinces, having regard to groundwater resource and other environmental constraints."

The Immediate Objectives of Phase 2 of the study, as stated in the Terms of Reference, are presented in the Table 1 along with the corresponding activities defined in the Scope of Services. The activities conducted during this study in fulfillment of the Immediate Objectives and Scope of Services are also presented along with the relevant section in this report.

The study Terms of Reference are included in Annex A.

1.4 Study Team

The study team for this project included the following individuals:

- Mr. Michael Roberts, Project Coordinator
  IDE Cambodia, Phnom Penh, Cambodia
- Mr. Christopher Neville, Senior Hydrogeologist
  S. S. Papadopulos & Associates, Inc., Waterloo, Ontario, Canada
- Mr. Jinhui Zhang, Project Hydrogeologist
  S. S. Papadopulos & Associates, Inc., Waterloo, Ontario, Canada
- Mr. So Im Monichot, Intermediate Hydrogeologist
  CADTIS Consultants, Co. Ltd., Phnom Penh, Cambodia
- Mr. Chiep Piseth, Junior Hydrogeologist
  CADTIS Consultants, Co. Ltd., Phnom Penh, Cambodia
- Mr. Pang Peng, Technical Assistant
  Ministry of Water Resources and Meteorology, Phnom Penh, Cambodia
- Mr. Preap Sameng, Technical Assistant
  Ministry of Water Resources and Meteorology, Phnom Penh, Cambodia

[2] Reports of declining groundwater tables were confirmed by NGO personnel, well driller, and government authorities at two stakeholder meetings held during Phase 1 of this study in Prey Veng and Svay Rieng provinces (IDE Cambodia, 2005).

Table 1: Fulfillment of Study Requirements as Defined in the Terms of Reference

Immediate Objectives from the ToR	**Scope of Services and Relevant Section from the ToR**	**Activity Undertaken During this Study and Relevant Section in this Report**
Develop a three-dimensional numerical groundwater flow model for Prey Veng and Svay Rieng provinces, capable of being used to inform strategic decisions on management of groundwater resources	[3.1.1] Familiarisation with the existing situation regarding regulation of groundwater extraction in Prey Veng and Svay Rieng and with the findings and recommendations of Phase 1 of the study	Review of PRASAC depth-to-groundwater records (Section 3) Field trip to Prey Veng and Svay Rieng by the modeling team (Annex C)
	[3.1.2] Compilation and review of existing data by: • Developing a well database and populate with existing data; • Checking the locations of the wells recorded in the database; • Preparing maps and tables of hydrologic data.	Review and correction of well elevation data (Section 3.3, Annex B) Development of the groundwater model (Section 4, Annex D)
	[3.1.3] Development of a conceptual model of groundwater flow in the two provinces.	Development of the groundwater model (Section 4, Annex D)
	[3.1.4] Setup of the numerical model using appropriate software.	
	[3.1.5] Calibration of the model through a “trial and study” approach.	
	[3.1.7] Identification of data required to further refine the model.	Develop conclusions and recommendations (Section 6.4)
Improve the level of understanding of the groundwater resource and the impacts of possible changes in extraction rates, Mekong River hydrology etc by analysing a number (from 3 to 5) of alternative model scenarios	[3.1.6] Development and analysis of 3 to 5 model scenarios of alternative management of groundwater resources.	Application of the groundwater model to analyze seven scenarios (Section 4, Annex D)
Train MoWRAM staff to use and maintain the model	[4.0] Train MoWRAM staff in use and maintenance of the groundwater flow model.	Training and information dissemination (Section 5, Annex E, Annex F, Annex G, Annex H)
Train PDoWRAM staff to understand the implications of the model and the relevance of its predictions to their work	[4.0] Involve a wider group of concerned MoWRAM and PDoWRAM staff in the study through seminars at key stages of the project. [4.0] Train the Intermediate and Junior Hydrologists to build local technical capacity in this field.	
Disseminate the lessons learned in developing the model with a view to encouraging possible replication for other areas of the country		

2 Hydrogeology of the Study Area

This section provides an overview of the geology and groundwater dynamics in the Prey Veng and Svay Rieng study area. A basic understanding of local hydrogeology will help the reader to follow the descriptions and discussions in this report.

The geologic formations underlying the study area are made up of river sediments overlaying deep bedrock. Good aquifer materials tend to occur at lower elevations and poor aquifer materials occur closer to the surface. Although the boundary between the good and poor aquifer material is not sharply defined, two broad sedimentary layers can be defined:

- The lower layer, or *old alluvium*, consists mainly of coarse-grained sand and gravel that form a good aquifer. The layer is up to 200 m thick.
- The upper layer, or *young alluvium*, covers much of the study area to a depth of 10 to 40 m and consists mainly of fine-grained silts and clays.

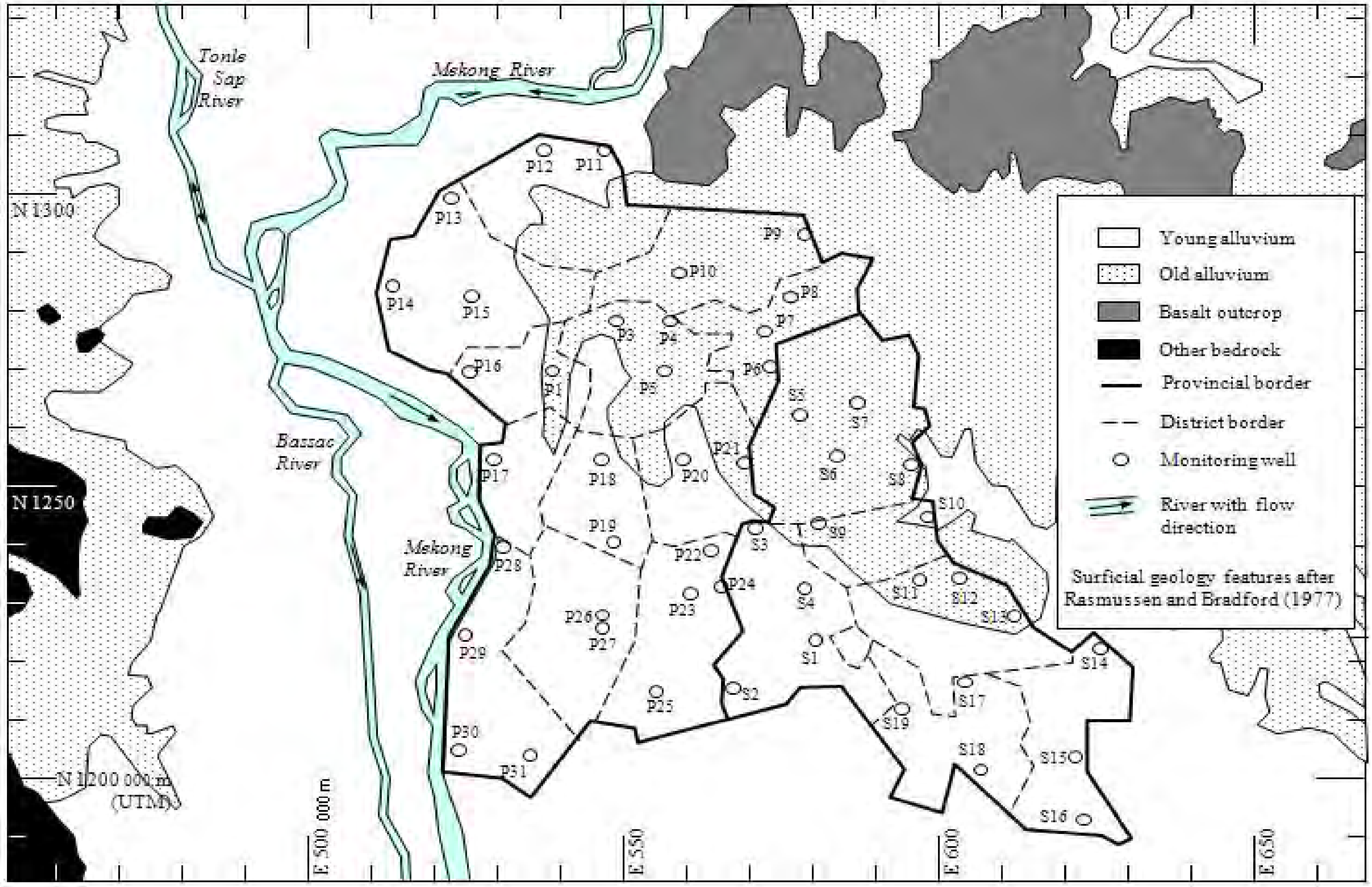
The young alluvium acts as impermeable blanket overlaying the old alluvium aquifer across much of the study area. At higher elevations in the northeast portion of the study area, the young alluvium thins out to nothing and the coarser-grained old alluvium layer is exposed (see Figure 1).

Important implications of these geologic conditions include the following:

- The upper, impermeable young alluvium layer prevents the annual flood waters from directly recharging the underlying aquifers.
- Instead, the aquifers are recharged from the following sources:
    - Infiltration from the Mekong River in places where the river is deep enough to cut through the young alluvium into the underlying old alluvium,
    - Infiltration of rainwater runoff through the exposed old alluvium in the northeast portion of the study area and beyond.
- The water in the old alluvium aquifer, being recharged from higher elevation sources, is held under pressure by the overlaying blanket of the young alluvium. When boreholes are drilled through the young alluvium into the aquifer, the water level rises in the borehole to within a few meters of the ground surface.
- The dominant direction of groundwater flow in the study area is from north, where the recharge areas lay, to south.
- Close to the Mekong River, east-west flow also occurs:
    - In the dry season, when the Mekong River water level is low, groundwater flows generally westward from the aquifer into the river;
    - In the wet season, when the Mekong River water level is high, water flows generally eastward from the river into the aquifer

The area modeled for this study includes the full extent of Prey Veng and Svay Rieng provinces and extends beyond to natural hydrologic boundaries. The modeled area is shown in Figure 2. Cross-sections showing the ground surface, top of old alluvium, and top of bedrock elevations in the modeled are shown in Figure 3 and Figure 4.

Figure 1: Surface Geology of the Study Area and Location of PRASAC Monitoring Wells



Source: Roberts (1998)

Figure 2: Extent of Modeled Area

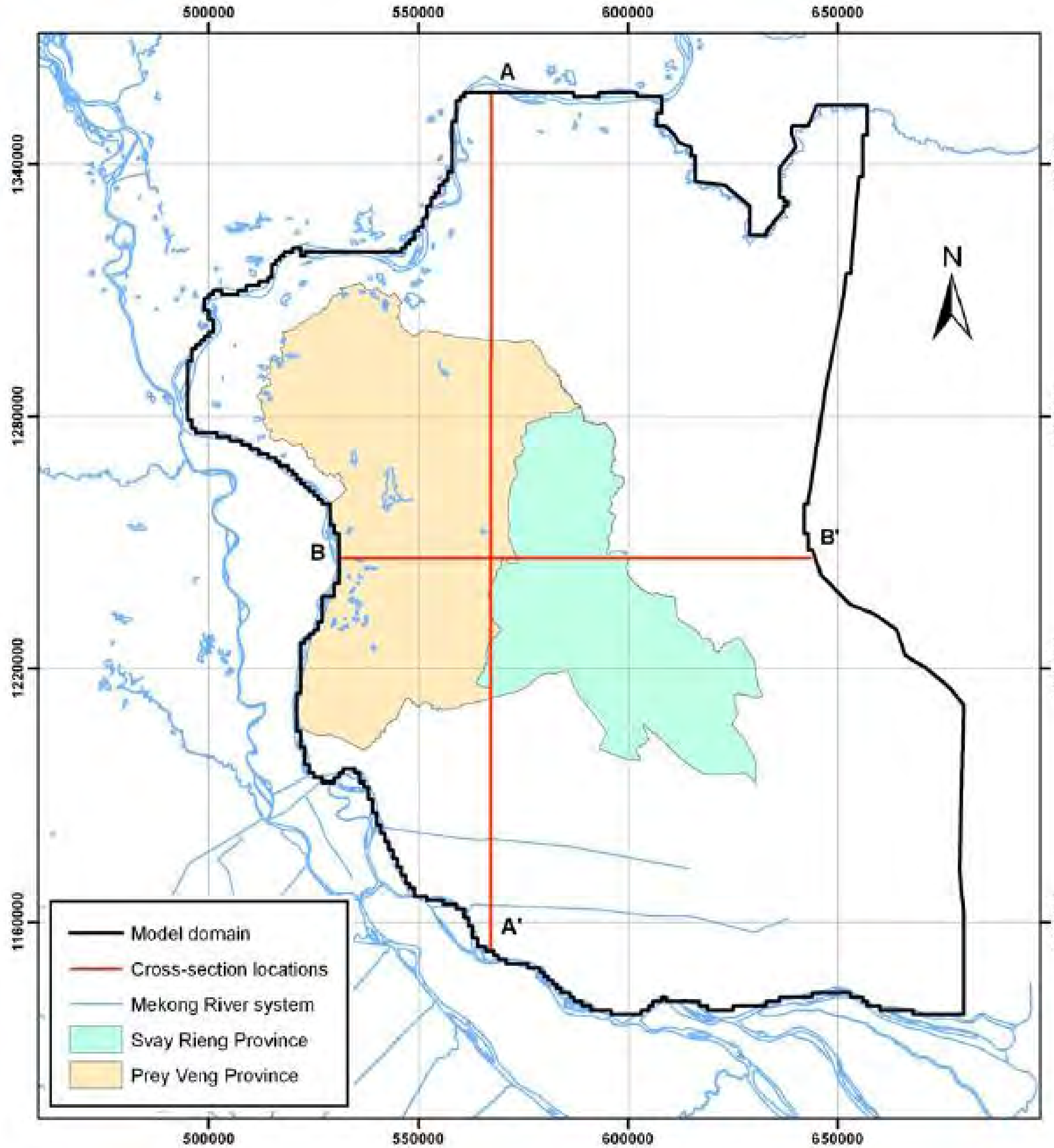


Figure 3: North - South Cross Section through Modeled Area

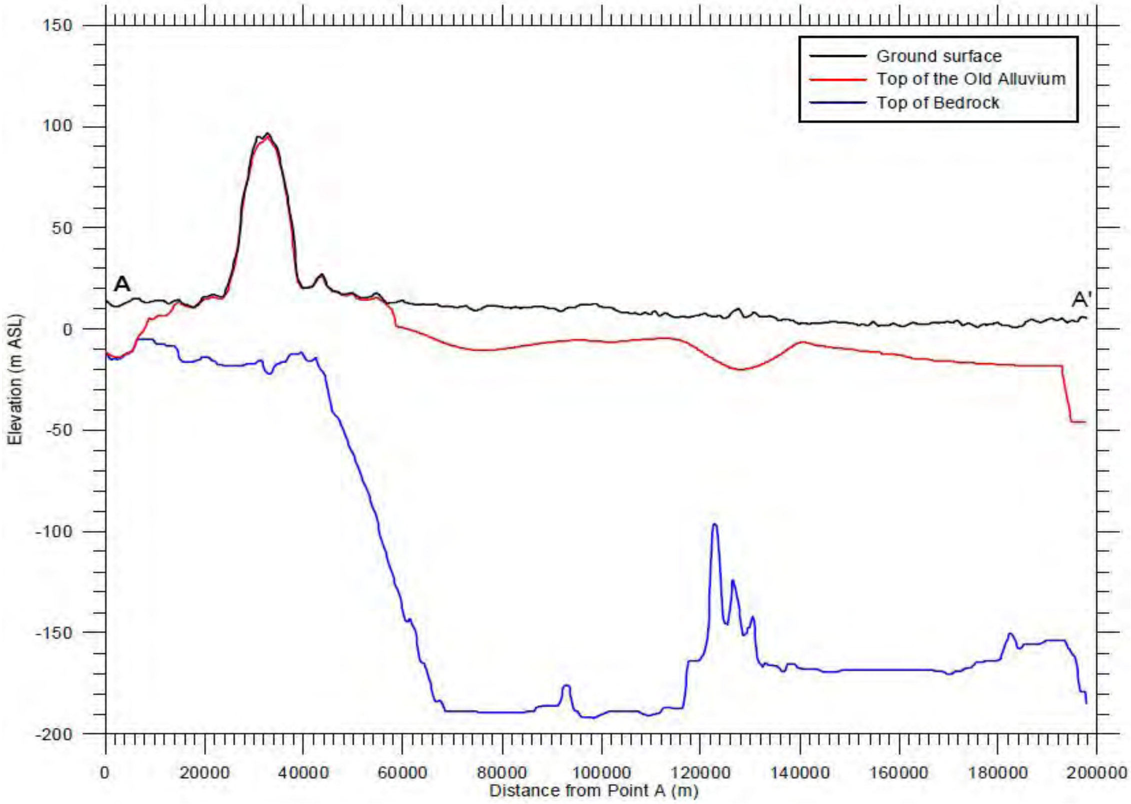
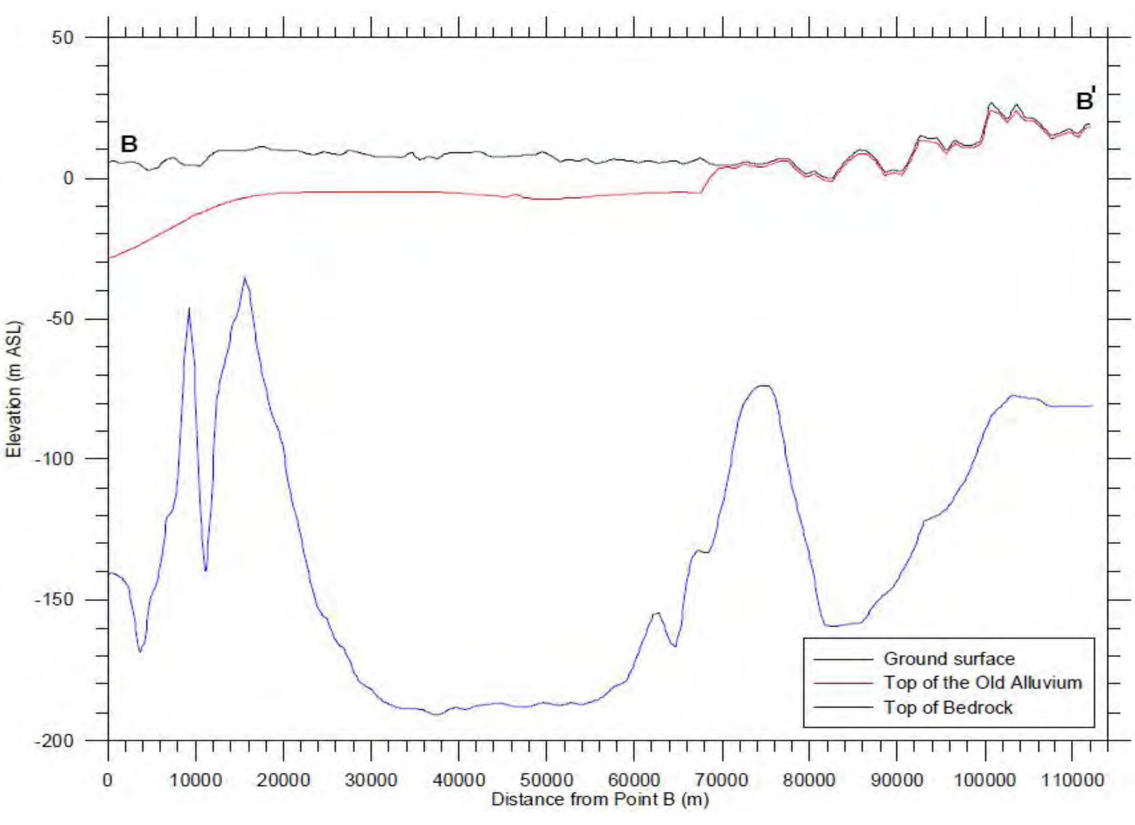


Figure 4: West - East Cross Section through Modeled Area



3 Review of Groundwater Level Data

3.1 Groundwater Monitoring Wells

The *Programme de Réhabilitation et d'Appui au Secteur Agricole du Cambodge* (PRASAC) was a program of the European Union in Prey Veng and Svay Rieng Provinces. In 1996, PRASAC initiated a groundwater-monitoring project to collect data from 49 wells to evaluate groundwater resources. Personnel from the Provincial Departments of Water Resources and Meteorology (PDoWRAM) in Prey Veng and Svay Rieng collected and continue to collect data from the PRASAC wells.[3]

Data collection began in February 1996 in Prey Veng and in April 1996 in Svay Rieng. Since then, monthly measurements of the static groundwater levels have been made with some gaps ranging in duration from single months to over one year. At the end of the data gathering phase of this study, about 10 years of static water level data was available for use in the computer modeling. An update of an additional three years of data was obtained for the completion of this final report. An Excel spreadsheet with the complete water level records is included in the CD accompanying this report.

Field observations by the Senior Hydrogeologist indicated that the measuring technique used by the groundwater monitoring teams was good. However, the measurement procedure is not well documented, which leads to some uncertainty about how consistently it has been applied over the data collection period. We are told that the static water levels are measured from the surface of the water in each well to the top of the well casing, which extends above the concrete apron. The data is then adjusted by subtracting the distance between the well casing and the ground surface before recording the data in the log book.[4] On-site calculations like this provide an opportunity for errors to be introduced. It was also not clear if the top-of-casing measurement is adjusted by subtracting only the height of the casing above the apron or if the height of the apron above the ground surface is also subtracted. Neither of these correction heights is recorded. It was not clear if a standard correction is used each month or if the correction height is re-measured each time. The height of the top-of-casing above the apron can be easily and accurately measured but the height of the apron above the ground surface would have to be estimated unless a level is used.

Measuring depth to groundwater at PRASAC monitoring well S4

3.2 Declining Groundwater Levels

The depth-to-groundwater data from two of the PRASAC wells (P24 and S14) are plotted in Figure 5. These two wells—typical of most of the other monitoring wells—show a downward trend in groundwater levels from 1996 through 2008, as indicated by the dashed regression analysis trend line.

[3] Of the 49 original monitoring wells, two Prey Veng wells were abandoned in 1996 soon after data collection began, one Svay Rieng well was abandoned in 2003, and two new Svay Rieng wells were added in 2005. Thus, monthly water level measurements are currently being taken from 48 monitoring wells in the two provinces.

[4] Personal communication (June 2009) with the PDoWRAM authorities responsible for collection of groundwater levels: Mr. Chum Sophy at Tel 012 909 639 in Prey Veng and Mr. Keo Ravy at Tel 099 812 142 in Svay Rieng

The slope of the trend line from each monitoring well (measured in m/year) is presented in Table 2 and Figure 6. Trend line slope was only calculated for those wells with reliable data records extending from 1996 through 2008.[5] Results indicate that, with one exception (P13), the groundwater table shows a downward trend at monitoring locations across the two provinces. The rate of decline is lowest close to the Mekong River and highest near the center of the study area. The average rate of decline for all wells is 0.14 m/year from 1996 through 2008 (13 years).

These observations, however, should be qualified by noting that short-term trends, even over periods of 13 years, may result from natural variations and are not necessarily evidence of long-term or man-made trends. If the rate of groundwater decline during the past 13 years is, in fact, indicative of future trends, the lowest dry season groundwater table in many of the monitoring wells will be more than 6 m below the ground surface in less than five years (as indicated in Table 2). This condition already exists for several wells.

A drawdown of this amount threatens rural domestic water supplies because the surface-mounted suction pumps commonly used for drinking water are not able to pump from depths exceeding about 6 m. This includes the VN6 pump and various locally-manufactured PVC pump designs, which numbered more than 130,000 units in the two study provinces in 2005.[6] These pumps will need to be replaced with more expensive (>$100) positive displacement pumps that can pump from greater depths. The poorest households will feel the impact most acutely since they are least able to adapt to changing conditions by installing a new hand pump.

Suction pumps like this VN6 in Prey Veng will be out of service if the depth-to-groundwater falls below 6 m

[5] Data for 2006-2008 from several of the Prey Veng monitoring wells (including P05, P06, P07, P08, P17, P18, P26, P29 and P30) are questionable due to mean annual water levels that are significantly different from previously established trends and/or annual variations in groundwater depth that are significantly different from previously established trends. Also, 2006-2008 data are available at two monitoring wells (P02 and P20) that had previously been abandoned in 1996.

[6] Estimate of hand pump numbers based on the Groundwater Usage Survey in Phase 1 of the current study (IDE Cambodia, 2005)

Figure 5: Depth to Groundwater Level at Two Representative Monitoring Wells

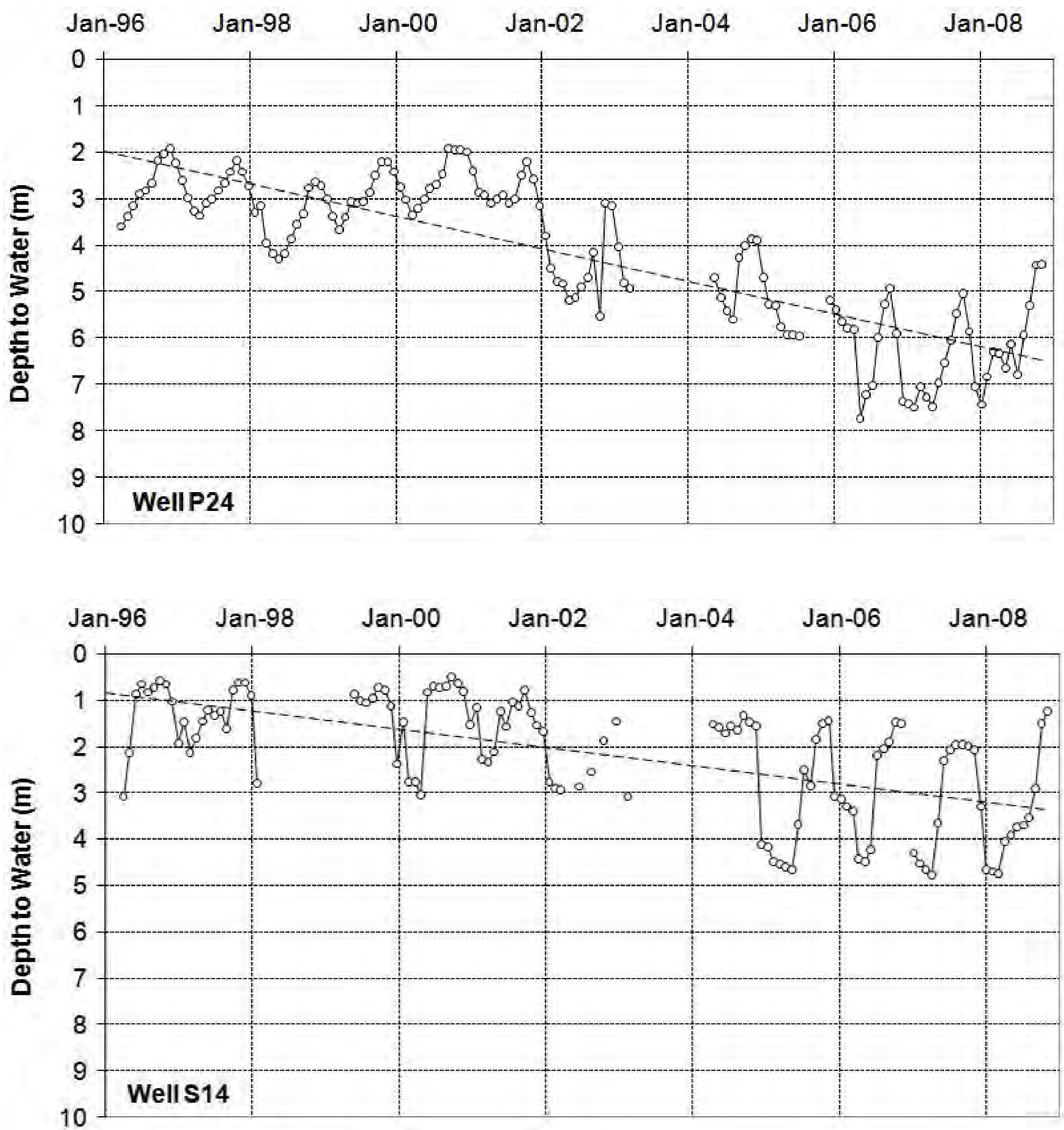


Table 2: PRASAC Monitoring Wells and Rate of Groundwater Decline 1996-2008

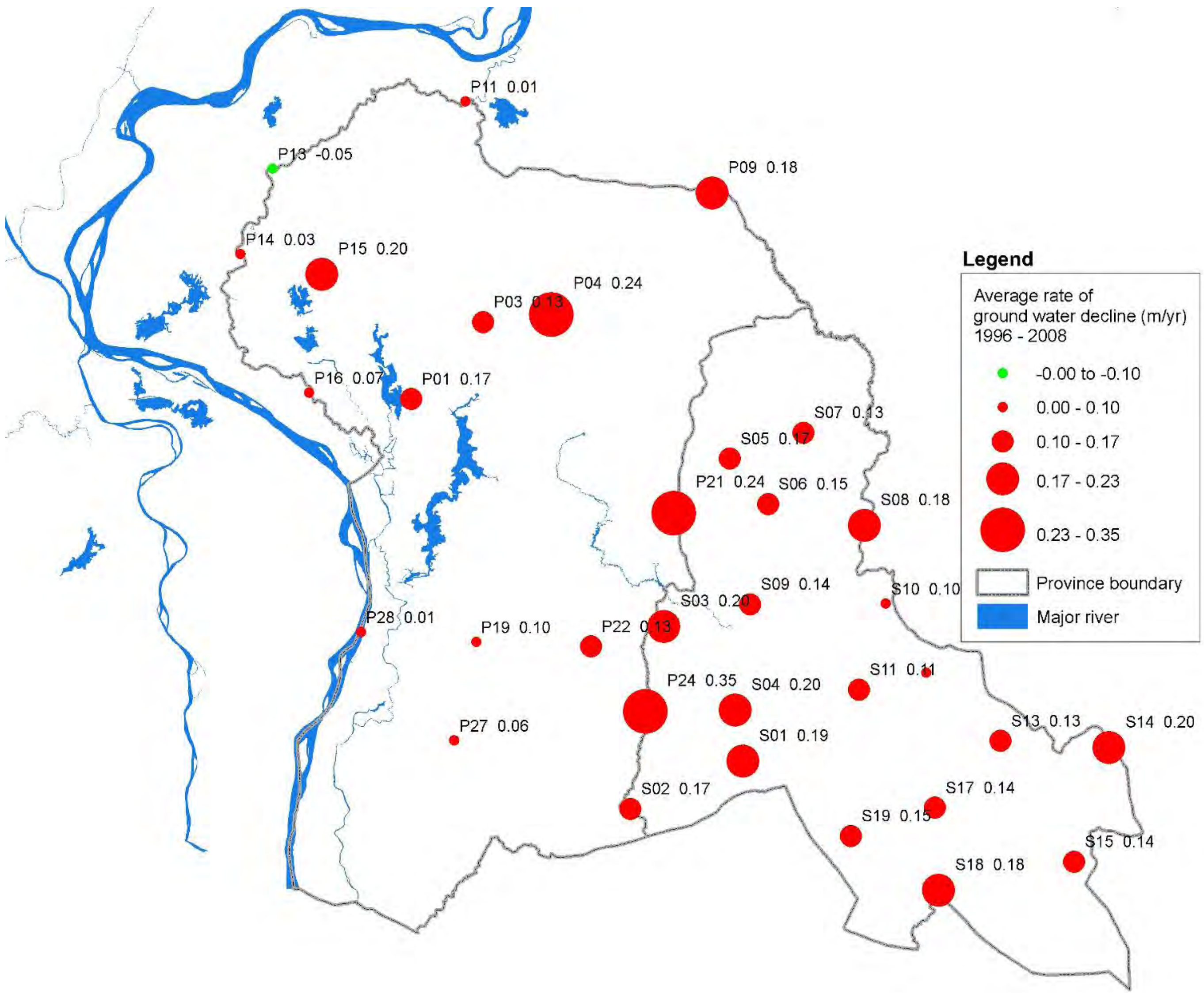
Prey Veng				
Well ID	**UTM Coordinates (m)**		**Elevation (m)**	**Slope of Trend Line † Apr 96 – Dec 08 (m/year)**
	Easting	**Northing**		
P01	536456	1270058	7.6	0.17*
P03	545867	1280132	9.1	0.13*
P04	554822	1281161	10.4	0.24*
P05	554820	1270411	9.5	---
P06	571907	1270317	8.9	---
P07	572704	1280617	7.8	---
P08	573809	1285911	9.1	---
P09	575830	1297037	14.1	0.18
P10	554782	1290034	12.0	---
P11	543562	1309032	13.0	0.01*
P12	531439	1305235	11.5	---
P13	518345	1300222	10.9	-0.05*
P14	514160	1289059	10.1	0.03*
P15	524801	1286371	8.5	0.20*
P16	523143	1270907	9.8	0.07*
P17	528281	1258983	8.5	---
P18	543257	1257356	8.6	---
P19	544973	1238261	6.6	0.10
P20	559700	1256300	---	---
P21	570848	1255129	7.3	0.24*
P22	559992	1237658	6.9	0.13*
P23	558191	1229288	6.1	---
P24	567107	1229161	5.9	0.35*
P25	557660	1217403	5.2	---
P26	542178	1226452	5.9	---
P27	542111	1225401	6.6	0.06*
P28	529893	1239572	6.8	0.01
P29	523492	1224180	6.9	---
P30	521655	1207018	5.1	---
P31	536600	1206000	---	---

Svay Rieng				
Well ID	**UTM Coordinates (m)**		**Elevation (m)**	**Slope of Trend Line † Apr 96 – Dec 08 (m/year)**
	Easting	**Northing**		
S01	579871	1222651	4.9	0.19
S02	565152	1216431	4.0	0.17
S03	569551	1240269	5.9	0.20
S04	578846	1229364	4.8	0.20
S05	578172	1262249	7.7	0.17
S06	583157	1256328	6.4	0.15
S07	587773	1265673	9.5	0.13*
S08	595754	1253514	6.5	0.18*
S09	580839	1243188	6.0	0.14
S10	598560	1243319	6.9	0.10
S11	595046	1232018	5.3	0.11
S12	603856	1234280	6.7	0.07
S13	613589	1225313	4.5	0.13
S14	627785	1224451	3.0	0.20
S15	623193	1209509	3.4	0.14
S16	625212	1198937	1.5	---
S17	604982	1216563	5.0	0.14
S18	605498	1205735	3.6	0.18
S19	594012	1212852	4.4	0.15
S20	578150	1235770	6.4	---
S21	573964	1231024	4.9	---
Mean (both provinces)				0.14

† Slope of trend line not calculated for wells with short data record (i.e., record starts after 1996 or ends before 2007)

* Indicates wells where the maximum 2008 groundwater depth was > 6 m below ground level or will be > 6 m below ground level in ≤ 5 years if present trends continue.

Figure 6: Average Rate of Groundwater Decline from Apr 96 to Dec 08



3.3 Correction of Surveyed Well Elevations

The data collected from the PRASAC monitoring wells are *depths to groundwater* measured from the ground surface. To be useful for groundwater modeling, this data must be converted to *groundwater elevations* by subtracting it from the ground surface elevation at the monitoring sites.

To determine the ground elevation at the monitoring sites, a Differential Global Positioning System (DGPS) survey of the 49 monitoring wells (plus several additional points) was completed by Geomatic Consulting International (GCI). The survey was conducted under a separate contract between GCI and the Client. Results of the DGPS survey were presented in a May 2007 report entitled *DGPS Survey of 60 Monitoring Wells, Prey Veng and Svey Rieng.*

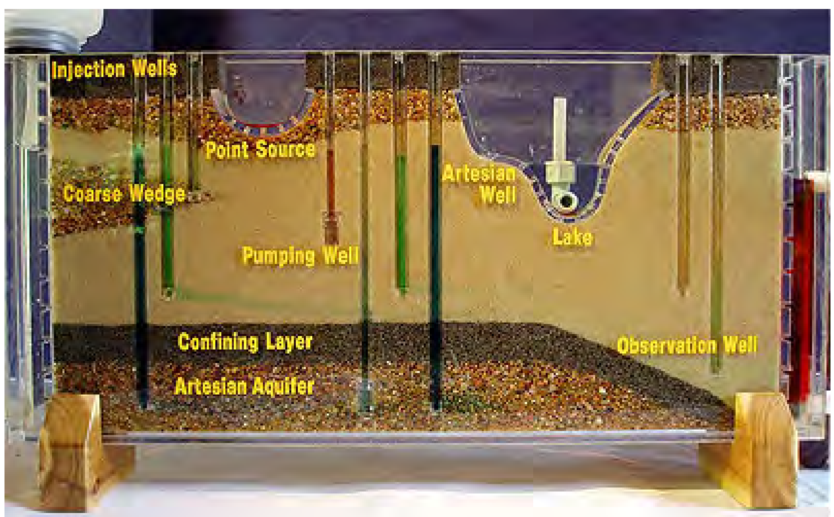
There was some concern about whether the accuracy of the elevations was within the specified requirement of +/- 0.50 m. Reliable elevations are particularly important because differences in groundwater elevation are relatively small over the study area. The Client requested IDE to verify the DGPS survey accuracy under an extension to the contract for the current study. This work resulted in a set of corrected elevations and revised error estimates for the monitoring wells as detailed in the February 2008 report included in Annex B. The corrected well elevations are referenced to the Ha Tien datum in Vietnam.[7]

4 Groundwater Modeling

4.1 What is a Groundwater Model

A groundwater model is a simplified version of a real-world groundwater flow system. Because it is a simplification, a model cannot replicate the real-world in all its detail but it does simulate certain aspects of the real-world system, such as water level and flow rates. A groundwater model can be used to predict how the real-world system will react to changes in inflows (e.g., rainfall), outflows (e.g., pumping), or water levels.

Figure 7: Example of a Small-scale Physical Model

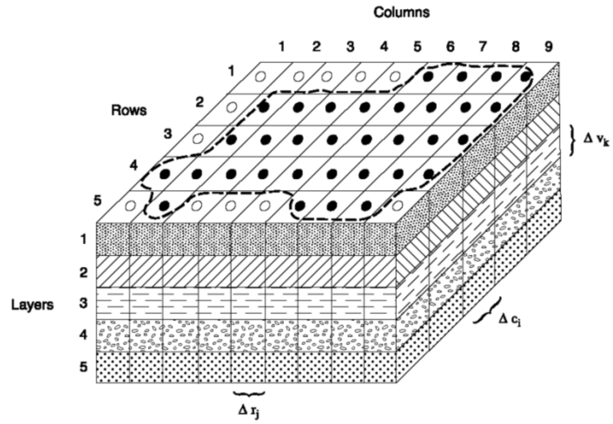


One type of groundwater model is a <u>small-scale physical model</u> (Figure 7), which uses real gravel, sand, clay placed in a tank or between two vertical sheets. Water is added to or extracted from the model and the effects on water levels and flows can be observed, sometimes using colored dyes to reveal flow streams.

[7] Based on the *Nivellement Général Khmer* (NGK) datum reference system established 1938-44.

Another type of model, the type used in this study, is a numerical groundwater model. The study area is divided into a grid of cells and the characteristics of each cell are defined (e.g., hydraulic conductivity and thickness of various soil and rock layers). The water level in each cell and the flow between cells are described by mathematical equations. A computer is used to complete the large number of calculations required to solve the equations for each grid cell.

Figure 8: Example of Grid Cells for a Three-dimensional Numerical Groundwater Model



Modeling is an important method for understanding complex natural systems like groundwater systems. A model can:

- Provide a rational basis for water resource management and planning,
- Predict impacts of future development scenarios,
- Compare the relative impacts of alternative development options,
- Conduct "what if" analyses,
- Link with other models (hydrological, ecological, economic, social, etc.), and
- Guide the design of data collection programs.

4.2 Building the Groundwater Model

The modeling work for this study was conducted by S. S. Papadopulous and Associates (SSP&A). The process began with the compilation and review of existing data. Information sources included the PRASAC depth-to-groundwater data, information gathered during Phase 1 of this study, additional geologic and topographic data gathered during Phase 2, and a field trip by the Senior Hydrogeologist and Intermediate Hydrogeologist to Prey Veng and Svay Rieng provinces (the field trip report is presented in Annex C).

From these sources, a conceptual model was developed synthesizing all that is known about groundwater in and around southeastern Cambodia. Based on this conceptual understanding of the aquifer, a three-dimensional numerical groundwater flow model was constructed using the *MODFLOW* and *Groundwater Vistas* software packages.[8] The model was calibrated to match, as closely as possible, observed water levels. The resulting groundwater model constitutes a significant contribution from this study that is of genuine lasting value for Cambodia. SSP&A's detailed report on the model development is included in Annex D.

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[8] MODFLOW is a computer program for three-dimensional groundwater simulation developed and freely distributed by the United States Geological Survey. As recommended in Phase 1 of the study, MODFLOW was selected as the most appropriate modeling package because it offers flexibility and features that meet the study requirements, it is widely used and accepted in the international groundwater research and consulting community, and it is compatible with a variety of user-friendly graphical user interface programs for entering model parameters and visualizing model outputs. The graphical user interface program *Groundwater Vistas* was selected for this project based on price and the Senior Hydrogeologist's familiarity with the software.

4.3 Predictive Scenarios

The completed and calibrated groundwater model was used to run predictive scenarios to determine the ***sustainable withdrawal*** from the aquifer underlying Prey Veng and Svay Rieng. Sustainable withdrawal is defined as the maximum rate of groundwater extraction that will result in a regional water table drawdown not exceeding a specified level when water is withdrawn uniformly across Prey Veng and Svay Rieng provinces. The term "sustainable withdrawal", as used here, should not be interpreted to mean the following:

- It is not the rate at which groundwater may be withdrawn from the aquifer without affecting the local ecosystem. Large-scale withdrawals necessarily affect the environment. Any additional supplies that are developed represent the interception of water that would have discharged elsewhere. Even without referring specifically to water rights, it is true that all water is allocated. Water that is not currently extracted for human uses, such as municipal supply and small-scale irrigation, discharges to the stream and river system, or to the wetlands that surround the mouths of the Mekong River.
- It does not refer to the capacity of individual wells to withdraw the water without causing excessive local declines in groundwater levels. That determination is site-specific, and depends on the local-scale characteristics of the aquifer, details of well construction, and proximity to existing wells.
- It also does not refer to the rate of extraction that can be made without affecting groundwater quality. The analyses developed here do not consider the potential effects of additional groundwater resource development on the chemical characteristics of the water.

It is also important to place the modeling and results in proper perspective. As with any model, the results from the predictive scenarios should be used with caution and with an understanding of the underlying model assumptions and limitations. In particular, the model is based on a simplified conceptual model of the groundwater flow in Prey Veng and Svay Rieng and each of the parameters used to define the model has an associated level of uncertainty. Nevertheless, based on standard criteria for model acceptance, the calibrated model provided a good match with observed water levels.

In total, seven predictive scenarios were analyzed, each scenario corresponding to a different criterion for sustainable withdrawal. In the first four scenarios (Set 1), withdrawals are constrained by a minimum allowable groundwater level in the aquifer. In these scenarios, the sustainable withdrawal is defined as the maximum withdrawal that can occur before drawing down the water table below 5.0 m, 3.5 m, 2.5 m, or 1.0 m above the top of the old alluvium aquifer. Avoiding drawdown below the top of the old alluvium is important to the development of large-scale pumping facilities where the water level needs to remain above the level of the well screens.

In the next three scenarios (Set 2), withdrawals are constrained by a maximum allowable decline in groundwater level relative to the ground surface. In these scenarios, the sustainable withdrawal is defined as the maximum withdrawal that can occur before drawing down the water table more than 5.0 m, 6.0 m, or 7.0 m below the ground surface. These criteria are relevant to the protection of domestic groundwater sources.

The sustainable withdrawal is also dependent upon the assumed rate of rainwater recharging the aquifer through the exposed old alluvium in the northeast part of the modeled area (discussed further in Section 5 of Annex D). Based on a review of the available data, the recharge rate is most likely within the range of 3 to 6 mm/year. The more conservative estimate of 3 mm/year is assumed for the sustainable withdrawal results presented in Table 3 below.[9]

[9] As an indication of sensitivity of results to the assumed recharge rate, the sustainable withdrawal for a 6-m drawdown below ground surface is 0.29 mm/day for a recharge rate of 3 mm/year compared to 0.51 mm/day for a recharge rate of 6 mm/year. The relationship between recharge rate and sustainable withdrawal is plotted in Figure 56 of Annex D.

Table 3: Sustainable Withdrawal for Various Drawdown Criteria with 3 mm/year Recharge

Scenario	Criteria for Sustainable Withdrawal	Sustainable Withdrawal	
		Maximum Time-averaged Discharge Rate (m^3/day)	Equivalent Depth of Water (mm/day)
Set 1	Minimum height of water table above the top of the old alluvium layer (m)		
1	5.0	7,900,000	1.01
2	3.5	8,700,000	1.11
3	2.5	9,000,000	1.15
4	1.0	9,700,000	1.24
Set 2	Maximum depth of water table below the ground surface (m)		
5	5.0	1,800,000	0.23
6	6.0	2,300,000	0.29
7	7.0	2,600,000	0.33

The results in Table 3 above represent the maximum amount of water that can be withdrawn from the aquifer without exceeding the specified drawdown limits. The sustainable withdrawal values are averaged over a year-long period and expressed as a daily rate (cubic meters per day). Dividing this rate by the total area of the two provinces (7,849 km^2) and adjusting for units gives the sustainable withdrawal in equivalent depth of water (millimeters per day).

These results can be used as a guide for development planning. However, as with any model, the results need to be interpreted and used with an understanding of the inherent and unavoidable uncertainties in the modeling process and the underlying model assumptions. The predictive scenarios all assume a uniform rate of water withdrawals across the study area. Thus it is not possible to say, for instance, that one area can withdraw twice the sustainable withdrawal if another equal-sized area withdraws no groundwater.[10] Although 'quick-and-dirty' calculations like this are not possible, the model can be applied to analyze additional scenarios that answer questions related to specific development options.

Another limitation of the model is that it does not calculate the drawdown profile around any particular well, although it does model the broader influence of such a drawdown. The model operates by "draining" water out of each 1-km grid cell. The model does not distinguish whether the water is drained through one well or many wells.

4.4 Implications of Predictive Scenarios

The scenarios in Set 2 impose the more conservative limits on the maximum sustainable withdrawal and, if met, would protect against negative impacts on domestic water sources. For a maximum water table depth of 6.0 m (Scenario 6), the estimated sustainable withdrawal is 0.29 mm/day. The current rate of groundwater withdrawal appears to be approaching the sustainable withdrawal already as evidenced by the declining groundwater levels in the PRASAC monitoring wells (Section 3). A rough estimate of total daily water usage in the study provinces in 2005 (Table 4 below) suggests that groundwater was being extracted at a rate equal to 53% of the sustainable withdrawal for a maximum groundwater depth of 6.0

[10] The MODFLOW model includes head-dependent groundwater sources and sinks, which are nonlinear features. Thus, it is not always possible to generalize the effects of localized developments by superposition.

m. This estimate could be improved and updated by a more detailed survey of groundwater usage in Prey Veng and Svay Rieng.

Table 4: Estimate of Daily Groundwater Use in Prey Veng and Svay Rieng for 2005

Domestic uses		
A. 2005 population in the study provinces (extrapolated from 2003 census data)	1,500,000	people
B. Percentage of population using groundwater (2003 census data)	80	%
C. Average per capita water use based on rapid assessment in Svay Rieng	50	liters/person/day
D. Daily groundwater extraction = (A x B/100 x C)/1000	60,000	m^3/day
Irrigation uses – engine-powered pumps		
E. Number of pumps in 2005*	13,500	pumps
F. Average pumping rate (estimated)	20	m^3/hour
G. Average pumping time averaged over a year (estimated)	4	hours/day
H. Daily groundwater extraction = E x F x G	1,080,000	m^3/day
Irrigation uses – treadle pumps		
J. Number of pumps in 2005*	14,400	pumps
K. Average pumping rate, (estimated)	3	m^3/hour
L. Average pumping time averaged over a year, (estimated)	2	hours/day
M. Daily groundwater extraction, = J x K x L	86,000	m^3/day
N. Total daily water extraction, = D + H + M	**1,226,000**	**m^3/day**
P. Sustainable withdrawal for 6.0 m drawdown with 3 mm/year recharge (Table 3)	2,300,000	m^3/day
Q. Total daily water extraction as a percentage of sustainable withdrawal = (N/P) x 100	**53**	**%**

* Estimates of pump numbers based on Groundwater Usage Survey in Phase 1 of this study (IDE Cambodia, 2005)

As indicated in Table 4, the irrigation uses of groundwater far outweigh domestic uses and thus agricultural developments are more likely to have significant impacts on groundwater levels than domestic water developments. Taking rice irrigation development as an example, the calculations in Table 5 below indicate that the maximum area of dry-season rice crops that could be irrigated amounts to 5.8% of the total area of Prey Veng and Svay Rieng, or about 45,000 ha, assuming that the irrigated area is uniformly distributed across the study area.

Table 5: Estimate of Irrigable Area for a Maximum Groundwater Depth of 6.0 m

A. Crop water requirement for dry-season rice *	10	mm/day
B. Sustainable withdrawal averaged over a full year for a max water depth of 6.0 m (Table 3)	0.29	mm/day
C. Sustainable withdrawal if all pumping occurs within a 6-month period = B x 2	0.58	mm/day
D. Sustainable withdrawal as a percentage of crop water requirement = C / A x 100	5.8	%
E. Total area of Prey Veng and Svay Rieng	784,900	ha
F. Maximum area of dry-season rice crops that can be irrigated with groundwater = D x E	45,524	ha

* Typical crop water requirements for rice in tropical regions are 6 to 7 mm/day in the dry season (DeDatta, 1981). When allowances for distribution and evaporation losses are added, the total groundwater withdrawal required for rice irrigation may be estimated as 10 mm/day.

5 Training and Information Dissemination

One objective of this study was to develop local technical capacity and disseminate the study results. Specific points from the Terms of Reference related to training and dissemination include:

- Train MoWRAM staff and local consultants to use and maintain the model.
- Train PDoWRAM staff to understand the implications of the model and the relevance of its predictions to their work.
- Involve a wider group of concerned staff of MoWRAM and PDoWRAM in the study through conducting a series of seminars at key stages of the project.
- Disseminate the lessons learned in developing the model with a view to encouraging possible replication for other areas of the country.
- Train local Hydrogeology consultants to build local technical capacity in this field.

These points were addressed through the training and dissemination activities summarized in the following sections.

5.1 Model Use and Maintenance

Training in the design, development, use, and maintenance of the groundwater model was directed toward the two local hydrogeologist consultants from CADTIS and the two MoWRAM technical personnel who were assigned to the project.

Two week-long training workshops were conducted by the Senior Hydrogeologist covering theoretical and practical aspects of groundwater modeling. The training workshops occurred during the Senior Hydrogeologist visits to Cambodia in February and June 2007. This was supplemented with on-the-job mentoring by the Senior Hydrogeologist while he was in Cambodia and later by E-mail support from Canada. Extensive training materials and technical notes were also prepared to support the training process. These materials are included in Annex H.

Hands-on training for study team members So Im Monichoth (left) and Chiep Piseth (centre) by Senior Hydrogeologist Christopher Neville (right)

The local hydrogeologist consultants worked closely with the Senior Hydrogeologist. The two MoWRAM technical personnel participated in training sessions and provided support to the data compilation and model development, although not on a full-time basis. As a result, capacity was substantially developed in the four local project assistants. Some of the benefits were lost, however, when the assistants moved on to other assignments before the end of the project (this occurred during a six-month break in the project to resolve issues with the accuracy of the DGPS well elevation survey). Nevertheless, the skills that were developed continue to make a valuable contribution to Cambodia and the Mekong Region. As evidence of this, Mr. So Im Monichoth, one of the local CADTIS consultants, secured a position with the Mekong River Commission as a modeling specialist based partly on the experience he gained in this project.

5.2 Understanding and Application of Model Outputs

The study team conducted dissemination activities to increase awareness and understanding of the modeling project and to provide an introduction to the application of groundwater modeling outputs to natural resource management planning. This was accomplished through a series of workshops aimed at senior managers, planners, and policy makers at national and provincial levels.

Three half-day workshops were conducted:

- The first workshop, conducted on 28 February 2007, introduced the project objectives, methods, and uses of groundwater modeling for resource management and policy making. The workshop was led by the Senior Hydrogeologist with Khmer translation.
- The second workshop, conducted on 8 June 2007, presented a project update and discussed recommendations for the scenarios to be modeled. The workshop was led by the Senior Hydrogeologist with Khmer translation.
- The third workshop, conducted on 28 August 2009, was led by the Project Coordinator in the Khmer language with support from the Intermediate Hydrogeologist. The objectives of this final stakeholder workshop were to help the participants understand:
    1. What a groundwater model is and what it can and cannot be used for,
    2. The results from the PVG-SVG groundwater model,
    3. The potential uses of the PVG-SVG groundwater model in the future.

Stakeholder workshop presented by Christopher Neville in Feb 2007

Presentations from the workshops are attached in Annex E, Annex F, and Annex G.

6 Conclusions and Recommendations

6.1 Depth-to-Groundwater Monitoring

The long-term record of monthly groundwater levels in wells of the PRASAC monitoring networks in Prey Veng and Svay Rieng is a remarkable achievement and has been a crucial component of the hydrogeologic analyses. The water level data are important for understanding groundwater resources and monitoring the potential effects of future development. ***We strongly recommend that this monitoring program be continued.***

Field observations by the Senior Hydrogeologist indicated that the measuring technique used by the groundwater monitoring team was good. The procedure would benefit, however, from better documentation. We are told that the monthly water levels are measured from the top of the well casing (which extends above the concrete apron) and that the height from the measuring point to the ground surface is subtracted before recording the data in the log book.[11] On-site calculations like this provide an opportunity for errors to be introduced. It was also not clear if the top-of-casing measurement is adjusted by subtracting only the height of the casing above the apron or if the height of the apron above the ground surface is also subtracted. Neither of these correction heights is recorded. It was not clear if a standard correction is used each month or if the correction height is re-measured each time. The height of the top-of-casing above the apron can be easily and accurately measured but the height of the apron above the ground surface would have to be estimated unless a level is used.

We recommend that the measurement procedure be clearly defined and documented. Measurements should be taken from the exact same point on the well casing each time and the correction height from measurement point to the ground surface should be precisely surveyed, recorded, and consistently applied. Procedures for storing and safeguarding the collected data should also be reviewed and documented. Clear documentation of procedures will help to ensure consistency, assist in training new personnel, and provide a historical record of measurement practices for data users.

For the preparation of this report, IDE obtained updates of groundwater level records for the period 2006 through 2008. There are anomalies in the data from some of the Prey Veng wells that suggest possible errors in data collection or record keeping. The 2006-2008 data from P05, P06, P07, P08, P17, P18, P26, P29, and P30 exhibit mean annual water levels that are significantly different from previously established trends and/or annual variations in groundwater depth that are significantly different from previously established trends. Also, 2006-2008 data are available at two monitoring wells (P02 and P20) that had previously been abandoned in 1996. It seems unusual that collection would be started again after such a long time. ***We recommend that these questionable data be reviewed with Prey Veng PDoWRAM staff to identify, and resolve where possible, the causes for the anomalous data.***

6.2 Elevation of Monitoring Wells

The importance of accurate measurements of elevations of the PRASAC monitoring wells in Prey Veng and Svay Rieng cannot be over stated. Any errors in the elevations of the monitoring points translate directly into errors in the target water levels that are used in the calibration of the groundwater model. We are confident that most of the corrected well elevations are accurate within +/- 0.50 m. Even so, the total decline in hydraulic head across the two provinces is only about 13 m (from a high of about 15 m in the north to a low of about 2 m in the south), which means that an accuracy of +/- 0.50 m still represent a significant fraction of the total decline in hydraulic head.

The quality of model results from the current analyses and any future analyses can be improved by conducting a more careful survey of the elevations of the monitoring points. The survey should be executed by professional surveyors, referenced to the Ha Tien datum, and should measure the precise point from which monthly depth-to-water measurements are recorded at each well. The survey should also include the elevations of the zero-stage points on the Mekong River water level gauging stations at Kratie, Kampong Cham, Chroy Changvar, and Neak Loeung in Cambodia and at Tan Chau in Vietnam.

6.3 Sustainable Withdrawal

The historical water level measurements in the PRASAC wells indicate a trend of declining groundwater tables across both study provinces. The average rate of decline is estimated at 0.14 m per year. If the observed groundwater decline is in fact part of a long-term trend, the maximum dry season groundwater depth in many locations will be more than 6.0 m below the ground surface in less than five years. This condition already exists in many areas. This trend poses a threat to the drinking water supply of the rural

[11] Personal communication (June 2009) with the PDoWRAM authorities responsible for collection of groundwater levels: Mr. Chum Sophy at Tel 012 909 639 in Prey Veng and Mr. Keo Ravy at Tel 099 812 142 in Svay Rieng

population in the study area. The poorest households will feel the impacts most acutely since they are least able to adapt to changing environmental conditions (by installing a new hand pump for instance). ***We recommend that the Royal Cambodian Government investigate strategies to protect against further groundwater drawdown and/or ways to mitigate the potential negative impacts.***

This study has produced a range of estimates for sustainable withdrawal from the aquifer for various conditions as discussed above in Section 4. The sustainable withdrawal values represent the maximum amount of water that can be withdrawn from the aquifer without exceeding specified drawdown limits when water is withdrawn uniformly over the entire study area. For the specified drawdown limit of 6.0 m below the ground surface, the estimated sustainable withdrawal is 0.29 mm/day (mean annual average). ***This value can be used, with appropriate caution, as a guide for development planning, although major groundwater development programs planned in the future should be individually modeled to assess impacts***.

Preliminary estimates of water use in the study provinces suggest that the rate of groundwater withdrawal in 2005 was already at about half of the sustainable withdrawal (for maximum groundwater depth of 6.0 m). ***We recommend that a detailed inventory of current groundwater resource use be undertaken to determine how much of the sustainable withdrawal is currently being utilized.***

6.4 Future Use of the Model

The majority of the effort in this study was spent on the development of the conceptual groundwater model and building the MODFLOW numerical model of the groundwater system. To our knowledge, this is the first time a groundwater model of this level of detail has been developed in Cambodia. Certainly, this is the first attempt to model the Prey Veng and Svay Rieng study area in detail. The model thus represents a significant achievement of lasting value for Cambodia.

Within the limits of the current study, only a small portion of the model's ultimate value and potential has been realized. The groundwater model can and should be used and developed further by other researchers to assess additional development scenarios and to extend the understanding of the groundwater system.

We strongly recommend that the Client seek ways and means to make use of the model to analyze and inform future development plans. The MODFLOW data files and supporting documentation should be made freely available and actively promoted to regional and international research institutions as a research topic for Master's and Ph.D. level students. Options for posting the results and source data files from this study on the Internet should also be explored.

We further recommend that a follow-on project be developed to investigate future plans for agricultural and domestic water supply developments and to promote stronger interaction between planners and modelers (see Section 6.6). Following is a non-exhaustive list of additional development scenarios that could be modeled individually or in combination:

- The scenarios modeled in this study estimated sustainable withdrawals over the entire study area (i.e., a two-province average). It would also be possible to specify sustainable withdrawals for smaller areas such as Districts or 10 km x 10 km grid squares, for example.
- Determine the groundwater levels that would result from current or future extraction rates that are estimated based on current or future land uses (wet-season, dry-season, or recession rice; field crops; grassland, etc.)
- Determine the groundwater levels that would result from increasing rural domestic water use due to population growth.

- Determine the groundwater levels that would result from developing urban domestic water supply systems.
- Determine the impacts on groundwater quality that would result from changes in groundwater use.
- Determine the effects of potential groundwater management policies (e.g., government regulation to limit groundwater withdrawals or a donor subsidy for irrigation pumps, which could encourage groundwater use),
- Determine the effects of community groundwater management strategies,
- Determine the effects of variations in annual rainfall and Mekong River levels due to climate change,
- Determine the effects of reservoir developments in the upper Mekong River basin.

Over time, additional information about the groundwater system in the study area will become available. ***We recommend that new groundwater information be used to improve the model as it becomes available.*** As noted above, the model could be improved by a more accurate determination of the monitoring well elevations and ongoing collection of water level data from the network of PRASAC wells. In addition, the model would also benefit from:

- Additional hydraulic testing (especially long-duration pumping tests with multiple observation wells) to improve the characterization of hydraulic conductivity in the old alluvium,
- Infiltration tests to improve the characterization of recharge rates through the exposed old alluvium, and
- Additional borehole logs and geophysical investigations to refine the top of old alluvium and top of bedrock elevations.

6.5 Capacity Building

Training groundwater modelers is a challenging but essential activity of applied groundwater modeling. To build skills and gain confidence as a modeler, *extensive and continuous* practice is required to strengthen abstract thinking skills, deepen proficiency with the model's underlying mathematics, and develop good professional judgment. Hydrogeology is taught at the graduate level in university engineering and applied geology programs. Within those programs groundwater modeling is introduced as a specialized course of study with a significant amount of background knowledge taken for granted. For this reason, it is not realistic to expect high-level capacity for groundwater modeling to result from any single modeling project.

If the development of local modeling capacity is a high priority in Cambodia, we recommend that resources be concentrated to create centralized expertise within an appropriate institution at the national level. This strategy would allow for a team of modelers to develop and maintain the necessary "critical mass" of skills and experience gained through numerous modeling projects, specialized training opportunities, and support from a variety of advisors over time. Decentralized modeling centers, at the provincial level for instance, would be unlikely to undertake sufficient modeling projects to develop the necessary skills and experience.

6.6 Integration of Modeling and Development Planning

The risk with any modeling project is that it may become an academic exercise with limited practical application. To avoid this, modeling projects must allow for meaningful and frequent interaction between modelers, development planners, and other stakeholders. Such interaction would aim to ensure that the model is of an appropriate design and level of detail to answer relevant questions with appropriate precision. Effective use of models in development planning is also enhanced by utilizing multi-disciplinary teams that are able to link models of the physical world to ecosystem models, social-economic models, and policy implications. Interaction between multi-disciplinary teams and development planners also improves the level of understanding that each participant has for the others' priorities and constraints.

In a recent publication, the Mekong River Commission summarized lessons learned from their experience with water resource modeling in the Mekong River basin. Many of these lessons are relevant to the present study as well (after Sarkkula et al., 2007):

- Modeling has a potentially important role in water management planning, especially for analyzing future scenarios and resulting impacts in complex systems (such as groundwater systems).
- In order to better link modeling with real-world problems, the modeling project needs to be designed from the very beginning to include clear and purposeful links with ecosystem, social, economic, and policy analysis.
- Modeling projects need to focus on cooperation and communication by enhancing dialogue with decision-makers and other stakeholders and by improving the transparency and intelligibility of the models and their results.
- Communicating new information in a compelling and easily understood form to decision makers and the public requires specialized skills (e.g., policy advocacy, journalism, graphic communication) that should be incorporated into modeling projects.
- The quality of modeling depends in large part on the availability and quality of hydrological, environmental, social, and economic information. Long-term historical data series are especially important for determining trends, establishing baseline conditions, and calibrating models. A commitment to careful, consistent collection and open access to this information is essential.

When modeling projects are well-integrated with the development planning process, a virtuous cycle is created. Multi-disciplinary teams, in close collaboration with development planners, are able to develop appropriate models and clearly communicate practical answers to relevant development questions. Planners, in turn, are motivated to invest in quality data collection and additional modeling projects, which further strengthens modelers' skills, experience, and ability to deliver useful results. ***We recommend that future modeling projects, including future applications of this groundwater model, be designed and budgeted to ensure that this integration of modeling and development planning occurs.***

7 References

DeDatta, S. K., 1981, *Principles and Practices of Rice Production*. John Wiley, New York.

IDE Cambodia, 2005, Strategic *Study of Groundwater Resources in Prey Veng and Svay Rieng (Phase 1) Final Report*, Rural Poverty Reduction Project, Seila Task Force Secretariat, IFAD Loan No: 623-KH, Phnom Penh

Rasmussen, W.C., and G.M. Bradford, 1977: *Ground-Water Resources of Cambodia*, Water-Supply Paper 1608-P, United States Geological Survey, Washington DC.

Roberts, M.S., 1998: *Groundwater Irrigation in the Mekong Delta of Cambodia*, M.Sc Thesis, Cornell University, Ithaca, New York.

Sarkkula, J., Keskinen, M., Koponen, J., Kummu, M., Nikula, J., Varis, O., Virtanen, M., 2007, Mathematical Modeling in Integrated Management of Water Resources: Magical Tool, Mathematical Toy, or Something in Between?, in Lebel, L., Dore, J., Daniel, R., Yang Saing, K., eds., *Democratizing Water Governance in the Mekong*, USER, Mekong Press, Chiang Mai.

Annex A: Terms of Reference

Terms of Reference

Strategic Study of Groundwater Resources in Prey Veng and Svay Rieng (Phase 2)

Project:	Rural Poverty Reduction Project
Project Number:	
Funding Agency:	International Fund for Agricultural Development
Employing Agency:	Seila Task Force Secretariat (STFS)
Cooperating Agency:	Ministry of Water Resources and Meteorology (MoWRAM)
Location:	Phnom Penh, Prey Veng, Svay Rieng
Duration:	Approximately 33 weeks beginning in October 2006

Summary

Seila Task Force Secretariat (STFS), in cooperation with the Ministry of Water Resources and Meteorology (MoWRAM) has received funding from International Fund for Agricultural Development (IFAD) under the Rural Poverty Reduction Project (RPRP) for a strategic study of groundwater resources in Prey Veng and Svay Rieng provinces. The objective of the study is to estimate the potential for development of sustainable groundwater irrigation in Prey Veng and Svay Rieng provinces, having regard to groundwater resource and other environmental constraints. The first phase of this study was completed in December 2005. STFS now wishes to engage consultants to implement the second phase, consisting of development of a 3D model of groundwater flow in the two provinces.

1.0 Background

Rural Poverty Reduction Project (RPRP) is a project of the Royal Government of Cambodia, receiving loan funding from the International Fund for Agricultural Development (IFAD). Overall responsibility for execution of the project is with the Seila Task Force Secretariat (STFS). Component activities are implemented by the Ministry of Agriculture, Forestry and Fisheries (MAFF), the Minstry of Womens Affairs (MoWA), Ministry of Water Resources and Meteorology (MoWRAM) and Provincial Rural Development Committees of Prey Veng and Svay Rieng Provinces. The planned period of the project is six years, 2004 – 2009.

Prey Veng and Svay Rieng Provinces comprise the south-eastern part of Cambodia and are among the country's largest, poorest and most densely populated provinces. Most of the land area of these provinces is used for rice growing, but irrigation systems are limited in extent and in most places only a single annual crop, watered by rain or by flood recession, is possible. Both provinces suffer from unpredictable rainfall so that there is a high risk of failure of the annual rice crop. Prey Veng province is also liable to flooding. Therefore, there is an urgent need to improve irrigation and water management practices to improve crop reliability, improve food security, alleviate poverty and encourage growth of agriculture and related sectors of the rural economy. Increased availability and reliability of irrigation would allow increased rice production and diversification to higher value crops.

Both provinces are of mainly flat topography. Prey Veng is bordered by the Mekong River on the west side and a large part of the province is floodplain subject to annual inundation. Surface geology is Quarternary alluvium except for a small outcrop of pre-Hercynian granite in Ba Phnom Distict, Prey Veng.

Both provinces have fairly abundant groundwater resources which can be accessed by shallow open wells or hand pump wells. In the past, wells were used mainly for domestic water supplies and the rate of extraction was not sufficient to endanger the resource. However, there appears to be a rapid and unregulated growth of groundwater irrigation in districts where the access to groundwater is easiest, using simple flush bored wells and diesel pumps. Phase 1 of the present study found some evidence that the rate of installation of new wells has moderated recently but it is not known whether this will prove to be a long-term phenomenon. Farmers using this system report encouraging results. Farmers are able to exercise local control over time and rates of pumping and over operation and maintenance of the system. Large increases in rice production on the irrigated fields, and diversification into other crops, have been achieved. Thus, the potential benefits of expansion of groundwater irrigation are clear, but these must be set against risks which have not been quantified.

It is not known what the long term consequence of continued unregulated growth of groundwater irrigation will be. There have already been some reports of domestic water supply wells becoming dry as a result of irrigation pumping activities nearby. The official policy of MoWRAM is to exercise caution and to discourage expansion of groundwater exploitation for irrigation. However, MoWRAM and is Provincial Departments do not have the capacity to enforce effective regulation at present.

Since 1997, with support from the EU-PRASAC project and now from RPRP, the Provincial Departments of Water Resources and Meteorology (PDoWRAM) in Prey Veng and Svay Rieng have monitored static water levels in selected wells on a monthly basis and have also recorded some basic chemical test parameters. In 2004 the PDoWRAMs also initiated pilot groundwater irrigation projects with funding from RPRP, and which include acquifer pumping tests amongst the activities. Therefore, a certain amount of data is already available. However, there is a need for expert advice on interpretation of current data, on requirements for future data collection, and on development of an overall assessment of the resource and a framework for sustainable exploitation.

Phase 1 of the present study resulted in:

- An outline of a suitable model for estimation of groundwater storage, recharge and sustainable extraction rates in Prey Veng and Svay Rieng;
- Identification of additional data needed for development and initial calibration of the model;
- A workplan for development, calibration of the model and initial tests of the model to improve understanding of sustainable extraction levels, suitable for practical use in a regulatory system, and training of MoWRAM staff to operate and maintain the model; and
- A survey the current extent of groundwater use for irrigation and other purposes in Prey Veng and Svay Rieng.

The report of Phase 1 of the study is available from the Seila website (www.seila.gov.kh) or via the following link:

http://203.223.42.59:8080/downloads/SSGWRPVSR_STFS-FinalReport_05-12-23.pdf

2.0 Objectives

The objective of the strategic groundwater study is “To estimate the potential for development of sustainable groundwater irrigation in Prey Veng and Svay Rieng provinces, having regard to groundwater resource and other environmental constraints.”

The immediate objectives of Phase 2 of the study, covered by this Terms of Reference, will be to:

- Develop a three-dimensional numerical groundwater flow model for Prey Veng and Svay Rieng provinces, capable of being used to inform strategic decisions on management of groundwater resources;
- Improve the level of understanding of the groundwater resource and the impacts of possible changes in extraction rates, Mekong river hydrology etc by analysing a number (from 3 to 5) of alternative model scenarios;
- Train staff of the Ministry of Water Resources and Meteorology to use and maintain the model;
- Train staff of the Provincial Departments of Water Resources to understand the implications of the model and the relevance of its predictions to their work;
- Disseminate the lessons learned in developing the model with a view to encouraging possible replication for other areas of the country.

3.0 Scope of Services

3.1. Groundwater Flow Modeling

The Consultant will proceed to develop, test and carry out analysis with the groundwater flow model by the following general stages:

1. Familiarisation with the existing situation regarding regulation of groundwater extraction in Prey Veng and Svay Rieng provinces,and with the findings and recommendations of Phase 1 of the Strategic Study of Groundwater Resources in Prey Veng and Svay Rieng;
2. Compilation and review of existing data by:
    - Developing a well database and populate with existing data;
    - Checking the locations of the wells recorded in the database;
    - Preparing maps and tables of hydrologic data.
3. Development of a conceptual model of groundwater flow in the two provinces, with the purpose of:
    - Establishing an understanding of regional conditions;
    - Defining the groundwater problem for development of a numerical model; and
    - Informing the selection of an appropriate numerical modeling platform.

4. Setup of the numerical model using appropriate software. The software package recommended in Phase 1 of the study is MODFLOW. The consultant may recommend alternative software but in this case will be required to demonstrate that the functionality of the proposed software is at least equivalent to MODFLOW.
5. Calibration of the model through a "trial and study" approach. Results of alternative model structures should be examined carefully to evaluate the consistency of the model results with both qualitative and quantitative assessments of the groundwater flow system assembled in the conceptual model.
6. Development and analysis of model scenarios of alternative management of groundwater resources; from 3 to 5 alternative scenarios based on assumptions about extraction rates, irrigation patterns and potential changes in the hydrology of the Mekong river).
7. Identification of data required to further refine the model, and to the extent possible collect available data. This is expected to be limited to relatively straightforward tasks such as:
   - Confirming the existence and reporting on the condition of prominent wells (both monitoring and supply wells); and
   - Checking the coordinates of wells with a hand-held GPS unit.

3.2 Consultant's Team

The composition of the Consultant's team proposed here and the allocation of time is that recommended in the report of Phase 1 of the study. The Consultant may propose variations to the details of these arrangements provided that the overall objectives and detailed tasks itemised above are accomplished, and subject to agreement of STFS. The envisaged composition of the team is as follows:

Project Coordinator (23 person-days)

The project coordinator will be a senior professional with a higher degree in a relevant discipline and a minimum of fifteen years professional experience, including significant experience in management or team leadership positions. The Project Coordinator will be responsible for overall management of the study, coordination of the team and liaison with STFS and with MoWRAM.

It is envisaged that the Project Coordinator will be based in Cambodia and able to provide flexible time inputs to the study as need arises.

Senior Hydrogeologist (57 person-days)

The Senior Hydrogeologist will be a senior international expert in the development and application of groundwater models for water-resources applications. The Senior Hydrogeologist will have overall responsibility for model development and will oversee the work of the Intermediate Hydrogeologist. It is envisaged that the Senior Hydrogeologist will be based overseas and will conduct the majority of his/her work at home base, communicating with the team in Cambodia by e-mail. Provision will be made for the Senior Hydrogeologist to make two visits to Cambodia of 2-3 weeks each.

Intermediate Hydrogeologist (114 person-days)

The Intermediate Hydrogeologist will be qualified to Master's degree level in hydrogeology, groundwater hydrology or a closely related field and will have a minimum of 5 years professional experience including familiarity with development, calibration, testing and analysis of 3-dimensional groundwater flow models. The Intermediate Hydrogeologist will be based in Cambodia for the duration of his/her assignment and will work under the direction of the Senior Hydrogeologist to develop and test the groundwater flow model.

Junior Hydrogeologist (65 person-days)

The Junior Hydrogeologist will be a Cambodian professional with a minimum of a bachelor's degree in hydrology, hydrogeology or engineering and at least five years'professional experience in a relevant field. The Junior Hydrogeologist will be fluent in English and have a high level of computer literacy. The Junior Hydrogeologist, together with staff members of MoWRAM, will be trained in groundwater modeling during the course of the assignment.

GIS Support Staff (18 person-days)

GIS support staff will be a Cambodian professional with relevant qualifications and experience who will be deployed by the consultant to assist with database development and mapping tasks.

3.3 Consultant-Client Liaison

For administrative matters the consultant will liaise with the Chief of the Programme Operations Unit of STFS. For technical matters, the consultant will liaise directly with the Director of the Department of Groundwater and Domestic Water Supplies of MoWRAM. He will also discuss progress and findings with the Programme Adviser of the Partnership for Local Governance (PLG) project, a UNDP-donor partnership which provides funding and technical assistance to STFS.

4.0 Training and Technology Transfer

Training and transfer of technology forms a core part of this assignment. The long-term usefulness of the study will be contingent upon developing a local technical capacity to understand, manage and maintain the groundwater model; as well as an understanding of the purposes and value of the model at a senior level within MoWRAM.

Two staff members of the Minstry of Water Resources and Meteorology will be attached to the Consultant's team for the duration of the study. Salary and field expenses of these staff members will be the responsibility of MoWRAM with support from the Seila Program and will not be the responsibility of the Consultant. The Consultant is expected to train these staff members in use and maintenance of the groundwater flow model.

The training to be received by the Junior Hydrologist is also envisaged as a significant contribution to building local technical capacity in this field.

The Consultant will also involve a wider group of concerned staff of MoWRAM and PDoWRAM in the study through conducting a series of seminars at key stages of the project, as recommended in the report of Phase 1 of the study.

5.0 Outputs and Time Schedule

5.1 Inception Report

The Consultant will present an Inception Report to STFS with copy to MoWRAM within two weeks of the commencement of the Mission. The Inception Report will present the Consultant's interpretation of the Terms of Reference, initial findings, a workplan for the remainder of the mission and an outline of the Final Report.

5.2 Draft Report

The Draft Report will be submitted to STFS with copy to MoWRAM within 30 weeks of the commencement of the Mission. The Draft Report will fully describe and document the development, testing and implications of results of the groundwater model as recommended in the report of Phase 1 of the study. In addition to the report contents listed in the Phase 1 report (pages 24-25) the consultant will make recommendations on the further institutionalisation of a groundwater modeling capability within MoWRAM and the potential implications for development of a groundwater resource management strategy.

5.3 Stakeholder Workshop

A presentation will be made to a Stakeholder Meeting. The Consultant will present his or her main findings in PowerPoint (or similar) format and will answer questions from stakeholders. The Stakeholder Workshop will be conducted primarily in the Khmer language. The Stakeholder Meeting is expected to be of length one half day.

5.4 Final Report

Following the Stakeholder Workshop and comments received on the Draft Report, the Consultant will prepare and submit the Final Report to STFS. All relevant data will be provided in electronic format and will be organised as annexes to the final report for easy reference and recovery.

The Inception, Draft and Final Reports will be in English. The Consultant should submit two hard copies plus electronic copy of each report. Final electronic versions of the main report texts (Inception and Final) should be in .pdf file format. The text of the Draft Report should be submitted in MS Word format to facilitate comments. Data annexes may be provided on CD ROM only.

Additional copying, reproduction and translation of the reports shall be the responsibility of STFS.

6.0 Data, Local Services, Personnel and Facilities to be Provided by the Client

6.1 Data

STFS will make available to the Consultant the existing data on groundwater resources in Prey Veng and Svay Rieng provinces, as described in the Report Phase 1.

STFS will also obtain from the Mekong River Commission such data as may be required on the hydrology of the Mekong River.

STFS will separately procure a survey by high accuracy GPS of the location and elevations of the PRASAC monitoring wells, and will make this data available to the Consultant.

6.2 Personnel

MoWRAM will nominate two staff members with suitable qualifications to work with the Consultant's team in carrying out the study. The costs of these staff members will be supported by STFS.

6.3 Facilitation and Support

STFS and MoWRAM will assist the Consultant to gather relevant information from government and other sources. STFS and MoWRAM will also facilitate liaison and cooperation between the consultant and Provincial authorities and agencies.

STFS and Provincial ExCom will provide support for communication and liaison between the Consultant and Commune Councils, particularly in relation to the groundwater use survey. Completion of the groundwater use survey will be dependent upon the willingness and ability of Commune Councils to collect and return this information within the timescale required.

STFS will host the seminars and the stakeholder workshop and will fund the costs of these as described below. The role of the Consultant's staff in these events will be that of resource personnel.

6.4 Other costs to be met by STFS

The following costs will be met by STFS:

- Purchase of necessary computer hardware and software for the study (1 computer set to be located at MoWRAM);
- Workshop and seminar expenses including premises, copying and distribution of materials, refreshments etc but not preparation of materials
- Translation, reproduction and distribution of the report.

Administration, office and transport costs will be the responsibility of the Consultant.

Annex B: Corrections to Well Elevations

NATIONAL COMMITTEE FOR THE MANAGEMENT OF D&D REFORM
RURAL POVERTY REDUCTION PROJECT

STRATEGIC STUDY OF GROUNDWATER RESOURCES
IN PREY VENG AND SVAY RIENG (PHASE 2)

REPORT ON CORRECTIONS TO DGPS WELL ELEVATIONS

4 February 2008

Prepared by

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1. Introduction

In May 2007, a Differential Global Positioning System (DGPS) survey of 60 monitoring wells was completed by Geomatic Consulting International (GCI). The survey was associated with the *Strategic Study of Groundwater Resources in Prey Veng and Svay Rieng - Phase 2* (SSGWPVSR2) but was contracted as a separate project by the Client.[1]

Concerns arose regarding whether the survey met the required specifications, especially the requirement that the vertical elevations be within ± 0.50 m of actual. Following a meeting on 30 October 2007 between IDE, GCI, and the client, IDE agreed to extend its scope of work under the SSGWPVSR2 to include the following:

- Conduct a manual leveling survey to independently check the locations and elevations of at least three of the monitoring wells relative to an established benchmark.
- Obtain qualified technical review of the DGPS survey methods and results.
- Provide interpretation and recommendations based on above.

This report presents the results of this work.

2. Leveling Survey

Leveling surveys of three wells were conducted by Aruna Technology Ltd. from a known benchmark at Neak Loeung in Prey Veng.

The Neak Loeung benchmark used was established by FINNMAP in 2004 as part of the *Study on the Construction of the Second Mekong Bridge in the Kingdom of Cambodia* (description card attached). The accuracy of this benchmark is not known with certainty but given its intended purpose we expect that it is second or third order.

The leveling surveys were conducted in closed loops with minimal closure error indicating cm-level accuracies.

Table 1: Leveling Survey Results

<table>
<tr><th>Well</th><th>GCI elevation (m)</th><th>Offset* (m)</th><th>Leveling survey elevation (m)</th><th>Difference between GCI and leveling survey (m)</th><th>Leveling survey length (km)</th><th>Leveling survey closure error (m)</th></tr>
<tr><td>PVN5</td><td>8.9</td><td>0</td><td>7.405</td><td>1.495</td><td rowspan="2">3.582</td><td rowspan="2">-0.002</td></tr>
<tr><td>PVN3</td><td>8.4</td><td>9.34</td><td>7.303</td><td>1.097</td></tr>
<tr><td>PV28</td><td>8.2</td><td>8.32</td><td>6.945</td><td>1.255</td><td>8.432</td><td>-0.012</td></tr>
</table>

* Offset refers to the horizontal distance between the well location and the GCI measurement location.

Significant variance (>1m) was found between the GCI elevations and the leveling survey results.

[1] At the time of contracting, the Client was the Seila Task Force Secretariat. Responsibility for both the DGPS Survey and the Strategic Study of Groundwater Resources was later transferred to the National Committee for the Management of D&D Reform (NCDD).

3. Review of DGPS Survey Methods and Results

After seeking comment from Aruna Technologies Ltd. in Phnom Penh and GPS specialists at BLOM Aerofilms in the U.K., we note the following.

GCI elevations are measured relative to the Earth Gravity Model 1996 (EGM96), a geoid surface which is a representation of the mean ocean surface elevation around the globe if the oceans were to extend through the continents. The desired datum for the well elevations is the Ha Tien datum based on mean sea level at Ha Tien in Vietnam. Thus, a conversion needs to be made to translate the EGM96 elevations to the Ha Tien reference system.

A number of previous surveys by Aruna and BLOM Aerofilms have calculated the separation between EGM96 and Ha Tien datum as indicated in Table 2 below. The calculated separations vary relative to the mean separation by about ± 10 cm over distances similar in scale to the area covered by the DGPS Survey. This suggests that similar accuracies can be expected if the mean separation value is applied as a block shift to the GCI elevations in order to convert elevations from the EGM96 to the Ha Tien datum. (Ideally, it would be best to have more than one leveling benchmarks at widespread locations throughout the survey area. Unfortunately, the second or third order leveling network in Cambodia does not extend into Prey Veng and Svay Rieng except for the one benchmark at Neak Loeung mentioned above.)

Table 2: Separation between Ha Tien and EGM96

Location	Order of leveling network	EGM96 - Ha Tien separation (m)	Approx. distance from PVN05 (km)
Kampong Thom, avg. of 2 points	2	1.420	150
Control point on Aruna office roof, Phnom Penh	2	1.316	50
PVN05 observation well, Prey Veng *	2 or 3	1.495	0
Mean separation		1.410	

* Values from PVN03 and PV28 in Table 1 are not included because of the potential error introduced by the offset distance between the measurement locations and the actual well locations.

GCI field notes and personal communication with GCI personnel indicate that, for 60% of the wells, the ground elevation was measured at a distance offset from the well where an unhindered view of the sky was available. For those wells that had an offset, the average offset distance was 6.2 m and the maximum was 17.9 m. The elevation difference between the offset location and the well location was not measured during the survey. Thus, the elevations reported in the GCI report are the elevations at the offset locations and not the elevation at the actual well location. GCI made the assumption that the error introduced here was within the ± 50 cm tolerance specified for the project. IDE estimates that an elevation difference of up to 4% of the offset distance is possible and would be difficult to discern by eye. This would amount to 40 cm for a 10 m offset distance.

The horizontal offset distance was measured at each site but it is not clear whether this information was used to correct the reported horizontal location of the wells. This may cause some wells locations to be outside of the specified horizontal accuracy of ± 5 m. Horizontal location, however, is less critical to the groundwater modeling than the vertical elevations and so any horizontal error introduced is not likely significant.

In addition to the errors introduced by the datum conversion and the measurement location offsets, there are also errors inherent to the DGPS survey itself. These errors vary by well location and were calculated by GCI in their May 2007 report.

Table 3: Sources of Error

Source of error	Approx. magnitude (cm)
DGPS survey error (previously calculated by GCI)	± 0 to 40
Datum conversion (EGM96 to Ha Tien)	± 10
Offset measurement (depends on offset distance)	± 0 to 70

Table 3 above presents the potential sources of error in the well elevation measurements. Depending on the magnitude of the DGPS error and the offset error, the cumulative error for individual wells may fall within or outside of the specified tolerance of ± 50 cm.

Tables 4 and 5 below apply the block shift to the original GCI elevations (relative to EGM96) to obtain elevations relative to the Ha Tien datum. The Tables also calculate the error at each well resulting from the sources described above. In total, 57 of the 69 measured points (83%) were within the specified tolerance of ± 50 cm.

4. Conclusions and Recommendations

The wide variance (>1 m) between the well elevations measured by GCI and those measured in the leveling survey is due primarily to the use of different reference datum. It is possible to apply a block shift to the GCI elevations in order to convert them from the EGM96 datum used by GCI to the desired Ha Tien datum. There is sufficient information available within Cambodia to calculate the appropriate block shift value of 1.41 m.

The total expected error at each of the measured well points is the sum of three sources: the error in the original DGPS survey (± 0 to 40 cm), the error due to the datum conversion (± 10 cm), and the error due to the offset of the measurement location from the actual well location (± 0 to 70 cm). The latter source of error would have been easy to eliminate if the vertical difference between the offset location and the well location had been measured during the DGPS survey.

When the block shift is applied to the original GCI data and the various sources of error are accounted for, the elevations for 57 of the measured points fall within the survey specifications of ± 50 cm. This is close to the 60 well elevations required in the contract.

We recommend the following regarding additional work to be done by GCI:

- It is not necessary for CGI to resurvey the PV and SR base stations and reprocess the survey data as discussed at the 30 Oct 2007 meeting and proposed in their 2 Nov 2007 Action Plan.
- It is not necessary for GCI to conduct additional field work to improve the accuracy of wells with errors > ± 50 cm, considering (a) the number of wells specifications is close to the number required by the contract (57 out of 60, or 95%), (b) mobilization costs for GCI to resurvey three additional wells would be high, and (c) the delays encountered in evaluating GCI's work and providing feedback.
- GCI should review the analysis in this report and provide comment.
- GCI should update the original report and appendices to reflect the elevation changes recommended herein.

Table 4: Corrected Elevations and Error Estimates in Prey Veng

Well No.	Northing (m)	Easting (m)	Elevation (EGM96) (m)	Elevation (Ha Tien) (m)	Horizontal offset (m)	Sources of vertical error (± m)			Total error * (± m)
						Offset	DGPS	Datum conversion	
PREY VENG									
PV01	1270058	536456	9.0	7.6	2.36	0.1	0.1	0.1	0.3
PV03	1280132	545867	10.5	9.1	0	0.0	0.0	0.1	0.1
PV04	1281161	554822	11.8	10.4	13.7	0.5	0.1	0.1	**0.7**
PV05	1270411	554820	10.9	9.5	9.5	0.4	0.1	0.1	**0.6**
PV06	1270317	571907	10.3	8.9	1.3	0.1	0.1	0.1	0.3
PV07	1280617	572704	9.2	7.8	2.33	0.1	0.1	0.1	0.3
PV08	1285911	573809	10.5	9.1	0	0.0	0.1	0.1	0.2
PV09	1297037	575830	15.5	14.1	0	0.0	0.1	0.1	0.2
PV10	1290034	554782	13.4	12.0	6.6	0.3	0.1	0.1	0.5
PV11	1309032	543562	14.4	13.0	4.32	0.2	0.2	0.1	0.5
PV12	1305235	531439	12.9	11.5	0	0.0	0.1	0.1	0.2
PV13	1300222	518345	12.3	10.9	12.3	0.5	0.1	0.1	**0.7**
PV14	1289059	514160	11.5	10.1	0	0.0	0.1	0.1	0.2
PV15	1286371	524801	9.9	8.5	5.24	0.2	0.0	0.1	0.3
PV16	1270907	523143	11.2	9.8	0	0.0	0.1	0.1	0.2
PV17	1258983	528281	9.9	8.5	3.1	0.1	0.1	0.1	0.3
PV18	1257356	543257	10.0	8.6	1.3	0.1	0.0	0.1	0.2
PV19	1238261	544973	8.0	6.6	10.05	0.4	0.1	0.1	**0.6**
PV21	1255129	570848	8.7	7.3	0	0.0	0.1	0.1	0.2
PV22	1237658	559992	8.3	6.9	0	0.0	0.1	0.1	0.2
PV23	1229288	558191	7.5	6.1	5.7	0.2	0.2	0.1	0.5
PV24	1229161	567107	7.3	5.9	9.83	0.4	0.1	0.1	**0.6**
PV25	1217403	557660	6.6	5.2	0	0.0	0.1	0.1	0.2
PV26	1226452	542178	7.3	5.9	0	0.0	0.1	0.1	0.2
PV27	1225401	542111	8.0	6.6	7.3	0.3	0.2	0.1	**0.6**
PV28	1239572	529893	8.2	6.8	8.32	0.3	0.1	0.1	0.5
PV29	1224180	523492	8.3	6.9	0	0.0	0.2	0.1	0.3
PV30	1207018	521655	6.5	5.1	10.25	0.4	0.2	0.1	**0.7**
PV32	1295919	546667	13.6	12.2	0	0.0	0.1	0.1	0.2
PV33	1243021	558450	8.8	7.4	0	0.0	0.1	0.1	0.2
PV0F	1233365	558067	7.5	6.1	8.49	0.3	0.1	0.1	0.5
PVN3	1243626	531106	8.4	7.0	9.34	0.4	0.1	0.1	**0.6**
PVN5	1244126	531132	8.9	7.5	0	0.0	0.1	0.1	0.2
PVN17	1284503	540026	12.6	11.2	0	0.0	0.0	0.1	0.1
PVN18(1)	1260804	552546	9.8	8.4	4.17	0.2	0.0	0.1	0.3
PVN18(2)	1260826	552540	9.8	8.4	9.45	0.4	0.0	0.1	0.5
PVN19	1274496	540126	10.5	9.1	3.35	0.1	0.1	0.1	0.3
PVN20	1242195	552548	8.7	7.3	0	0.0	0.1	0.1	0.2

* Error values in bold are outside of the 50 cm specification.

Table 4: Corrected Elevations and Error Estimates in Svay Rieng

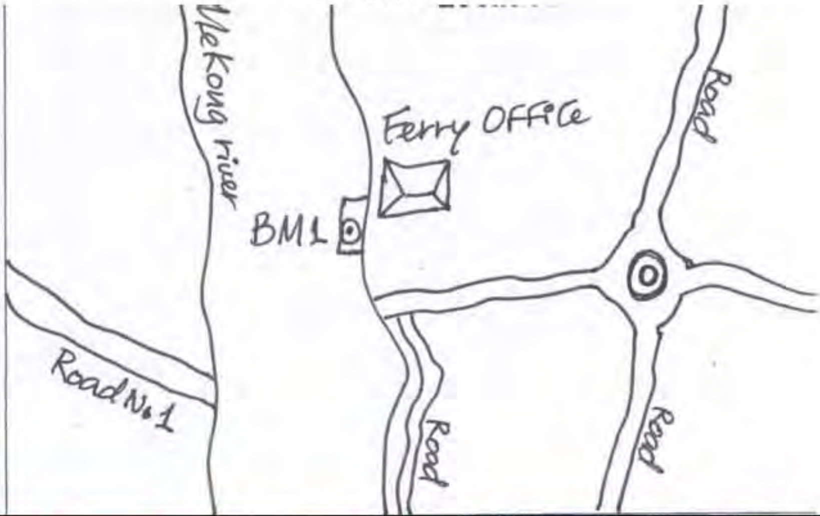
Well No.	Northing (m)	Easting (m)	Elevation (EGM96) (m)	Elevation (Ha Tien) (m)	Horizontal offset (m)	Sources of vertical error (± m)			Total error * (± m)
						Offset	DGPS	Datum conversion	
SVAY RIENG									
SR01	1222651	579871	6.3	4.9	0	0.0	0.3	0.1	0.4
SR02	1216431	565152	5.4	4.0	4.23	0.2	0.1	0.1	0.4
SR03	1240269	569551	7.3	5.9	4.38	0.2	0.1	0.1	0.4
SR04	1229364	578846	6.2	4.8	5.3	0.2	0.2	0.1	0.5
SR05	1262249	578172	9.1	7.7	0	0.0	0.1	0.1	0.2
SR06	1256328	583157	7.8	6.4	5.3	0.2	0.1	0.1	0.4
SR07	1265673	587773	10.9	9.5	3.44	0.1	0.1	0.1	0.3
SR08	1253514	595754	7.9	6.5	4.15	0.2	0.1	0.1	0.4
SR09	1243188	580839	7.4	6.0	3.55	0.1	0.1	0.1	0.3
SR10	1243319	598560	8.3	6.9	0	0.0	0.0	0.1	0.1
SR11	1232018	595046	6.7	5.3	0	0.0	0.3	0.1	0.4
SR12	1234280	603856	8.1	6.7	2.5	0.1	0.1	0.1	0.3
SR13	1225313	613589	5.9	4.5	5.02	0.2	0.1	0.1	0.4
SR14	1224451	627785	4.4	3.0	0	0.0	0.2	0.1	0.3
SR15	1209509	623193	4.8	3.4	3.8	0.2	0.1	0.1	0.4
SR16	1198937	625212	2.9	1.5	4.67	0.2	0.1	0.1	0.4
SR17	1216563	604982	6.4	5.0	0	0.0	0.0	0.1	0.1
SR18	1205735	605498	5.0	3.6	0	0.0	0.1	0.1	0.2
SR19	1212852	594012	5.8	4.4	6	0.2	0.0	0.1	0.3
SR20A	1235770	578150	7.8	6.4	7.3	0.3	0.4	0.1	**0.8**
SR20B	1235760	578145	7.8	6.4	8.9	0.4	0.4	0.1	**0.9**
SR20C	1235730	578128	7.8	6.4	0	0.0	0.4	0.1	0.5
SR21A	1231024	573964	6.3	4.9	0	0.0	0.1	0.1	0.2
SR21B	1231055	573962	6.2	4.8	8.4	0.3	0.1	0.1	0.5
SR21C	1231065	573965	6.2	4.8	3	0.1	0.4	0.1	**0.6**
SR0A	1234708	592811	6.9	5.5	0	0.0	0.0	0.1	0.1
SR0B	1221023	594758	5.8	4.4	0	0.0	0.0	0.1	0.1
SR0C	1223852	624048	6.1	4.7	0	0.0	0.1	0.1	0.2
SR0E	1232947	567498	7.0	5.6	0	0.0	0.1	0.1	0.2
SRN4	1224307	587297	5.1	3.7	17.91	0.7	0.1	0.1	**0.9**
SRN6	1266521	581194	9.9	8.5	0	0.0	0.2	0.1	0.3

* Error values in bold are outside of the 50 cm specification.

Attachment 1: Neak Loeung Benchmark Description Card

Benchmark Description Card		
Site: Neak Luong Ferry Office, Prey Veng Province		Date 2004
Marker No… BM1……	Height…8.1134 m	
Coordinates	E 530944	
	N 1245026	WGS84/UTM 48
History: Elevation transferred from western bank by FINNMAP using dual frequency GPS. Mark on western bank was part of a leveling loop taken from Phnom Penh for the “Study on the construction of the Second Mekong Bridge in the Kingdom of Cambodia”		

Location Plan



Annex C: Field Trip Report

Field Visit Report:
Prey Veng and Svay Rieng - February 14-16, 2007

Christopher J. Neville
S.S. Papadopulos & Associates, Inc.
Last update: June 4, 2007

Summary

Between February 14 and 16, 2007, the groundwater modeling team traveled from Phnom Penh to the provinces Prey Veng and Svay Rieng. The trip provided an invaluable opportunity to become familiar with the physical setting of the model area, and gain an appreciation of agricultural conditions during the dry season. There were a few instances when we could see the important effects of irrigation in an area that is otherwise arid during this season. During our visit we also had important opportunities to meet with local officials responsible for managing municipal and provincial groundwater resources and the staff responsible for data collection. During these meetings we introduced the modeling team and explained our objectives and data needs. The provincial authorities discussed their concerns with us, and it is clear that there resources are limited. At each of these meetings we made a special point of emphasizing the importance of their work in collecting water level data and maintaining digital records, that they data was crucial to our efforts and that we would share the results of our studies with the provincial staff.

This note includes notes from the following visits:

- Pre-trip meeting with Department of Land Administration, February 14, 2007;
- Meeting with Provincial Department of Water Resources and Meteorology;
- Inspection of Prey Veng PRASAC well P1;
- Meeting with Mr. Chun Sophy, head of the Prey Veng Provincial Water Resources Department;
- Visit to Prey Veng PRASAC well P3;
- Meeting with Prey Veng municipal water supply provider;
- Visit to drilling site, Prey Veng;
- Visit to drilling workshop, Prey Veng;
- Meeting with Prey Veng provincial representatives;
- Visit to Svay Rieng municipal water supply wells;
- Visit to new municipal supply well at Kandieng Reay;

1. Pre-trip meeting with Department of Land Administration, February 14, 2007

A pre-trip meeting was held at the Ministry of Interior, Department of Land Administration (DoLA), at 8:30 AM on Wednesday, February 14. The meeting was held to introduce our study team, and to discuss the overall objectives of the project and the specific purpose for the field visit. We were introduced to two staff from DoLA who accompanied us on the trip.

During the meeting we discussed the performance of the DGPS survey of the Prey Veng and Svay Rieng wells. We indicated that the results of the survey did not achieve the required performance standards. DoLA staff are aware that there are limitations in the accuracy of the survey elevations; however, it is apparent that there is no contractual mechanism is engage the services of another GIS specialist who could help resolve the problems. Michael Roberts indicated that we will attempt to resolve outstanding issues with a conference call with the GIS firm in Ho Chi Minh City that conducted the DGPS survey.

During the meeting we also discussed the scope of the training session that will be prepared for DoLA. The elements of the training session are:

- Half-day duration;
- General nature (not specifics of groundwater modeling);
- PowerPoint presentation; and
- Approximately 50-60 attendees.

2. Trip to Prey Veng, February 14, 2007

The team departed in two vehicles to Prey Veng immediately after the meeting with DoLA. Travel was relatively slow on Highway 1, due to extensive road reconstruction. We arrived at the Neak Loeung ferry crossing of the Mekong River at 11:50 AM. We stopped for lunch on the Prey Veng side at about 12:20 PM. We arrived at the town of Prey Veng at 1:35 PM.

2.1 Meeting with Provincial Department of Water Resources and Meteorology

At 3:00 PM, a meeting was held with Provincial Department of Water Resources and Meteorology staff at the Prey Veng municipal headquarters. There were 12 attendees at the meeting, including our delegation of six. As with the remainder of the meetings on the trip, the meeting was held almost exclusively in Khmer, with Monichoth translating.

We began the meeting by introducing ourselves and describing the purpose of the groundwater modeling.

The provincial staff then described their groundwater level monitoring program. One staff measures water levels at <u>26</u> wells on a monthly basis. [These are the PRASAC-3 wells.] The water levels represent non-pumping levels. [Since water levels are not measured continuously it is not possible to assess whether these levels represent fully-recovered levels.]

Groundwater withdrawals are not recorded for the wells. The water levels are recorded in an Excel spreadsheet. We requested a copy of this spreadsheet.

[CJN: 26 wells? There were originally 31 in the PRASAC-3 well network for Prey Veng, which was reduced to 28 with the loss of P2, P20, and P31. My understanding from the meeting is that an additional two wells have been removed from the network because the water supply at these locations is no longer potable.]

The provincial representatives indicated that the only municipal groundwater withdrawals are at the town of Prey Veng.

CJN asked about any groundwater investigations in Prey Veng province. The provincial representatives were not aware of any investigations, and appeared to be aware of/responsible only for the PRASAC-3 monitoring program. Peng Pang (MOWRAM) indicated that there were no investigations since the 2005 drilling and testing conducted at Neak Loeung and Prasat, as part of the Cambodia Provincial and Peri-Urban Water and Sanitation Project (CPPUWSP). Peng further indicated that there are plans to develop additional groundwater resources in the center of the province.

CJN concluded by making the following points:

- The provincial water level collection program is fundamental with respect to understanding and managing water resources;
- The data collected during the ongoing provincial water level collection program is crucial to our efforts;
- We will be grateful for any data that are provided to us; and
- We will share the results of our analyses with the provincial staff.

[CJN: Following this up, according to the draft CPPUWSP Environmental Assessment Summary Report dated February 24, 2003, development of groundwater supplies for municipal use are planned at four additional locations in Prey Veng: Svay Antor, Preaek Changkran, Chheu Kach, and Roka.]

It did not appear that anyone at the meeting knew where there were copies of the original well logs for the PRASAC wells.

2.2 Inspection of Prey Veng PRASAC well P1

The team visited Prey Veng PRASAC well P1 located close to the town of Prey Veng, at the headquarters of the Prey Veng Provincial Water Resources Department.

While at P1, we noticed that there is a climate station at the Prey Veng Provincial Water Resources Department, which we were told measures precipitation, temperature and evaporation. We were also told that there are simple rain gauges in every district in the province.

Photo 1: Water tower at Prey Veng PRASAC well P1

2.3 Meeting with Mr. Chun Sophy, head of the Prey Veng Provincial Water Resources Department

The team planned to meet the head of the provincial Water Resources Department, Chum Sophy, on the morning of February 15; however, due to a scheduling conflict he was obliged to meet with us at 4:00 PM on February 14.

Contact information:

Chum Sophy
Tel: 012 909 639
E-mail: pdwrmpvg@comintel.com

We introduced ourselves and described our objectives and the significance of his work with respect to achieving those objectives.

Chum Sophy suggested that regional groundwater levels have shown a long-term decline between the start of monitoring in 1997 [correction: should be April 1996] and the present.

[CJN: Is that consistent with the available data? The following data are extracted from the 2003 report prepared by Douk Bon Thon and Ieng Dam, Rural Engineer Section.

Date	Depth to water (m)
1996/Apr	5.50
1997/Apr	4.87
1998/Apr	5.41
1999/Apr	5.65
2000/Apr	5.73
2001/Apr	4.48
2002/Apr	6.21
2003/Apr	5.68

These data do not suggest a systematic long-term decline. I may have misunderstood; we'll check for any trend when we receive the spreadsheet.]

Chum Sophy also indicated that there was a lack of funding for well maintenance.

CJN emphasized the importance of ongoing data collection. CJN also indicated that he understood that it was crucial that adequate resources be available for the monitoring program, not only for the collection of water level data, but for the updating of digital records, the reporting of problems with wells, the diagnosis of well problems, and rehabilitation of wells. CJN also indicated that the modeling team would share any data they assembled and communicate the results of our study.

Chum Sophy indicated that he is willing to share the spreadsheet of water levels and to provide copies of well logs and construction diagrams if required. Chum Sophy also indicated that he is willing to share data from the climate station located at this headquarters (the station measures precipitation, temperature and evaporation rate). There are also rainfall gauges in each district in Prey Veng province. Chum Sophy indicated that he had copies of the well logs, and well construction details, and would have copies made for us, but he could not do it immediately.

Action: So Im Monichoth will follow-up on the request for water level monitoring data since April 1996, copies of the well logs, and any climate data that Chum Sophy has available.

The meeting end at 4:50 PM.

2.4 Visit to Prey Veng PRASAC well P3

The team visited Prey Veng PRASAC well P3 located in a small village outside of the small town of Svay Antor, about 15 km northeast of Prey Veng town, along Highway 11. The inscription in the concrete base of the well indicated a well depth of 38.30 m. [This value agrees well with the value of 39.23 m given in Roberts (1998; Table A-1).]

The entire village appeared to join us around the well for a lively discussion, which unfortunately was exclusively in Khmer, with no simultaneous translation. CJN was told later that the man who appeared to be the village elder indicated that it would be an excellent idea if their well was also equipped with a water tower, but everyone recognized that this was an expensive proposition.

The day ended at 5:30 PM with a return to Prey Veng town.

Photo 2: Water Visit to Prey Veng PRASAC well P3

3. February 15, 2007: Prey Veng town

3.1 Meeting with Prey Veng municipal water supply provider

At 9:00 AM, a meeting was held with the person responsible for Prey Veng town's municipal water supplies, Mr. Sok Pheng.

Photo 3: Prey Veng municipal water supply well

Sok Pheng indicated that there are two supply wells. Pumping rates are recorded hourly by hand; we noted that the water line is fitted with a totalizing flowmeter. He also indicated that water levels are recorded once or twice per season. Water levels are not measured in any observation wells.

[CJN: I have no idea where these data are recorded, or whether the data can be provided to us.]

The facilities and wells appear to have changed somewhat from those shown in Roberts (1998; Figure 4-3). The well that pumped during the test conducted by Roberts in 1997, PV1, appears to have been abandoned and replaced by a well installed within the westernmost building on the waterworks property. There has not been any water level monitoring in observation well PV2 and the observation well PV5 has been built over.

CJN was told that the current well was installed by SAWA in 1996 [this may refer to PV1 instead.] During the visit I indicated that the drilling log and construction details be sought for the current production well. The chief of water supply was going to check whether he had the logs. He provided the log for one well. We'll have to review it to decide whether it is one of the wells shown in Roberts (1998).

3.2 Visit to drilling site, Prey Veng

At 11AM, the team visited the site of drilling of a domestic water supply on the outskirts of the town of Prey Veng. This visit provided an excellent opportunity to understand the drilling technology and construction details for typical domestic wells.

Photo 4: Domestic well drilling, Prey Veng

Drilling is conducted by a team of two with a hand auger; water was being used, and it appeared that drilling mud (bentonite slurry) was also being used to support the borehole. The drilling director indicated that drilling continues until a softer stratum is reached; this is likely the fine/medium sand of the Old Alluvium. In this area, the boreholes are typically 40 m deep.

Typical well construction details:

- 40 m depth (typically);
- 49 mm diameter PVC riser piper;
- 2 lengths of 2 m slotted PVC screen with a sand pack; the screen segments are joined with a PVC coupling; and
- 2 m surface casing.

The wells are typically development for about 3 hours with a surging device.

The wells are pumped with a hand pump, and have a typical capacity of 2 m^3/hr (30 L/sec).

A typical well can be completed in one day.

This driller had two teams: one “hand” (manual driller with a hand auger) team, and one team with a drilling rig [CJN: I am not clear whether this refers to a drilling rig or to a diesel-powered auger]. One of the teams operated in Prey Veng province. The driller had started in 1996 and completed on average 30 wells per year.

3.3 Visit to drilling workshop, Prey Veng

The team then traveled to the driller’s workshop about 2 km away, where we met the proprietor of the drilling firm.

The proprietor of the firm showed us a diesel-powered auger and a pump with a diesel generator. I understand that he did not have a drilling rig. I asked the proprietor who could afford to have their well installed with a drilling rig. He replied that the drilling rig was used for agency-supported irrigation wells.

His firm was limited to wells with a maximum depth of 60 m [CJN: I interpret this to mean the maximum depth possible with the diesel-powered auger.]

The maximum capacity of the large-diameter wells, with a diesel-powered centrifugal pump, is 3.6 m^3/hr (6 L/s). The proprietor indicated that about 100 large-capacity wells had been drilled since 1990. When asked to qualify this figure, the proprietor indicated that this referred to wells both inside and outside the province of Prey Veng [Prey Veng and the adjacent 4 provinces]. Within Prey Veng province, approximately 70 small and large diameters wells have been installed each year.

The drilling proprietor indicated that there are 3 companies with diesel-powered augers, and upwards of 10 with hand augers.

We asked the proprietor about his reporting requirements. He indicated that submission of well logs depended on the sponsoring agency (for example, well logs are submitted for wells that are drilled for UNICEF). The proprietor had no idea what was done with the well logs after they are submitted. However, the proprietor does keep his own detailed records, which he showed us in a meticulous notebook. The drillers are out making informal measurements of static water levels across the countryside. Neither the well locations nor elevations are surveyed, so it difficult to imagine what use could be made of these rough data. CJN doubts that it is worth assembling digital records of these data.

4. February 15, 2007: Svay Rieng town

4.1 Meeting with Prey Veng provincial representatives

The team arrived at the offices of the Svay Rieng Executive Offices (EXCOM) at about 2:20 PM, for a 2:30 PM meeting with the PLU (Provincial Local [Administration] Unit). The meeting was attended by 7 local managers and technicians and our team of 6.

The Svay Rieng representatives indicated that there were 21 observation wells in the Svay Rieng but that this had been reduced to 20 because one of the wells had started pumping brackish water.

The Svay Rieng representatives were able to list the following wells in the province:

- 19 PRASAC wells;
- 6 RPRP wells;
- 2 large-diameter supply wells (irrigation wells) plus 2 observation wells at distances of 10 m from the pumping wells. These wells were 40 m deep;
- 3 city wells. These are 200 m deep wells. The Ministry of Mines, Industry and Energy (MIME) has the well logs; and
- 5 municipal water supply wells drilled in the district (with funding from the World Bank). These wells are 50-68 m deep. Their drilling and testing are documented in CPPUWSP reports. The Svay Rieng contacts indicated that these wells were one week old, and that two wells were now operating.

The Svay Rieng representatives could not provide us with any information on the Svay Rieng city observation wells that were monitored during the Roberts (1998) pumping test.

The Svay Rieng representatives indicated that for the wells screened at 200 m depth, water treatment was required to address excessive iron, but that the water is otherwise fresh.

The Svay Rieng representatives indicated that Tonle Kompong Tran is affected by tidal fluctuations, and that the river is gauged [CJN: I was subsequently unable to locate this feature on a map.] They also indicated that there is a climate station at Svay Rieng town.

The Svay Rieng representatives indicated that funds are available for maintaining the PRASAC monitoring wells. A total of 10 wells were cleaned last year; this year another 10 wells are scheduled for cleaning.

The meeting ended at 3:35 PM.

4.2 Visit to Svay Rieng municipal water supply wells

The team examined the town water supply wells and met with those responsible for the wells. This part of the trip was somewhat puzzling. There had been a considerable amount of new drilling at the waterworks. CJN's understanding of the discussion is that the pumping well that was tested in Roberts (1998) had been abandoned due to declining water levels. The well was replaced by a new supply well drilled to a depth of 200 m; bedrock was encountered at this depth. As far as we aware, there has been no documentation of the reason for abandonment of the original supply well. Water levels were not collected that could be used to assess whether the well was abandoned due to declining performance, or declining water levels as suggested in the discussions.

Photo 5: New deep municipal supply well at Svay Rieng

4.3 Visit to new municipal supply well at Kandieng Reay

A new well was installed recently at Kandieng Reay, with funding from the World Bank under the CUPPWSP program. The well is located approximately 10 km outside of Svay Rieng town. The well is drilled to a depth of about 50 m, with a diameter of 150 mm. The capacity of the well is 20 m^3/hr, with pumping for 5 hours per day. The pumped water is treated to remove iron and manganese.

Photo 6: New well at Kandieng Reay

The facilities at Kandieng Reay are very impressive. However, we noted the following:

- The design of the production well did not appear to accommodate a means of measuring the water level in the well [no access tube];
- There was no dedicated observation well installed close to the production well; and
- There did not appear to be a straightforward means for removing the pump for maintenance, and we did not see a backup production well.

The day at Svay Rieng ended at 5 PM.

5. February 16, 2007: Svay Rieng town

5.1 Meeting at Svay Rieng provincial service of the Ministry of Water Resources and Meteorology

The team met with the technician responsible for measuring water levels in the PRASAC Svay Rieng monitoring network. The team discussed a map of monitoring well locations, Map of Locations of Wells.

The technician indicated that the monitoring network was being expanded. Wells 20 and 21 are installed irrigation wells, and Wells 22, 23, 24, and 25 are planned irrigation wells. These wells have not been drilled as funding is not presently available.

Well S16 is the only well that has been abandoned.

5.2 Visit to S-4 monitoring well

The team then traveled with the water level technician to PRASAC well S-4. The technician demonstrated excellent technique in measuring water levels, and the water level tape was well maintained.

Photo 7: Measuring water level at S-4

Annex D: Groundwater Modeling Report

Analysis of groundwater flow in Prey Veng and Svay Rieng Provinces Southeastern Cambodia

Final Report

S.S. PAPADOPULOS & ASSOCIATES, INC.
Waterloo, Ontario

July 22, 2009

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Analysis of groundwater flow in Prey Veng and Svay Rieng Provinces Southeastern Cambodia

Final Report

Prepared For:

International Development Enterprises Cambodia
Phnom Penh, Cambodia

Prepared By:

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Executive Summary

Hydrogeologic analyses of southern Cambodia have been developed for the area encompassing the two provinces Prey Veng and Svay Rieng. A regional-scale groundwater model of the study area has been developed, calibrated and applied for predictive scenarios. The calibrated model provides a relatively good match to observed water levels, as demonstrated by comparison with suggested criteria for model acceptance. The key parameter in the calibration is the horizontal hydraulic conductivity of the Old Alluvium aquifer where it underlies the low conductivity sediments of the Young Alluvium.

The potential utility of the calibrated groundwater model is demonstrated by its application for the estimation of the potential long-term sustainable yield. Seven scenarios have been investigated, based on two constraints on a minimum allowable water level in the Old Alluvium aquifer. The model developed for this study may assist in the future for the evaluation of the potential effects of alternative groundwater resources development plans.

The long-term record of groundwater levels in wells of the EU-PRASAC monitoring networks in Prey Veng and Svay Rieng is a remarkable achievement, and has been a crucial component of the hydrogeologic analyses. The water level data are important for understanding groundwater resources and monitoring the potential effects of additional development. We recommend that this monitoring program be continued. In our opinion, the quality of the water level data is not yet consistent with its potential value. The depth-to-water measurements are reliable; however, the depth-to-water measurements provide an incomplete impression of the movement of groundwater. Rather, groundwater flow is evaluated in terms of the water level with respect to a common datum, and is calculated at each well as the difference between the elevation of the monitoring point and the depth-to-water. A complete set of elevations of monitoring points that is based on high-accuracy surveying of the precise points from which depth-to-water measurements are made is not presently available. We recommend that developing such a set be assigned a high priority. The range of water levels across a large area is relatively small; to reliably assess regional changes in water levels it is essential that the elevations of the monitoring points be established.

It is important to place the modeling and results of the analyses in perspective. The analyses represent a first attempt at developing a quantitative framework for understanding groundwater flow in southern Cambodia. This first attempt is deliberately simplified and caution is recommending in utilizing the results of the predictive scenarios. The key parameter in the analyses is the hydraulic conductivity of the Old Alluvium aquifer. Bulk property values have been estimated through calibration of the numerical model; these values may not be representative of local conditions. Differences in the hydraulic conductivity of factors of ten or more are possible, and these differences will be reflected directly in local changes in water levels due to the development of additional groundwater supplies.

REPORT

Section 1
Introduction

This report documents the hydrogeologic analyses that have been conducted for Phase 2 of the Strategic Study of Groundwater Resources in Prey Veng and Svay Rieng. The study was initiated under the SEILA Task Force Secretariat Rurual Poverty Reduction Project. S.S. Papadopulos & Associates, Inc. (SSP&A) has analyzed groundwater flow in the provinces of Prey Veng and Svay Rieng, southeastern Cambodia, with the assistance of International Development Enterprises-Cambodia (IDE) and CADTIS Consultants Co. This final report on the groundwater modeling presents the methodology and results of the analyses. A first version of this report was submitted on May 28, 2009. The analyses have been revised significantly since that time, and this version of the report reflects the additional work conducted since May 2009.

The analyses have been conducted to support a region-wide assessment of groundwater resources in Prey Veng and Svay Rieng. The locations of the two provinces are indicated in Figure 1. The analyses extend beyond the limits of the two provinces to incorporate the major regional sources and sinks for groundwater in southern Cambodia.

The analyses have included the review of regional and local geologic and hydrogeologic data, and the development, calibration and application of a numerical groundwater model. SSP&A conducted the groundwater modeling, and staff of International Development Enterprises and CADTIS Consultants Co. provided assistance in procuring maps, hydrologic and hydrogeologic data, and with geologic interpretations. Christopher J. Neville, Senior Hydrogeologist, has been responsible for the conception and documentation of the groundwater modeling study, and Jinhui Zhang, Project Hydrogeologist, has been responsible for the detailed analyses.

The numerical groundwater model developed for this study simulates steady and transient groundwater flow in the region encompassing Prey Veng and Svay Rieng. The groundwater model has been developed to synthesize the data collected and the interpretations developed during the study of the project area. As far as the study team is aware, the analyses described in this report represent the first attempt to develop a regional groundwater flow model of southern Cambodia. It is anticipated that the model developed for this study will provide a framework for evaluating the potential effects of groundwater resources development, and for interpreting new hydrogeologic data.

This report follows the outline presented in final report for Phase 1 of the Strategic Study of Groundwater Resources in Prey Veng and Svay Rieng (IDE, 2005).

Section 2
Conceptual Model

A conceptual model is an idealization of the real world that summarizes the current understanding of the groundwater flow system (Spitz and Moreno, 1996). As far as the project team is aware, the work undertaken for this study represents the first attempt to develop a quantitative framework for understanding groundwater flow in southern Cambodia. As such, there is no existing comprehensive reference that describes hydrogeologic conditions in the study area. The conceptual model described in this report has been developed from four key reference documents:

- Ground-Water Resources of Cambodia (Rasmussen and Bradford, 1977);
- Hydrogeologic Reconnaissance of the Mekong Delta in South Vietnam and Cambodia (Anderson, 1978);
- Groundwater Irrigation in the Cambodian Mekong Delta (Roberts, 1998); and
- The Study on Groundwater Development in Southern Cambodia (Kokusai Kogyo Co., Ltd., 2002).

The limits of the hydrogeologic analyses are shown in Figure 2. These limits were established by reviewing a large-scale interpretation of groundwater flow in southern Cambodia and Vietnam (Anderson, 1978). The study area encompasses the full extents of Prey Veng and Svay Rieng and extends to natural hydrologic boundaries. The northern, southern and western limits of study area are the Mekong River and its tributaries. The study area extends a significant distance east and south of the provinces and the rationale for this extension is discussed in Section 4.

The key hydrosgratigraphic unit in the study area is the Old Alluvium. The sediments of the Old Alluvium comprise the water-supply aquifer. The key surfaces for the study are:

- Ground surface;
- The top of the Old Alluvium aquifer; and
- The bottom of the Old Alluvium aquifer (top of bedrock).

Interpolated ground surface elevations are shown in Figure 3. Ground surface elevations range from sea level to in excess of 200 m in the northern part of the study area. The ground surface elevations for the study area are taken from SRTM (*Shuttle Radar Topography Mission*) data. The original SRTM data have a resolution of 30 m (grid size). For the groundwater model, the ground surface elevations from the SRTM Digital Elevation Model have been interpolated onto a regular grid with a grid spacing of 1 km by 1 km. The interpolation scheme that has been adopted is kriging (Journel and Huijbregts, 1978; Isaaks and Srivastava, 1989). Kriging is a formal technique of geostatistics that incorporates the correlation of the elevation between adjacent points. An introduction to kriging, along with an extensive set of references, can be found at the Wikipedia web site http://en.wikipedia.org/wiki/Kriging.

The data sources for the development of the surface of the top of the Old Alluvium aquifer are shown in Figure 4. The most important source of information on the stratigraphy is the compilation of the borehole logs for the EU-PRASAC wells in Prey Veng and Svay Rieng (schematic logs are presented in Roberts, 1998). The logs for the EU-PRASAC wells provide information for only a portion of the study area, and generally are terminated at shallow depths in the Old Alluvium. To supplement the EU-PRASAC logs, borehole logs have been reviewed from Kokusai Kogyo (2002). In addition, the study team scanned, georeferenced and digitized geologic cross-sections presented in large-scale plates in Rasmussen and Bradford (1977) and Anderson (1978). The elevations of the top of the Old Alluvium developed through interpolation are shown in Figure 5.

The Old Alluvium aquifer is underlain by bedrock. Therefore, the surface of the bottom of the Old Alluvium corresponds to the surface of the top of bedrock. The data sources for the development of the surface of the top of bedrock are shown in Figure 6. Relatively little is known about the thickness of the Old Alluvium aquifer. The bedrock surface has been developed with the georeferenced cross-sections in Rasmussen and Bradford (1977) and Anderson (1978), and the results of a resistivity survey conducted by Kokusai Kogyo (2002). The closely spaced lines in Figure 6 represent the contours of the top of bedrock interpreted by Kokusai Kogyo (2002). The results of the resistivity survey suggest an abrupt thinning of the Old Alluvium aquifer west of the Mekong River, and across the northern portion of the study area. The elevations of the top of the bedrock surface developed through interpolation are shown in Figure 7.

The locations of cross-sections through the hydrostratigraphic model developed for the study are shown in Figure 8. A north-south cross-section (A-A') is shown in Figure 9; this section is aligned approximately along the boundary between Prey Veng and Svay Rieng. An east-west cross-section through the center of the study area is shown in Figure 10. Cross-section B-B' is located 110 000 m along the north-south cross-section (A-A'), and Cross-section A-A' is located 36 800 m along the east-west cross-section (B-B'). The profiles plotted in both cross-sections suggest that there are significant variations in the thickness of the Young and Old Alluvium across the study area. The Old Alluvium aquifer has a maximum thickness of about 200 m within Prey Veng and Svay Rieng.

The study team compiled and analyzed large-scale geologic maps that are available for Cambodia. The compilation of maps is presented in Appendix A.

The available geologic logs suggest that where the Young Alluvium is present it consists of fine-grained sediments that limit the infiltration of precipitation. The areas where the Young Alluvium is absent therefore represent locations where infiltration of precipitation can recharge the Old Alluvium aquifer directly. In the northern part of the study area, the areas where the Young Alluvium is absent also represent locations where the Mekong River is in direct contact with the Old Alluvium. In light of the significance of these areas, the geologic maps in Appendix A were scanned, georeferenced, and the outlines of the areas where the Young and Old Alluvium are absent were digitized.

Alternative interpretations of the limits of the Young Alluvium are assembled in Appendix B. These interpretations have been reviewed for consistency and the interpretation adopted for this study is shown in Figure 4 and 5. The area where the Young Alluvium is absent is referred to as the Old Alluvium outcrop. The limits of the Old Alluvium outcrop are reflected in the distributions of hydraulic conductivity and recharge discussed in Section 5.

As shown in Figures 4 and 5, there are areas where bedrock is at surface within the limits of the outcrop of the Old Alluvium. In these areas the two model layers are each assigned a nominal thickness of 1 m, and the layers represent a weathered top-of-rock zone.

A fundamental limitation for this study is the relative scarcity of high-reliability data to support estimates of hydraulic conductivity. Roberts (1998) presented specific capacity values from relatively brief pumping of the EU-PRASAC wells in Prey Veng and Svay Rieng. The specific capacity is defined as the ratio of the pumping rate and the observed drawdown in the well. Estimates of transmissivity are available from 9 short-term pumping tests conducted in the study area as part of the JICA 2002 study (Kokusai Kogyo, 2002). Estimates of transmissivity are also available from 11 pumping tests conducted on large-capacity wells installed under the Cambodia Provincial and Peri-Urban Water and Sanitation Project (CPPUWSP) (Cambodia Construction & Engineering Co., Ltd., 2005a,b; SinCam Water Technology Co. Ltd., 2005a,b;c; Vary Phol Company Ltd., 2005).

Transmissivities at the locations of the 46 EU-PRASAC wells have been estimated from correlations with the specific capacity (Roberts, 1998). We consider these estimates to have relatively low reliability. These wells are screened across only the uppermost portion of the Old Alluvium. Although an approximate correction has been applied to the specific capacities to account for partial penetration (assuming isotropic hydraulic conductivity), the specific capacities are not corrected for skin effects. Our review of the data from some of the CPPUWSP tests suggests that a skin zone may account for a significant portion of the total drawdown in the pumping wells.

Although we regard the estimates of the transmissivities at the locations of the EU-PRASAC wells as rough approximations, they provide important insights into the characteristics of the Old Alluvium, in particular its local variability. The specific capacity of a well is a direct indication of its potential short-term yield. Therefore, if current well installation practices are continued, the specific capacities provide a suggestion of the variability of potential yields of new wells. The distribution of the specific capacities of the EU-PRASAC wells is plotted in Figure 11. The specific capacities have a relatively wide range, from 15 to 290 m^3/d/m. Although the specific capacities of the wells in Prey Veng are generally higher than in Svay Rieng, no distinct zones are evident in Figure 11. The statistical distribution of the specific capacities is shown in Figure 12. The specific capacities appear to be random, following a log-normal distribution with a median value of about 100 m^3/d/m. Estimates of hydraulic conductivities derived from the transmissivities are plotted in Figure 13. These estimates are derived by dividing the transmissivities reported in Roberts (1998) by the thickness of the Old Alluvium estimated at each location.

The distribution of hydraulic conductivity estimates derived from the JICA 2002 and CPPUWSP pumping tests is shown in Figure 14. These estimates have higher reliability than those developed for the EU-PRASAC wells. For both sets of tests, sufficient data are available to estimate the transmissivity from a Cooper-Jacob semi-log analysis. This analysis effectively removes the effects of a well skin, partial penetration, and nonlinear well losses from the estimation of transmissivity and hence hydraulic conductivity. However, it is important to note that for both sets of tests only the water level in the pumped well was reported. These tests therefore yield only an impression of conditions in the immediate vicinity of each of the wells. The transmissivities estimated from the pumping tests range from 140 m^2/day to 3 000 m^2/day. The hydraulic conductivities estimated by dividing the transmissivities by the thickness of the Old Alluvium at each location range from about 0.9 m/day to 40 m/day. This range is typical for clean sand (Freeze and Cherry, 1979; p. 29).

The results from the CPPUWSP testing also provide important qualitative information regarding the potential yields of new wells installed in the study area. During the CPPUWSP program, a well was immediately abandoned after installation if the preliminary indication was that its yield would be low. This happened in three instances in close proximity to the four wells that were installed at Neak Loeung (Vary Phol Company Ltd., 2005).

Section 3
Computer Code Description

The numerical groundwater flow model is developed using the United States Geological Survey three-dimensional groundwater simulator, MODFLOW-2000 (Harbaugh and others, 2000). MODFLOW is chosen for this application because it offers flexibility and generality in representing three-dimensional stratigraphic structure, boundary conditions, and sources and sinks. The MODFLOW source code is distributed freely, and MODFLOW is the most widely used groundwater flow modeling code in the world. MODFLOW enjoys widespread acceptance in North America and the international groundwater research and consulting communities (Anderson and Woessner, 1992).

The open source and modular structure of the code have made it possible for researchers and practitioners to enrich its functionality. Since the first version of MODFLOW was released in 1988 (McDonald and Harbaugh, 1988), many publicly-available packages have been developed to extend the application of MODFLOW for the simulation of complex hydrogeological conditions and processes including groundwater and surface water interaction, such as interactions with rivers and streams, optimal groundwater management; parameter estimation, groundwater flow pathline calculation, and contaminant migration.

The numerical model for this study has been developed within the graphical user interface, Groundwater Vistas, Version 5 (Environmental Simulations Inc., 2007). Groundwater Vistas provides a user-friendly, graphical framework for visualizing the model parameterization and model calculations.

MODFLOW can simulate steady-state and transient groundwater flow in an irregularly shaped flow system. Aquifer layers may be confined, unconfined, or a combination of confined and unconfined. Contributions and withdrawals from sources or sinks, such as wells, recharge from infiltration of precipitation, evapotranspiration, drains, and aquifer-river interactions can be simulated. Hydraulic conductivities or transmissivities may vary spatially and be anisotropic. Storage coefficients may be assigned to represent confined or unconfined processes, and may be heterogeneous. Prescribed-head, specified-flux and head-dependent flux boundaries can be simulated.

MODFLOW is designed to simulate aquifer systems subject to the following general conditions:

- The porous medium is saturated;
- Darcy's Law applies;
- The density of groundwater is constant; and
- The principal directions of horizontal hydraulic conductivity or transmissivity are parallel to axes of the model grid.

Each of the above conditions is satisfied in the analysis of groundwater flow for the study area:

- The model considers saturated unconsolidated materials of the Young Alluvium and the Old Alluvium;
- Fluid velocities are relatively low;
- The groundwater in the unconsolidated materials is assumed to be fresh; and
- The hydraulic properties of the overburden are assumed to be isotropic in the horizontal direction and anisotropic in the vertical direction.

Section 4
Model Construction

The analyses of groundwater flow in the provinces Prey Veng and Svay Rieng are regional in scale and designed to address large-scale groundwater management issues. Two key factors are considered in establishing the limits of the groundwater model that has been developed for the analyses. First, the model covers the entire study area of the two provinces, Prey Veng and Svay Rieng. Second, to the extent possible, the model is extended to natural hydrologic boundaries.

The limits of the groundwater model are shown in Figure 15. These limits have been established by reviewing the large-scale interpretation of groundwater flow in southern Cambodia and Vietnam (Anderson, 1978; Plate 1).

The simplest approach for establishing the limits of a groundwater model is to conceive of two choices for boundary conditions, specified-head boundaries (surfaces over which water levels are specified through time) and no-flow boundaries (surfaces across which there is no groundwater flow, that is, groundwater divides).

The western boundary of the model is aligned along the dominant surface water feature in the study area, the Mekong River. The depth of the influence of the river is not known; however, the available water level data suggest that the river controls groundwater levels in the shallow subsurface. For the purposes of this analysis, it is assumed that the river establishes specified-head conditions across the full thickness of the model along the Western boundary shown in Figure 15.

The northern boundary of the model is aligned along the Mekong River and a westward flowing tributary of the river, the Prek Chhlong River, which flows into the Mekong River between Kratie and Kampong Cham. The Prek Chhlong River is assigned specified-head boundary conditions in the same manner as the Mekong River. The coordinates of the rivers are extracted from a basemap of the Lower Mekong Basin developed by the Mekong River Commission.

The limits of the Mekong River watershed as delineated by the Mekong River Commission lie close to the boundary between Prey Veng and Svay Rieng (see for example Mekong River Commission, 2003; Figure 1). To include the entire province of Svay Rieng it is necessary to extend the eastern limits of the analyses beyond the delineated surface watershed of the Lower Mekong River Basin.

In the original version of the groundwater model, the eastern boundary was aligned along a groundwater divide inferred from the water level mapping and interpretations of Anderson (1978; Plate 1). A no-flow condition was specified implicitly along this boundary. The study team has re-examined the Anderson map and concluded that although a divide can be inferred, it is more appropriate to conceive of this divide as a trough into which groundwater discharges to streams and rivers that flow south and east towards Vietnam and the South China Sea. The conditions along the eastern boundary have been revised to reflect this revised conception. The model has been extended eastwards, with the following conditions specified along the eastern boundary:

- Along the southern portion of the boundary, groundwater levels are specified to increase linearly from sea level to an elevation of 5 m;
- Along the central portion of the boundary, drain boundary conditions are assigned, with the control levels set close to ground surface. This condition allows groundwater to discharge across this portion of the boundary; and
- Along the northern portion of the boundary, no-flow conditions are specified. It is expected that west of the divide groundwater will flow west and south towards the Mekong River, east of the divide, groundwater will flow towards Vietnam and the South China Sea.

It is assumed that the position of the eastern boundary is not affected significantly by seasonal fluctuations. Groundwater flows across this boundary are significant with respect to the overall water budget; however, the boundary is sufficiently far from the study area that its location is not expected to have a significant influence on the results of the analyses.

Anderson (1978) mapped a freshwater-saltwater interface in the Old Alluvium between Svay Rieng and the coast. The southern boundary of the model shown in Figure 15 is aligned parallel to and between the positions of the freshwater-saltwater interface inferred by Anderson (1978; Plates 1 and 3) for the wet and dry seasons. It is likely that shallow and deep groundwater discharge to surface water bodies in the delta of the Mekong River. A specified-head of 0.0 is assigned along the Southern boundary, representing groundwater levels close to sea level. Groundwater is free to exit the model along this boundary.

After the outer limits of the groundwater model have been established, the next step in developing a MODFLOW-based groundwater flow model is the design of the finite-difference grid. With the MODFLOW simulator, the study area is divided into rows and columns, forming a regular grid that is referred to as the finite-difference grid.

A finite-difference grid is conceptually simple; it consists of a lattice of rows and columns aligned along the assumed principal directions of the horizontal hydraulic conductivity tensor. Although finite-difference grids are straightforward to implement, the design of the grid requires careful consideration. Not only does the grid control the resolution of the calculations, it incorporates implicit decisions regarding the level of refinement of boundary conditions, material property distributions and sources and sinks. Grid design has important implications with respect to the future model applications. If the grid is too coarse, the model may not be capable of adequately resolving processes and details to meet the objectives of the analyses. If the grid is too fine, the model may be unwieldy and may take excessive time and effort to assemble, diagnose and correct errors and misconceptions, and to calibrate and apply for predictive simulations. It is crucial to bear in mind that the key to modeling success lies in the execution of many simulations. It is preferable to execute many approximate analyses than fewer, more complex analyses.

Several factors have been considered in designing the finite-difference grid for the study. These factors include:

- What are the objectives of the analysis?
- Is a relatively detailed, physically appropriate conceptual model already available for the study area?
- Is it important to incorporate relatively fine features along the model boundaries?
- How well have material properties been characterized over the study area? and
- How long might it take to develop model surfaces and property distributions?

The first objective of the Prey Veng-Svay Rieng groundwater modeling study is to synthesize the available information within a regional framework analysis that extends to physical hydrologic boundaries. Relatively little information is available on the properties of the aquifer within the study area. Furthermore, the analysis represents a first attempt to quantify groundwater flow in this area. Therefore, in our opinion it makes little sense to consider a highly refined analysis. Indeed, designing too fine an analysis defeats the purpose of understanding the structure of the hydrogeologic system and the processes for groundwater flow.

A straightforward grid consisting of rows and columns with uniform spacing has been adopted for the analyses. Adopting a uniform grid has several advantages. First, it simplifies many of the data assignment tasks. For example, it is simpler to map the data from a Digital Elevation Model (DEM) onto a uniform grid. Use of a uniform grid also simplifies the development of model surfaces from contouring programs, which typically produce interpolated values over a uniform grid (for example, SURFER [Golden Software, Inc., 2006]). Second, a uniform grid simplifies displaying model results with typical plotting programs. Finally, although the resolution may be limited, the overall results of a flow simulation over a uniform grid are more accurate.

The finite-difference grid for the groundwater model developed for this study is shown in Figure 16. A uniform grid spacing of 1 km has been adopted. The model extends 219 km in the north-south direction, and 185 km in the east-west direction. The total number of grid blocks per model layer is 40,515.

The subsurface is discretized into two model layers. The upper layer represents the Young Alluvium. Where the Young Alluvium is absent the layer is assigned a minimal thickness and the properties of the Old Alluvium aquifer. The lower layer represents the Old Alluvium. The grid blocks that are beyond the boundaries of the model are not active. The grey areas in Figure 15 indicate these blocks. The total number of active grid blocks in the groundwater model is 48,696.

The analyses have been developed to represent long-term conditions in the groundwater system. Therefore, a steady-state groundwater flow solution is selected for the analyses. Monthly stress periods with monthly time steps are specified for the transient versions of the model that have been applied for model testing and for the predictive scenarios.

The Preconditioned Conjugate-Gradient solver package, PCG2, is used to solve the finite-difference equations (Hill, 1990). The parameters used for this solver are tabulated below, along with the identifier of the names of the parameters within the Groundwater Vistas graphical user interface.

PCG2 Parameter	GW Vistas Identifier	Value
MXITER	Maximum Outer Iterations	100
ITER1	Maximum Inner Iterations	50
HCLOSE	Head Change Criterion	0.0001
RCLOSE	Residual Criterion for Convergence	0.001
RELAX	Relaxation Parameter	1
NPCOND	Matrix Preconditioning Method	Cholesky
NBPOL	Maximum Bound on Eigenvalue	2
MUTPCG	Solver Printing Option	Print all
IPRPCG	PCG2 Summary Data Printed Every iteration	5
DAMP	Damping Factor (0.0 to 1.0)	0.98
-	Converge if Criteria Met for Outer Iterations	9,999

Section 5
Model Calibration

Model calibration refers to the process of adjusting model parameters within physically reasonable bounds to achieve a close correspondence between model calculations and observations. The process of model calibration involves six steps:

- Development of the calibration targets;
- Development of the calibration strategy and approach;
- Identification of sensitive parameters;
- Presentation of calibration results;
- Evaluation of the calibrated model; and
- Sensitivity analysis.

The model is calibrated for long-term average conditions. The targets for the model calibration are the time-averaged water levels observed at the wells in the EU-PRASAC monitoring networks in Prey Veng and Svay Rieng. More precisely, the targets are estimates of the water levels calculated by subtracting interpreted averages of the reported depth-to-water measurements from the estimated elevations of the measuring points. This qualification is important, as no high-reliability elevation measurements are currently available for the EU-PRASAC wells. The locations of the monitoring wells are shown in Figure 17. There are 26 targets in Prey Veng, wells P1 through P31. Wells P2, P20 and P31 were abandoned soon after they were installed, and wells P17 and P28 are located along the boundary of the model. There are 19 targets in Svay Rieng, S1 through S19. The records for S20 and S21 are not sufficiently long to support estimating an average water level. The estimated average water levels for the targets are listed on Table 1.

The calibration methodology consists of identifying key model parameters and varying these key parameters within physically realistic parameter bounds. The input parameters that are adjusted during model calibration are horizontal hydraulic conductivity and recharge. The hydraulic conductivities of the Young and Old Alluvium are assumed to be isotropic.

Both computer-assisted calibration techniques and the “trial-and-study” approach have been employed for the calibration. Optimal parameter values are estimated with the parameter estimation code PEST (Watermark Numerical Computing, 2005).

A deliberately simplified approach has been adopted to represent the properties of the subsurface. The hydraulic conductivity zones are shown in Figure 18. The Young Alluvium and Old Alluvium are assigned the same distributions of hydraulic conductivity. Referring to Figure 18, Zone 1 designates the area of the model over which the Young Alluvium is present above the Old Alluvium aquifer. Zone 2 designates that area where the Young Alluvium is absent and the Old Alluvium or bedrock is directly at surface.

The parameters that were initially considered for adjustment are:

- K_1: The hydraulic conductivity of model layer 1 in Zone 1, representing the properties of the Young Alluvium;
- K_2: The hydraulic conductivity of model layer 1 in Zone 2, representing the area where the Young Alluvium is absent;
- K_3: The hydraulic conductivity of model layer 2 in Zone 1, representing the Old Alluvium in Zone 1 where the Young Alluvium is present; and
- K_4: The hydraulic conductivity of model layer 2 in Zone 2, representing the Old Alluvium in Zone 2, the area where the Young Alluvium is absent.

The results of extensive sensitivity analyses revealed that the match to the calibration targets is not sensitive to the hydraulic conductivity assigned for model layer 1, either where the Young Alluvium it is present, or where it is absent. To improve the calibration process, the hydraulic conductivity of the Young Alluvium has therefore been removed from the parameters estimation process. For Zone 1, a hydraulic conductivity of 10^{-7} m/s (8.64×10^{-3} m/d) has been assigned for the Young Alluvium. This value is typical for silty sand (Freeze and Cherry, 1979; p. 29), and has been assumed to represent the properties of a relatively heterogeneous aquitard. For Zone 2, a hydraulic conductivity of 50 m/d has been assigned in model layer 1 where the Young Alluvium is absent. This high value eliminates the possibility that this layer offers vertical resistance to recharge of the Old Alluvium.

The assumed recharge zones are shown in Figure 19. The distribution of recharge is assumed to be the same as the distribution of hydraulic conductivity. Where the Young Alluvium is present, Zone 1, it is assumed to be an effective barrier to the infiltration of precipitation to the Old Alluvium. Recharge is assumed to occur only over Zone 2, over which a uniform rate is specified. The results of the sensitivity analyses also confirmed that the recharge rate is correlated directly to the hydraulic conductivity of the Old Alluvium. To estimate a unique set of parameters in the calibration it is necessary to constrain either the recharge or the hydraulic conductivity. In the calibration analysis, recharge has been treated as a fixed parameter. The correlation between recharge and hydraulic conductivity is addressed by developing calibrated models for a range of recharge rates.

The match of the model to the observations is evaluated using both quantitative and qualitative measures (ASTM, 1993). Quantitative evaluation consists of statistical comparison between observed and calculated water levels. Statistics are calculated on the weighted residuals, where a residual is defined as the difference between calculated and observed water levels at a particular observation point. The residuals are assigned uniform weights of 1.0; that is, they are all assumed to have the same reliability and significance with respect to the computer-assisted calibration. Typical statistics include the mean of the residual and the root mean squared of the mean residual.

Qualitative evaluation consists of the visual comparison of groundwater flow directions inferred from water level mapping. Qualitative evaluation also includes checking the calculated flow budget to ensure it falls within physically realistic bounds and is consistent with the conceptual model. Qualitative evaluation also includes the preparation of scatterplots of computed versus observed water levels. Scatterplots are a standard method of providing a visual impression of the quality of fit for a numerical groundwater flow model.

Calibrated model #1: Recharge rate of 15 mm/yr

For the first calibrated model, a recharge rate of 15 mm/yr is specified for Zone 2. Detailed results obtained with the calibrated groundwater flow model are presented on Table 2. The match between the observed and calculated water levels is illustrated in a scatterplot shown in Figure 20. As shown in the figure, the calibration points appear to be scattered randomly about the line of equality.

Table 2 includes a calculation of the difference between the calculated and observed water levels, which are designated the residuals. The residuals are calculated as:

$$R = h_{OBS} - h_{CALC}$$

here h_{CALC} and h_{OBS} are the calculated and observed water levels, respectively. Positive residuals indicate locations where the calculated water levels are lower than the observed levels. Negative residuals indicate locations where the calculated water levels exceed the observed levels. The quantitative objective of model calibration is to minimize the sum of the squared residuals.

Summary statistics for the residuals are assembled on Table 3. The mean residual is --0.17 m. The mean residual is relatively close to zero, indicating that the calibrated model has no systematic bias towards under or overestimating water levels. The minimum and maximum residuals are –1.83 m and +2.88 m, respectively, and the mean absolute residual is 0.87 m.

A key statistic for model acceptance is the normalized standard deviation of the residuals, defined as:

$$NRMS\left(\%\right)=\frac{\text{Root-mean-squared residual}}{\text{Range of observations}}\times 100$$

The root-mean-squared (RMS), equivalent to the standard deviation of the residuals, is 1.05 m. The observed groundwater levels across Prey Veng and Svay Rieng range over 11.88 m. The RMS residual corresponds to 8.8% of the range of the observed water levels. Spitz and Moreno (1996; corrected 2003) suggest that an RMS residual corresponding to 10% or less of the range of observation is acceptable for a groundwater flow model.

Hill (1998) has suggested that the residuals from the model calibration should be normally distributed. The cumulative probability distribution of the model residuals is plotted in Figure 21. The plot approximates a straight line, suggesting that most of the residuals are consistent with a normal distribution.

The spatial distribution of the model residuals is shown in Figure 22. In this figure the symbols are scaled with respect to the magnitude of the residual. The symbols are also color-coded: green symbols denote locations where the model-calculated water level exceeds the target and red symbols denote locations where the model-calculated water level is less than the target. The patterns of residuals suggest that there is an inherent variability in the calibration targets that cannot be resolved in the analysis. The results shown in Figure 22 also suggest that the calibration targets themselves have a relatively high degree of uncertainty; for example both positive and negative residuals are in close proximity at P26 and P27 and S11 and S12.

The residuals are generally within the range of reliability of the targets. There are three sources of errors in the targets. First, monthly water levels are used to estimate long-term average levels. The completeness of the water level records varies for the individual monitoring wells. Second, the elevations used to convert the depth-to-water measurements are approximate. They are not based on the results of high-reliability surveys. Our review of the available elevation data suggests that the elevations likely have a reliability of about ±1 m. Surveying the elevations of the monitoring points of the wells may reduce the scatter in the calibration. Third, local-scale variations in water levels are also characteristic of a heterogeneous system. Although the results shown in Figure 22 suggest a spatial bias in the residuals, the magnitudes of the residuals are generally within the likely range of the errors in the targets themselves.

The hydraulic conductivities estimated through model calibration for a recharge rate of 15 mm/yr are listed on Table 4. The key parameter value is the hydraulic conductivity of the Old Alluvium in the area where the Young Alluvium is present, K_3. The value estimated through calibration is 280 m/d (3.2×10^{-3} m/s). This is a reasonable value for clean sand; however, it corresponds to the high end of the range for the estimates developed for the EU-PRASAC wells shown in Figure 13, and is significantly higher than any of the higher reliability values shown in Figure 14.

The groundwater levels in the Old Alluvium calculated with the calibrated model are plotted in Figure 23. In general, groundwater flows from the upland areas southwards towards the mouths of the Mekong River. The groundwater levels in the northern portion of the model close to the Mekong River are about 10 m above sea level; significantly higher levels are calculated along the northeastern boundary of the model.

The overall water budget for the calibrated model for an assumed recharge rate of 15 mm/yr is indicated on Table 5. The overall discrepancy in the water balance is negligible. These results suggest that a converged solution has been achieved. The results summarized on Table 5 suggest that the primary components of the water budget are recharge in the upland areas and discharge to Mekong River and its tributaries.

Calibrated model #2: Recharge rate of 3 mm/yr

For the second calibrated model, a recharge rate of 3 mm/yr is specified for Zone 2. Detailed results obtained with the calibrated groundwater flow model are presented on Table 6. The match between the observed and calculated water levels is illustrated in a scatterplot shown in Figure 24. As shown in the figure, the calibration points appear to be scattered randomly about the line of equality.

Summary statistics for the residuals for the second calibrated model are assembled on Table 7. The mean residual is --0.11 m. The mean residual is relatively close to zero, indicating that the calibrated model has no systematic bias towards under or overestimating water levels. The minimum and maximum residuals are –2.27 m and +3.06 m, respectively, and the mean absolute residual is 0.84 m. The RMS residual corresponds to 8.7% of the range of the observed water levels. These statistics are nearly identical to the values obtained for the calibration with a recharge rate of 15 mm/yr.

The cumulative probability distribution of the model residuals plotted in Figure 25. The plot approximates a straight line, suggesting that most of the residuals are consistent with a normal distribution. The spatial distribution of the model residuals is shown in Figure 26. The magnitudes and pattern of the residuals are similar to those obtained for a recharge rate of 15 mm/yr.

The hydraulic conductivities estimated through model calibration for a recharge rate of 3 mm/yr are listed on Table 8. The estimated hydraulic conductivity of the Old Alluvium in the area where the Young Alluvium is present is reduced from 280 m/d to 50 m/d (5.9×10^{-4} m/s). This value is within the range of the most likely hydraulic conductivity estimates developed for the EU-PRASAC wells, and within the range of the higher reliability estimates shown in Figure 14.

The groundwater levels in the Old Alluvium calculated with the second calibrated model are plotted in Figure 27. The general groundwater flow pattern is similar to that obtained for a recharge rate of 15 mm/yr. The groundwater levels in the northern portion of the model close to the Mekong River are again about 10 m above sea level; elevated but somewhat lower water levels are calculated along the northeastern boundary of the model.

The components of the overall water budget for the calibrated model for an assumed recharge rate of 3 mm/yr are listed on Table 9. The overall discrepancy in the water balance is negligible. These results suggest that a converged solution has been achieved. The results summarized on Table 5 suggest that the primary components of the water budget are recharge in the upland areas, groundwater discharge to Mekong River and its tributaries, and discharge along the eastern boundary of the model.

Additional calibration analyses have been conducted to illustrate the correlation between recharge and the hydraulic conductivity of the Old Alluvium. The results of the additional analyses are shown in Figure 28. The results from four analyses that yield equally good matches to the target water levels are presented in this figure. As expected, there is a direct relation between the specified recharge rate and the hydraulic conductivity that is estimated through calibration. The existence of models that yield equally good matches to the calibration targets is referred to as nonuniqueness. Nonuniqueness is a characteristic of all groundwater models. The results obtained during calibration of the model developed for this study highlight the importance of obtaining estimates of either recharge or hydraulic conductivity to constrain the analyses. Based on our review of the available data, the likely range of the hydraulic conductivity of the Old Alluvium is from about 1 m/d to 100 m/d. This suggests that the likely range of the recharge rate is from less than 3 mm/yr to about 6 mm/yr.

The average annual precipitation is about 1,500 mm/yr. The recharge rate estimated during calibration corresponds to a relatively small fraction of the annual precipitation. When evaluating the recharge it is important to place recharge within the broader context of the overall allocation of precipitation. The allocation of precipitation can be expressed as:

$$P = ET + RO + InterF + RCH$$

where P is precipitation, ET is the evapotranspiration, RO is the runoff, $InterF$ is the discharge of shallow infiltration to surface water features, sometimes referred to as interflow, and RCH is the deep infiltration to the water table, which is the recharge. These quantities are assumed to represent long-term, annual-average rates.

The surplus, defined as the difference between precipitation and evapotranspiration, represents the quantity of water that is available to runoff or infiltrate:

$$Surplus = P - ET = RO + InterF + RCH$$

We have examined meteorological data from Prey Veng and Svay Rieng to assess the magnitude of the surplus. Climate data for the Prey Veng Municipality meteorological station for the years in which estimates of evaporation are available are tabulated below. We interpret the evaporation as the potential evaporation rate from bare soil, estimated from an evaporation pan. As shown on the table, the estimated surplus is negative. This suggests that the amount of water available to recharge the Old Alluvium aquifer may not be significant.

Year	Rainfall (mm)	Evaporation (mm)	Surplus (mm)
2001	1465	1763	-298
2002	1398	1896	-498
2003	1620	1866	-246
2004	1152	2091	-939
2005			
2006	1188	1397	-209

A complete record of precipitation is available for a climate monitoring station in Svay Rieng. However, estimates of evaporation are available for only the period 1968 through 1972, and complete records are available only for 1968 and 1970. The data for 1968 and 1972 are listed below. As shown on the table, the estimated surplus varies for the two years. The data suggest that there is a surplus available for infiltration only when the annual precipitation is significantly in excess of 1,500 mm. This again suggests that the amount of water available to recharge the Old Alluvium aquifer may not be significant.

Year	Rainfall (mm)	Evaporation (mm)	Surplus (mm)
1968	2012	2288	-276
1970	2431	1886	545

Section 6
Model Testing

Additional analyses have been developed to test whether the calibrated steady-state models can be extended for the simulation of transient conditions. Transient models have been developed to simulate conditions during a “typical” year. Synthetic time histories of the water levels at control points along the Mekong River have been developed from the stream gauging data summarized in Appendix C. The synthetic histories plotted in Figure 29 are intended to represent an average year rather than a specific time period. Average monthly climate data summarized in Rasmussen and Bradford (1977) are used to distribute the recharge through the year. These data are re-plotted in Figure 30 and the assumed temporal distribution of recharge is shown in Figure 31.

Transient analysis with calibrated model #1: Recharge rate of 15 mm/yr

The match between all of observed water levels and the calculated transient levels is illustrated in a scatterplot in Figure 32. The results suggest a general trend of agreement between the results. Results of sensitivity analyses suggested that a storage coefficient for the Old Alluvium of 5×10^{-5} yielded results that reproduced the general trends of the water level fluctuations.

Simulated groundwater levels in the Old Alluvium aquifer for annual low and high conditions are shown in Figures 33 and 34. The water levels suggest a distinct change in flow directions between wet and dry period each year. The residual statistics for the transient simulation with a recharge rate of 15 mm/yr are listed on Table 10.

Additional insights from the transient analysis can be gleaned from a comparison of the observed and calculated water level histories at observation wells. The results of the transient analysis have also been examined at four of the EU-PRASAC observation wells distributed over the model area. The results for wells P30, P16, P10, and S01 are shown in Figures 35-38, respectively. The results suggest that the transient model captures some of the essential aspects of the transient response.

Transient analysis with calibrated model #2: Recharge rate of 3 mm/yr

The match between all of observed water levels and the calculated transient levels is for a recharge rate of 3 mm/yr is shown in the scatterplot in Figure 39. The results again suggest a general trend of agreement between the results. Results of sensitivity analyses suggested that the storage coefficient needed to be reduced to 10^{-5} to obtain results that reproduced the general trends of the water level fluctuations. The reduction in the storage coefficient for the two calibrated models is in almost direct proportion to the reduction in the hydraulic conductivity of the Old Alluvium.

Simulated groundwater levels in the Old Alluvium aquifer for annual low and high conditions for a recharge rate of 3 mm/yr are shown in Figures 40 and 41. The residual statistics for the transient simulation with a recharge rate of 15 mm/yr are listed on Table 11.

Plots of groundwater levels versus time for wells P30, P16, P10, and S01 are shown in Figures 42 through 45. The results suggest that the transient model with a recharge rate of 3 mm/yr captures some of the essential aspects of the transient response.

Considering that the transient models are independent predictions that have not been optimized, the results of the transient analyses suggest that the models may be applied for the simulation of transient conditions.

Section 6
Sensitivity Analysis

Additional analyses have been conducted to assess the sensitivity of the calibrated model to the parameters adjusted during its calibration. The results of the sensitivity analysis provide additional insights into the calibration, and may assist in directing the collection of ongoing data from water level monitoring and hydraulic testing.

Sensitivity analyses are conducted automatically when PEST is used to adjust parameter values to improve the match to observations. The sensitivities are used in the PEST analyses to guide the adjustment of parameter values during the process of obtaining an optimal set of parameter values. The results of the sensitivity analysis are cast in terms of the dimensionless quantities $\frac{\Delta\Phi}{\Phi}$ and $\frac{\Delta K}{K}$. Here K represents the calibrated value of the hydraulic conductivity of each zone in the model, and ΔK represents the change in that value from the calibrated value. The quantity Φ represents the objective function, that is, the function that PEST attempts to minimize in its quest for an optimal set of parameter values for calibration. The objective function is the sum of the squared residuals, defined as:

$$\Phi = \sum_{i=1}^{n} \left(h_{obs} - h_{calc} \right)^2$$

The sensitivities of the calculated water levels with respect to the hydraulic conductivities specified in the model are illustrated in Figures 46 and 47 for recharge rates of 15 mm/yr and 3 mm/yr, respectively. Each curve plotted in Figures 31 shows how the model error changes as the value of the hydraulic conductivity is altered from its calibrated value. The results shown in Figures 46 and 47 confirm that parameter values are indeed optimal, for the analysis as it is currently structured. The relative steepness of each curve provides a visual indication of the relative sensitivity of the particular hydraulic conductivity. The results show that for both calibrated models, the relative sensitivities of the hydraulic conductivities are ranked as follows:

$S_1 < S_2 < S_4 < S_3$

where S_1: is the sensitivity of the calibration results with respect to the hydraulic conductivity of model layer 1 in Zone 1, representing the properties of the Young Alluvium, S_2 is the sensitivity of the calibration results with respect to the hydraulic conductivity of model layer 1 in Zone 2, representing the area where the Young Alluvium is absent, S_3 is the sensitivity of the calibration results with respect to the hydraulic conductivity of model layer 2 in Zone 1, representing the Old Alluvium in Zone 1 where the Young Alluvium is present, and S_4 is the sensitivity of the calibration results with respect to the hydraulic conductivity of model layer 2 in Zone 2, representing the Old Alluvium in Zone 2, the area where the Young Alluvium is absent.

The results from the PEST analyses reveal that the calibration is sensitive to the hydraulic conductivity of the Old Alluvium, and relatively insensitive to the other properties in the model. This in part reflects the fact that all of the available water level targets are located in the Old Alluvium.

Section 7
Predictive Simulations

Predictive scenarios have been developed to provide preliminary estimates of the sustainable yield of the Old Alluvium aquifer underlying the provinces of Prey Veng and Svay Rieng. In this context, the sustainable yield is interpreted as the amount of water that can be withdrawn without causing groundwater levels to decline below acceptable levels. This amount is different from that which may be withdrawn from the aquifer without affecting the ecosystem of southern Cambodia. Large-scale withdrawals necessarily affect the environment. Any additional supplies that are developed represent the interception of water that would have discharged elsewhere. Even without referring specifically to water rights, we note that in a general sense all water is allocated. Water that is not currently extracted for current uses, such as municipal supply and small-scale irrigation, discharges to the stream and river system, or to the wetlands that surround the mouths of the Mekong River.

The sustainable yield as used here also does not refer to the capacity of wells to withdraw the water without incurring excessive local declines in groundwater levels. That determination is site-specific, and depends on the local-scale characteristics of the aquifer, details of well construction, and proximity to existing pumping centers. The analyses developed here also do not consider the potential effects of the development of additional groundwater resources on the chemical characteristics of the water.

The development of the predictive analyses incorporates three important factors:

- The amount of groundwater resources that can be developed is constrained by the amount that existing groundwater levels can be decreased;
- Groundwater levels in the Old Alluvium aquifer vary through time, in response to changes in recharge rates and seasonal fluctuations in the level of the Mekong River; and
- It is not possible to predict the declines in the vicinity of individual wells installed to develop additional groundwater resources. The analysis considers average declines in water levels at the provincial scale. The local declines in water levels will depend on specific and local factors involved in groundwater exploitation.

Results obtained with the two calibrated models suggest that the variations in water levels of the Mekong River exert a major influence on groundwater levels in the Old Alluvium aquifer. These variations in water levels impose important physical constraints on the amount of water that can be withdrawn from the aquifer. These constraints are considered explicitly by developing a fully transient analysis that incorporates seasonal fluctuations in the level of the Mekong River, as shown in Figure 29. Seasonal fluctuations in the applied recharge rate are also incorporated in the analysis. The assumed temporal recharge distribution is shown in Figure 31.

Two approaches have been adopted to assess the sustainable yield of the Old Alluvium aquifer. In the first approach, the groundwater withdrawals from the aquifer are constrained by a minimum allowable groundwater level in the aquifer. In the second approach, the groundwater withdrawals are constrained by a maximum allowable decline in groundwater level with respect to the ground surface.

Predictive analyses #1: Minimum allowable groundwater level in the Old Alluvium aquifer

The simulation approach for the first set of predictive simulations is illustrated in Figure 48. The assessment of the sustainable yield developed for the first set of predictive scenarios begins with the question: What is an acceptable lower level for groundwater levels in the Old Alluvium aquifer with respect to the top of the aquifer? This constraint is critical with respect to the development of groundwater resources with large-scale pumping facilities. Declines in groundwater levels below the top of an aquifer and into the screens of existing large-scale wells represent a potentially damaging condition.

Four scenarios have been investigated for this study, designated Scenarios 1 through 4:

1. Minimum water level is set at 5.0 m above the top of the Old Alluvium aquifer;
2. Minimum water level is set at 3.5 m above the top of the Old Alluvium aquifer;
3. Minimum water level is set at 2.5 m above the top of the Old Alluvium aquifer; and
4. Minimum water level is set at 1.0 m above the top of the Old Alluvium aquifer.

The setting of the minimum levels is arbitrary; the levels considered here serve to ensure that the development of supplies will not lower the water level into the screens of existing or new wells, accommodating a margin of safety. A higher minimum level results in a more conservative analysis, yielding higher groundwater levels in the aquifer and lower estimates of the sustainable yield.

It is not possible to predict the magnitudes of declines in the vicinity of individual wells installed to develop additional groundwater resources. The head losses that will occur during development of additional groundwater resources will depend on the number of wells that are installed, the distances between wells, the dimensions of the wells, the methods used to install the wells, and the efforts made to develop the wells. The results of pumping tests conducted as part of the CPPUWSP program demonstrate that the yields of wells – even carefully developed municipal-scale wells – will be highly variable (see for example Vary Phol Company Ltd., 2005). There is no way to account for this variability in any precise way in a regional-scale analysis for which relatively little is known about the groundwater system.

The analyses are accomplished using the MODFLOW Drain Package, which in this context represents a “one-way constant-head” condition. The function of the MODFLOW Drain Package in each grid block is described mathematically by the following function:

$$Q_D = -C_D\left(h_{aquifer} - h_D\right) \qquad \text{when } h_{aquifer} > h_D$$
$$Q_D = 0 \qquad \text{when } h_{aquifer} \le h_D$$

Here Q_D denotes the groundwater withdrawn from each model grid block containing a drain, C_D is the conductance of the drain, $h_{aquifer}$ is the calculated head in the Old Alluvium in each grid block, and h_D is the control level of the drain. As indicated by the defining equations, there is no flow from the drain if the groundwater level declines below the control level h_D.

A MODFLOW drain is inserted in each grid block over the full extents of Prey Veng and Svay Rieng provinces. The control level for the drain in each grid block is specified to satisfy the criterion that it be a constant level above the top of the Old Alluvium aquifer. As shown in Figures 5, 9 and 10, the elevation of the top of the Old Alluvium varies over the study area. The control levels for the drains follow the variations in the surface of the Old Alluvium and specialized processing codes have been developed to assign a unique control level to the drain in each grid block. The total discharge from the two provinces is calculated by accumulating the flows from each grid block, for each time step in a simulation.

A maximum discharge rate is estimated when the water level in the grid block approaches the control level h_D, which in effect represents a constant-head condition. This is achieved by specifying very large values of the conductance. The crucial difference with respect to a constant-head condition is that during periods when groundwater levels in the aquifer are relatively high, the drains do not re-inject water back into the aquifer.

In practice, the conductance cannot be assigned arbitrarily large values, as the convergence properties of the simulation deteriorate. For the present analyses, the drain conductances are increased until the calculated cumulative discharge approach limiting values. The procedure is illustrated in Figure 49, for the case of a recharge rate of 15 mm/yr and a minimum groundwater level set 5 m above the top of the Old Alluvium. In Figure 49, the cumulative amount of water extracted from the Old Alluvium aquifer for a distributed withdrawal is plotted against time, for a range of conductance values. The results shown in the figure indicate that the amount of water that can be withdrawn safely depends on the assumed conductance, but as the conductance values are made progressively larger the differences between the results of the simulation diminish.

The significance of the drain conductance is illustrated more clearly in Figure 50, in which the time-averaged withdrawal rates from Figure 49 are plotted against the conductance. The results shown in Figure 50 confirm that above a certain magnitude of the conductance, the results are essentially independent of the specified conductance.

The drain condition approaching a constant-head condition in the Old Alluvium corresponds to a situation in which the groundwater level is lowered to a uniform level above the top of the Old Alluvium. The results for the highest conductances provide an upper bound of the rate at which water can be withdrawn from the aquifer. In other words, the results for the highest conductance for each case answer the question, "When the water level is uniformly lowered to a particular level, what is the maximum rate at which water can be extracted from the Old Alluvium aquifer underlying Prey Veng and Svay Rieng?"

The results shown in Figure 49 confirm that the discharge from the drains placed over the entire provinces of Prey Veng and Svay Rieng varies seasonally, in response to seasonal fluctuations in the aquifer levels. The transient results can be used to develop estimates of the time-averaged yield from the aquifer. The results of the analyses for Scenarios 1 through 4 are shown in Figures 51 and 52 for recharge rates of 15 mm/yr and 3 mm/yr, respectively. The results are summarized on Table 12.

<u>Predictive analyses #2: Maximum declines in the groundwater level in the Old Alluvium aquifer</u>

The conceptual model for the second set of predictive scenarios is shown schematically in Figure 53. The second set of scenarios differs in the treatment of the constraint on the minimum permissible groundwater levels in the aquifer. The assessment of the sustainable yield developed for the second set of predictive scenarios begins with the question: What is a maximum decline in water levels that will not interfere with small-scale groundwater withdrawals? For Scenarios 5 through 7, the groundwater withdrawals are subject to the constraint that the groundwater levels in the Old Alluvium aquifer cannot decline below a specified depth below the ground surface. It has been suggested that groundwater levels cannot decline below 6 m below ground surface. Groundwater levels below this depth exceed the lifting capacity of domestic hand pumps.

The three scenarios that have been investigated straddle the value of 6 m:

- Scenario 5: minimum groundwater level 5 m below ground surface;
- Scenario 6: minimum groundwater level 6 m below ground surface; and
- Scenario 7: minimum groundwater level 7 m below ground surface.

The results of the scenarios are shown in Figure 54 through 55, for recharge rates of 15 mm/yr and 3 mm/yr, respectively. Simulations were conducted with progressively higher values of the conductance until the results approached constant values. The results are summarized on Table 13.

It is important to note that the scenarios that have been developed represent fundamentally different constraints. The fundamental differences are reflected in the important differences in the magnitudes of the flows predicted for Scenarios 1-4 and Scenarios 5-7. The constraint imposed in Scenarios 5-7 is significantly more stringent, resulting in a reduction in the sustainable yield of the aquifer.

It is also important to note that the predicted yields depend upon the recharge rate. This dependence is illustrated in Figure 56. The cumulative time-average discharge for a minimum water level 6 m below ground surface is plotted against the assumed recharge rate. As noted previously, the model for each recharge rate provides an equally good match to the steady-state water level targets derived from the EU-PRASAC monitoring wells.

Section 8
Conclusions and Recommendations

Hydrogeologic analyses of southern Cambodia have been developed to synthesize the data collected and the interpretations developed for the area encompassing the two provinces Prey Veng and Svay Rieng. Regional-scale groundwater models of the study area have been developed, calibrated and applied for predictive scenarios. The calibrated models provide a relatively good match to observed water levels, as demonstrated by comparison with suggested criteria for model acceptance. The key parameter in the calibration is the horizontal hydraulic conductivity of the Old Alluvium aquifer where it underlies the low conductivity sediments of the Young Alluvium.

The potential utility of the calibrated groundwater model is demonstrated by its application for the estimation of the potential long-term sustainable yield. Seven scenarios have been investigated, based on two constraints on a minimum allowable water level in the Old Alluvium aquifer. The model developed for this study may also assist in the future for evaluations of the potential effects of groundwater resources developments.

The long-term record of groundwater levels in wells of the EU-PRASAC monitoring networks in Prey Veng and Svay Rieng is a remarkable achievement, and has been a crucial component of the hydrogeologic analyses. The water level data are important for understanding groundwater resources and monitoring the potential effects of additional development. We recommend that this monitoring program be continued. In our opinion, the quality of the water level data is not consistent with its potential value. The depth-to-water measurements are reliable; however, the movement of groundwater is not assessed in terms of depth-to-water. Rather, the movement of water is assessed in terms of the water level with respect to a common datum and is calculated at each well as the difference between the elevation of the monitoring point and the depth-to-water. A complete set of reliable elevations of monitoring points is not presently available. We recommend that developing such a set be assigned a high priority. The range of water levels across a large area is relatively small; to reliably assess regional changes in water levels it is essential that the elevations of the monitoring points be established.

It is important to place the modeling and results of the analyses in perspective. The analyses represent a first attempt at developing a quantitative framework for understanding groundwater flow in southern Cambodia. This first attempt is deliberately simplified and caution is recommending in utilizing the results of the predictive scenarios. The key parameter in the analyses is the hydraulic conductivity of the Old Alluvium aquifer. Bulk property values have been estimated through calibration of the numerical model; these values may not be representative of local conditions. Differences in the hydraulic conductivity of factors of ten or more are possible, and these differences will be reflected directly in differences in the predicted sustainable yield from the aquifer. We recommend that long-term hydraulic testing with multiple observation wells be implemented as additional groundwater supplies are developed.

Section 9
References

Anderson, M.P., and W.W. Woessner, 1992: **Applied Groundwater Modeling**, Academic Press, Inc., San Diego, California.

Anderson, H.R., 1978: Hydrogeologic Reconnaissance of the Mekong Delta in South Vietnam and Cambodia, Water-Supply Paper 1608-R, United States Geological Survey, Washington DC.

ASTM, 1993: Standard Guide for Comparing Ground-Water Flow Model Simulations to Site-Specific Information, ASTM Standard Guide D5490-93, American Society for Testing and Materials, Philadelphia, Pennsylvania.

Briese, E., 1996: Prefeasiblity Assessment of the Shallow Groundwater Resources of Cambodia and Proposal for Groundwater Pilot Project, Consultant Report, prepared for the Asian Development Bank, Community Irrigation Rehabilitation Project, June 1996.

Buschmann, J., M. Berg, C. Stengel, and M.L. Sampson, 2007: Arsenic and manganese contamination in drinking water resources in Cambodia: Coincidences of risk areas with low relief topography, Environmental Science & Technology, v. 41, pp. 2146-2152.

Cambodia Construction & Engineering Co., Ltd., 2005a: Design, Build and Lease of Water Supply Systems in Kandieng Reay Town, Svay Rieng Province, Summary Report on Water Source Investigation, Cambodia Provincial and Peri-Urban Water and Sanitation Project (CPPUWSP), June 2005.

Cambodia Construction & Engineering Co., Ltd., 2005b: Design, Build and Lease of Water Supply Systems in Kampong Chak Town, Svay Rieng Province, Summary Report on Water Source Investigation, Cambodia Provincial and Peri-Urban Water and Sanitation Project (CPPUWSP), June 2005.

Christen, K., 2007: Another Arsenic Hot Spot, Environmental Science & Technology, v. 41, p. 2074.

Cushman, R.V., 1958: A Report on a Program of Ground-Water Investigations for Cambodia, Open-File Report, United States Geological Survey, 72 p., 1 figure.

Douk Bon Thon, and Ieng Dam, 2003: Groundwater Research in Prey Veng Province, Prepared by Rural Engineer Section for PRASAC Prey Veng, July 2003.

Environmental Simulations, Inc., 2007: Guide to Using Groundwater Vista, Version 5.0, Environmental Simulations, Inc., Herndon, Virginia.

Feldman, P.R., and J.-W. Rosenboom, 2001: Drinking Water Quality Assessment in Cambodia, Main Report, January 2001.

Feldman, P.R., J.-W. Rosenboom, M. Saray, Peng Navut, Chea Samnang, and S. Iddings, 2007: Assessment of the chemical quality of drinking water in Cambodia, Journal of Water and Health, vol. 5, no. 1, pp. 101-116.

Freeze, R.A., and J.A. Cherry, 1979: **Groundwater**, Prentice-Hall, Inc., Englewood Cliffs, New Jersey.

Fujii, H., H. Garsdal, P. Ward, M. Ishii, K. Morishita, and T. Boivin, 2003: Hydrological Roles of the Cambodian Floodplain of the Mekong River, International Journal of River Basin Management, v. 1, no. 3, pp. 1–14.

Gartell, A., 1997: Resource Management in the Cambodian Mekong Basin, The Mekong Basin Series, Asia Research Centre, Murdoch University, Working Paper No. 70.

Golden Software Inc. 2006. SURFER. Version 8. Golden, CO: Golden Software, Inc.

Hapuarachchi, H.A.P., K. Takeuchi, K. Fukami, H. Inomata, and M. Zhou, no date: Importance of rainfall measurements for the flood forecasting of the Mekong River basin.

Harbaugh, A.W., E.R. Banta, M.C. Hill, and M.G. McDonald, 2000: MODFLOW-2000, The U.S. Geological Survey modular ground-water model - User guide to modularization concepts and the Ground-Water Flow Process: United States Geological Survey Open-File Report 00-92, 121 p.

Heng Chamnol Import Export Co., Ltd., 2002: Hydro-geological Investigation and Water Quality Testing Program, Provincial Towns Improvement Project ADB Loan No. 1725-CAM (SF), Parts A and B, Ministry of Industry, Mines and Energy, Department of Potable Water Supply, Final Report, May 2002.

Harbaugh, A.W., E.R. Banta, M.C. Hill, and M.G. McDonald, 2000: MODFLOW-2000, The U.S. Geological Survey modular ground-water model - User guide to modularization concepts and the Ground-Water Flow Process: United States Geological Survey Open-File Report 00-92, 121 p.

Hill, M.C., 1990: Preconditioned Conjugate-Gradient 2 (PCG2): A computer program for solving ground-water flow equations, United States Geological Survey, Water Resources Investigation Report 90-4048, Denver, Colorado.

Hill, M.C., 1998: Methods and Guidelines for Effective Model Calibration, United States Geological Survey, Water-Resources Investigation Report 98-4005.

International Development Enterprises (IDE), 2005: Strategic Study of Groundwater Resources in Prey Veng and Svay Rieng (Phase 1), prepared for the SEILA Task Force Secretariat Rural Poverty Reduction Project, December 23, 2005.

Journel, A.G., and C.J. Huijbregts, 1978: **Mining Geostatistics**, Academic Press, London, UK.

Isaaks, E.H., and R. M. Srivastava, 1989: **An Introduction to Applied Geostatistics**, Oxford University Press, New York, New York.

Kiem, A.S., H. P. Hapuarachchi, and K. Takeuchi, no date: Impacts of climate variability on streamflow in the Mekong River: An interesting challenge for hydrological modeling.

Kiem, A.S., H. P. Hapuarachchi, J. Magome, M.C. Zhou, M.V. Geogivesky, and K. Takeuchi, 2005: Long-term flood frequency analysis in the Mekong and Yellow River systems, Geophysical Research Abstracts, v. 7, n. 00876.

Kokusai Kogyo Co., Ltd., 2002: The Study on Groundwater Development in Southern Cambodia, Final Report, prepared for the Japan International Cooperation Agency and the Ministry of Rural Development, Cambodia, January 2002.

- Summary Report
- Main Report [SSP&A received Summary and Chapter 4, Groundwater Investigation]
- Supporting Report (1/2) [SSP&A received Chapters 1 through 4]
- Supporting Report (2/2)
- Monitoring Report

Lu, X.X., and R.Y. Siew, 2006: Water discharge and sediment flux changes over the past decades in the Lower Mekong River: Possible impacts of the Chinese dams, Hydrology and Earth System Sciences, vol. 10, pp. 181–195.

Margat, J., et L. Monition, 1967: Presentation d'une carte d'orientation des recherches d'eau souterraine du Cambodge, echelle 1/500,000, Bureau de Recherches Geologique et Minieres, 1 p + map.

McDonald, M.G., and A.W. Harbaugh, 1988: A Modular Three-Dimensional FiniteDifference Ground-Water Flow Model, Techniques of the United States Geological Survey, Book 6, Chapter A1.

Mekong River Commission, 2003: State of the Basin Report 2003: Executive Summary, Mekong River Commission, Vientiane, Lao P.D.R.

Mekong River Commission, 2005: Overview of the Hydrology of the Mekong Basin, Vientiane, Lao P.D.R., November 2005, 73 p.

Ministry of Industry, Mining and Energy, 2003: Cambodia Provincial and Peri-Urban Water and Sanitation Project, Environmental Assessment Summary Report, MIME Provincial Towns, First Batch, E687, Volume 22 Department of Potable Water Supply, Phnom Penh, Royal Kingdom of Cambodia, February 2003.

Nesbitt, H. J. 1996: "Topography, Climate and Rice Production" in Rice Production in Cambodia, H.J. Nesbitt, ed., Cambodia-IRRI-Australia Project, Phnom Penh.

Ngo Bunthan, no date. The Review of Current Situation of Water Resources Management and the Role of Agricultural Management in Cambodia, Royal University of Agriculture, Ministry of Agriculture, Forestry and Fisheries (MAFF), Phnom Penh, Cambodia.

Ockelford, J., and J.-W. Rosenboom, 1994: A Review of the Knowledge of Ground-Water Resources of Cambodia, Oxfam UK, August 1994.

Peterson, H.G., 1999a: Field Irrigation and Water Quality, Prairie Farm Rehabilitation Administration, Agriculture and Agri-Food Canada [http://www.agr.gc.ca/pfra/water/fieldirr_e.htm].

Peterson, H.G., 1999b: Water Quality Fact Sheet:Irrigation and Salinity, Prairie Farm Rehabilitation Administration, Agriculture and Agri-Food Canada [http://www.agr.gc.ca/pfra/water/irrsalin_e.htm].

Plate, E.J., and T. Insisiengmay, 2002: Early Warning System for the Mekong River, Keynote Lecture, in Proceedings of Flood Defense 2002, Wu et al. (eds.), Science Press Ltd., New York, New York, pp. 3-14.

Polya, D., A. G. Gault, N. Diebe, P. Feldman, J. W. Rosenboom, E. Gilligan, D. Fredericks, A. H. Milton, M. Sampson, H. A. L. Rowland, P. R. Lythgoe, J. C. Jones, C. Middleton, and D. A. Cooke, 2005: Arsenic Hazard in Shallow Cambodian Groundwaters, Mineralogical Magazine, v. 69, n. 5, pp. 807-823.

Rasmussen, W.C., and G.M. Bradford, 1977: Ground-Water Resources of Cambodia, Water-Supply Paper 1608-P, United States Geological Survey, Washington DC.

Roberts, M.S., 1998: Groundwater Irrigation in the Mekong Delta of Cambodia, M.Sc. Thesis, Cornell University, August 1998.

Rosenboom, J.-W., 1995: Notes on Hydrogeological Data Collection (OXFAM):

- Hydrogeological data collection in Cambodia: Anticipated developments, June 1995;
- Hydrogeological data collection and mapping in Cambodia: Progress report of the DoH National Well Mapping Project, June 1995;
- Hydrogeological data collection: July 1995 update; and
- Inter Ministerial Working Group on Ground Water Data Collection, Minutes of meeting, 1995/September/02.

Save Cambodia's Wildlife, 2006: The Atlas of Cambodia: National Poverty and Environment Maps, Save Cambodia's Wildlife, Phnom Penh, Cambodia.

SAWA-Cambodia, 1997: PRASAC-2, Pumping Tests for Irrigation Tube-Wells in Takeo Province, May 1997.

SinCam Water Technology Co. Ltd., 2005a: Design, Build and Lease of Water Supply Systems in Prasat Town, Prey Veng Province, Summary Report on Water Source Investigation, Cambodia Provincial and Peri-Urban Water and Sanitation Project (CPPUWSP), April 2005. [Well drilling and logging conducted by Vary Phol Company Ltd.]

SinCam Water Technology Co. Ltd., 2005b: Design, Build and Lease of Water Supply Systems in Kraol Kou Town, Svay Rieng Province, Summary Report on Water Source Investigation, Cambodia Provincial and Peri-Urban Water and Sanitation Project (CPPUWSP), April 2005. [Well drilling and logging conducted by Vary Phol Company Ltd.]

SinCam Water Technology Co. Ltd., 2005c: Design, Build and Lease of Water Supply Systems in Bavet Town, Svay Rieng Province, Summary Report on Water Source Investigation, Cambodia Provincial and Peri-Urban Water and Sanitation Project (CPPUWSP), April 2005. [Well drilling and logging conducted by Vary Phol Company Ltd.].

Snell, L.J., 1969: Program of Surface-Water Investigations for Cambodia, Open-File Report, United States Geological Survey, 4 p., 5 figures.

Spitz, K., and J. Moreno, 1996: **A Practical Guide to Groundwater and Solute Transport Modeling**, John Wiley & Sons, Inc., New York, New York.

Stanger, G., T. V. Truong, K.S. Le Thi, M. Ngoc, T.V. Luyen, and T.T. Thanh, 2005: Arsenic in Groundwaters of the Lower Mekong, Environmental Geochemistry and Health, v. 27, pp. 341-357.

Vary Phol Company Ltd., 2005: Summary Report on Ground Water Production Well and Testing, Neak Loeung, Cambodia Provincial and Peri-Urban Water and Sanitation Project (CPPUWSP), April 2005. [Prey Veng province -- work performed under contract to Kim Mex Construction & Investment Co., Ltd.].

Watermark Numerical Computing. 2005: PEST: Model-Independent Parameter Estimation. Version 5. Brisbane, Australia: Watermark Numerical Computing.

Zhou, M.C., H. Ishidaira, H.P. Hapuarachchi, J. Magome, A.S. Kiem, K. Takeuchi, 2006: Estimating potential evapotranspiration using Shuttleworth–Wallace model and NOAA-AVHRR NDVI data to feed a distributed hydrological model over the Mekong River basin, Journal of Hydrology, v. 327, p. 151–173.

FIGURES

Figure 1. Location map

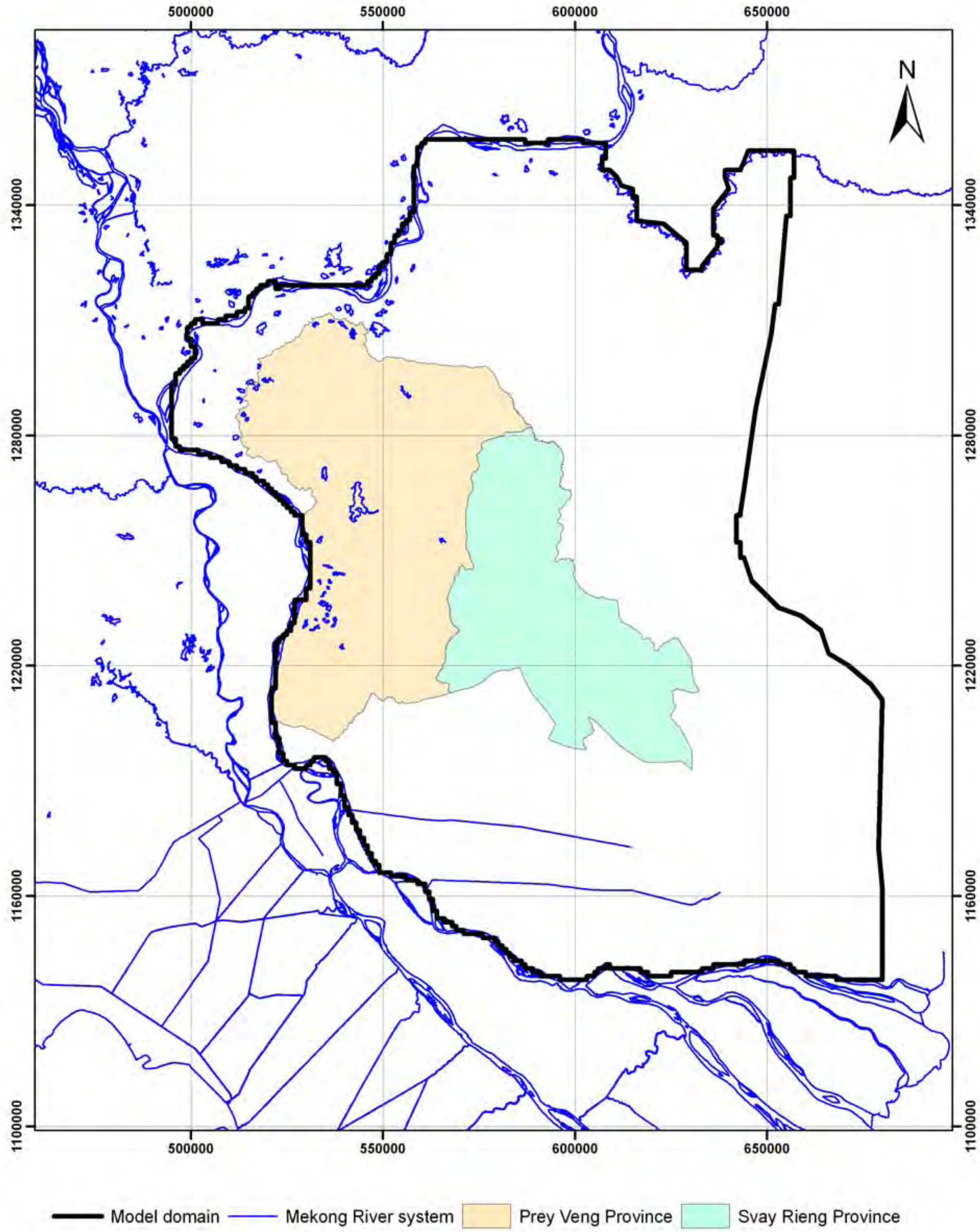


Figure 2. Limits of the hydrogeologic analyses

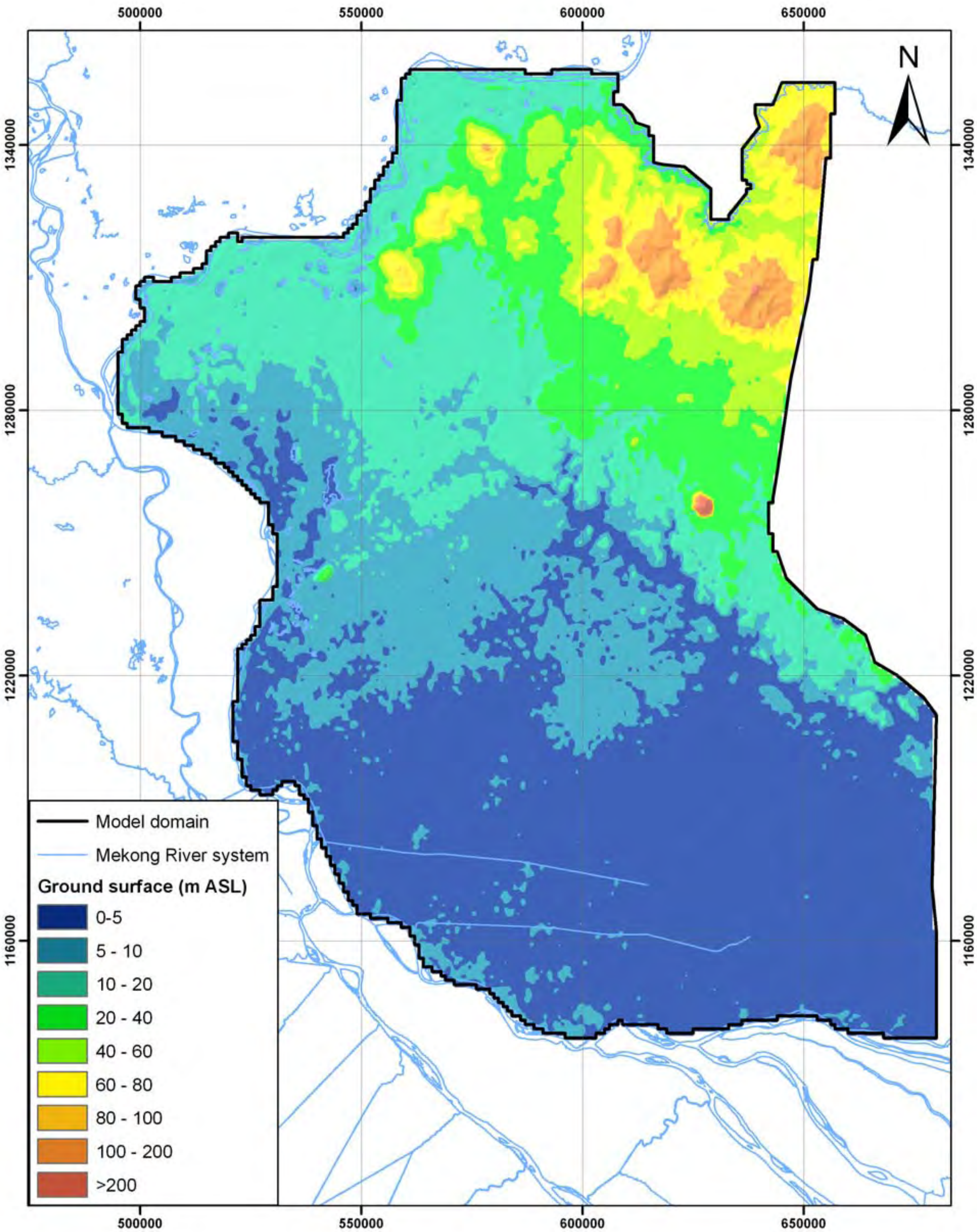


Figure 3. Interpolated ground surface elevations

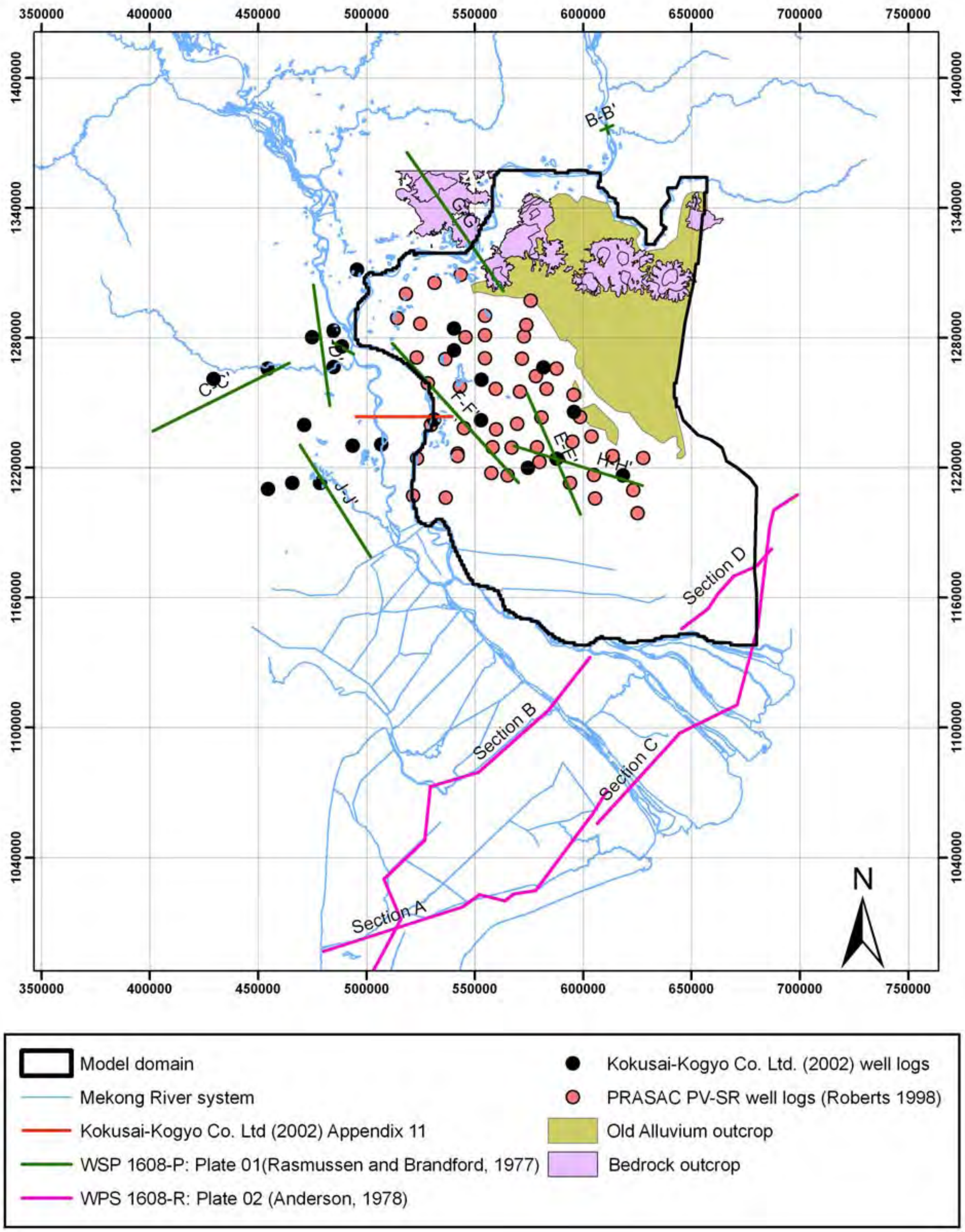


Figure 4. Data sources for the elevations of the top of the Old Alluvium

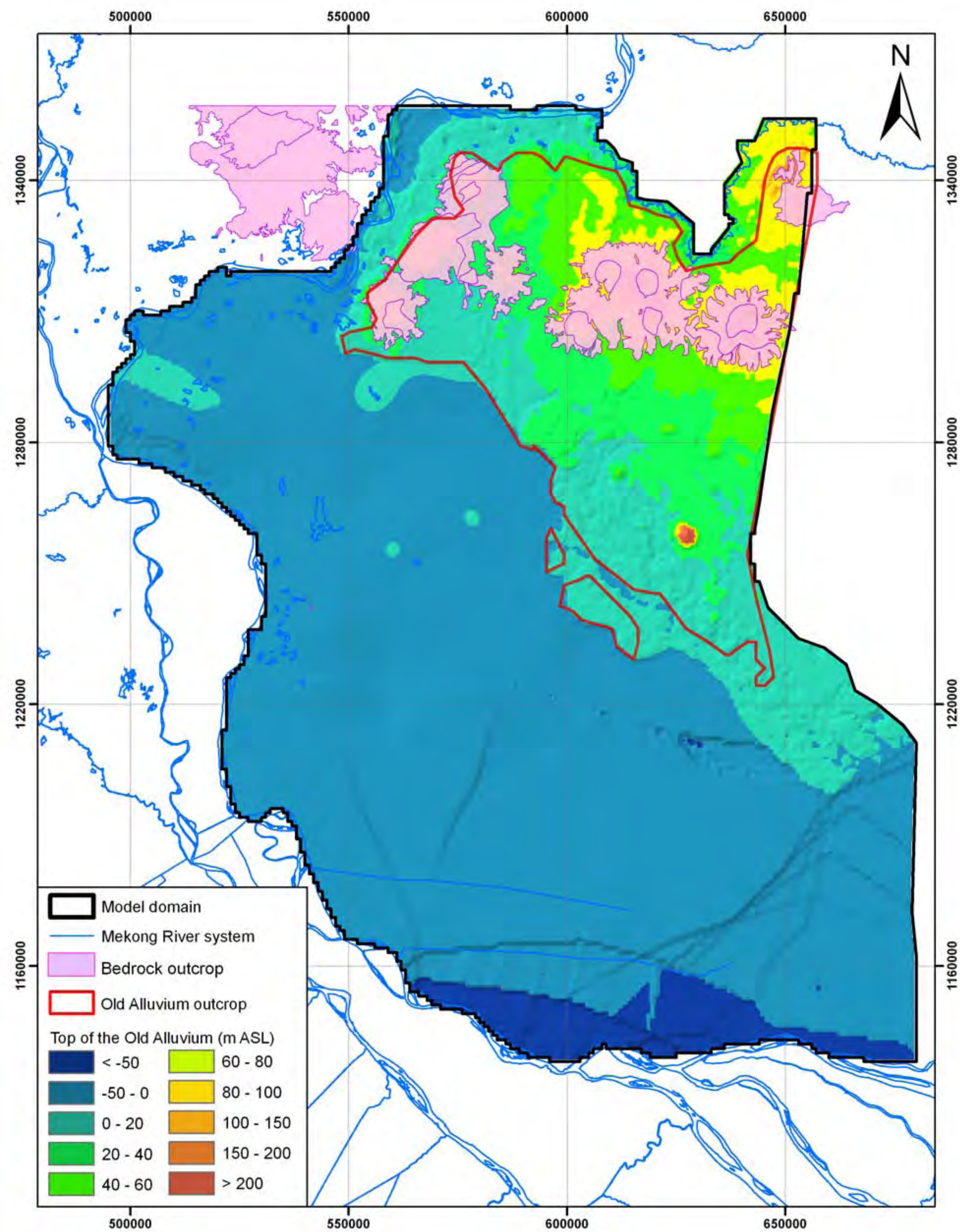


Figure 5. Interpolated elevations of the top of the Old Alluvium

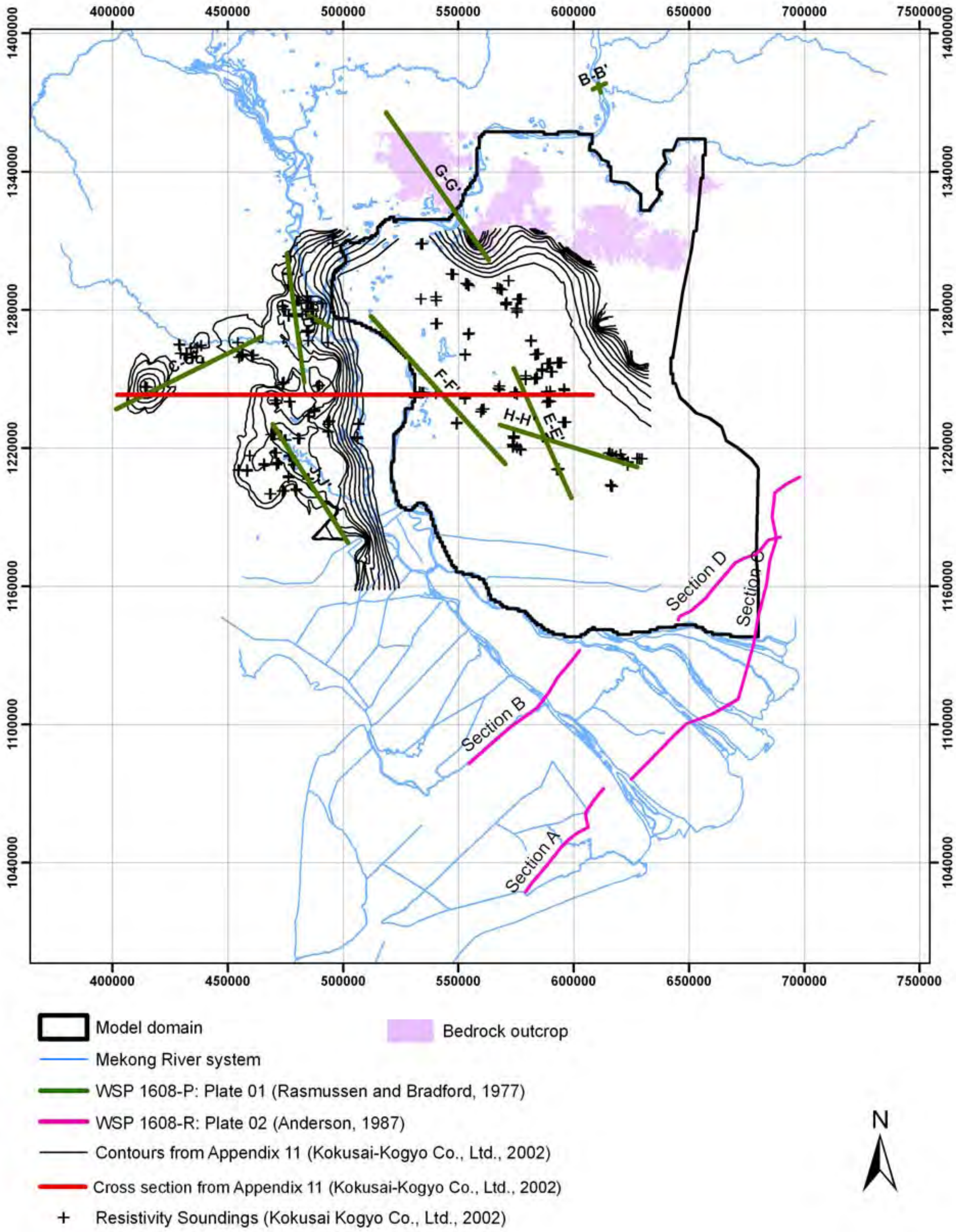


Figure 6. Data sources for the elevations of the top of bedrock

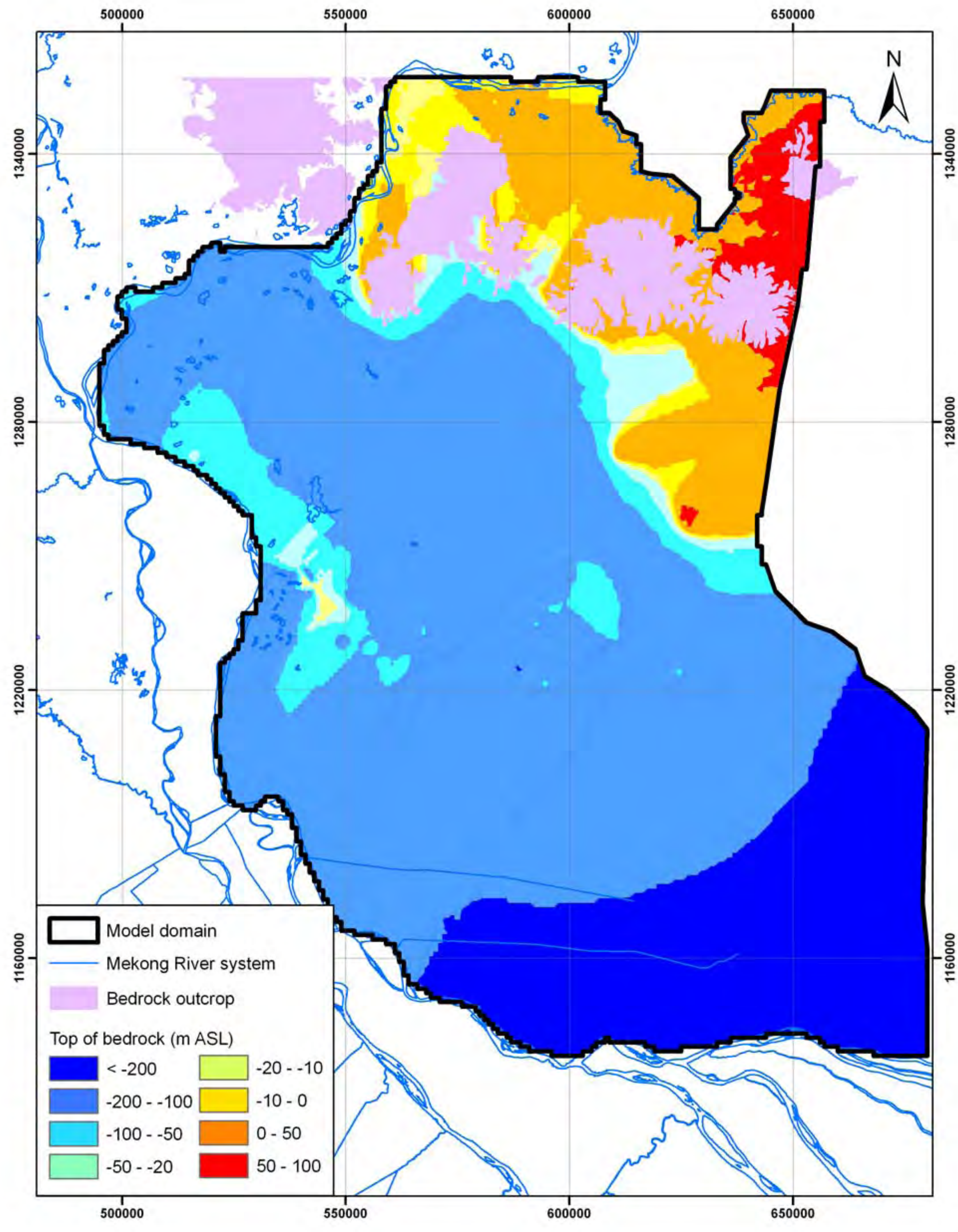


Figure 7. Interpolated elevations of the top of bedrock

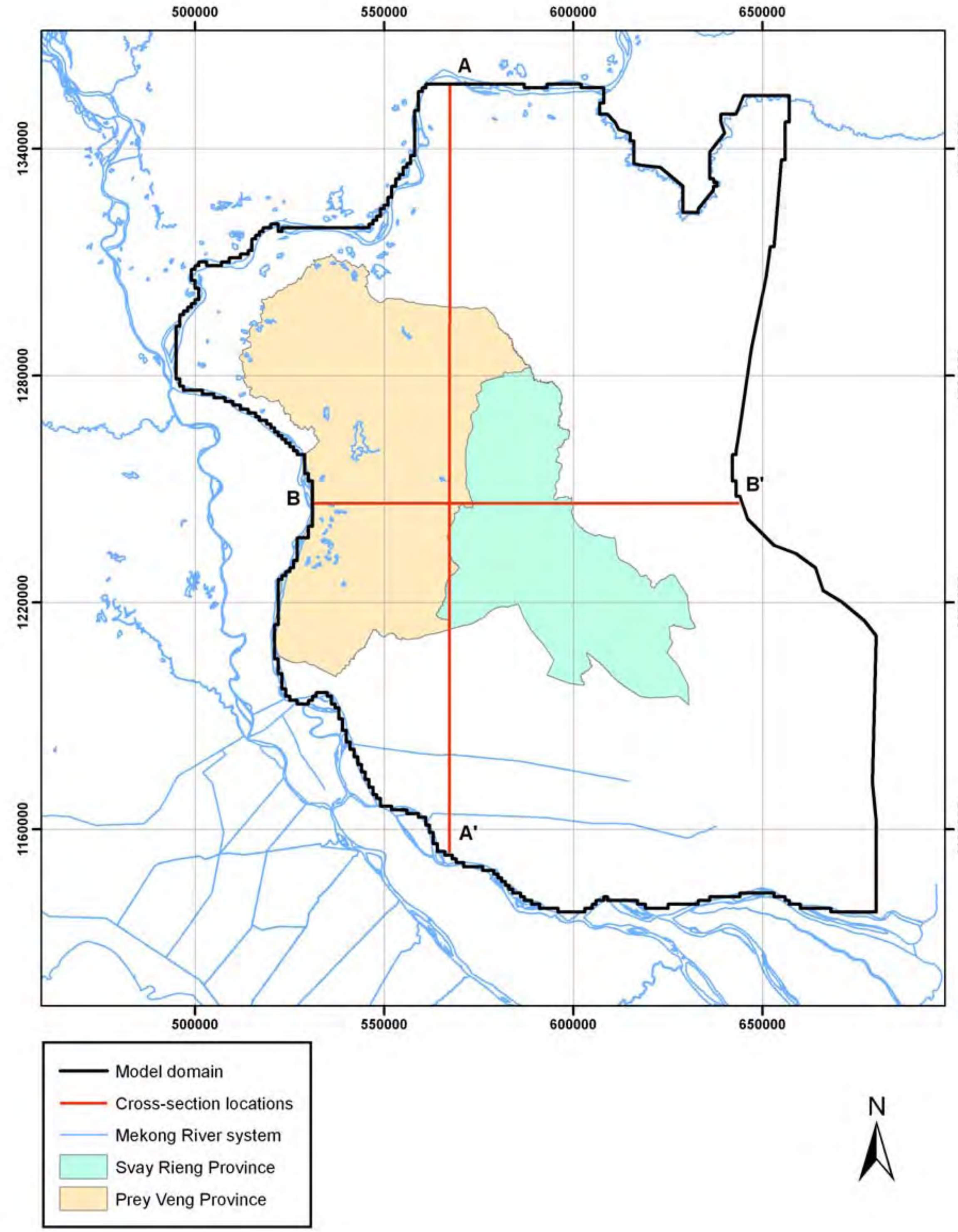


Figure 8. Locations of cross-sections

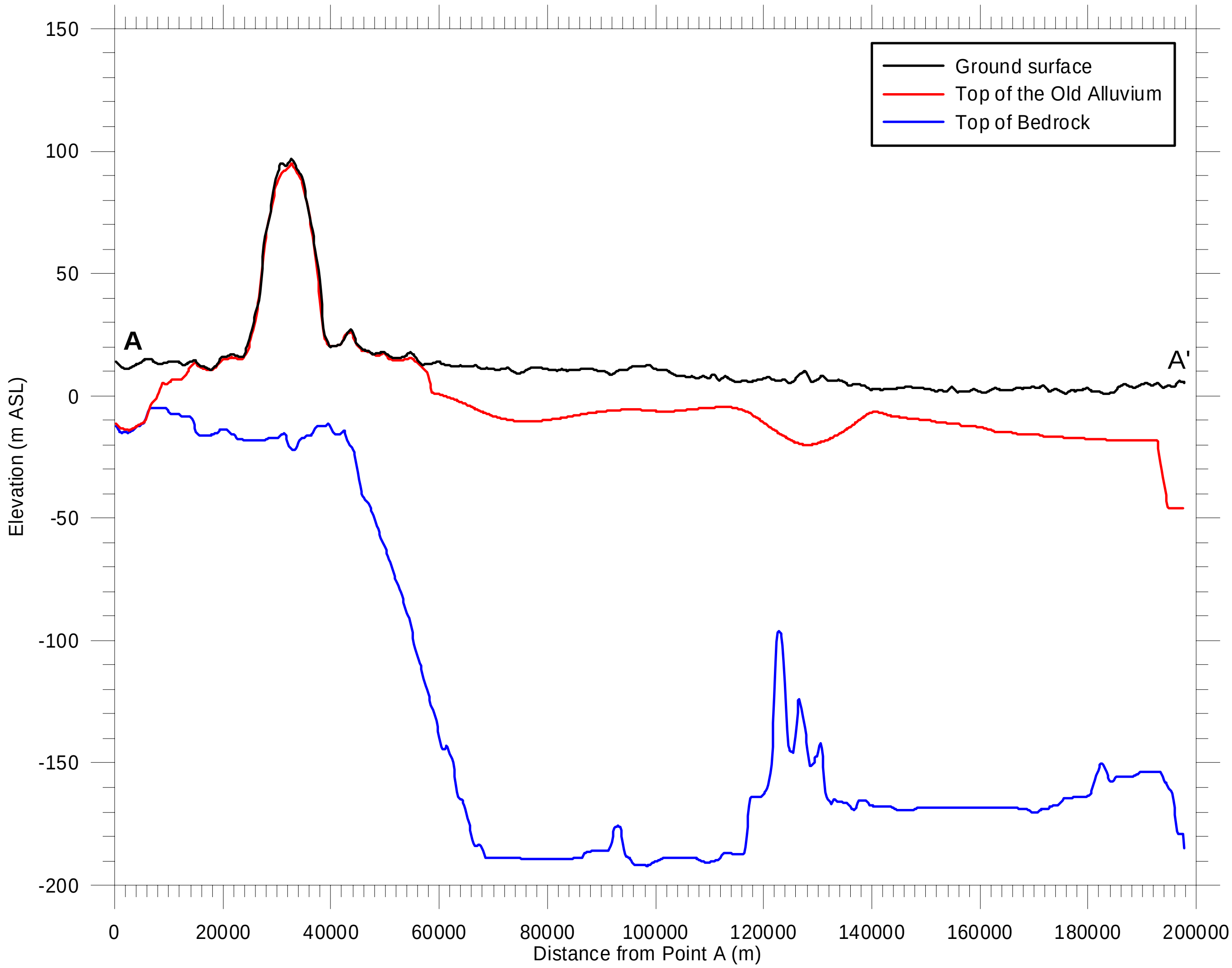


Figure 9. North-south cross-section

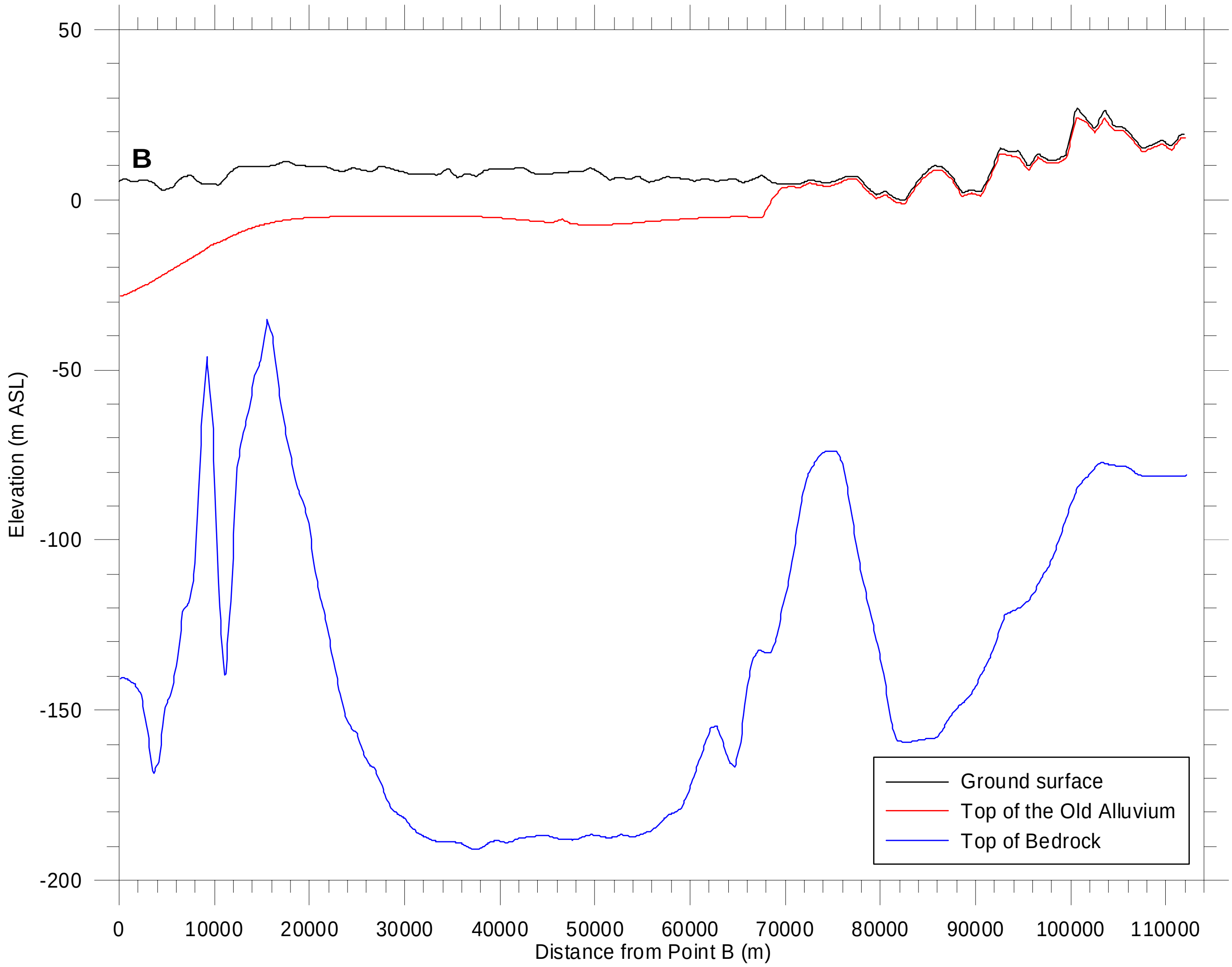


Figure 10. East-west cross-section

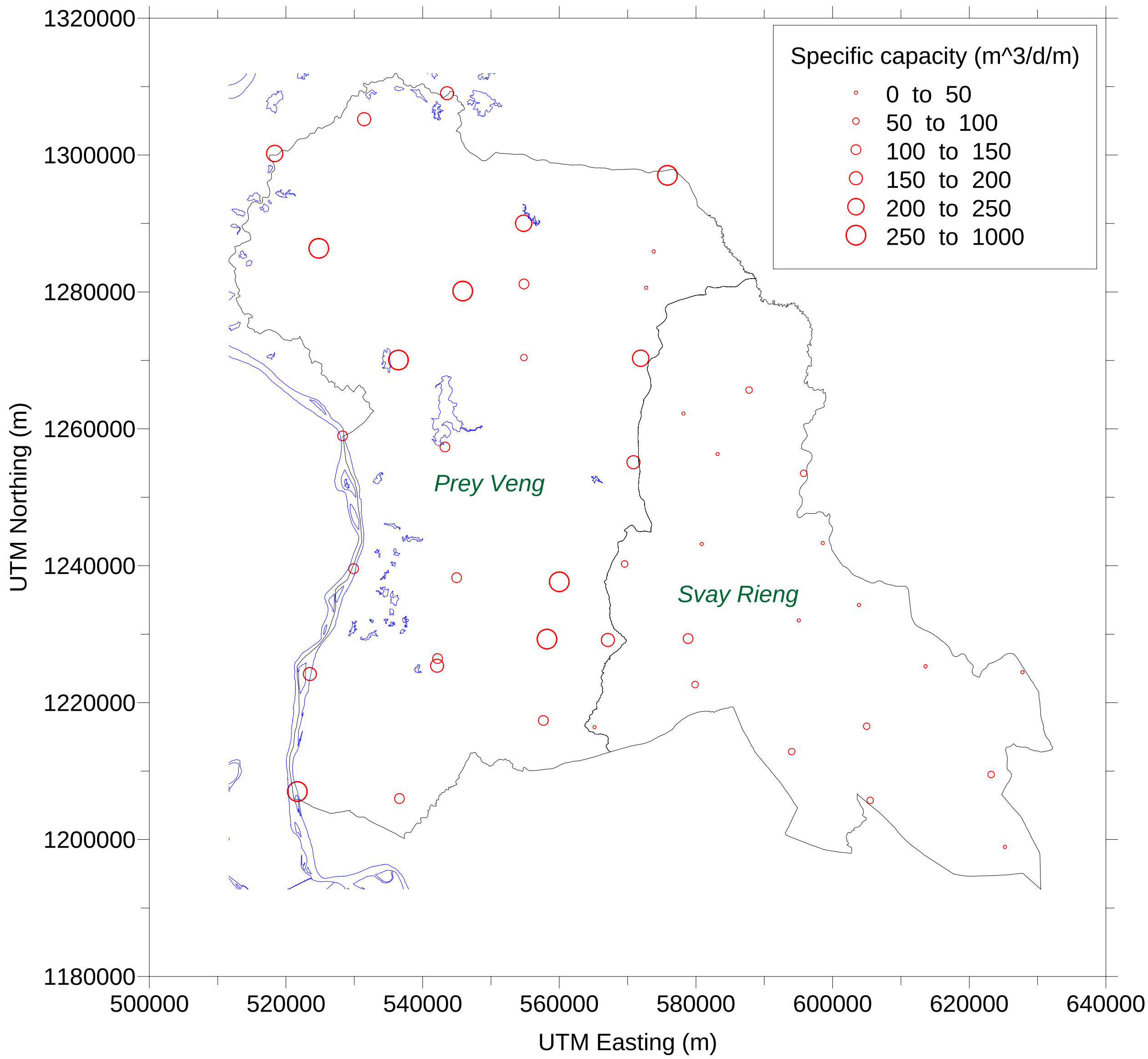


Figure 11. Specific capacity estimates, EU-PRASAC wells in Prey Veng and Svay Rieng

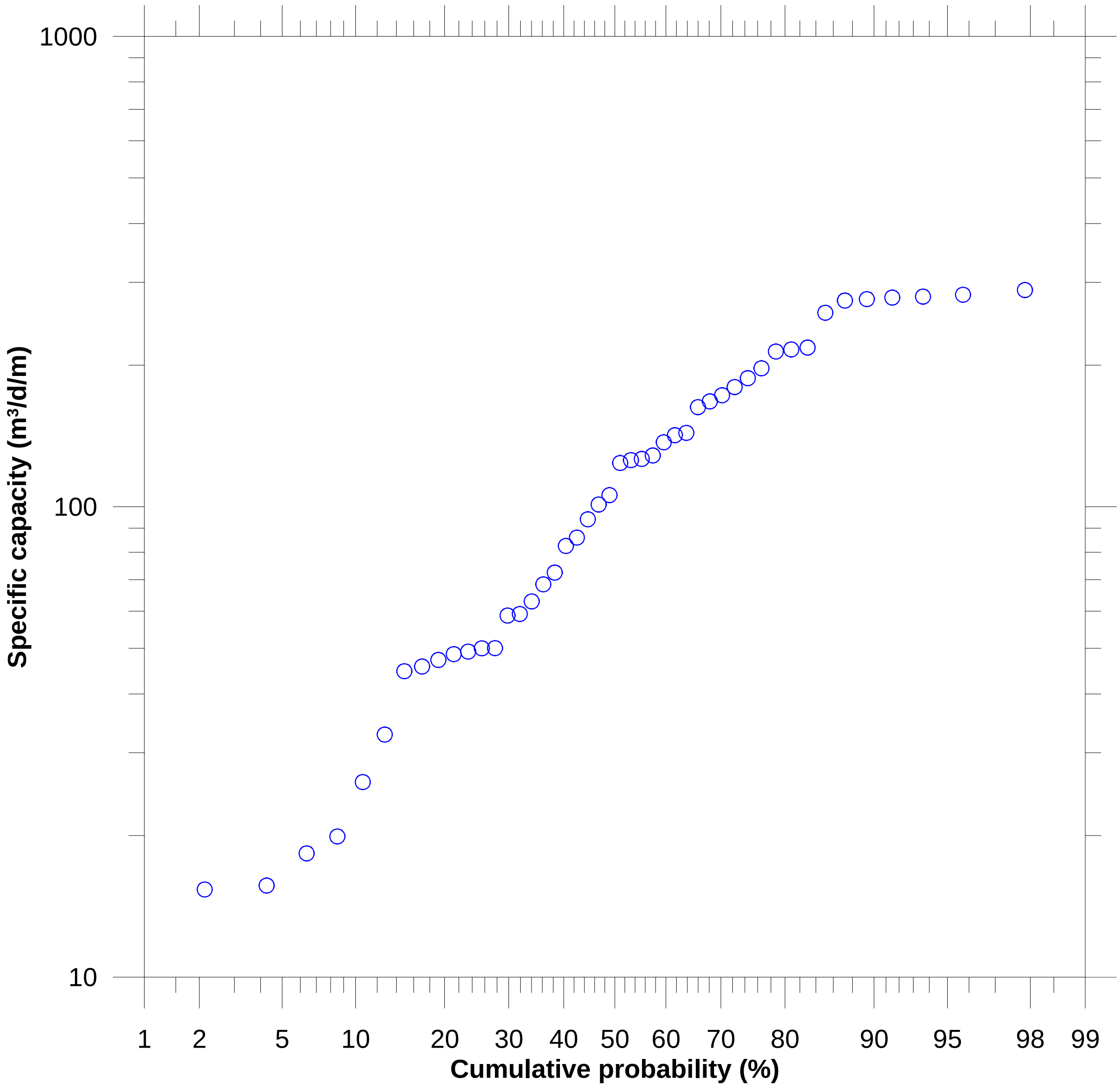


Figure 12. Statistical distribution of specific capacity estimates

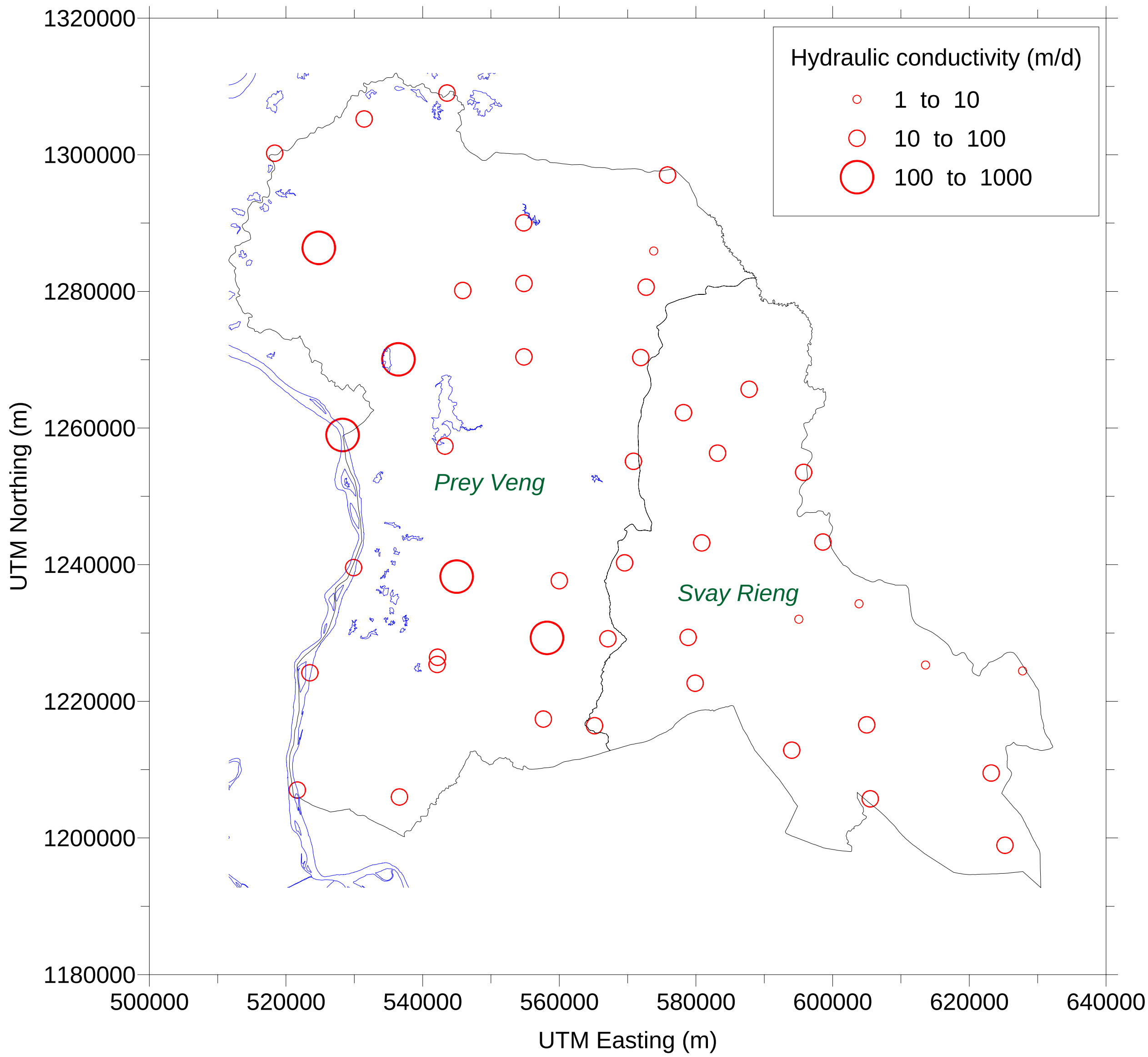


Figure 13. Hydraulic conductivities derived from specific capacity estimates, EU-PRASAC wells in Prey Veng and Svay Rieng

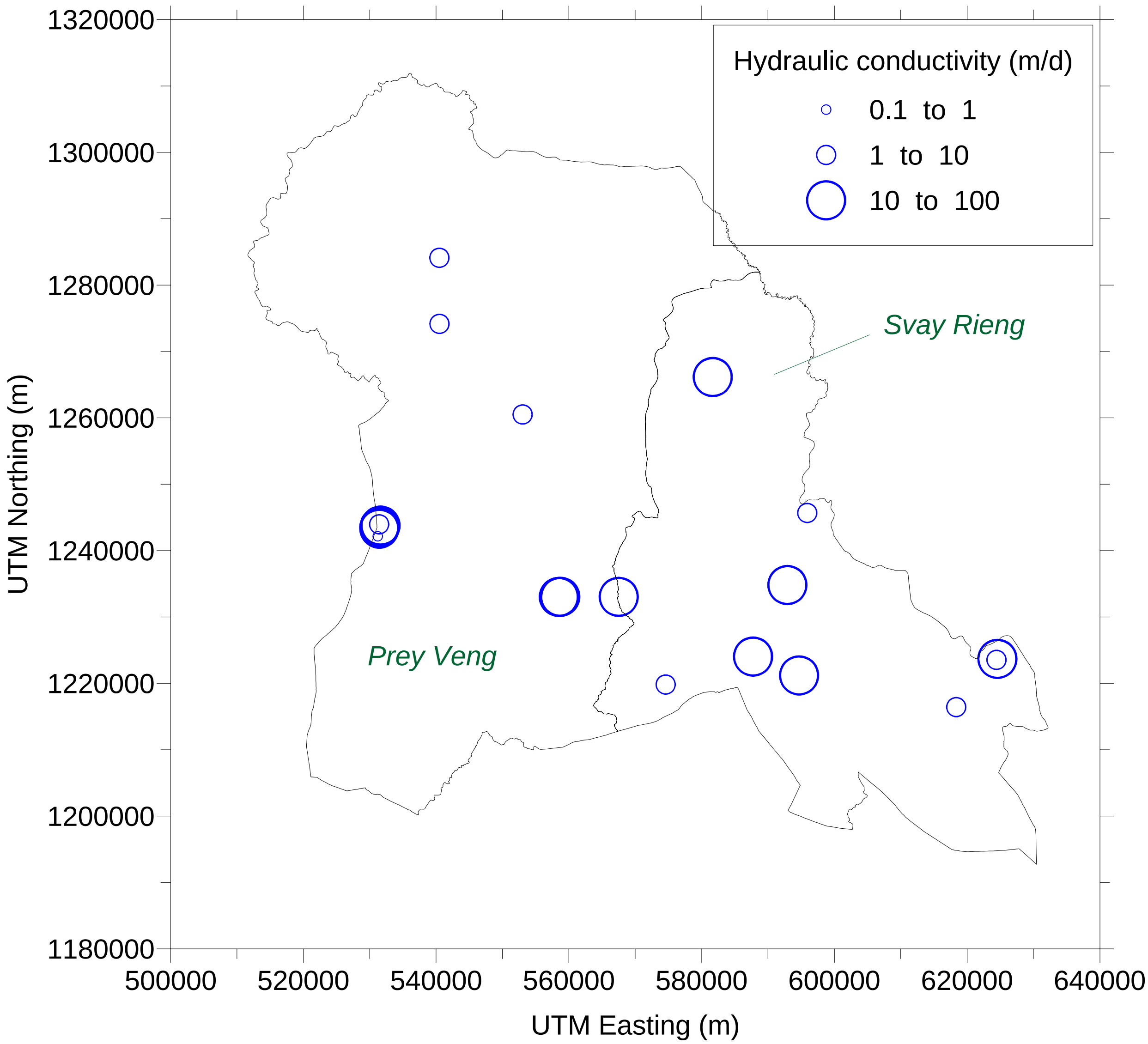


Figure 14. Higher reliability hydraulic conductivity estimates

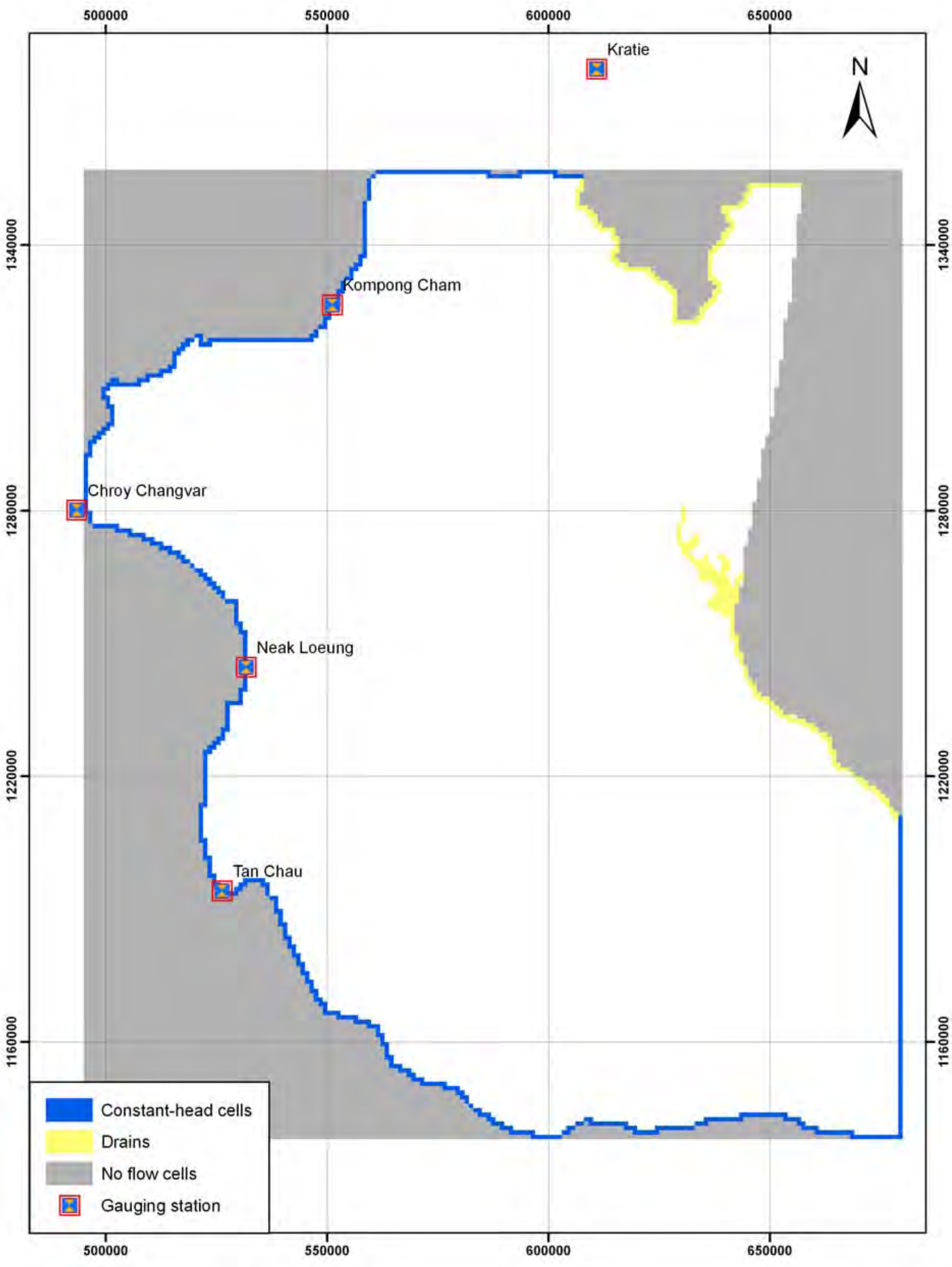


Figure 15. Model boundary conditions

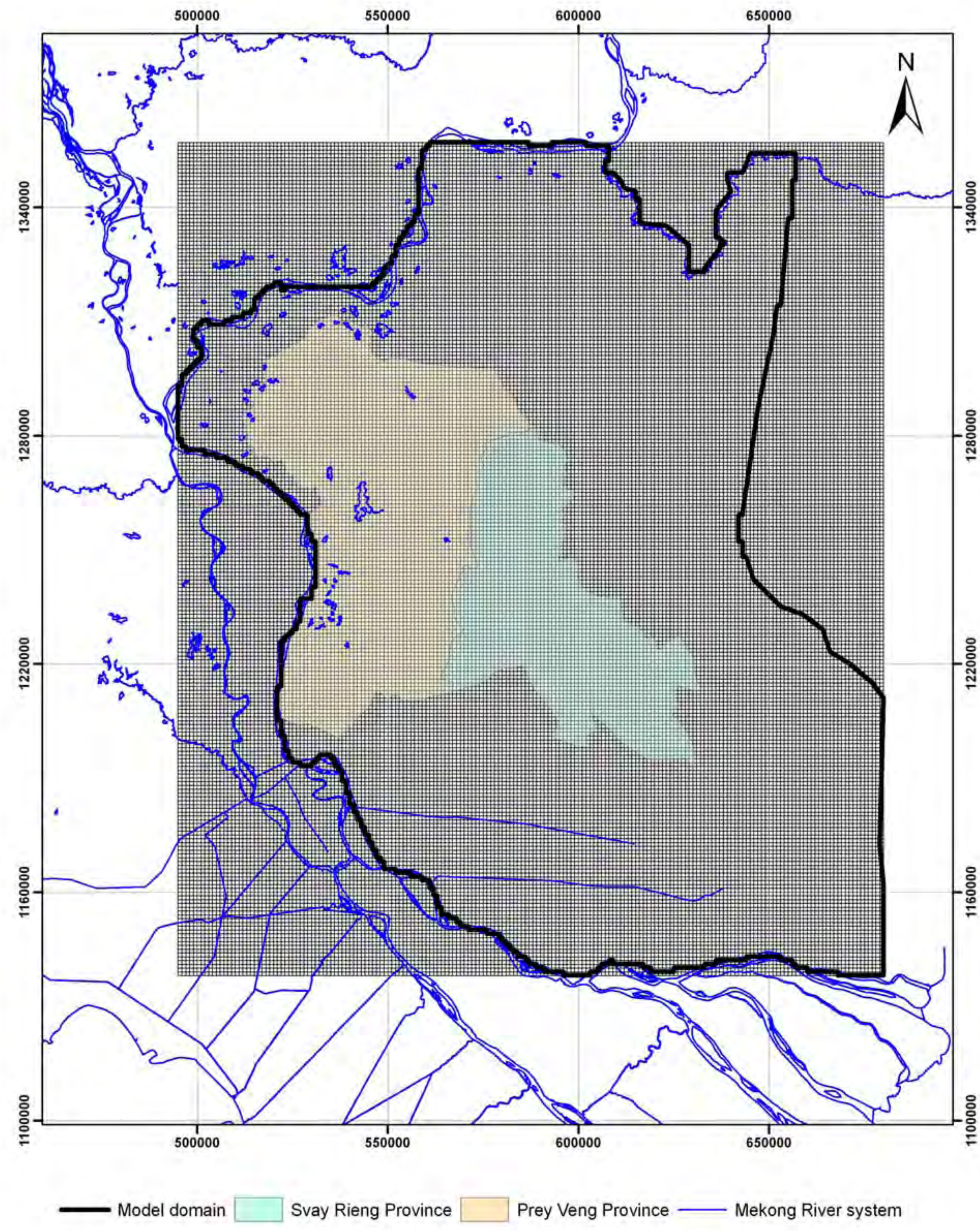


Figure 16. Groundwater model finite-difference grid

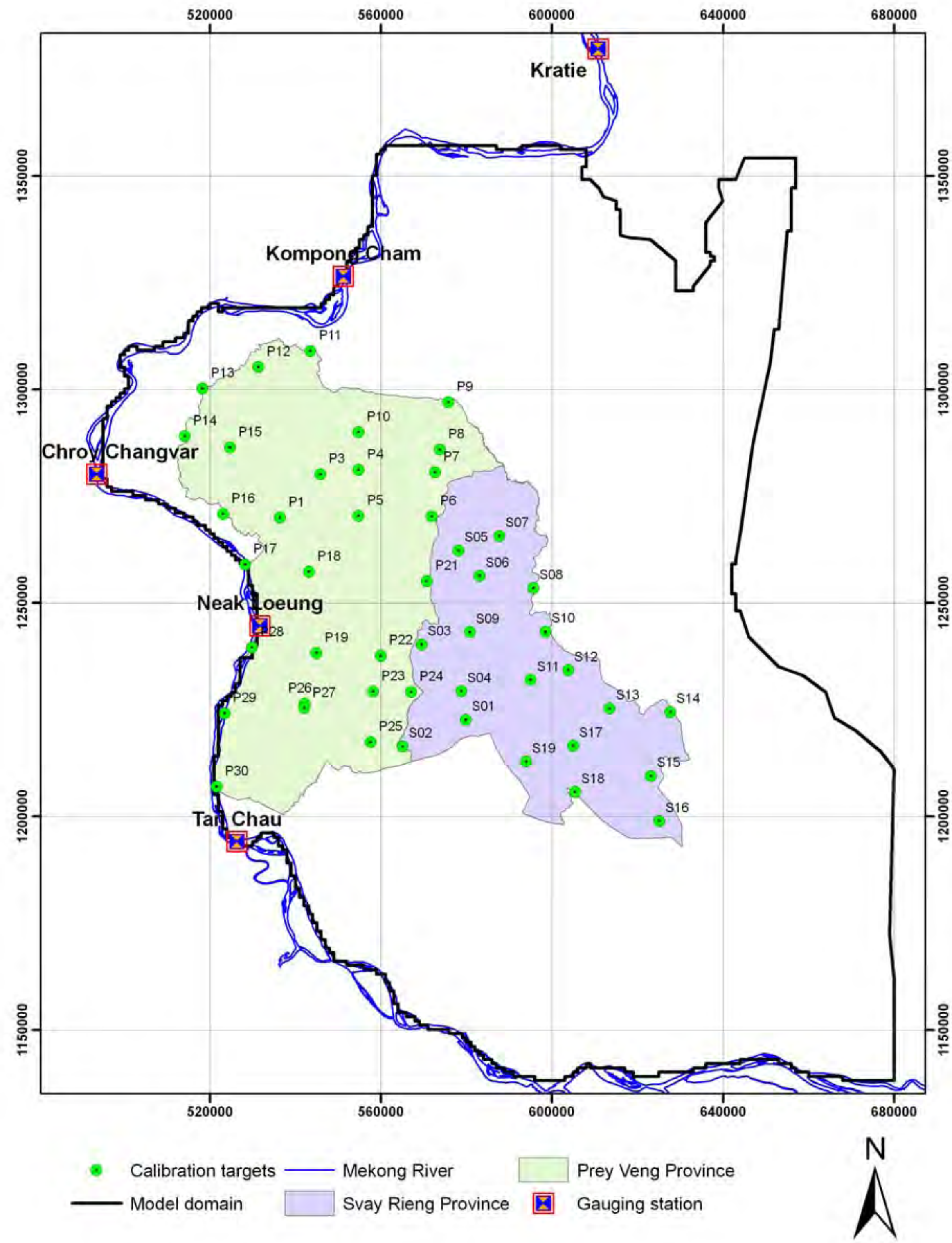


Figure 17. Locations of wells for model calibration targets

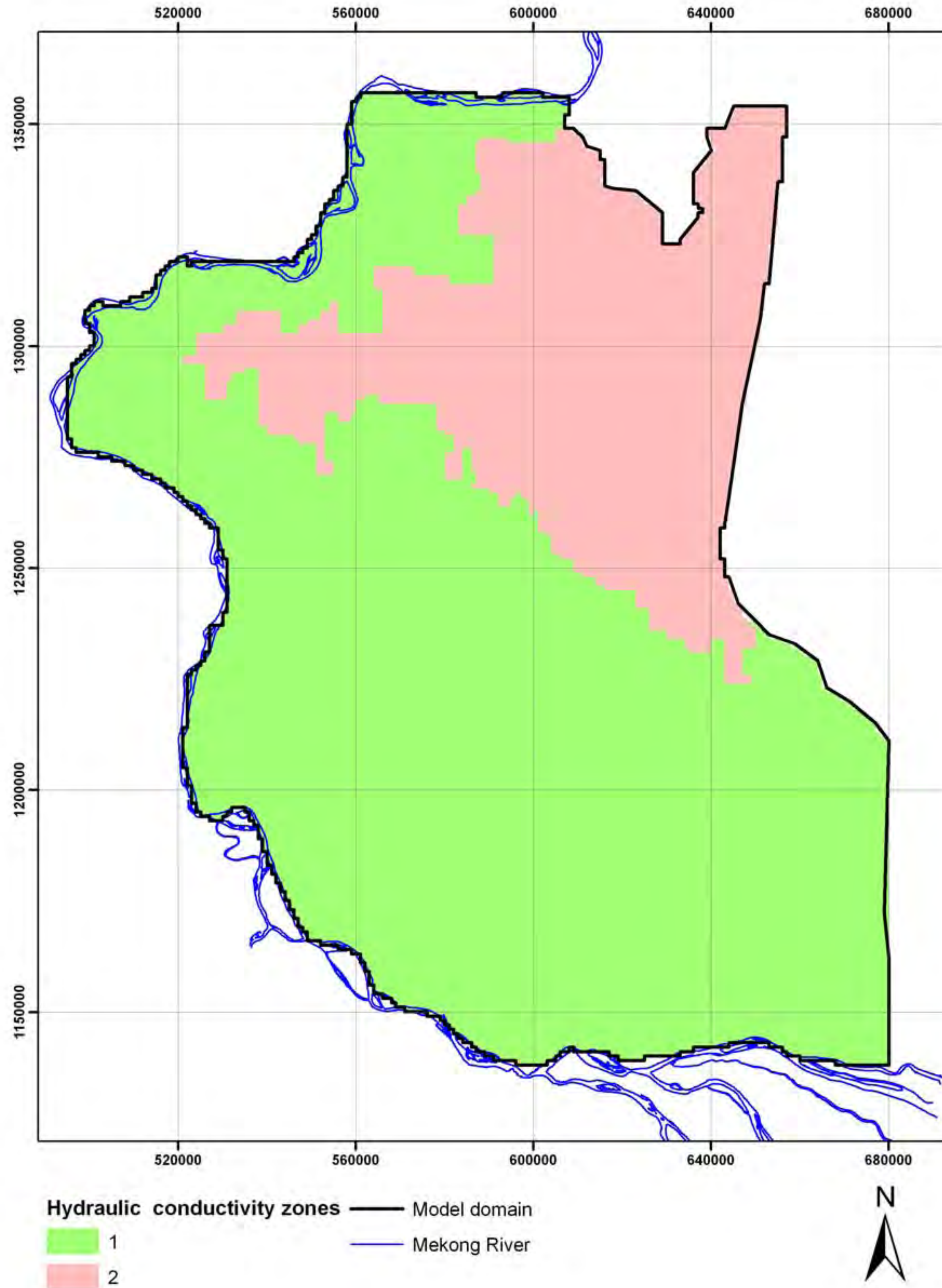


Figure 18. Hydraulic conductivity zones in the groundwater model

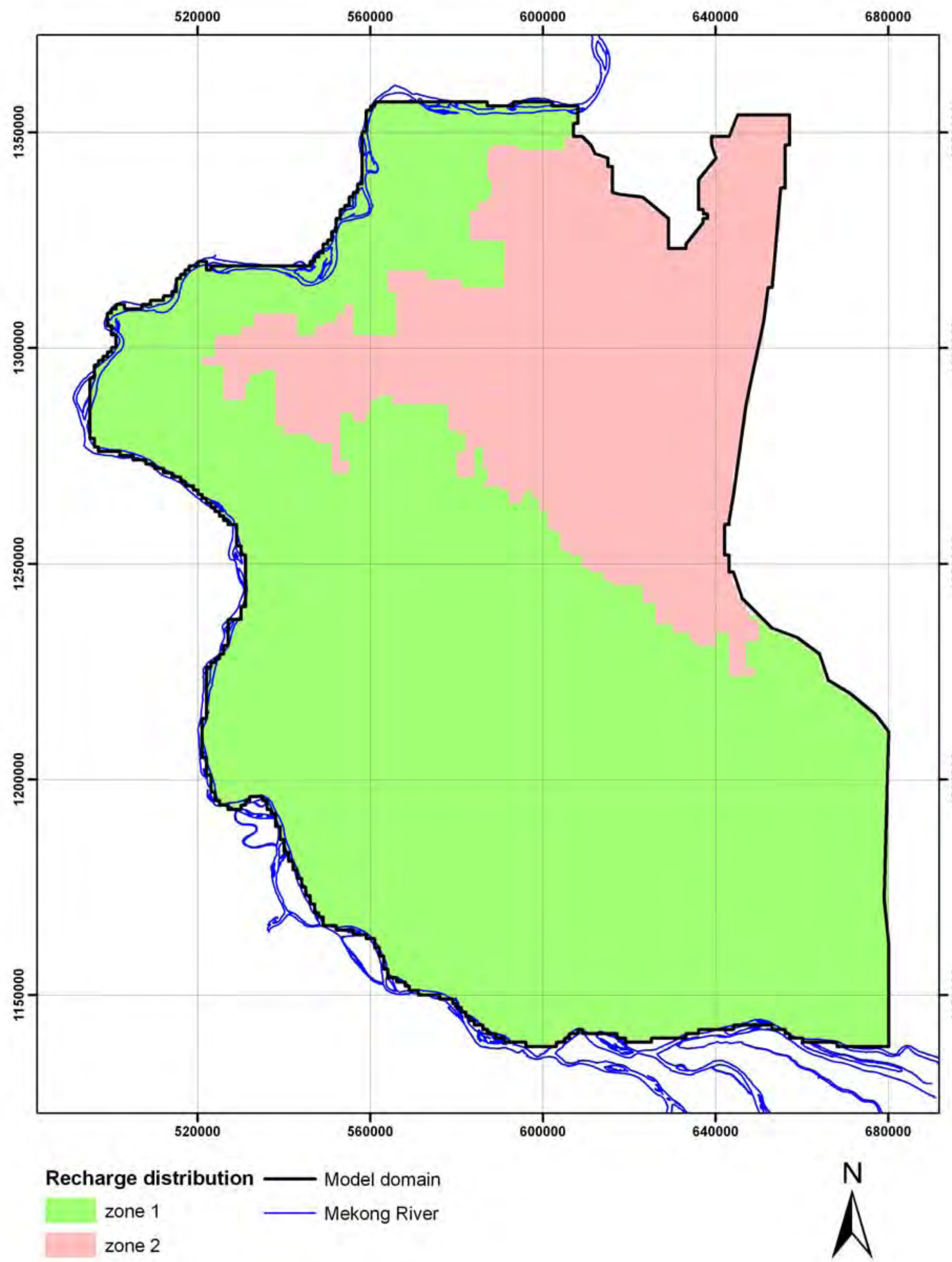


Figure 19. Distribution of recharge in the groundwater model

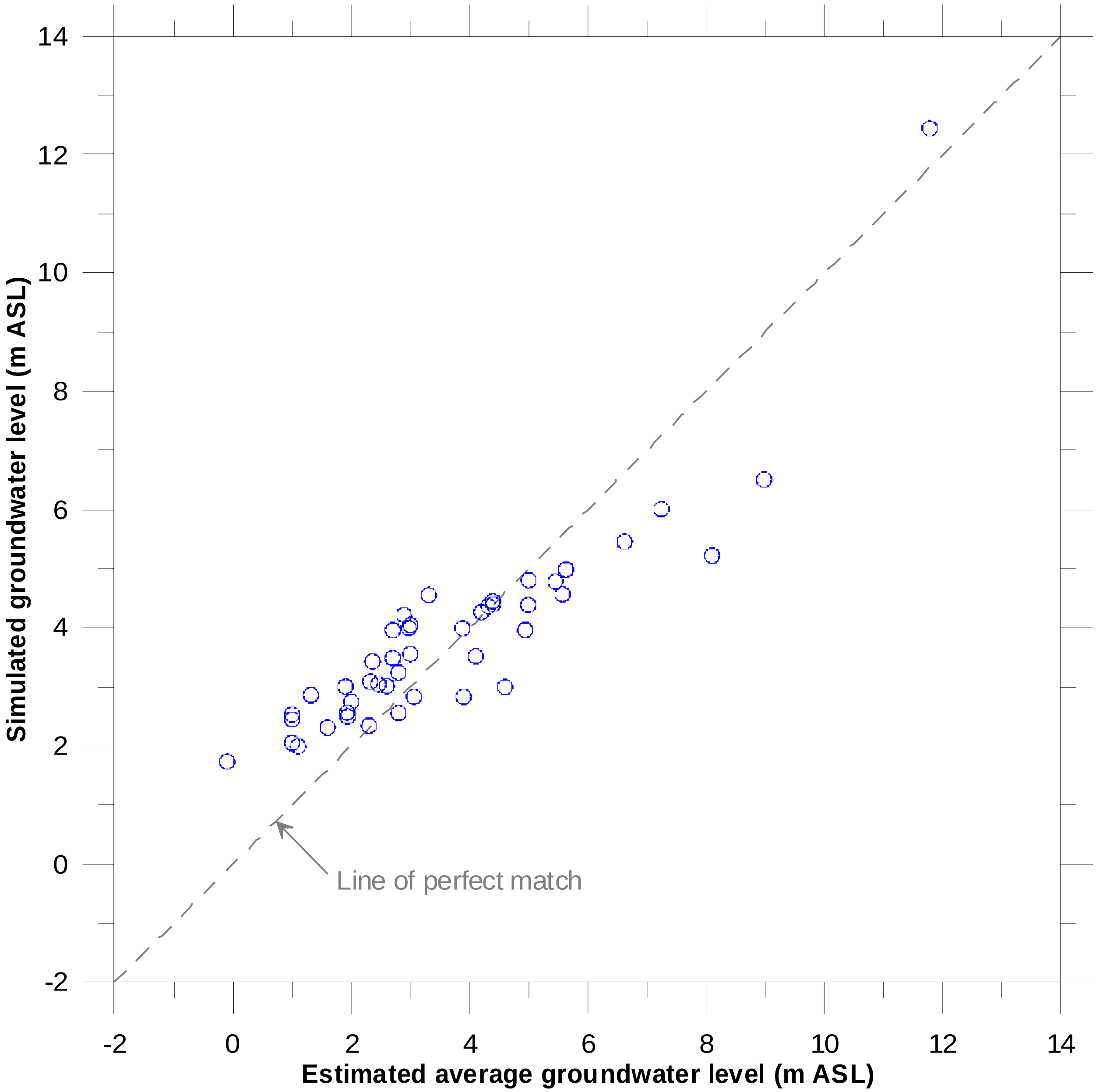


Figure 20. Scatterplot of steady-state residuals, 15 mm/yr recharge

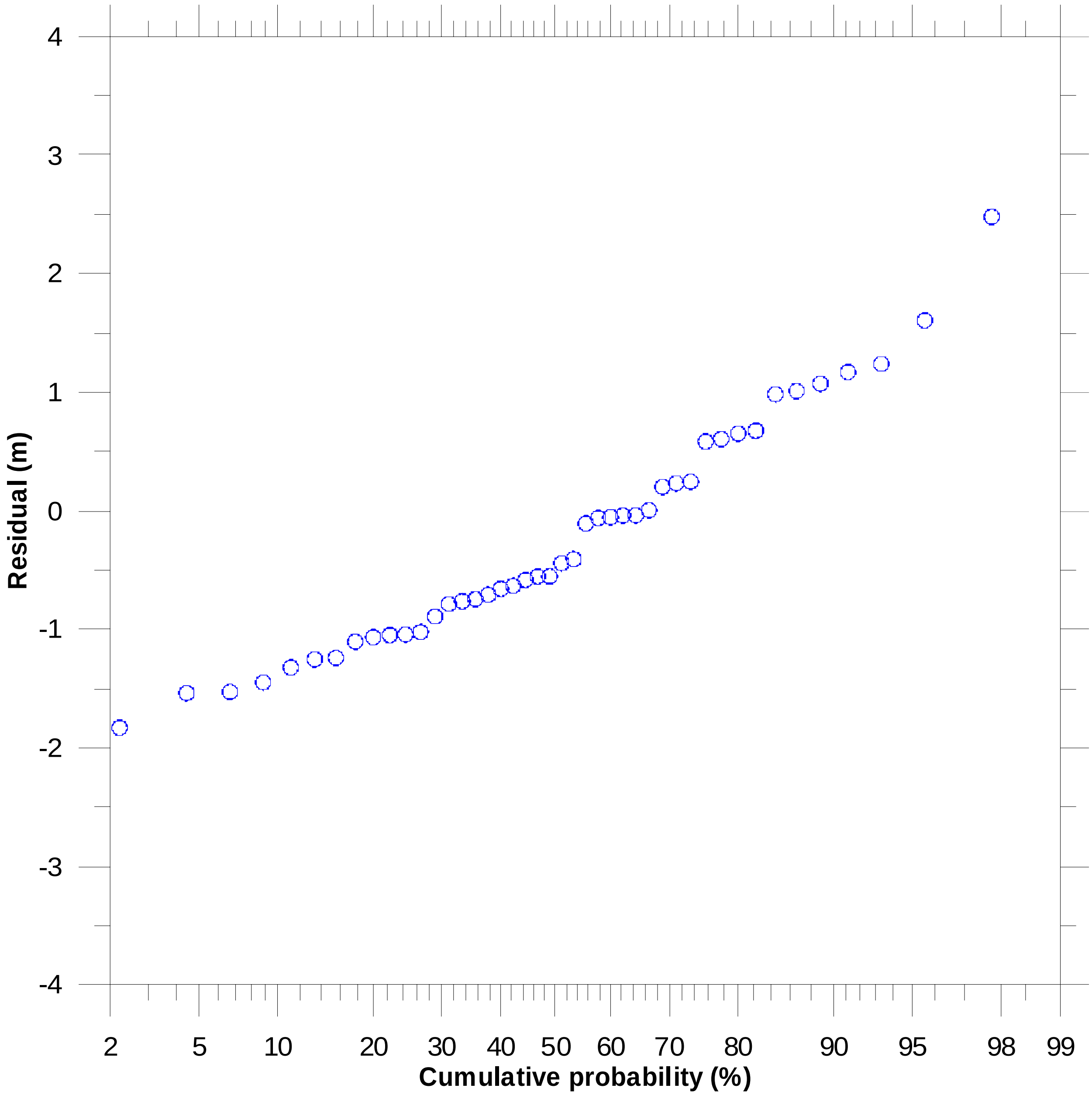


Figure 21. Cumulative probability plot of steady-state residuals, 15 mm/yr recharge

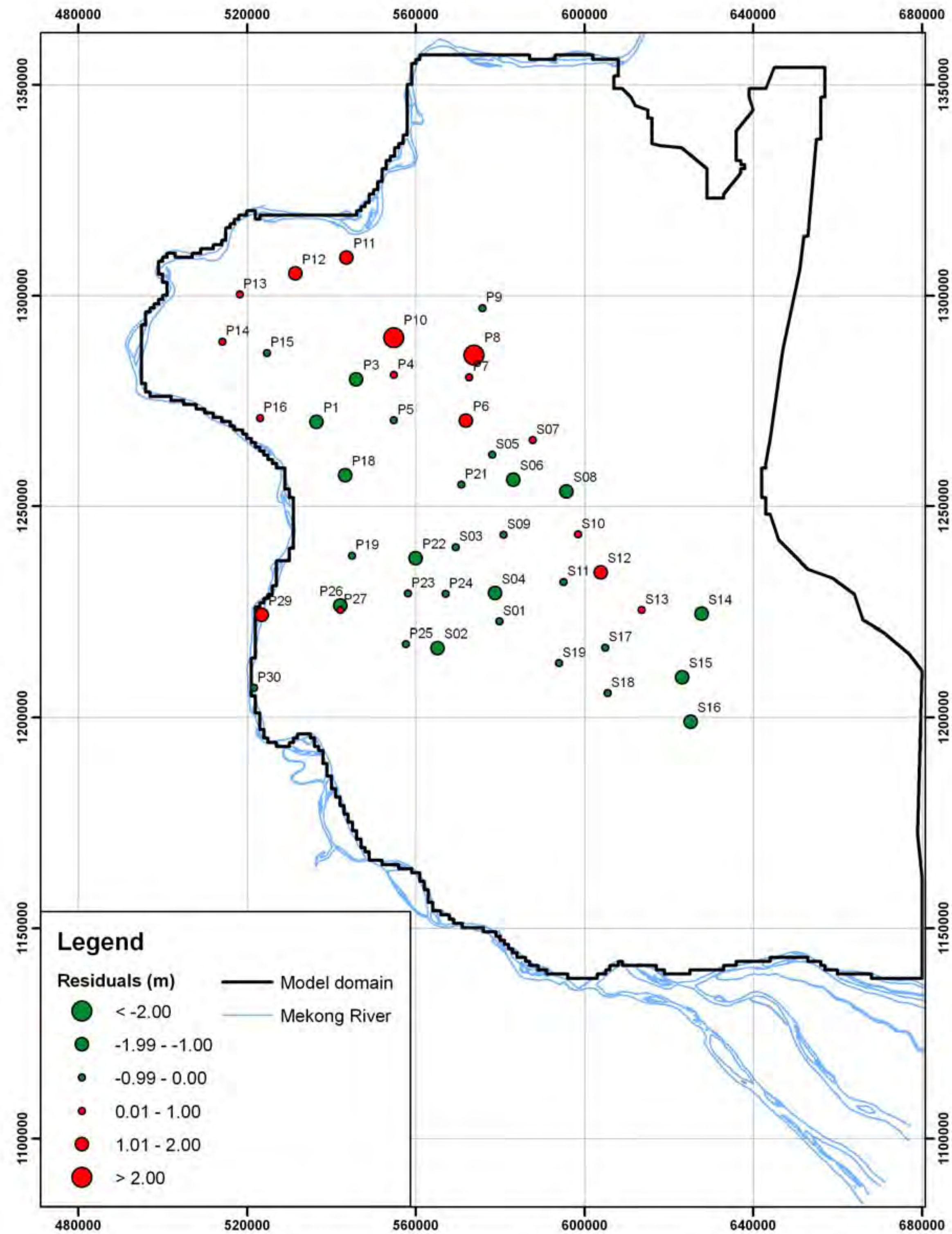


Figure 22. Distribution of steady-state residuals, 15 mm/yr recharge (Negative values represent calculated water levels is excess of observed levels.)

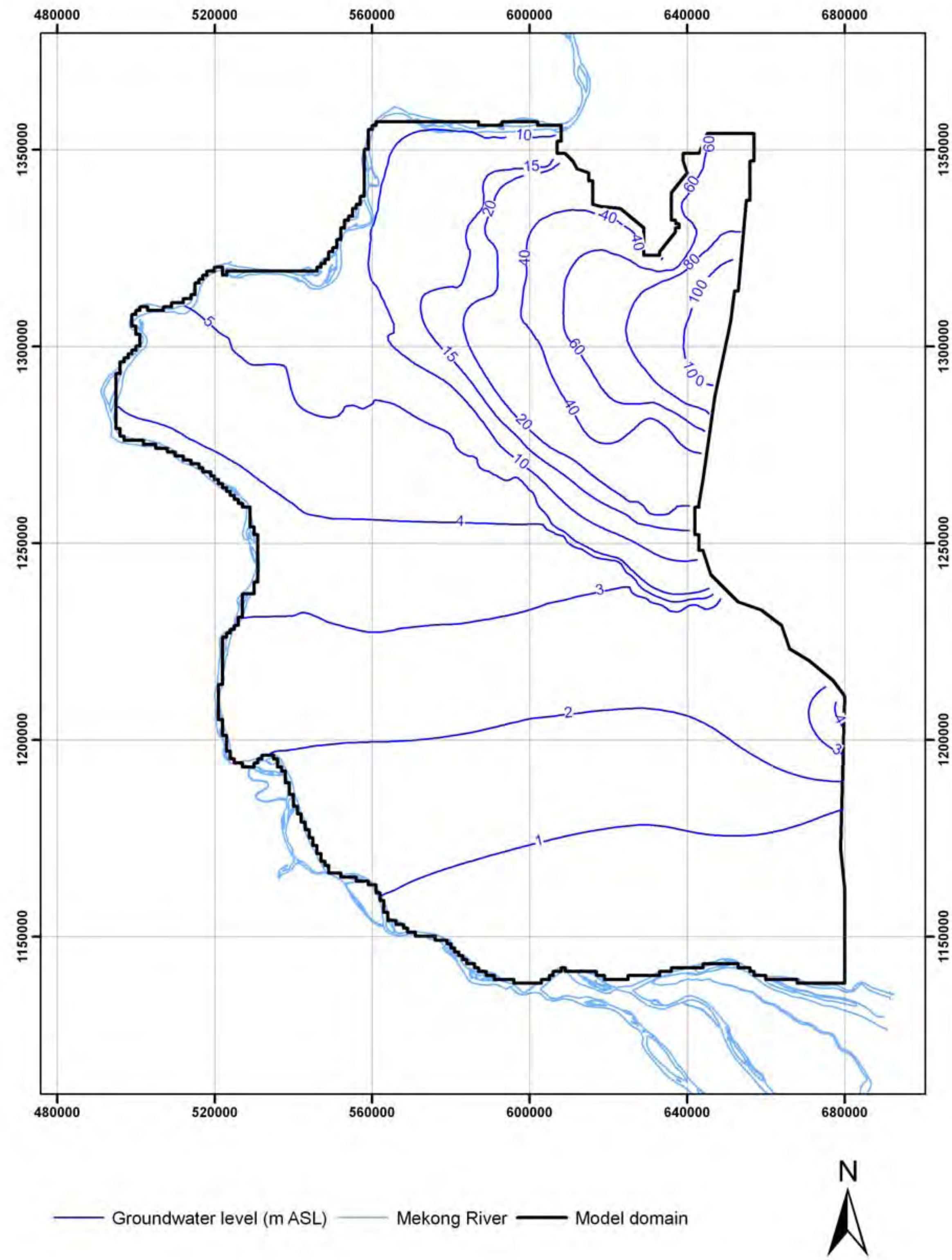


Figure 23. Simulated steady-state groundwater levels, 15 mm/yr recharge

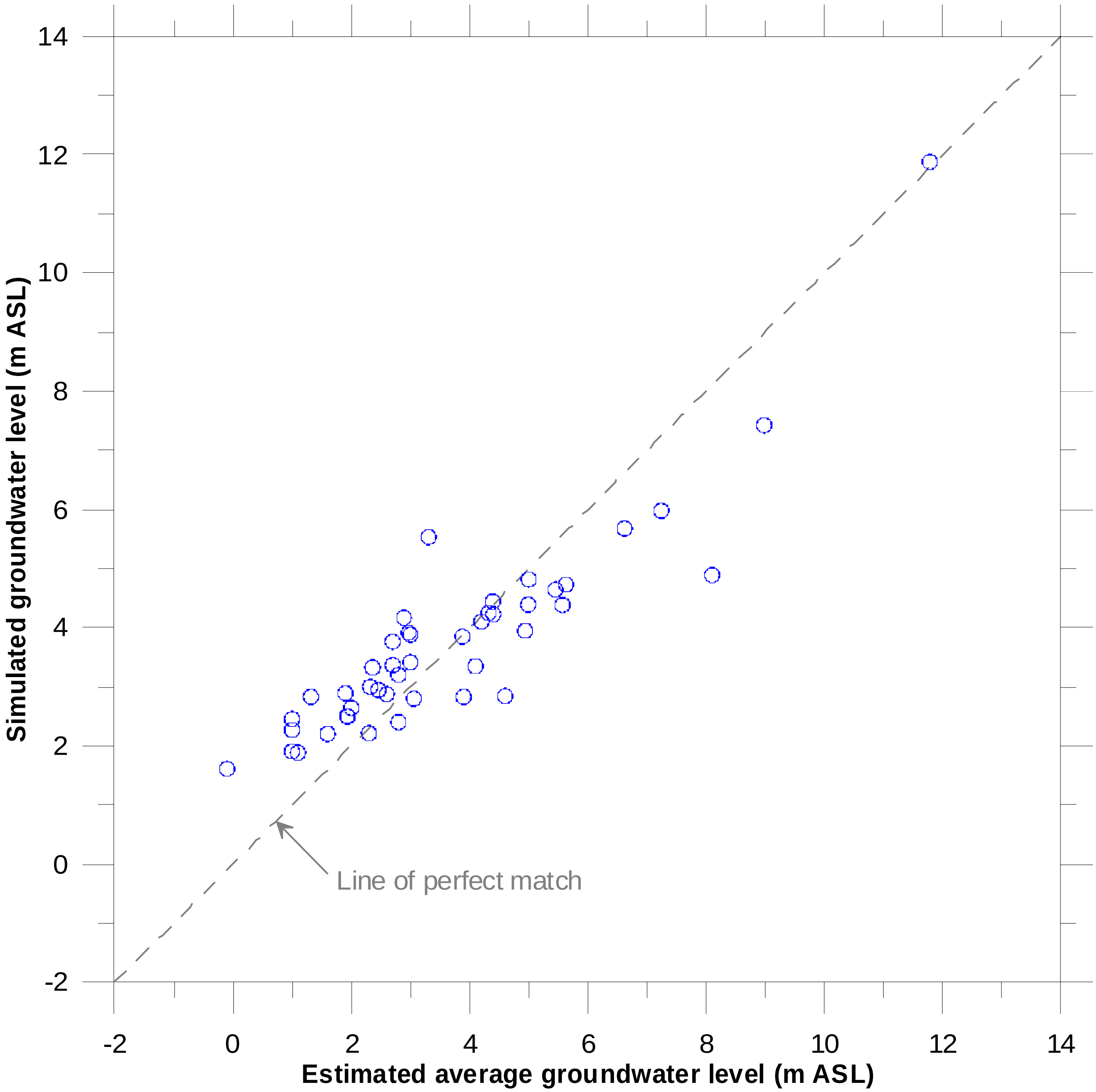


Figure 24. Scatterplot of steady-state residuals, 3 mm/yr recharge

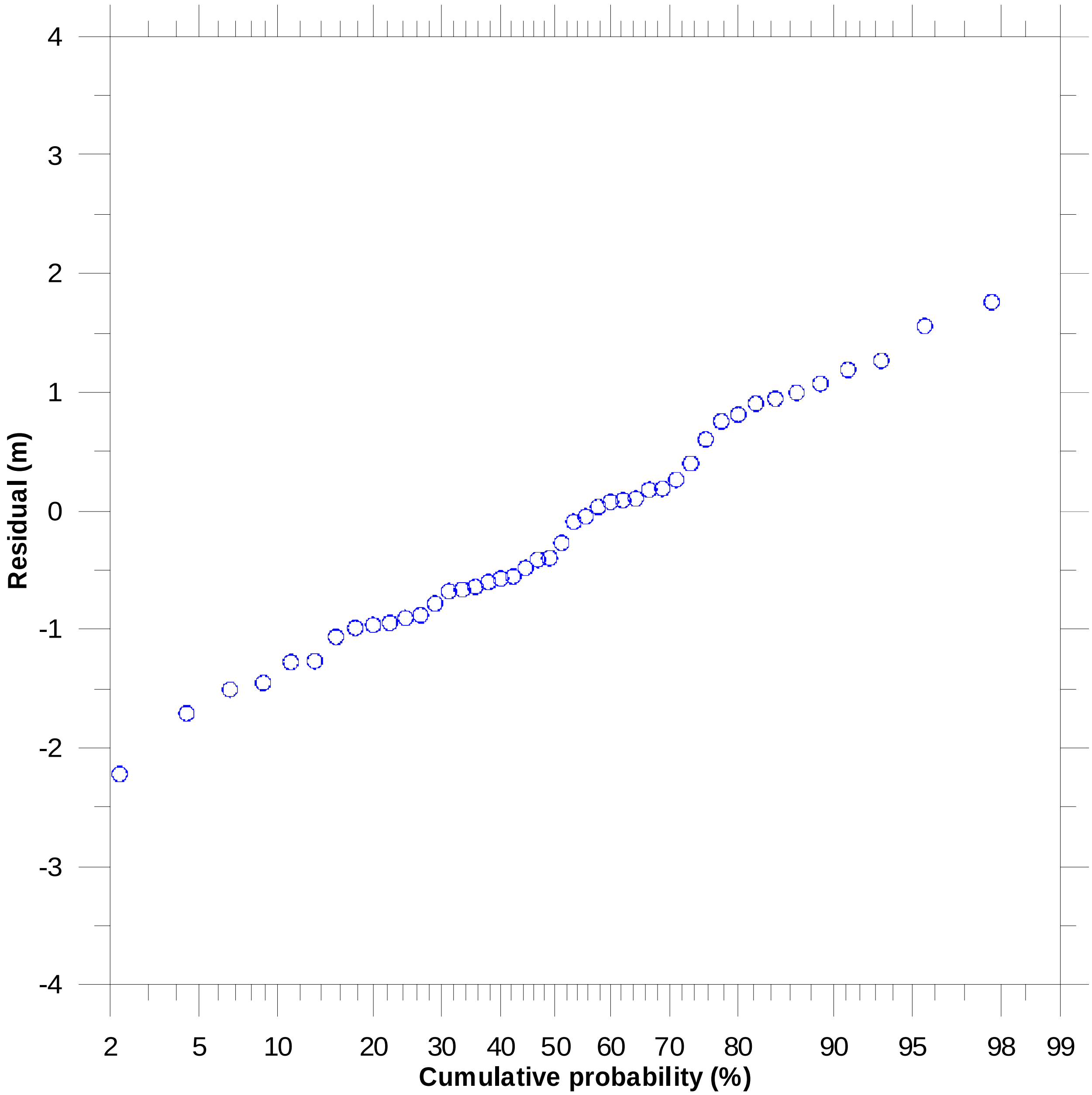


Figure 25. Cumulative probability plot of steady-state residuals, 3 mm/yr recharge

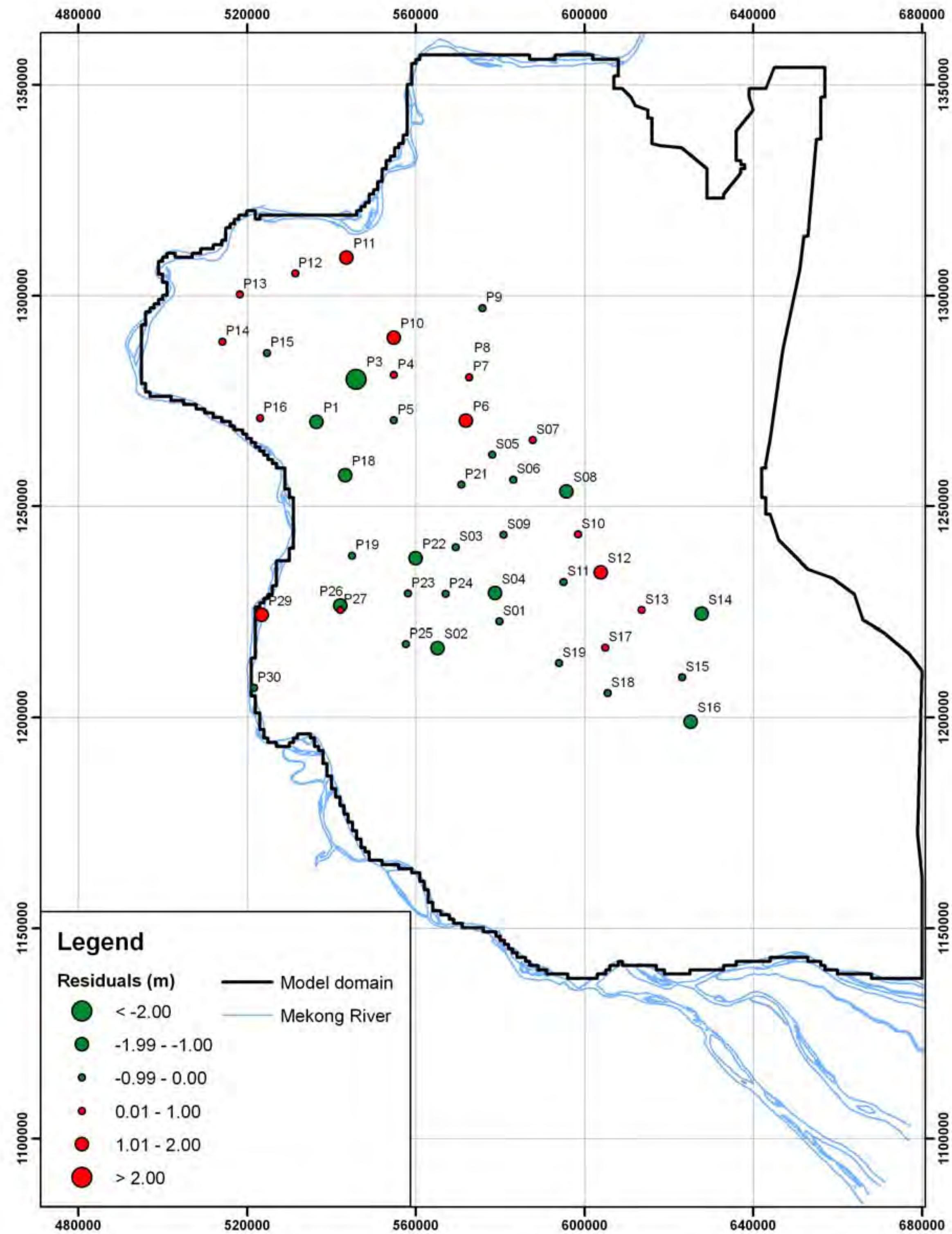


Figure 26. Distribution of steady-state residuals, 3 mm/yr recharge
(Negative values represent calculated water level is excess of observed levels.)

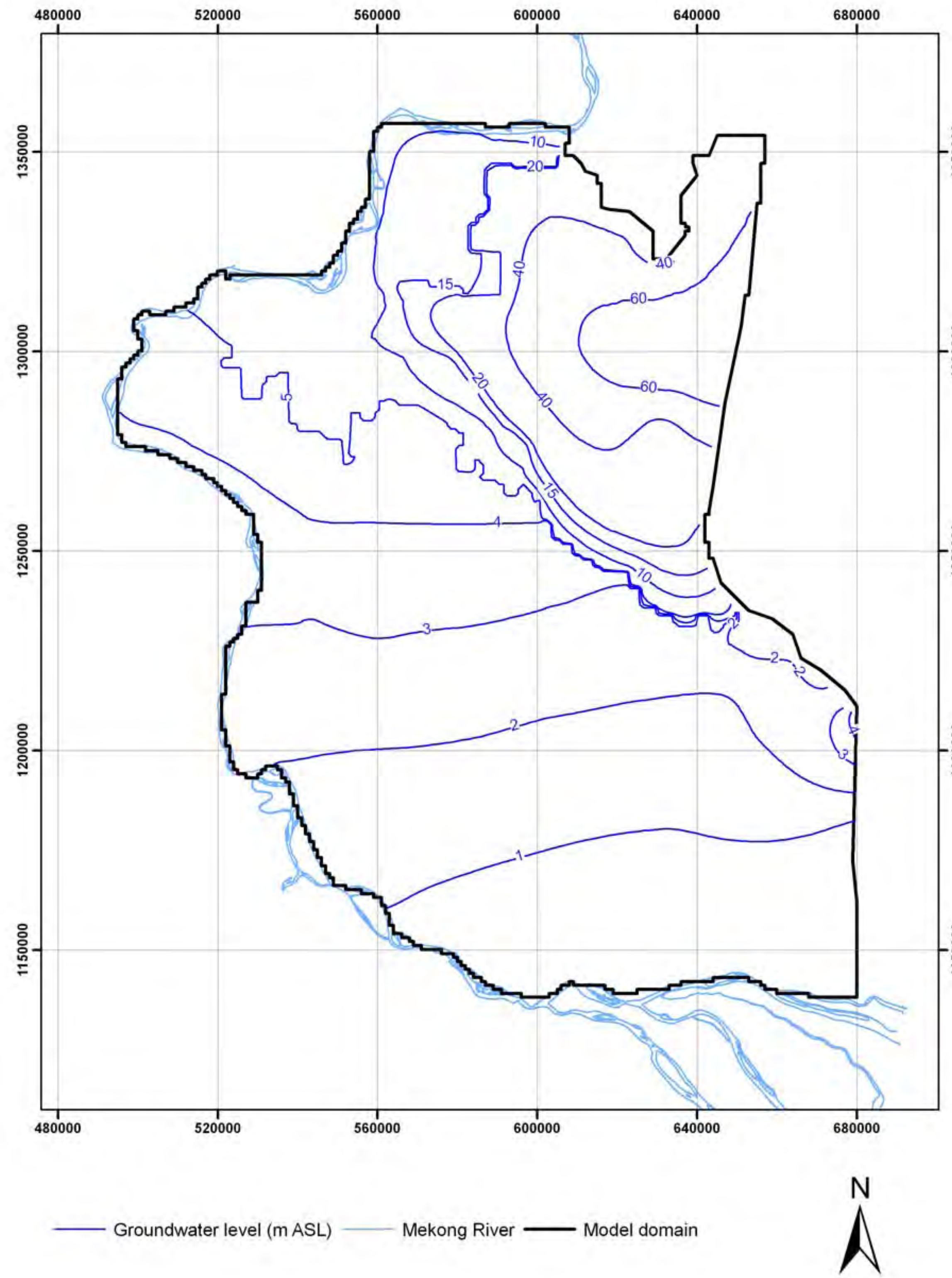


Figure 27. Simulated steady-state groundwater levels, 3 mm/yr recharge

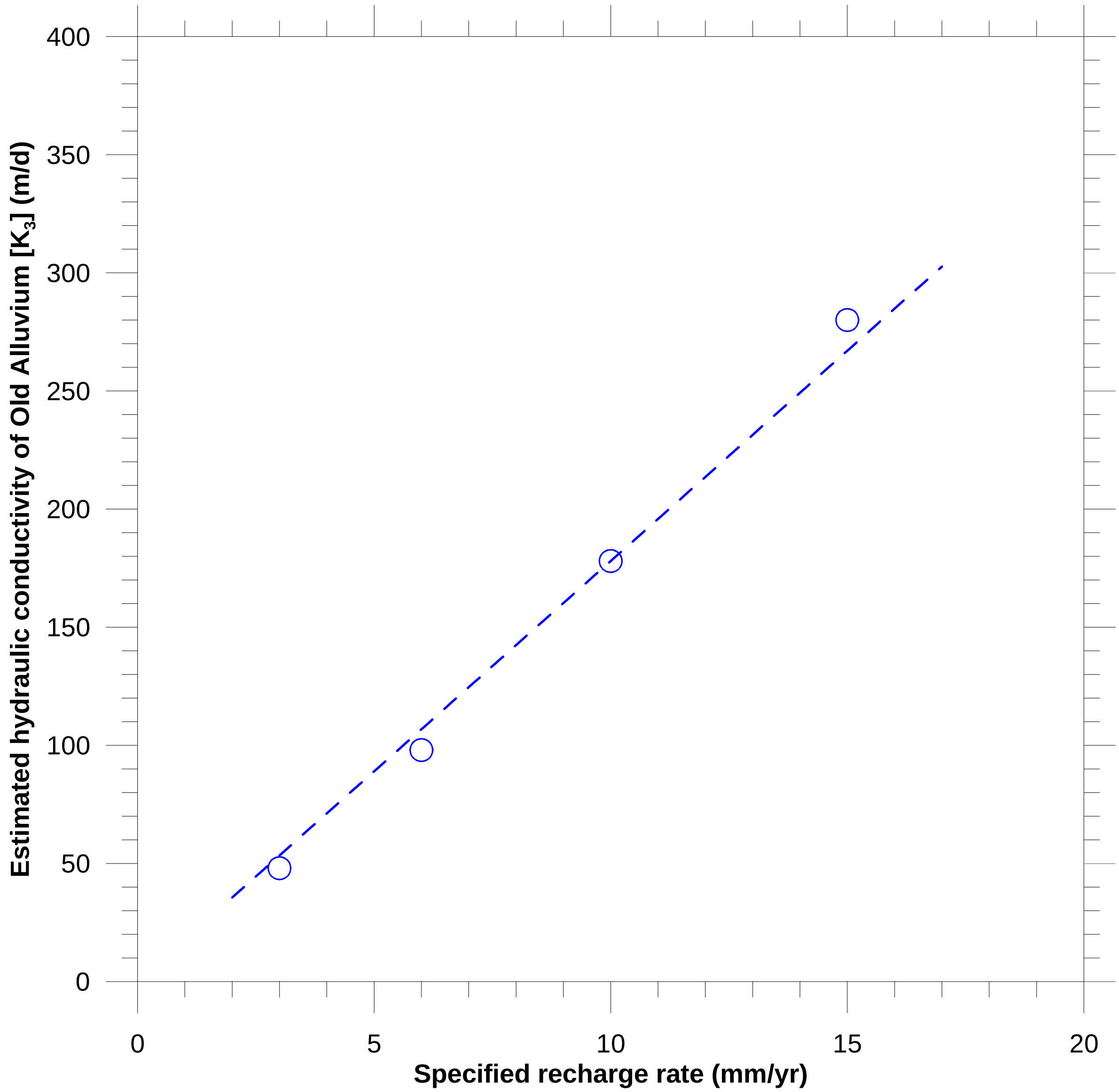


Figure 28. Correlation between recharge and estimated hydraulic conductivity of the Old Alluvium

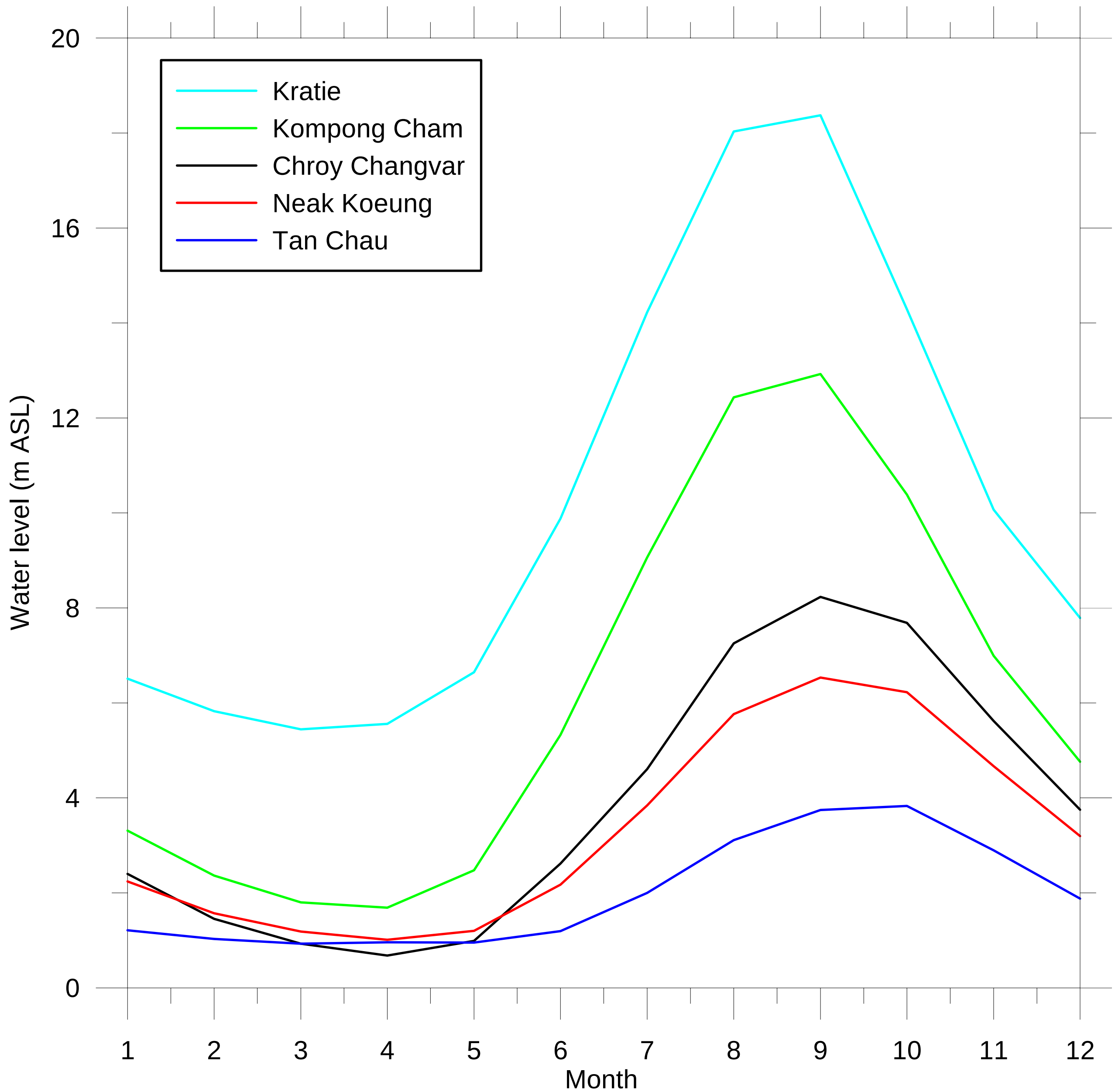


Figure 29. Synthesized monthly water levels along the Mekong River

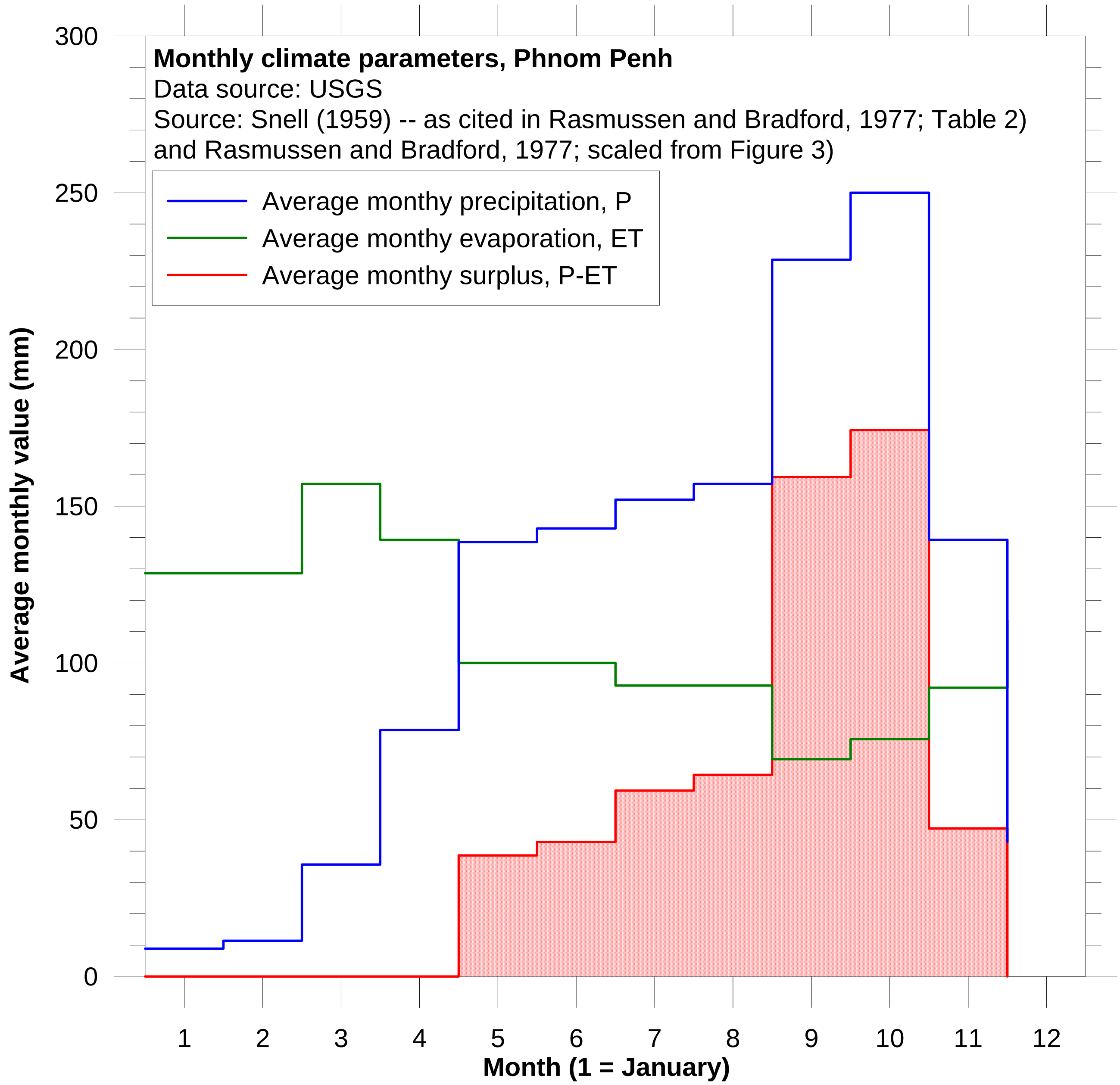


Figure 30. Monthly climate data for Phnom Penh

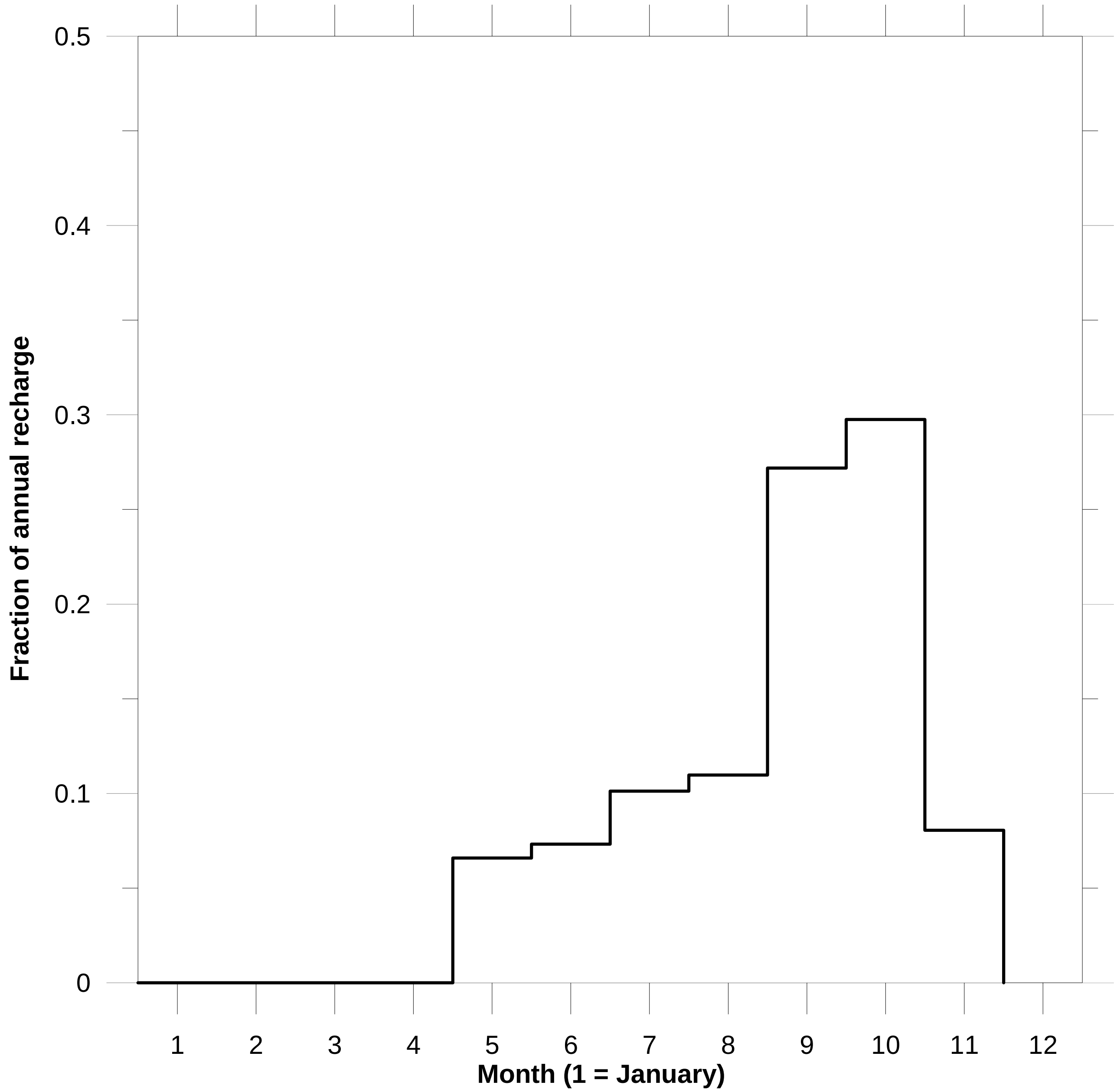


Figure 31. Assumed temporal distribution of recharge in the transient groundwater model

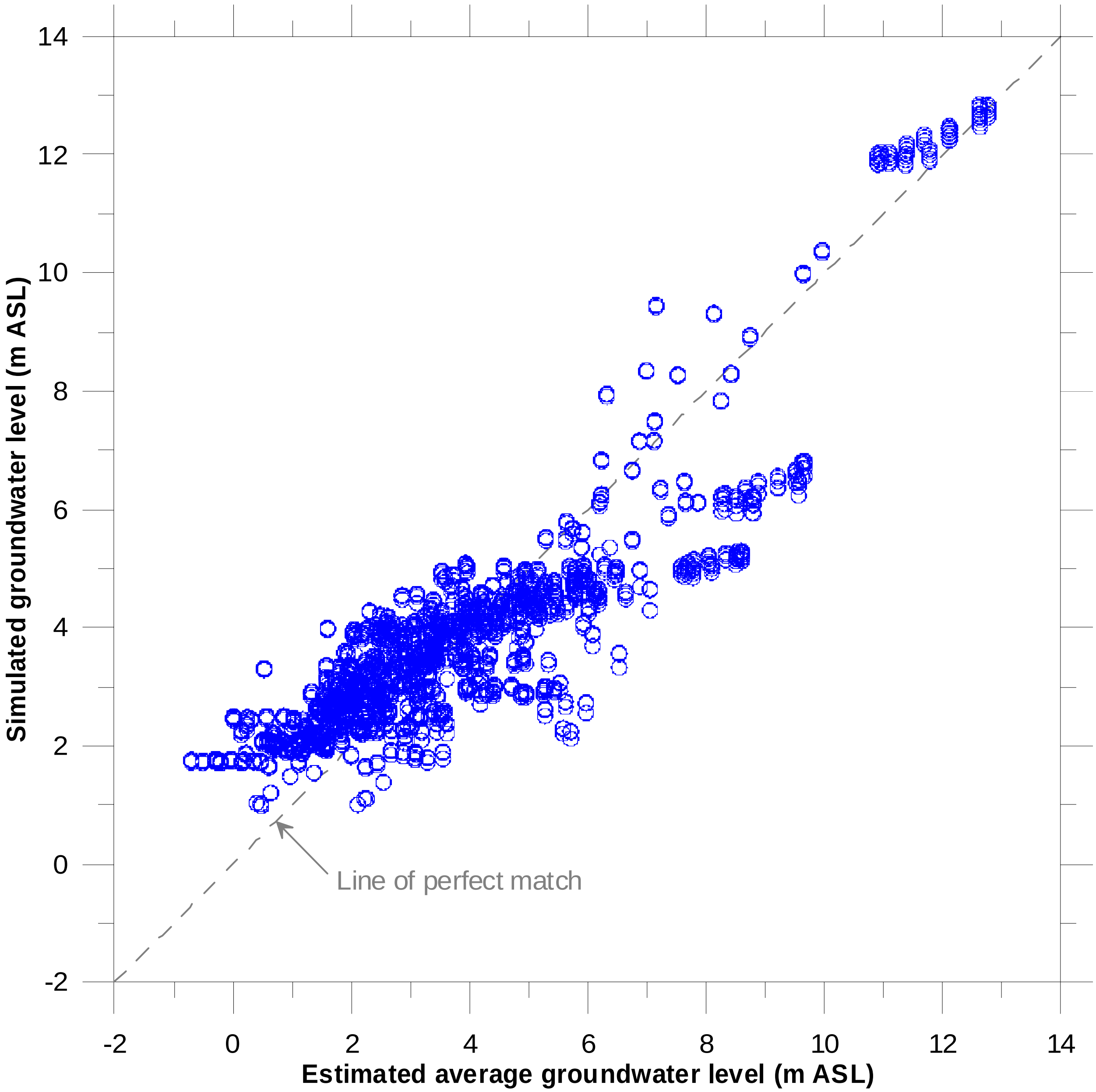


Figure 32. Scatterplot for transient simulation, 15 mm/yr recharge

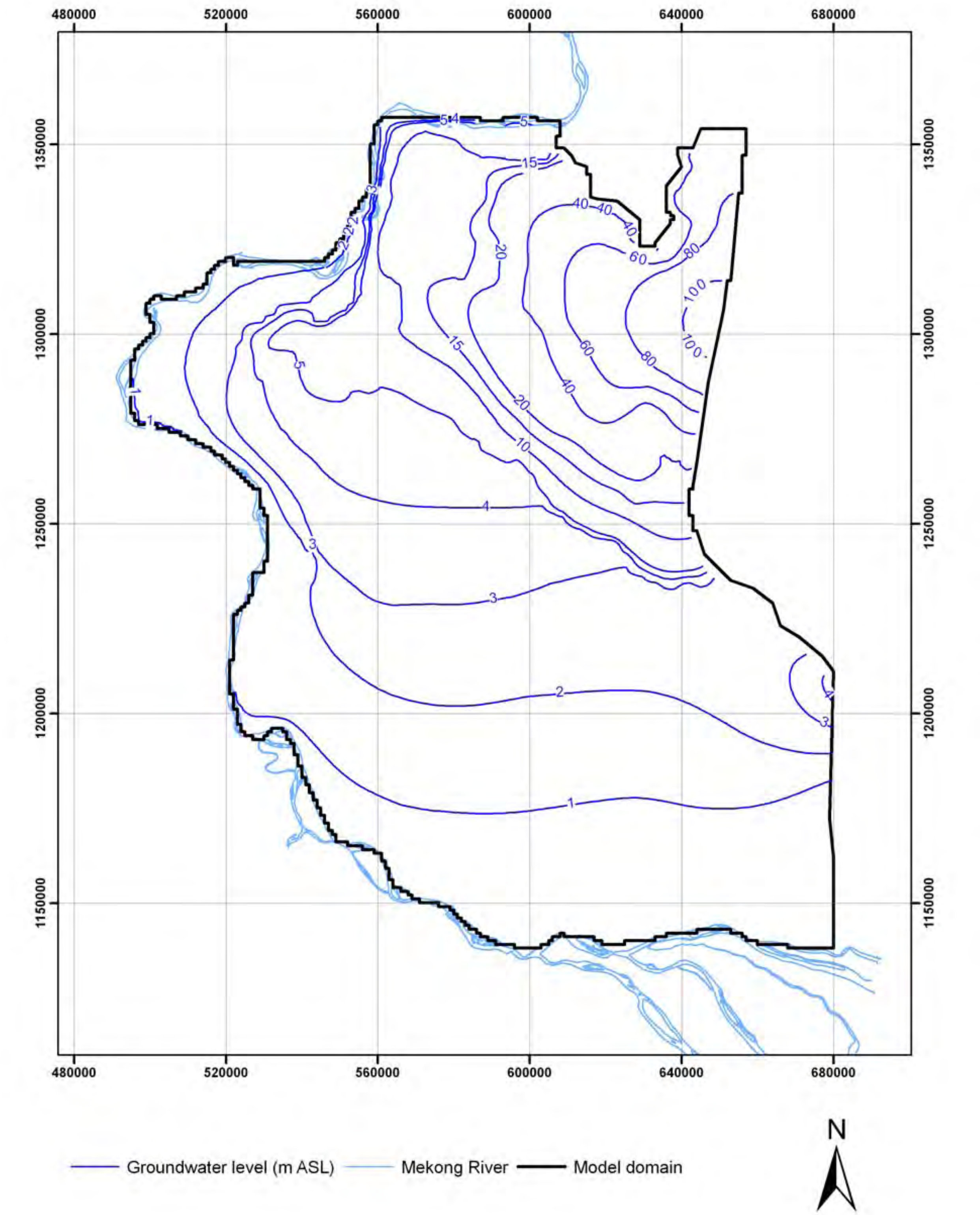


Figure 33. Simulated groundwater levels, annual low conditions, 15 mm/yr recharge

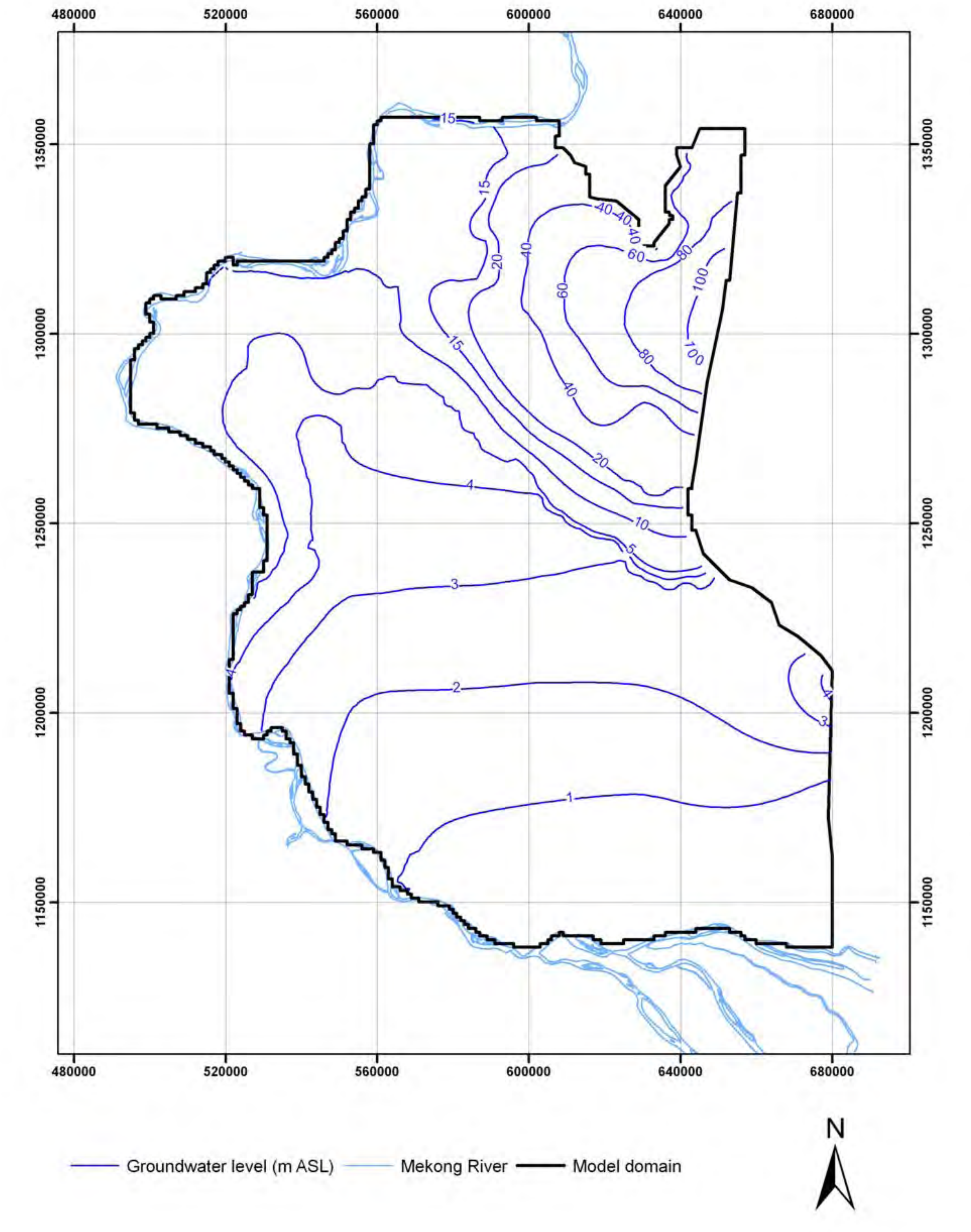


Figure 34. Simulated groundwater levels, annual high conditions, 15 mm/yr recharge

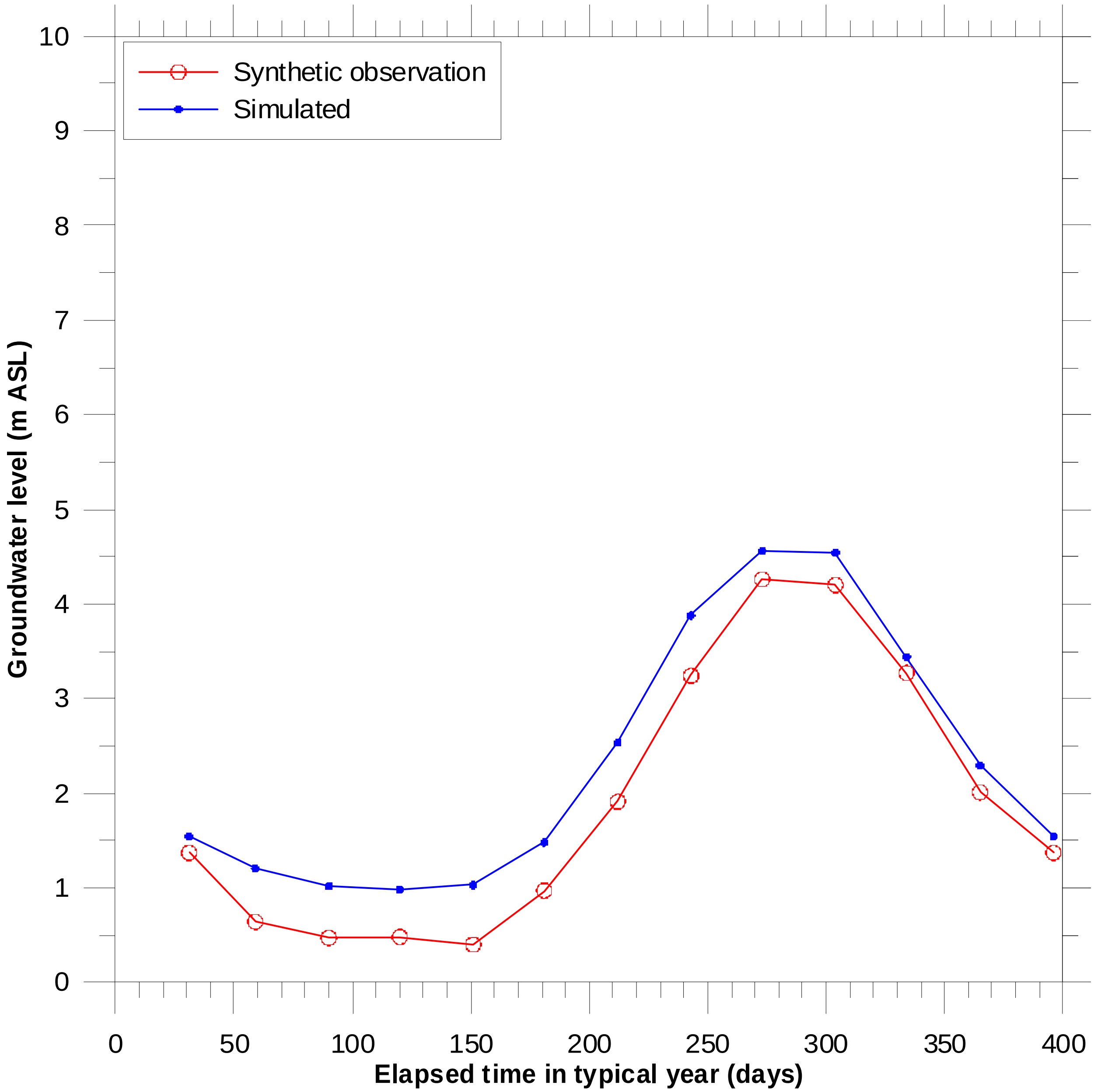


Figure 35. Simulated hydrograph for EU-PRASAC well P30, 15 mm/yr recharge

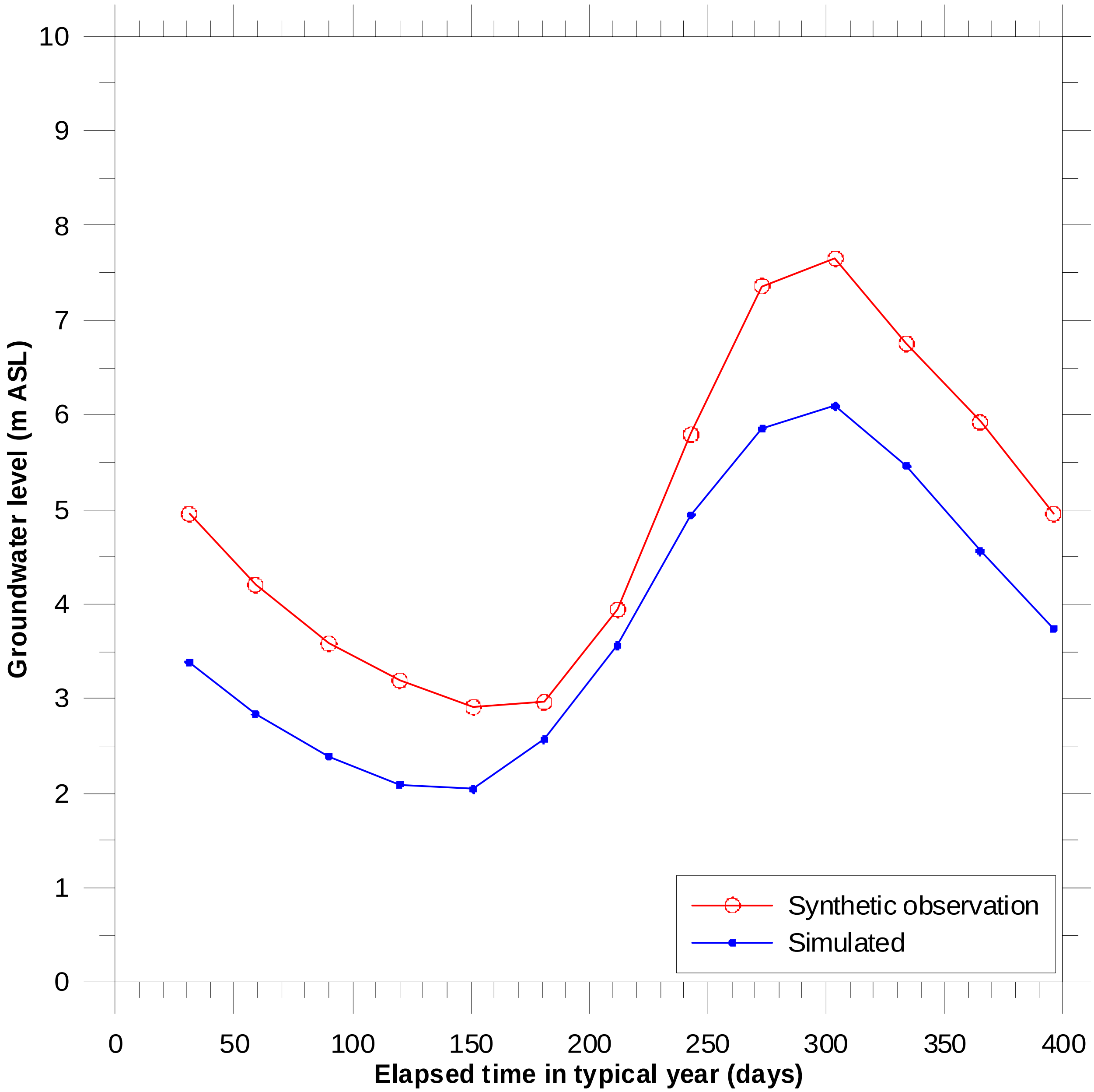


Figure 36. Simulated hydrograph for EU-PRASAC well P16, 15 mm/yr recharge

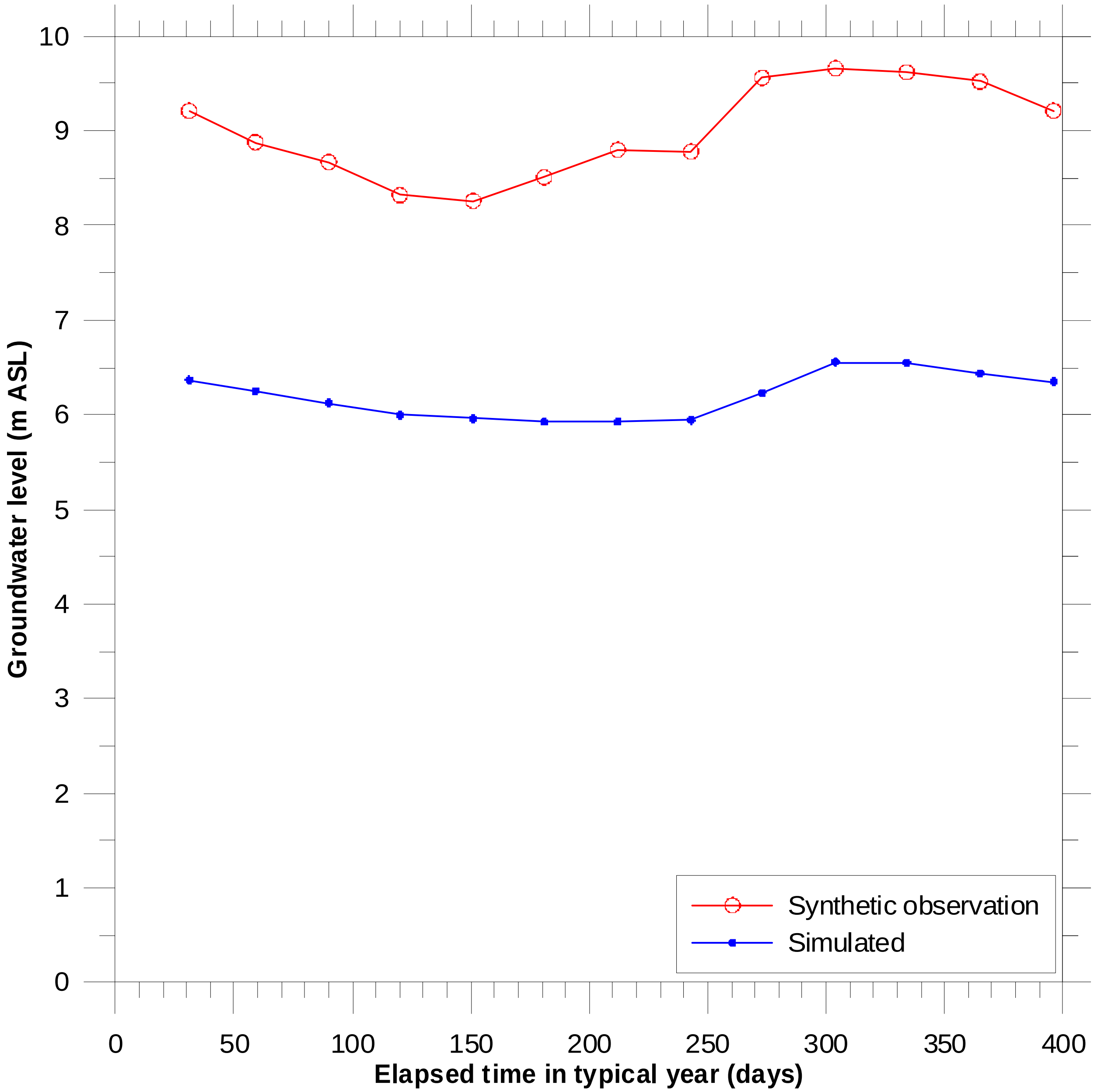


Figure 37. Simulated hydrograph for EU-PRASAC well P10, 15 mm/yr recharge

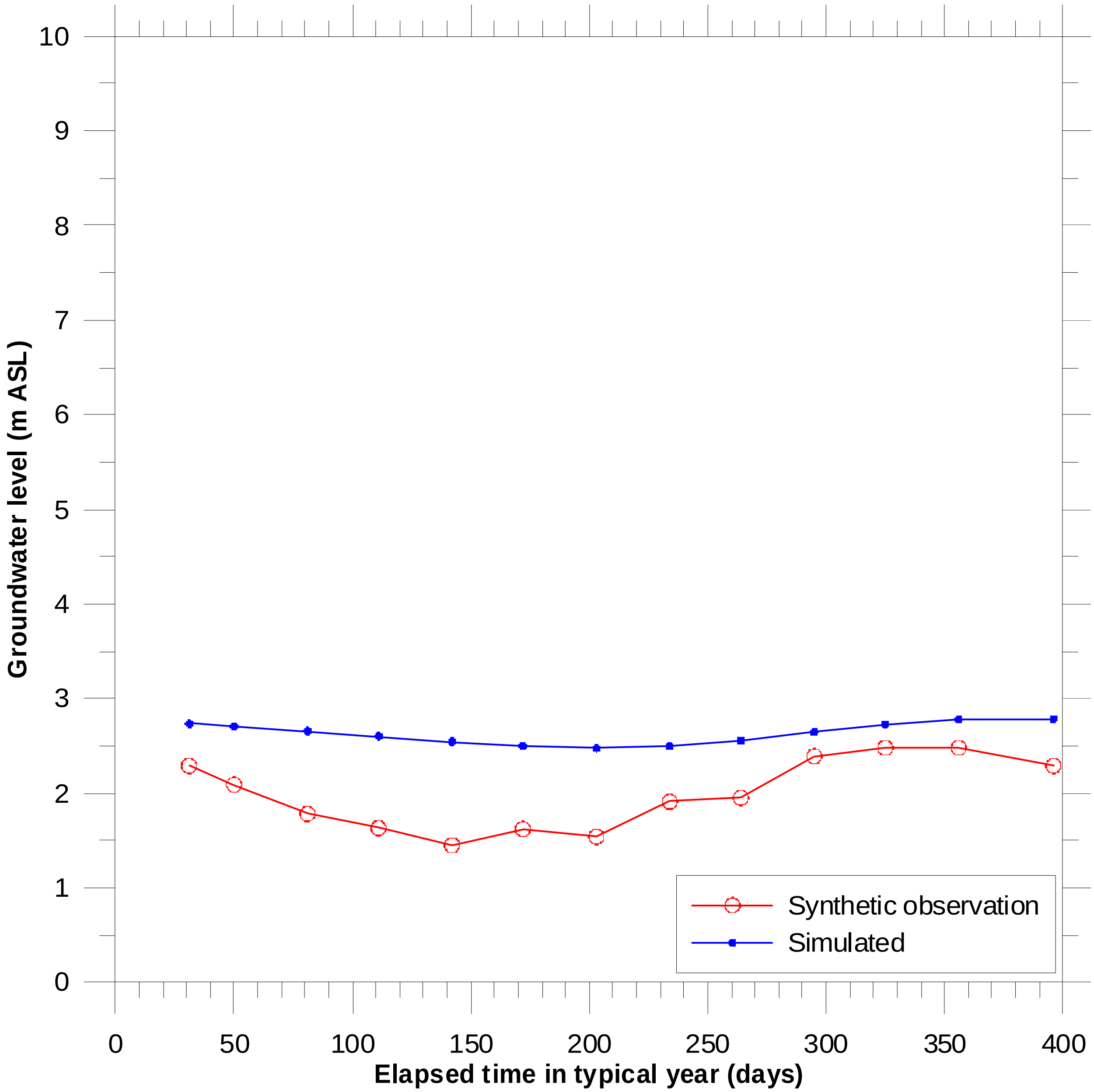


Figure 38. Simulated hydrograph for EU-PRASAC well S01, 15 mm/yr recharge

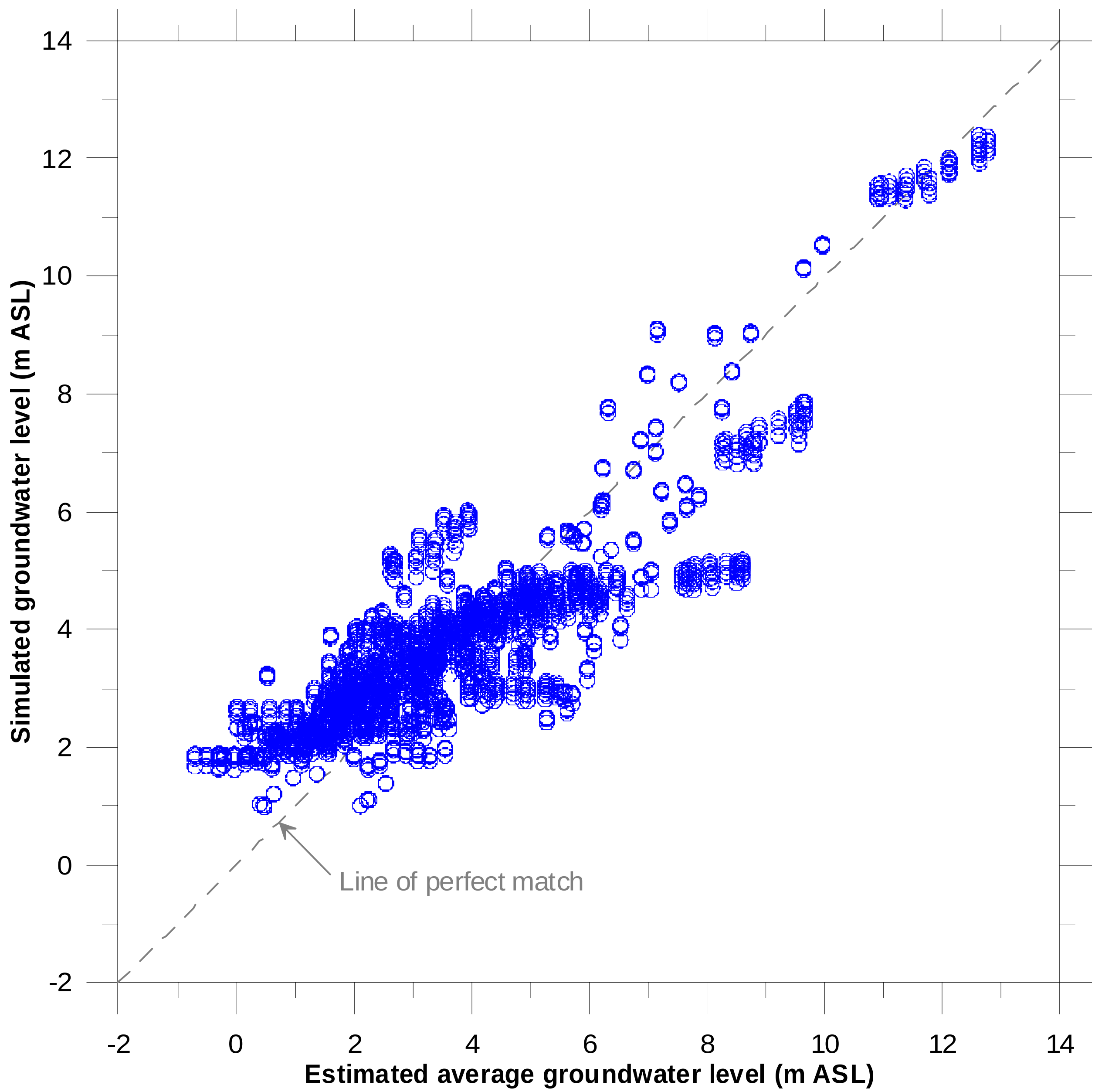


Figure 39. Scatterplot for transient simulation, 3 mm/yr recharge

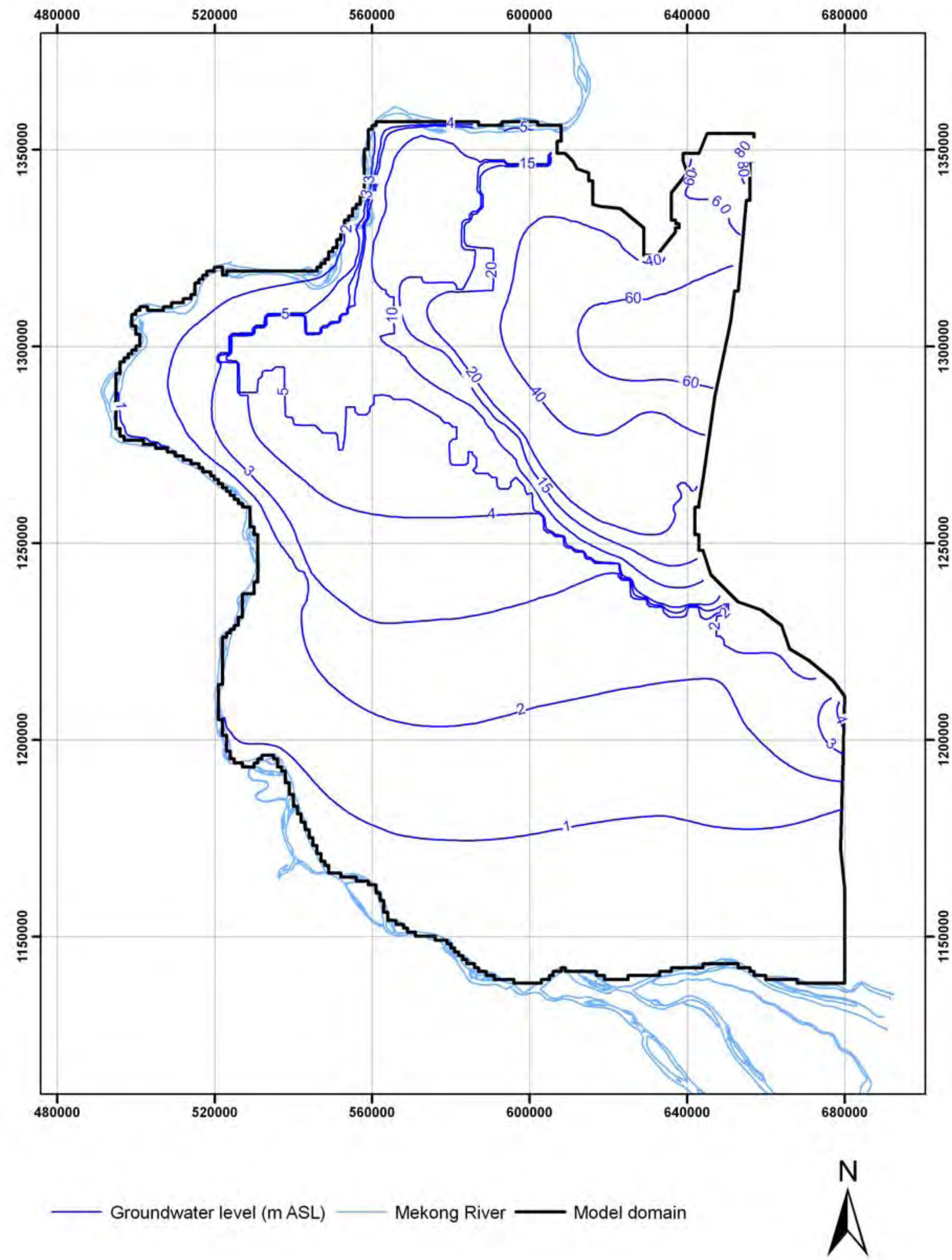


Figure 40. Simulated groundwater levels, annual low conditions, 3 mm/yr recharge

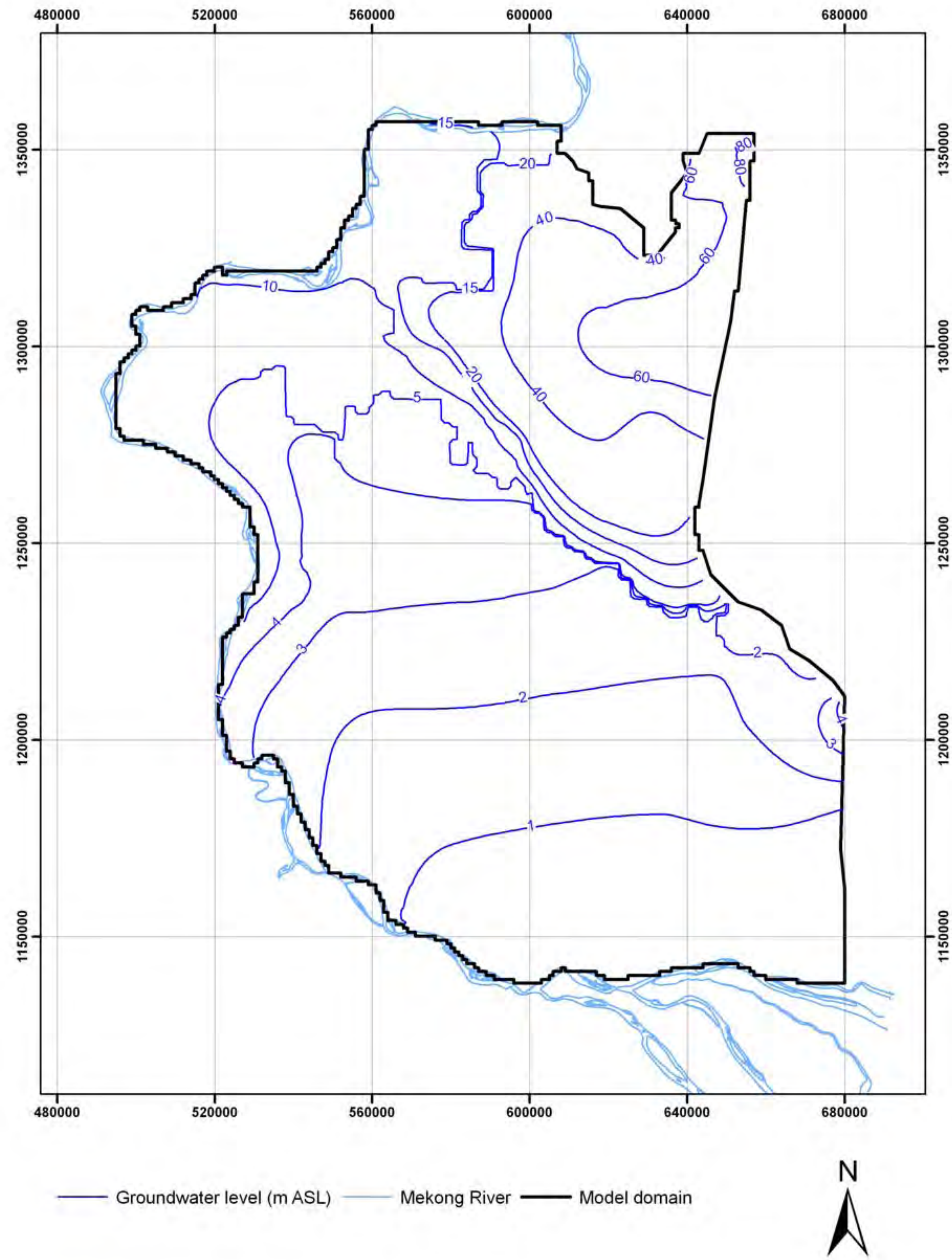


Figure 41. Simulated groundwater levels, annual high conditions, 3 mm/yr recharge

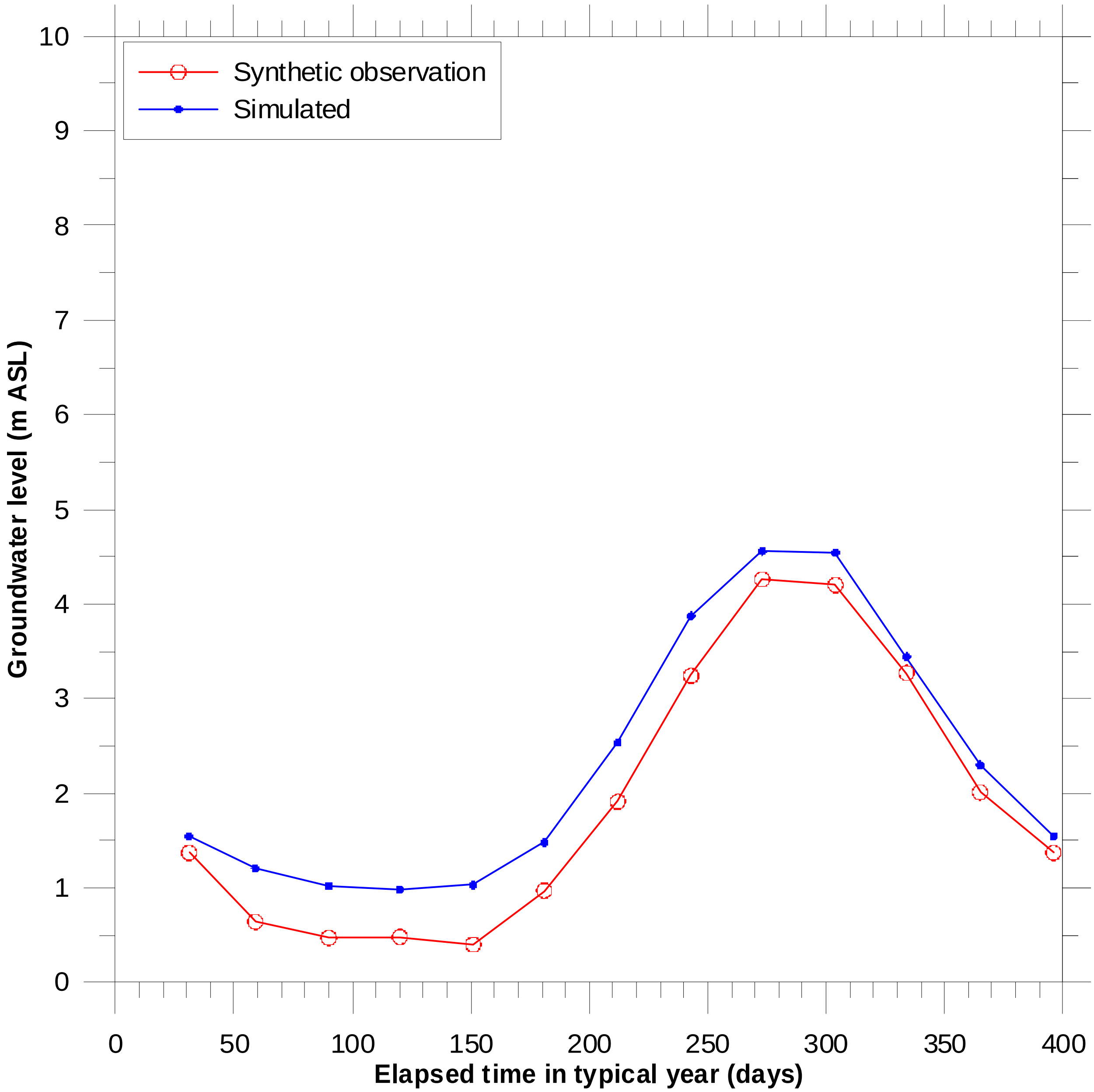


Figure 42. Simulated hydrograph for EU-PRASAC well P30, 3 mm/yr recharge

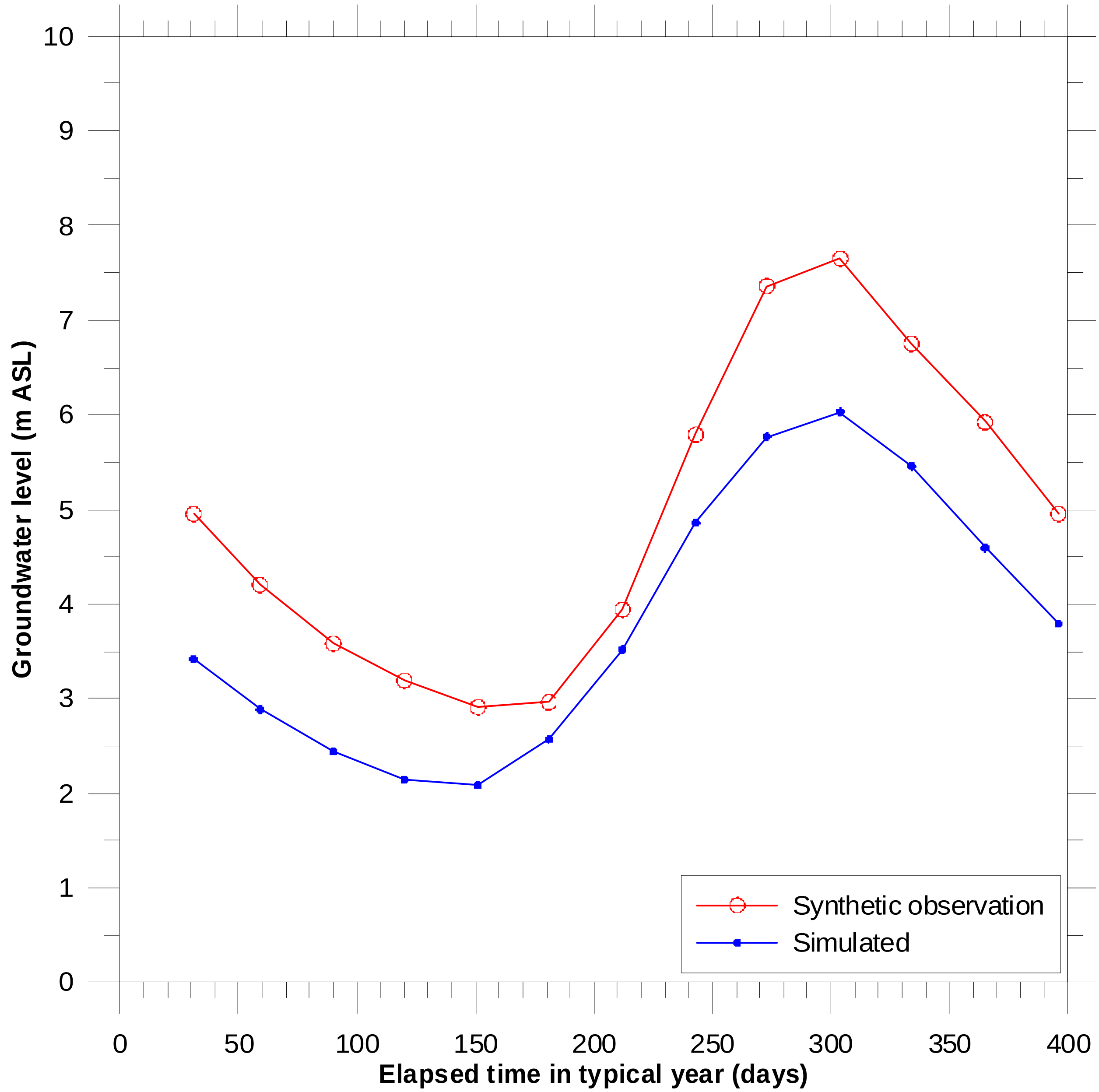


Figure 43. Simulated hydrograph for EU-PRASAC well P16, 3 mm/yr recharge

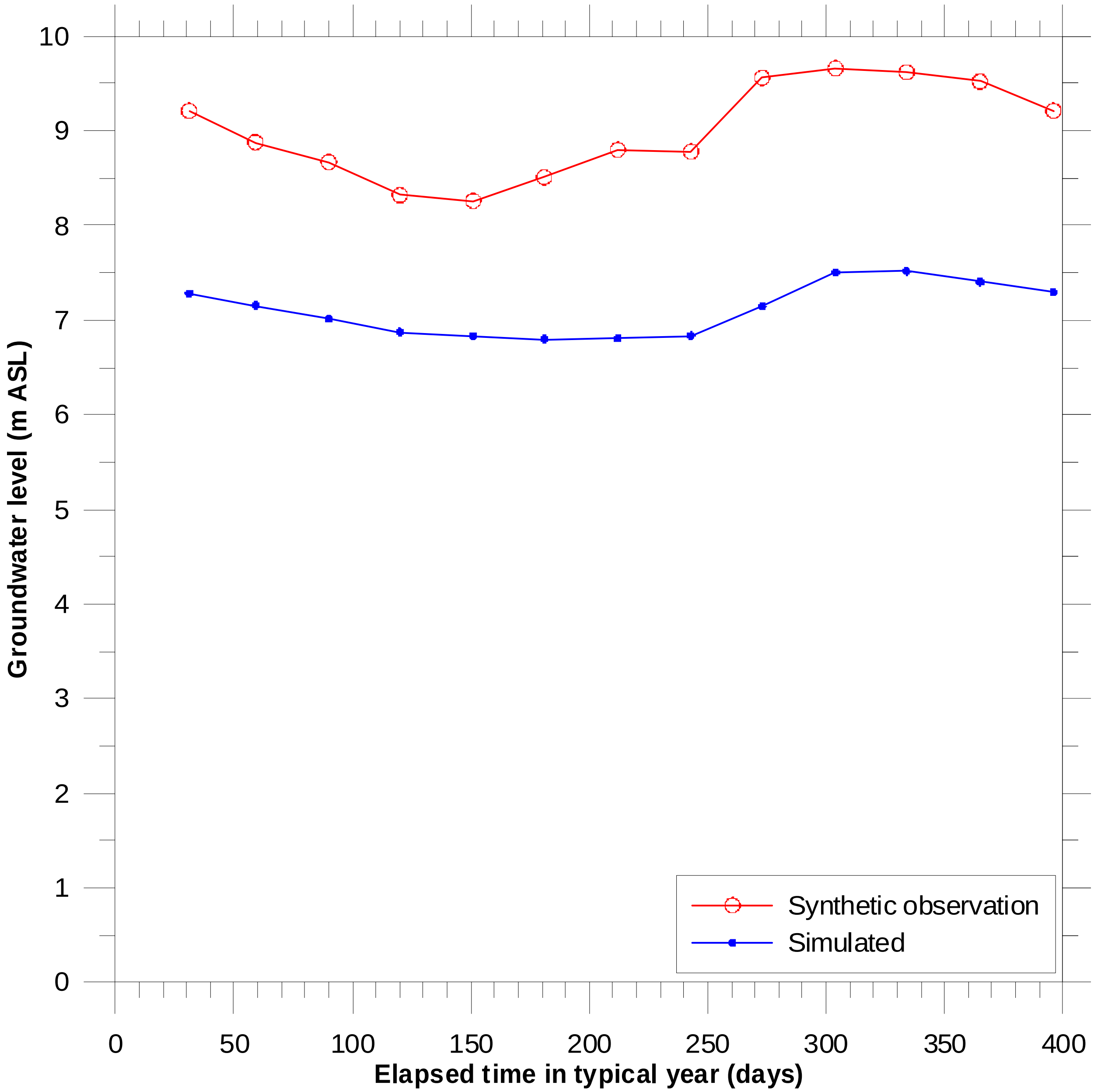


Figure 44. Simulated hydrograph for EU-PRASAC well P10, 3 mm/yr recharge

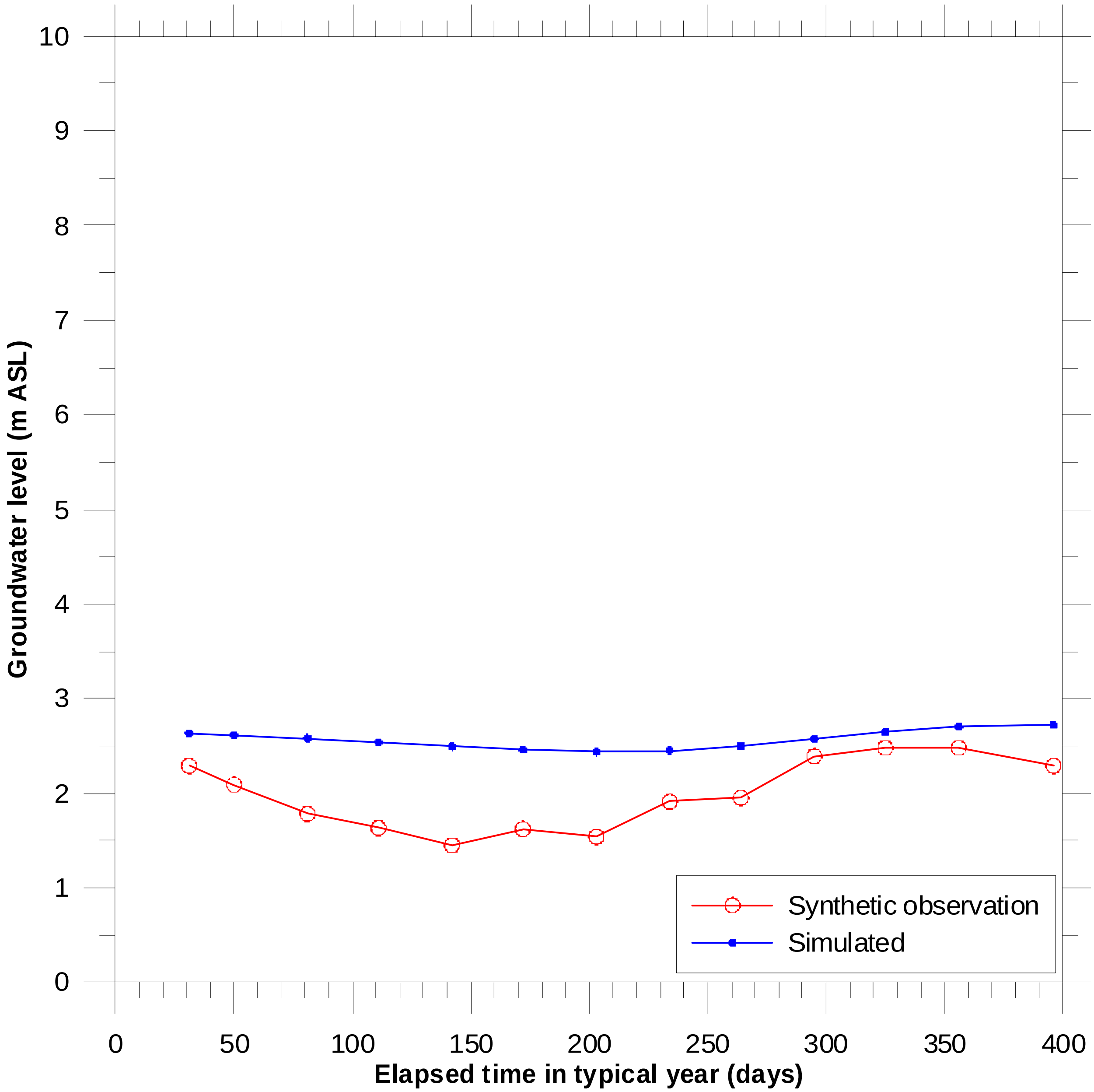


Figure 45. Simulated hydrograph for EU-PRASAC well S01, 3 mm/yr recharge

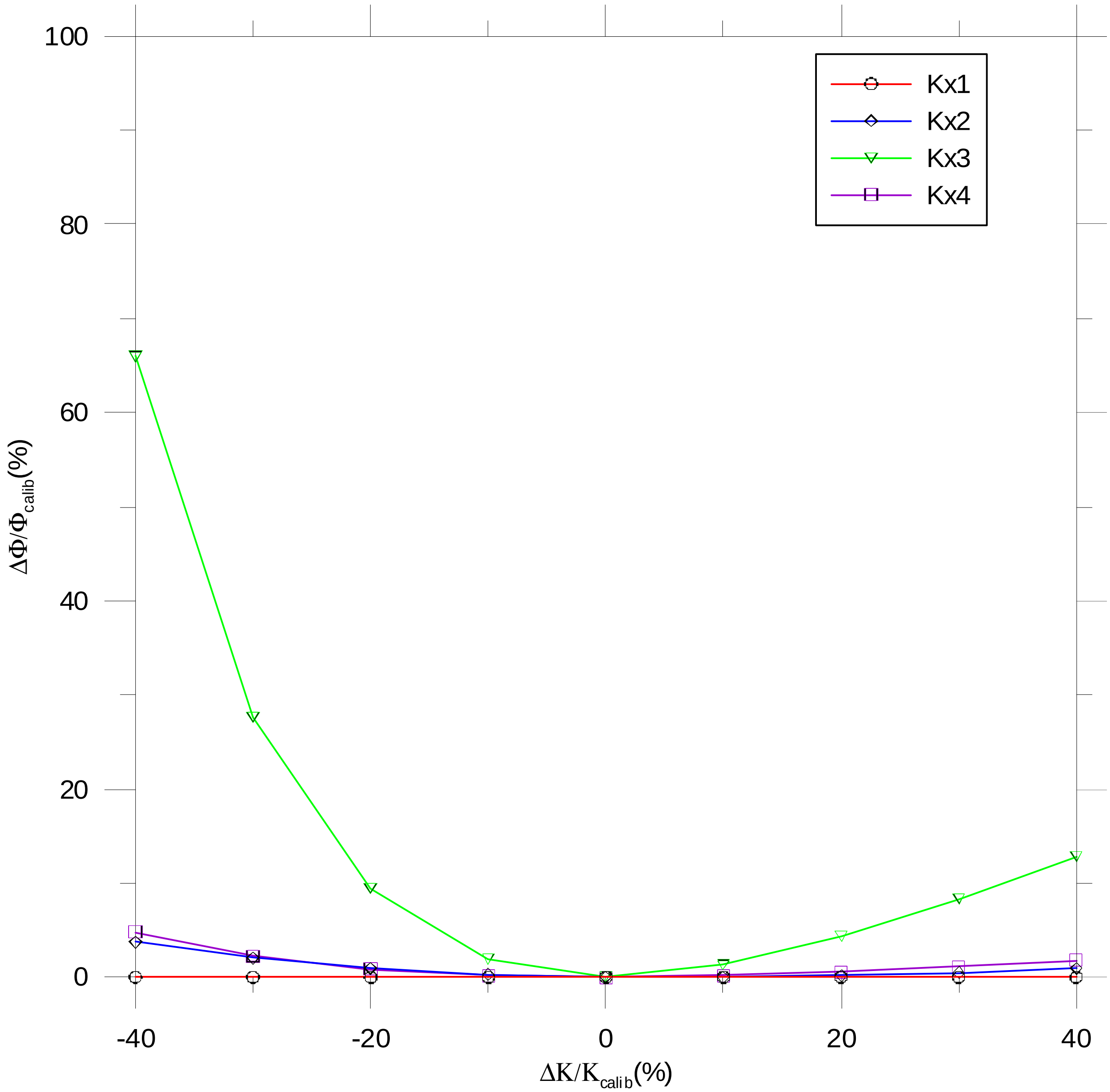


Figure 46. Sensitivities of model parameters, 15 mm/yr recharge

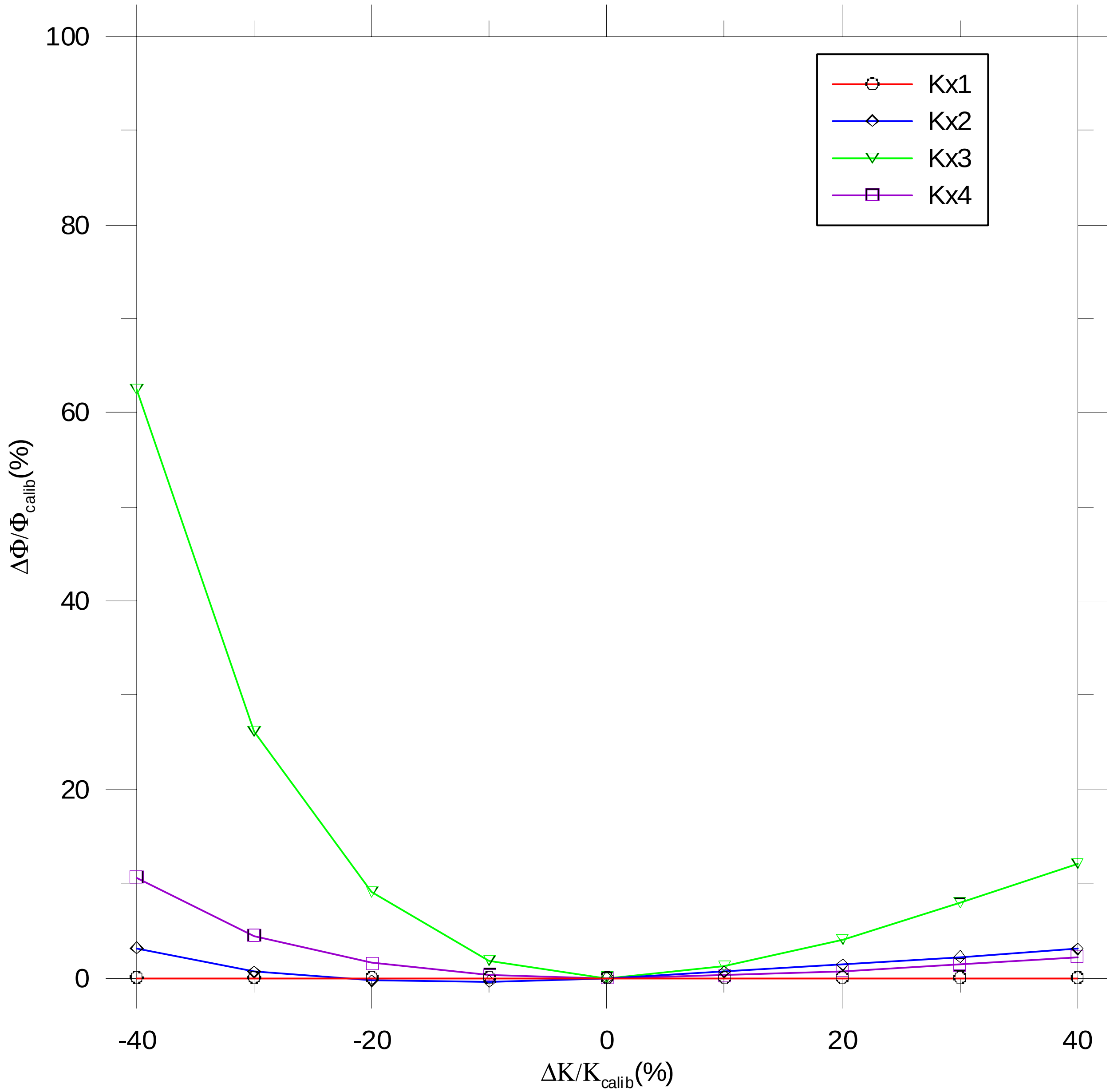


Figure 47. Sensitivities of model parameters, 3 mm/yr recharge

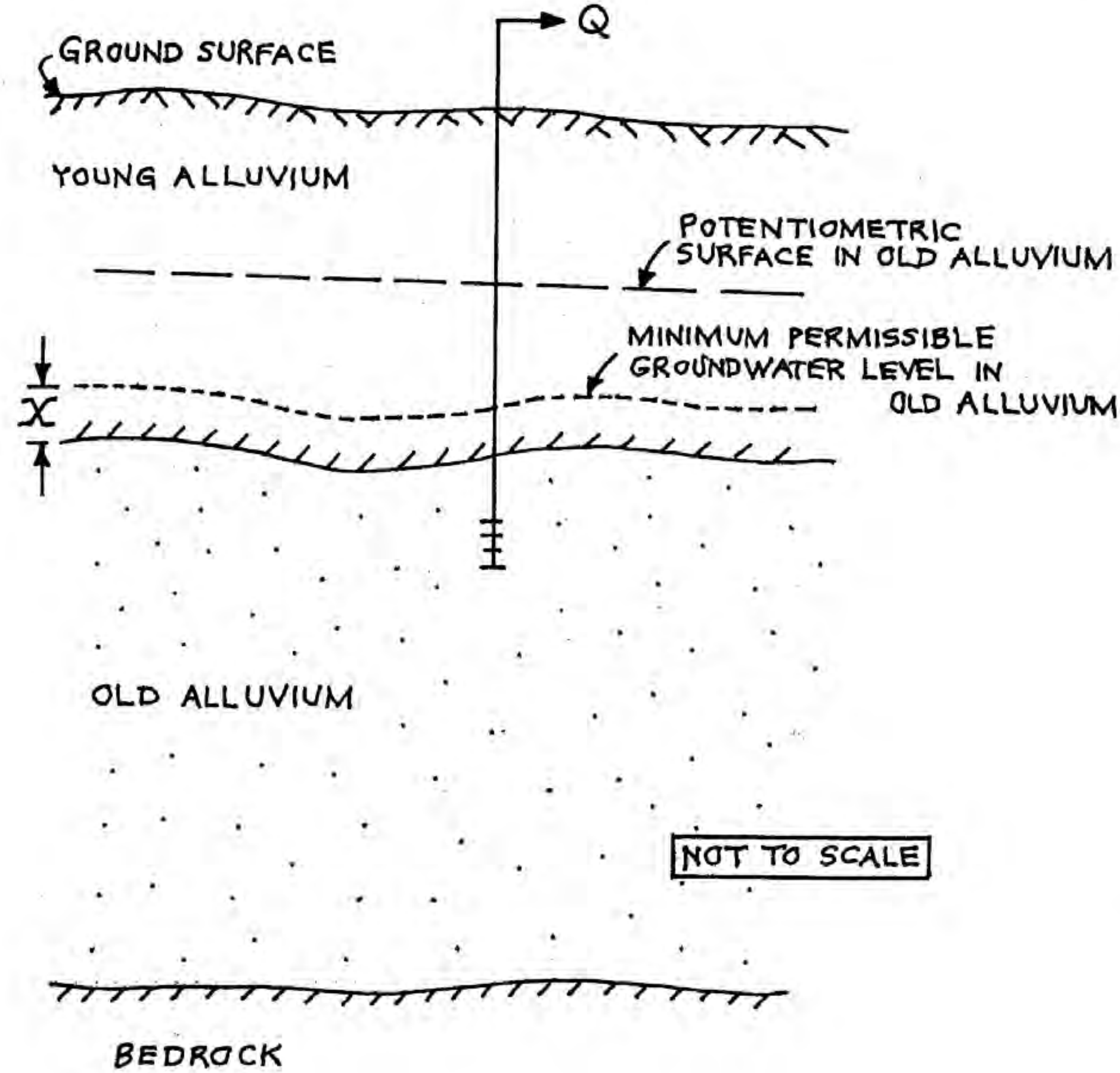


Figure 48. Conceptual model for groundwater resources development Scenarios 1-4

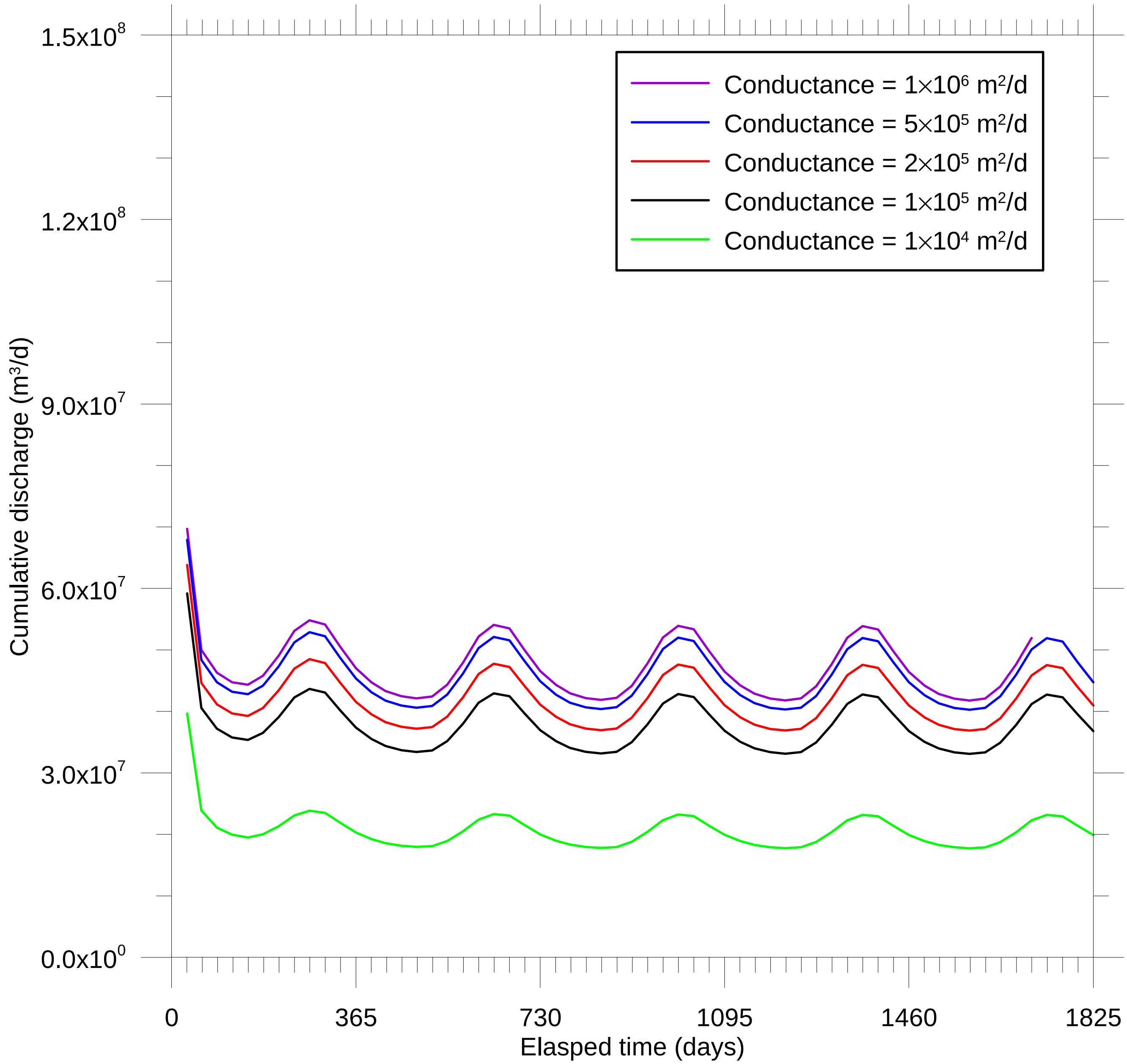


Figure 49. Results for Groundwater Development Scenario 1
Groundwater level to within 5 m of top of Old Alluvium, Recharge 15 mm/yr

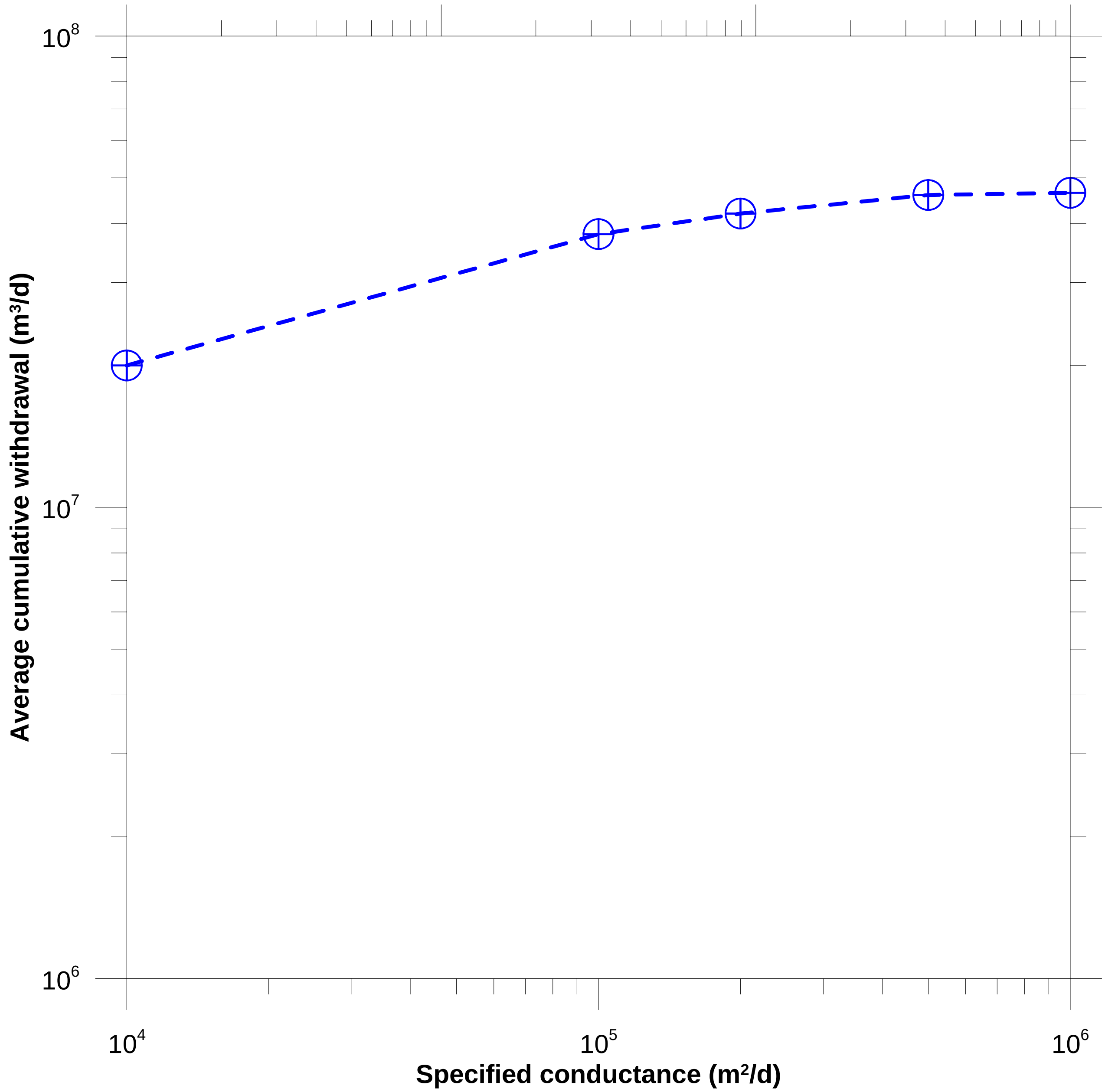


Figure 50. Results for Groundwater Development Scenario 1
Sensitivity of time-averaged withdrawal rate to the specified conductance

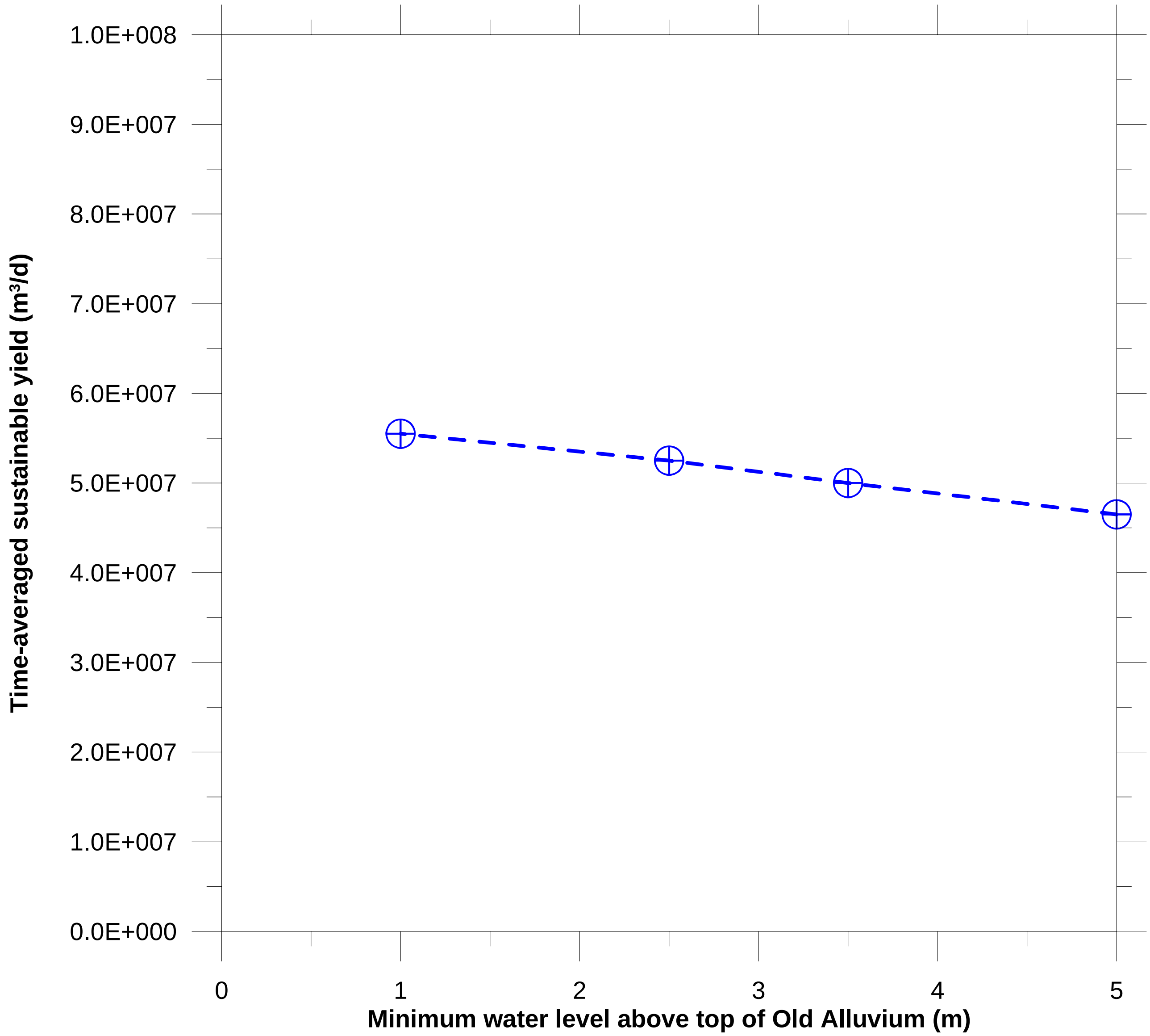


Figure 51. Results for Groundwater Development Scenario 1 through 4
Recharge 15 mm/yr

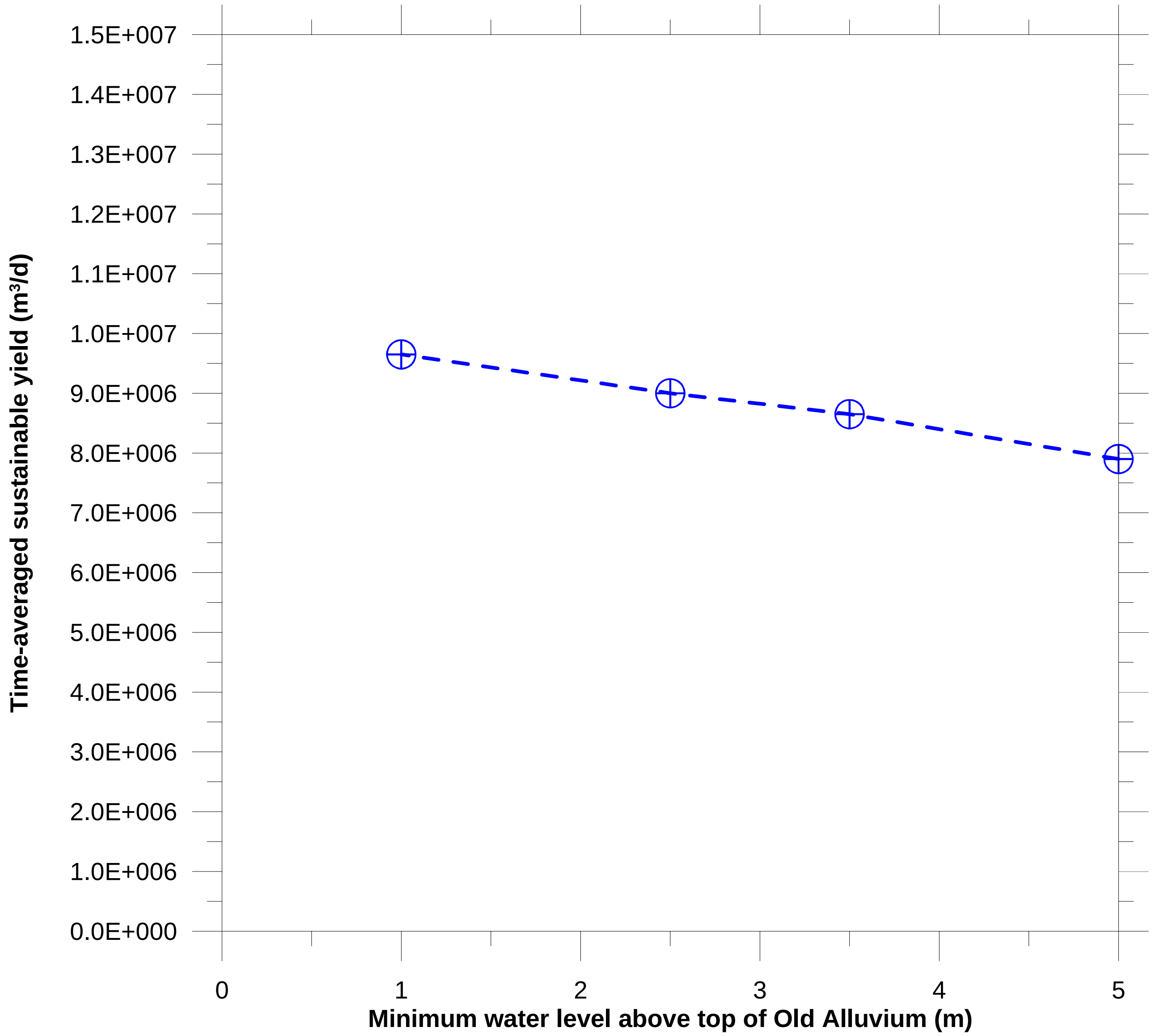


Figure 52. Results for Groundwater Development Scenario 1 through 4
Recharge 3 mm/yr

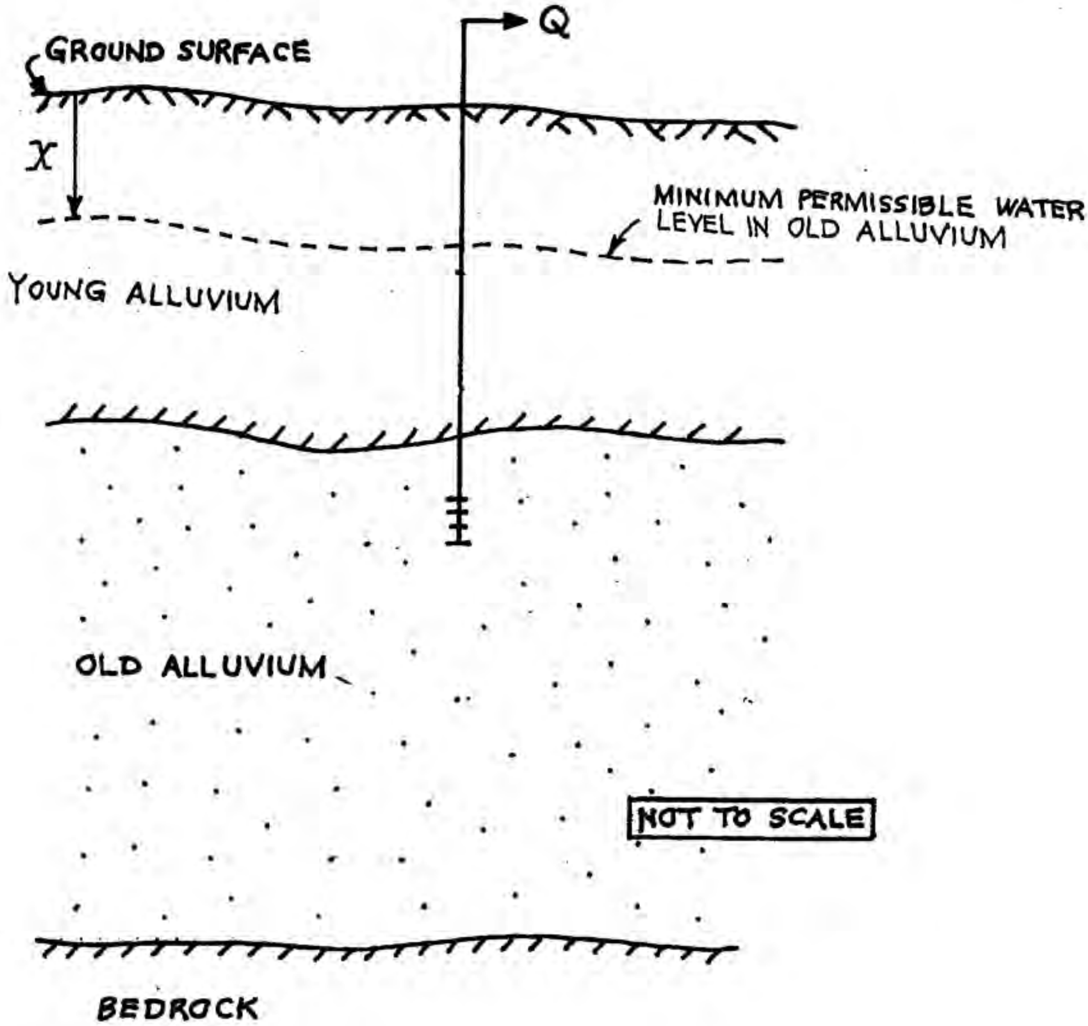


Figure 53. Conceptual model for groundwater resources development Scenarios 5-7

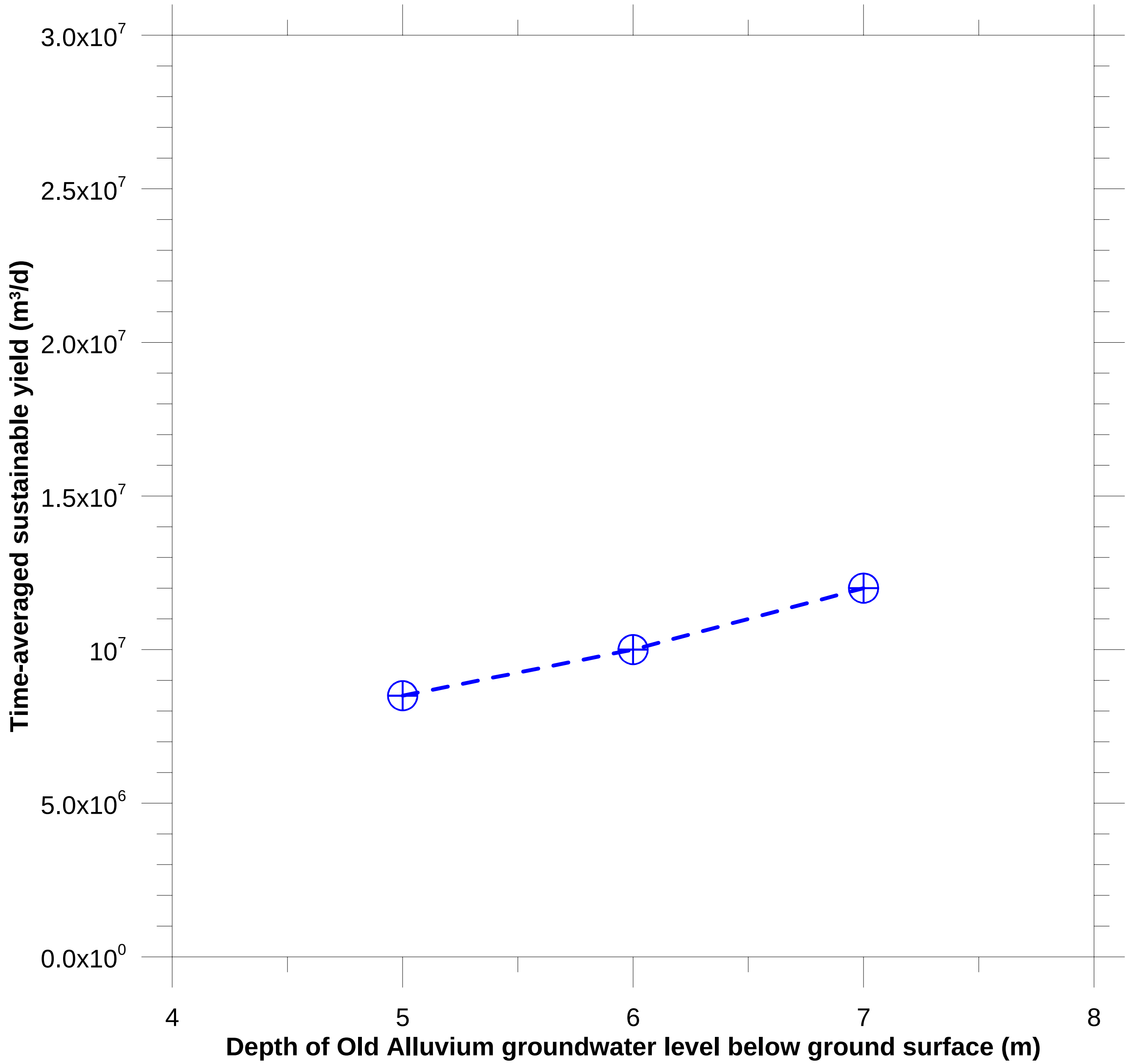


Figure 54. Results for Groundwater Development Scenarios 5 through 7
Recharge 15 mm/yr

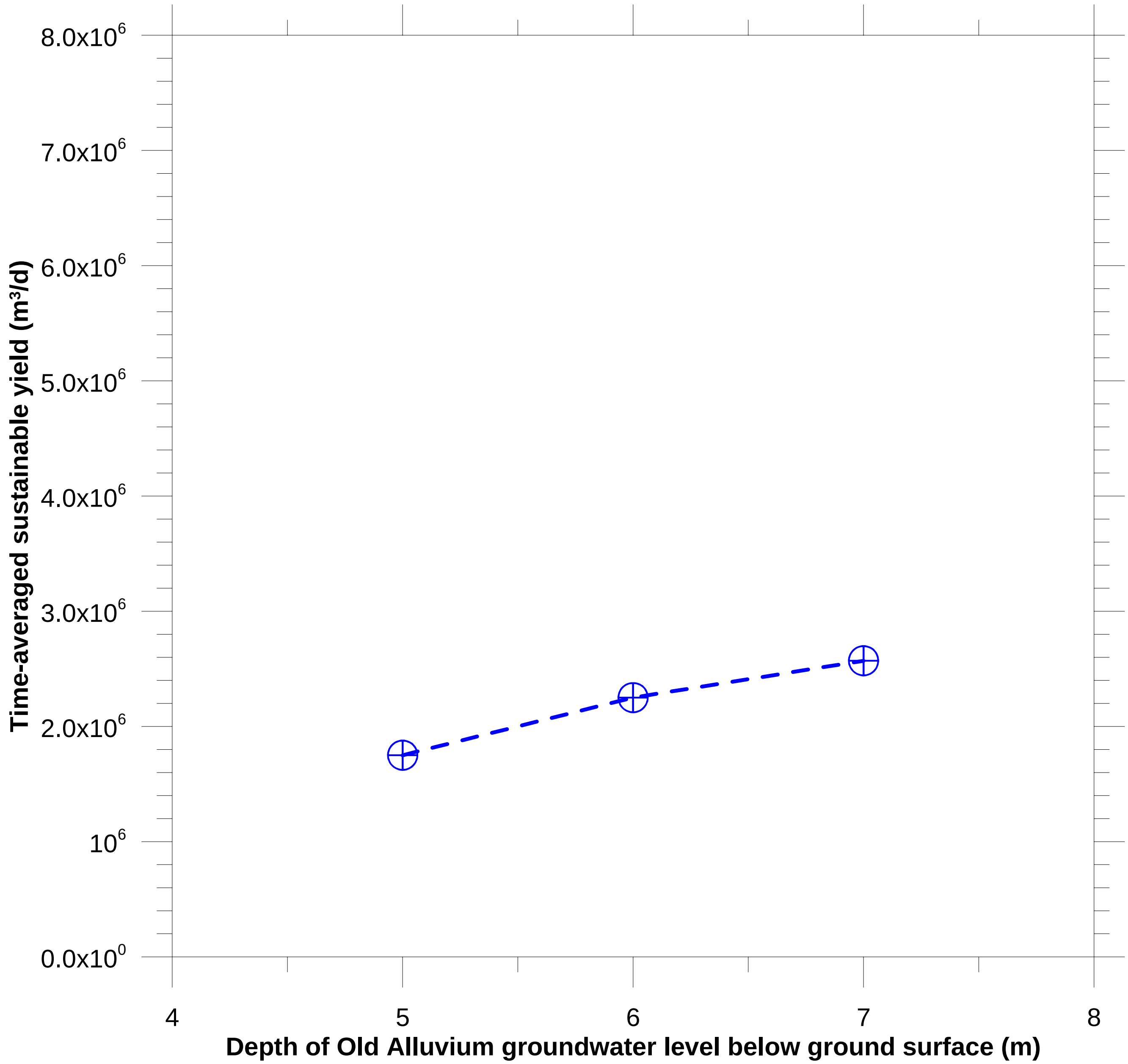


Figure 55. Results for Groundwater Development Scenarios 5 through 7
Recharge 3 mm/yr

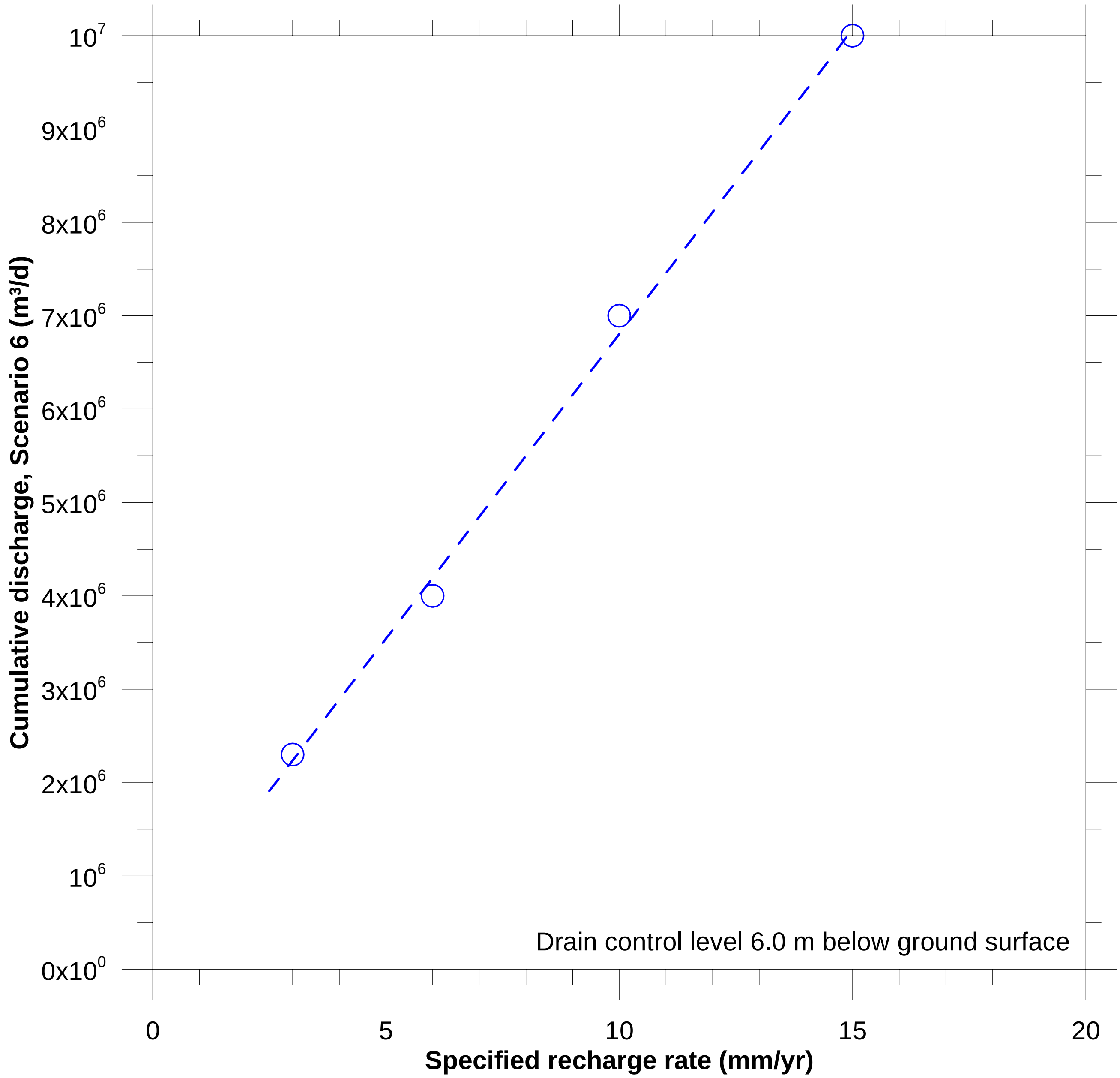


Figure 56. Sensitivity of groundwater yield to the assumed recharge rate

TABLES

Table 1. Steady-state calibration targets

Well ID	Easting (m)	Northing (m)	Layer	Estimated average groundwater level (m ASL)
P1	536455.7	1270057.7	2	2.89
P3	545866.9	1280132.3	2	3.31
P4	554821.5	1281160.9	2	5.45
P5	554819.5	1270411.4	2	4.32
P6	571906.5	1270317.0	2	5.57
P7	572703.8	1280616.9	2	5.63
P8	573809.3	1285910.8	2	8.10
P9	575830.2	1297036.5	2	11.78
P10	554781.9	1290034.2	2	8.98
P11	543561.5	1309031.5	2	7.24
P12	531438.5	1305235.0	2	6.62
P13	518344.6	1300222.2	2	5.00
P14	514159.9	1289058.8	2	4.99
P15	524800.5	1286370.8	2	4.39
P16	523143.2	1270906.9	2	4.94
P18	543256.8	1257355.9	2	2.97
P19	544972.5	1238260.8	2	2.80
P21	570848.1	1255129.2	2	3.88
P22	559992.1	1237658.1	2	2.36
P23	558190.6	1229287.7	2	2.32
P24	567107.0	1229161.0	2	2.46
P25	557660.1	1217402.5	2	1.93
P26	542178.4	1226451.9	2	1.32
P27	542110.5	1225400.8	2	3.06
P29	523491.7	1224180.4	2	3.90
P30	521654.9	1207017.6	2	1.94
S01	579870.5	1222651.3	2	2.00
S02	565151.6	1216431.2	2	1.00
S03	569550.9	1240269.3	2	2.70
S04	578846.0	1229364.1	2	1.90
S05	578172.2	1262248.7	2	4.20
S06	583156.9	1256328.3	2	3.00
S07	587772.6	1265673.1	2	4.40
S08	595753.8	1253514.0	2	2.70
S09	580839.3	1243188.3	2	3.00
S10	598559.5	1243319.4	2	4.10
S11	595046.1	1232018.4	2	2.60
S12	603855.9	1234279.7	2	4.60
S13	613589.4	1225313.4	2	2.80
S14	627785.2	1224450.6	2	1.00
S15	623193.0	1209508.9	2	1.00
S16	625212.4	1198936.6	2	-0.10
S17	604982.0	1216562.7	2	2.30
S18	605498.2	1205734.5	2	1.10
S19	594011.9	1212851.5	2	1.60

Table 2. Steady-state calibration targets and model results, 15 mm/yr recharge

Well ID	Easting (m)	Northing (m)	Layer	Target (m ASL)	Simulated (m ASL)	Weight	Group	Residual (m)
P1	536455.7	1270057.7	2	2.89	4.21	1	1	-1.32
P3	545866.9	1280132.3	2	3.31	4.55	1	1	-1.24
P4	554821.5	1281160.9	2	5.45	4.78	1	1	0.67
P5	554819.5	1270411.4	2	4.32	4.36	1	1	-0.04
P6	571906.5	1270317.0	2	5.57	4.56	1	1	1.01
P7	572703.8	1280616.9	2	5.63	4.98	1	1	0.65
P8	573809.3	1285910.8	2	8.10	5.22	1	1	2.88
P9	575830.2	1297036.5	2	11.78	12.44	1	1	-0.66
P10	554781.9	1290034.2	2	8.98	6.50	1	1	2.48
P11	543561.5	1309031.5	2	7.24	6.00	1	1	1.24
P12	531438.5	1305235.0	2	6.62	5.45	1	1	1.17
P13	518344.6	1300222.2	2	5.00	4.80	1	1	0.20
P14	514159.9	1289058.8	2	4.99	4.39	1	1	0.60
P15	524800.5	1286370.8	2	4.39	4.44	1	1	-0.05
P16	523143.2	1270906.9	2	4.94	3.96	1	1	0.98
P18	543256.8	1257355.9	2	2.97	3.99	1	1	-1.02
P19	544972.5	1238260.8	2	2.80	3.24	1	1	-0.44
P21	570848.1	1255129.2	2	3.88	3.99	1	1	-0.11
P22	559992.1	1237658.1	2	2.36	3.43	1	1	-1.07
P23	558190.6	1229287.7	2	2.32	3.08	1	1	-0.76
P24	567107.0	1229161.0	2	2.46	3.04	1	1	-0.58
P25	557660.1	1217402.5	2	1.93	2.56	1	1	-0.63
P26	542178.4	1226451.9	2	1.32	2.86	1	1	-1.54
P27	542110.5	1225400.8	2	3.06	2.83	1	1	0.23
P29	523491.7	1224180.4	2	3.90	2.83	1	1	1.07
P30	521654.9	1207017.6	2	1.94	2.49	1	1	-0.55
S01	579870.5	1222651.3	2	2.00	2.75	1	2	-0.75
S02	565151.6	1216431.2	2	1.00	2.53	1	2	-1.53
S03	569550.9	1240269.3	2	2.70	3.49	1	2	-0.79
S04	578846.0	1229364.1	2	1.90	3.00	1	2	-1.10
S05	578172.2	1262248.7	2	4.20	4.26	1	2	-0.06
S06	583156.9	1256328.3	2	3.00	4.04	1	2	-1.04
S07	587772.6	1265673.1	2	4.40	4.40	1	2	0.00
S08	595753.8	1253514.0	2	2.70	3.95	1	2	-1.25
S09	580839.3	1243188.3	2	3.00	3.55	1	2	-0.55
S10	598559.5	1243319.4	2	4.10	3.52	1	2	0.58
S11	595046.1	1232018.4	2	2.60	3.01	1	2	-0.41
S12	603855.9	1234279.7	2	4.60	3.00	1	2	1.60
S13	613589.4	1225313.4	2	2.80	2.56	1	2	0.24
S14	627785.2	1224450.6	2	1.00	2.45	1	2	-1.45
S15	623193.0	1209508.9	2	1.00	2.05	1	2	-1.05
S16	625212.4	1198936.6	2	-0.10	1.73	1	2	-1.83
S17	604982.0	1216562.7	2	2.30	2.34	1	2	-0.04
S18	605498.2	1205734.5	2	1.10	1.99	1	2	-0.89
S19	594011.9	1212851.5	2	1.60	2.31	1	2	-0.71

Table 3. Calibration statistics for the steady-state simulation, 15 mm/yr recharge

Statistic	Value
Sum of squared weighted residuals	50.60 m^2
Mean of weighted residuals	-0.17 m
Standard deviation of weighted residuals	1.05 m
Mean of absolute weighted residuals	0.87 m
Minimum residual	-1.83 m
Maximum residual	2.88 m
Range of target values	11.88 m
Normalized Standard deviation of residuals	8.8 %

Table 4. Hydraulic conductivity values estimated through calibration, 15 mm/yr recharge

Parameter	Value
K_1	8.6×10^{-3} m/d (fixed)
K_2	50 m/d (fixed)
K_3	280 m/d
K_4	6 m/d
Recharge	15 mm/a (fixed)

Table 5. Overall water budget for the steady-state calibrated model, 15 mm recharge

Quantity	Value (m^3/d)
Inflows	
Recharge	297 004.00
Net inflow from the eastern boundary of the model	934.03
Total inflow	**297 938.03**
Outflows	
Groundwater discharge to the Mekong River and its tributaries	297 938.03
Total inflow	**297 938.03**
Overall discrepancy (Total inflow – Total outflow)	**0.00**
Overall discrepancy (%)	**0.00**

Table 6. Steady-state calibration targets and model results, 3 mm/yr recharge

Well ID	Easting (m)	Northing (m)	Layer	Target (m ASL)	Simulated (m ASL)	Weight	Group	Residual (m)
P1	536455.7	1270057.7	2	2.89	4.17	1	1	-1.28
P3	545866.9	1280132.3	2	3.31	5.53	1	1	-2.22
P4	554821.5	1281160.9	2	5.45	4.64	1	1	0.81
P5	554819.5	1270411.4	2	4.32	4.25	1	1	0.07
P6	571906.5	1270317.0	2	5.57	4.38	1	1	1.19
P7	572703.8	1280616.9	2	5.63	4.73	1	1	0.90
P8	573809.3	1285910.8	2	8.10	4.89	1	1	3.21
P9	575830.2	1297036.5	2	11.78	11.87	1	1	-0.09
P10	554781.9	1290034.2	2	8.98	7.42	1	1	1.56
P11	543561.5	1309031.5	2	7.24	5.98	1	1	1.26
P12	531438.5	1305235.0	2	6.62	5.68	1	1	0.94
P13	518344.6	1300222.2	2	5.00	4.81	1	1	0.19
P14	514159.9	1289058.8	2	4.99	4.39	1	1	0.60
P15	524800.5	1286370.8	2	4.39	4.44	1	1	-0.05
P16	523143.2	1270906.9	2	4.94	3.95	1	1	0.99
P18	543256.8	1257355.9	2	2.97	3.92	1	1	-0.95
P19	544972.5	1238260.8	2	2.80	3.20	1	1	-0.40
P21	570848.1	1255129.2	2	3.88	3.85	1	1	0.03
P22	559992.1	1237658.1	2	2.36	3.32	1	1	-0.96
P23	558190.6	1229287.7	2	2.32	3.00	1	1	-0.68
P24	567107.0	1229161.0	2	2.46	2.94	1	1	-0.48
P25	557660.1	1217402.5	2	1.93	2.50	1	1	-0.57
P26	542178.4	1226451.9	2	1.32	2.83	1	1	-1.51
P27	542110.5	1225400.8	2	3.06	2.80	1	1	0.26
P29	523491.7	1224180.4	2	3.90	2.83	1	1	1.07
P30	521654.9	1207017.6	2	1.94	2.49	1	1	-0.55
S01	579870.5	1222651.3	2	2.00	2.64	1	2	-0.64
S02	565151.6	1216431.2	2	1.00	2.45	1	2	-1.45
S03	569550.9	1240269.3	2	2.70	3.37	1	2	-0.67
S04	578846.0	1229364.1	2	1.90	2.89	1	2	-0.99
S05	578172.2	1262248.7	2	4.20	4.10	1	2	0.10
S06	583156.9	1256328.3	2	3.00	3.88	1	2	-0.88
S07	587772.6	1265673.1	2	4.40	4.22	1	2	0.18
S08	595753.8	1253514.0	2	2.70	3.76	1	2	-1.06
S09	580839.3	1243188.3	2	3.00	3.41	1	2	-0.41
S10	598559.5	1243319.4	2	4.10	3.35	1	2	0.75
S11	595046.1	1232018.4	2	2.60	2.87	1	2	-0.27
S12	603855.9	1234279.7	2	4.60	2.84	1	2	1.76
S13	613589.4	1225313.4	2	2.80	2.40	1	2	0.40
S14	627785.2	1224450.6	2	1.00	2.27	1	2	-1.27
S15	623193.0	1209508.9	2	1.00	1.91	1	2	-0.91
S16	625212.4	1198936.6	2	-0.10	1.61	1	2	-1.71
S17	604982.0	1216562.7	2	2.30	2.21	1	2	0.09
S18	605498.2	1205734.5	2	1.10	1.88	1	2	-0.78
S19	594011.9	1212851.5	2	1.60	2.20	1	2	-0.60

Table 7. Calibration statistics for the steady-state simulation, 3 mm/yr recharge

Statistic	Value
Sum of squared weighted residuals	49.00 m^2
Mean of weighted residuals	-0.11 m
Standard deviation of weighted residuals	1.04 m
Mean of absolute weighted residuals	0.84 m
Minimum residual	-2.27 m
Maximum residual	3.06 m
Range of target values	11.88 m
Normalized Standard deviation of residuals	8.7 %

Table 8. Hydraulic conductivity values estimated through calibration, 3 mm/yr recharge

Parameter	Value
K_1	8.6×10^{-3} m/d (fixed)
K_2	50 m/d (fixed)
K_3	48 m/d
K_4	0.13 m/d
Recharge	3 mm/a (fixed)

Table 9. Overall water budget for the steady-state calibrated model, 3 mm recharge

Quantity	Value (m^3/d)
Inflows	
Recharge	59 400.90
Total inflow	**59 400.90**
Outflows	
Groundwater discharge to the Mekong River and its tributaries	48 913.04
Net outflow from the eastern boundary of the model	10 487.86
Total outflow	**59 400.90**
Overall discrepancy (Total inflow – Total outflow)	**0.00**
Overall discrepancy (%)	**0.00**

Table 10. Residual statistics for the transient simulation, 15 mm/recharge

Statistic	Value
Sum of squared weighted residuals	3 820 m^2
Mean of weighted residuals	-0.07 m
Standard deviation of weighted residuals	1.19 m
Mean of absolute weighted residuals	0.94 m
Minimum residual	-2.79 m
Maximum residual	3.59 m
Range of target values	13.46 m
Normalized Standard deviation of residuals	8.8 %

Table 11. Residual statistics for the transient simulation, 3 mm/recharge

Statistic	Value
Sum of squared weighted residuals	3 792.07 m^2
Mean of weighted residuals	-0.11 m
Standard deviation of weighted residuals	1.18 m
Mean of absolute weighted residuals	0.94 m
Minimum residual	-2.72 m
Maximum residual	3.75 m
Range of target values	13.46 m
Normalized Standard deviation of residuals	8.8 %

Table 12. Results of predictive analyses 1 - 4

<u>Recharge 15 mm/yr</u>

Scenario	Level above top of the Old Alluvium (m)	Maximum discharge rate, Time-average (m^3/d)
1	5.0	4.7×10^7
2	3.5	5.0×10^7
3	2.5	5.3×10^7
4	1.0	5.6×10^7

<u>Recharge 3 mm/yr</u>

Scenario	Level above top of the Old Alluvium (m)	Maximum discharge rate, Time-average (m^3/d)
1	5.0	7.9×10^6
2	3.5	8.7×10^6
3	2.5	9.0×10^6
4	1.0	9.7×10^6

Table 13. Results of predictive analyses 5 - 7

Recharge 15 mm/yr

Scenario	Minimum water level in Old Alluvium below ground surface (m)	Maximum discharge rate, Time-average (m^3/d)
5	5.0	8.5×10^6
6	6.0	1.0×10^7
7	7.0	1.2×10^7

Recharge 3 mm/yr

Scenario	Minimum water level in Old Alluvium below ground surface (m)	Maximum discharge rate, Time-average (m^3/d)
5	5.0	1.8×10^6
6	6.0	2.3×10^6
7	7.0	2.6×10^6

APPENDIX A

Geologic maps

Christopher J. Neville
S.S. Papadopulos & Associates, Inc.
Last update: May 1, 2009

Overview

As far as we are aware, there is no recent "definite" geologic map of the Prey Veng-Svay Rieng study area. We have tried to compile the available geologic maps, as part of the project. We have assembled the following four maps from various sources:

1. Geological Map of Cambodia Showing Location of Lithologic Sections [Rasmussen and Bradford, 1978; Plate 1];
2. Elevation of the Regional Water Table, Mekong River Delta Region, South Vietnam and Cambodia [Anderson, 1978; Plate 2];
3. Geological Map of Cambodia [Ministry of Water Resources and Meteorology, Department of Water Supply and Sanitation, Groundwater Unit]; and
4. geo-200k [Ministry of Industry, Mines, and Energy, Department of Geology].

In the following notes we have compiled the digital images of these maps, and the available background information. Where possible, we have attempted to cite the appropriate references.

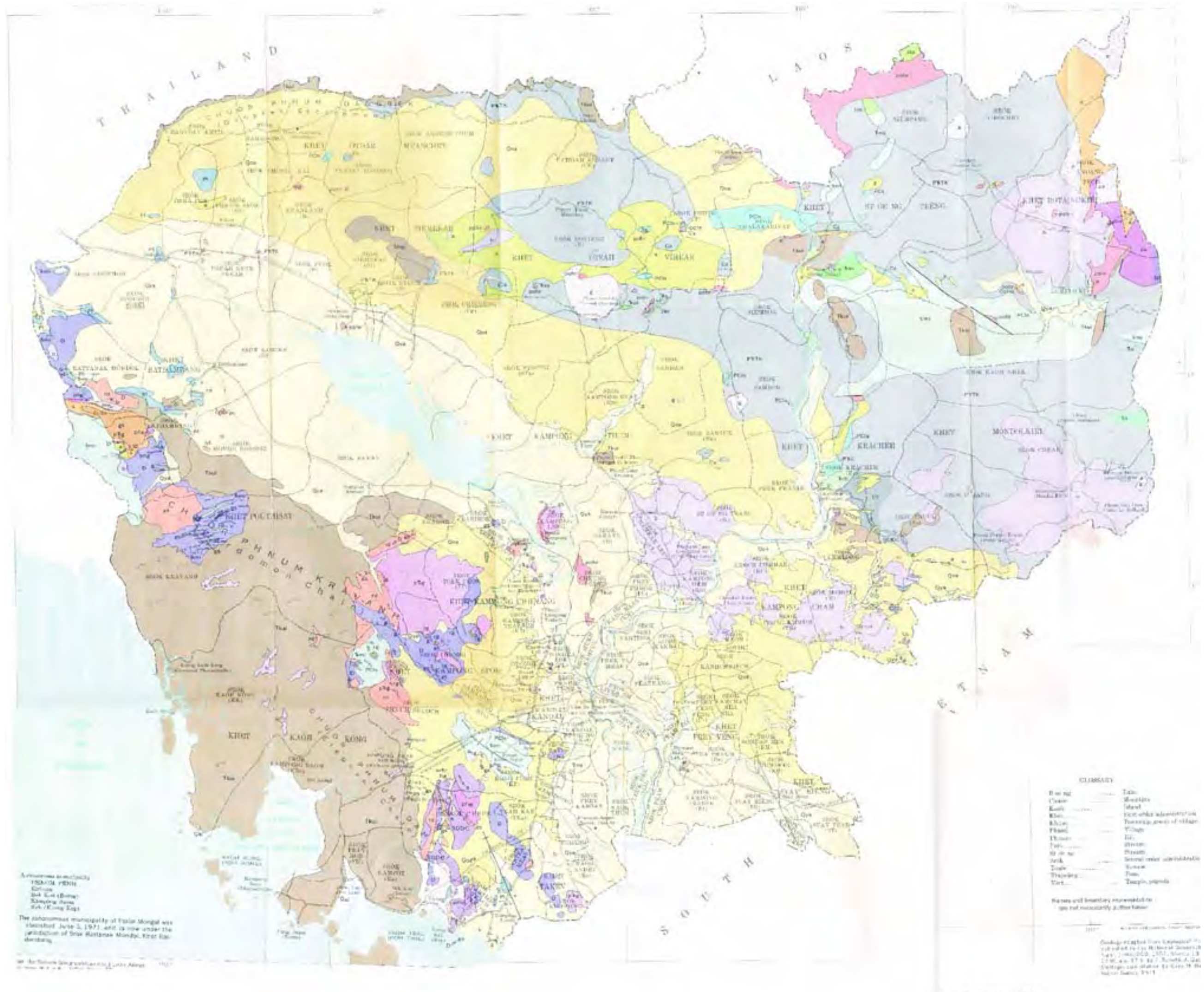
1. Geology_Map_01

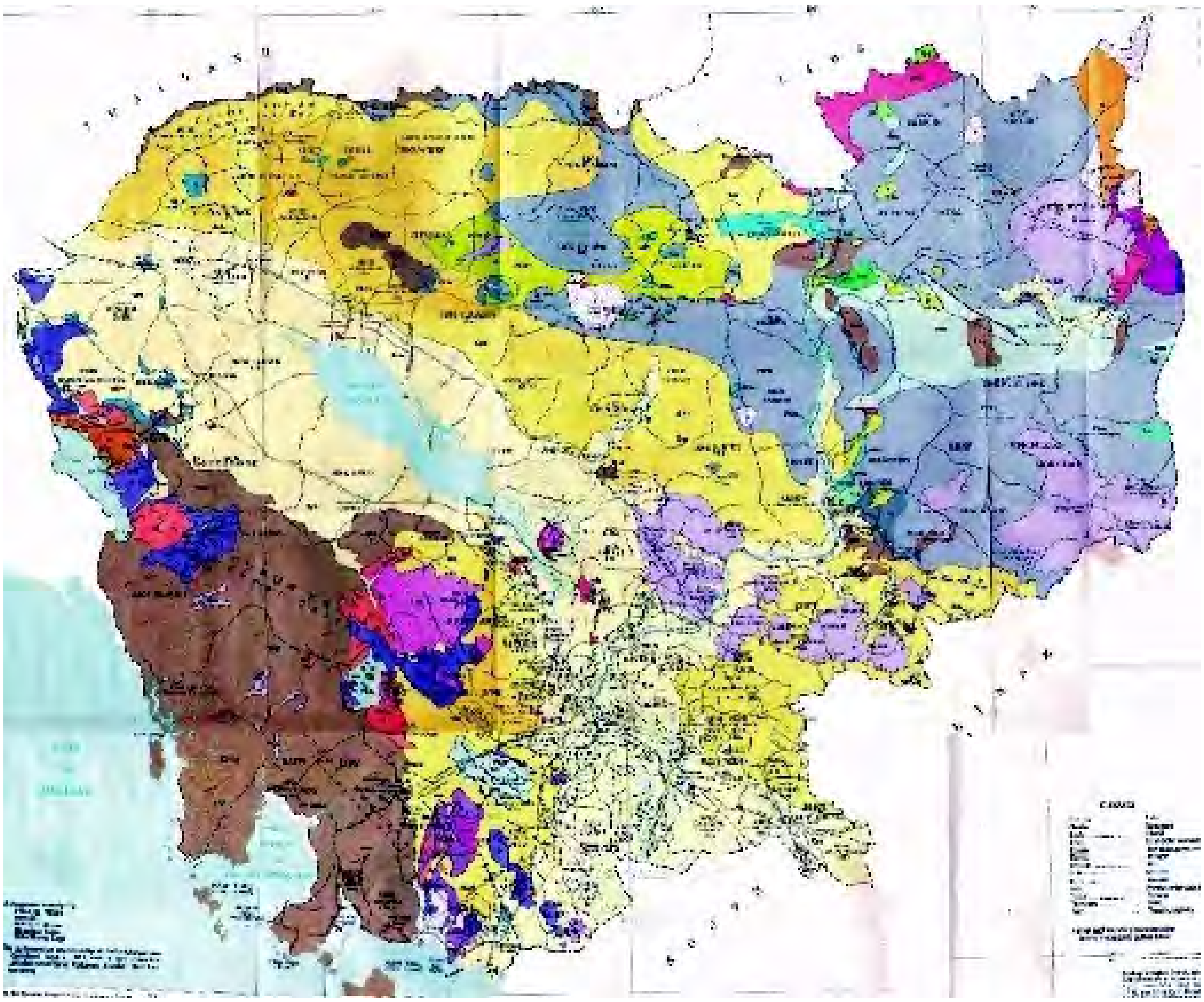
Geological Map of Cambodia Showing Location of Lithologic Sections
[Rasmussen and Bradford, 1978; Plate 1].

Scale: 1: 1,000,000

Data sources:

- Geology adapted from Geological Maps of Indo-China, published by the National Geographic Service of Viet Nam, 1961, Sheets 13, 14W, 14E, 16, 17W, and 17E, F. Boneli, J. Gubler, and E. Saurin, Scale: 1: 500,000.
- Geologic compilation by G.M. Bradford, USGS, 1971.


T H A I L A N D
L A O S



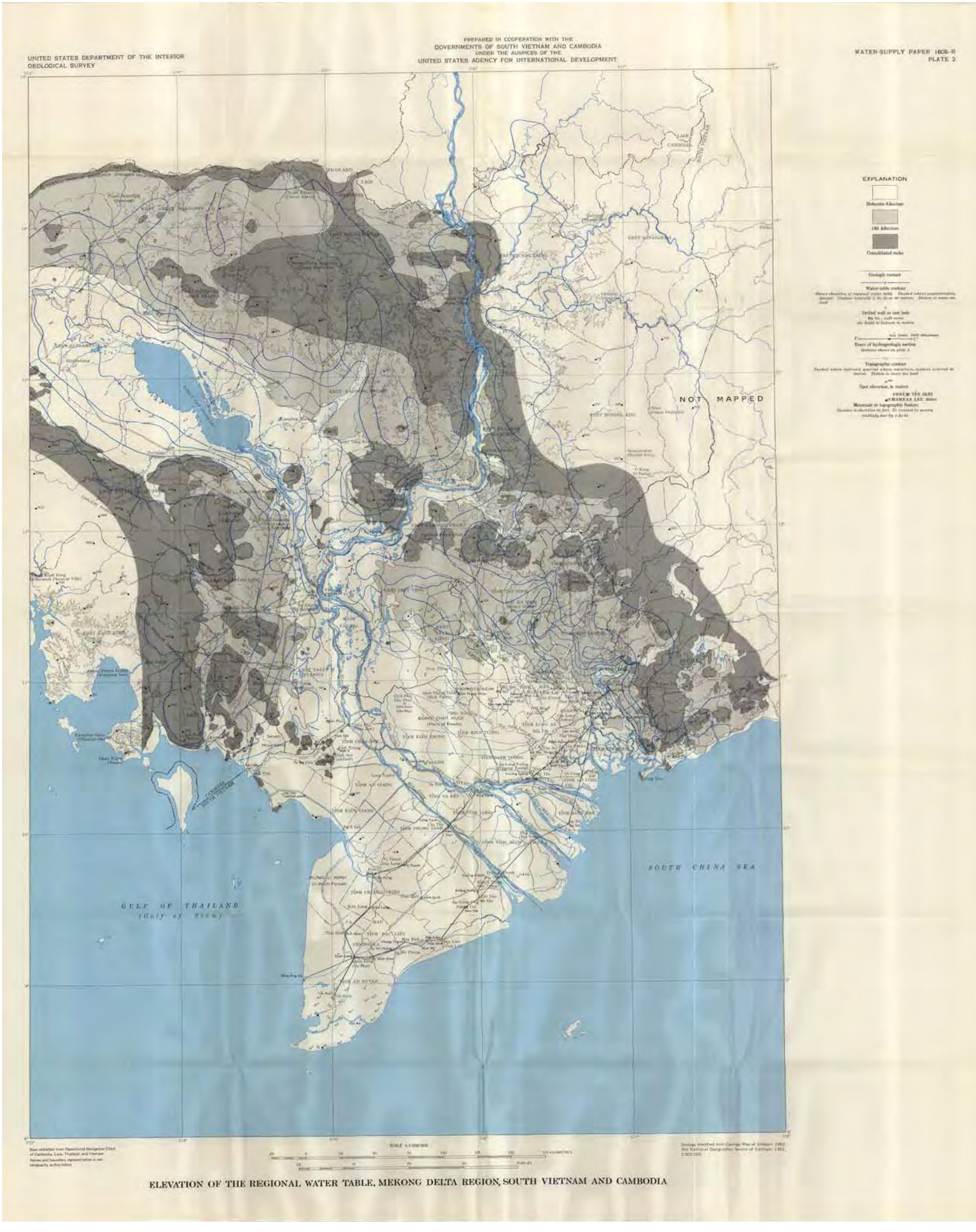
2. Geology_Map_02

Elevation of the Regional Water Table, Mekong River Delta Region, South Vietnam and Cambodia
[Anderson, 1978; Plate 2]

Scale: 1: 1,000,000

Data source:

Geology modified from Geologic Map of Vietnam, 1962, The National Geographic Service of Vietnam, 1961, Scale: 1: 500,000.



ELEVATION OF THE REGIONAL WATER TABLE, MEKONG DELTA REGION, SOUTH VIETNAM AND CAMBODIA

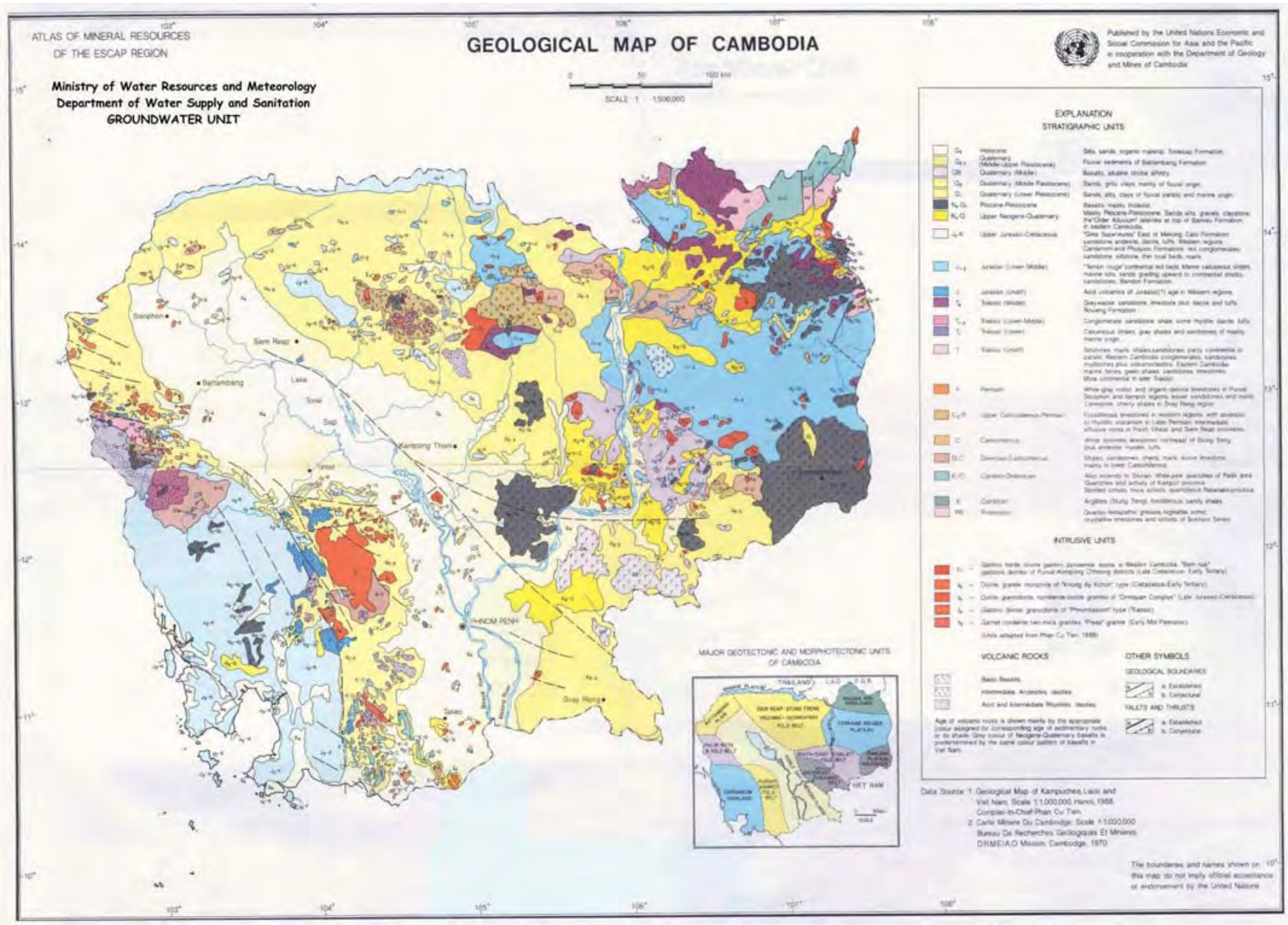
3. Geology_Map_03

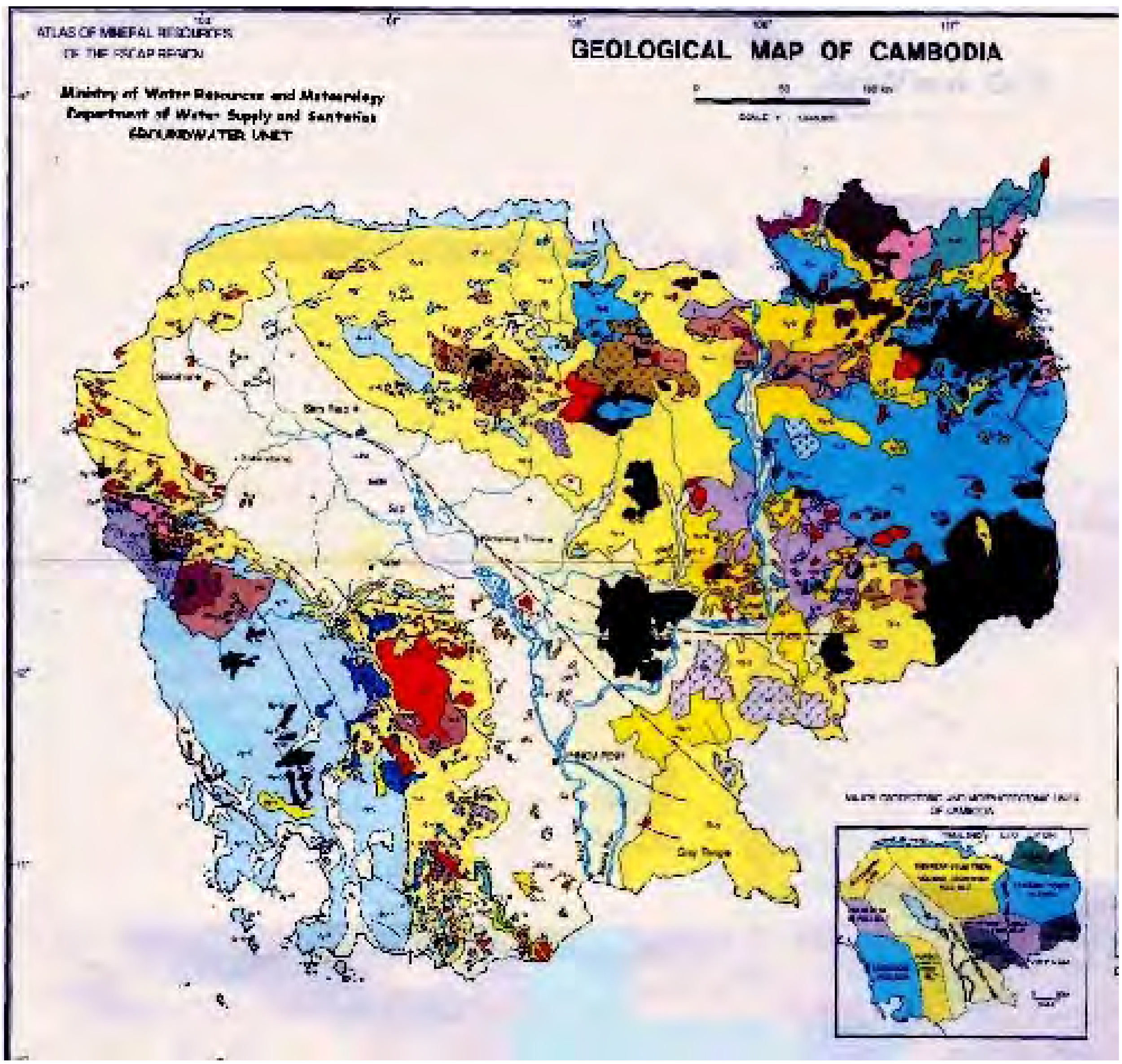
Geological Map of Cambodia
[Ministry of Water Resources and Meteorology, Department of Water Supply and Sanitation, Groundwater Unit]

Originally published by:
United Nations Economic and Social Commission for Asia and the Pacific [ESCAP] in cooperation with the Department of Geology and Mines of Cambodia [as part of the Atlas of Mineral Resources of the ESCAP Region?]

Data sources:

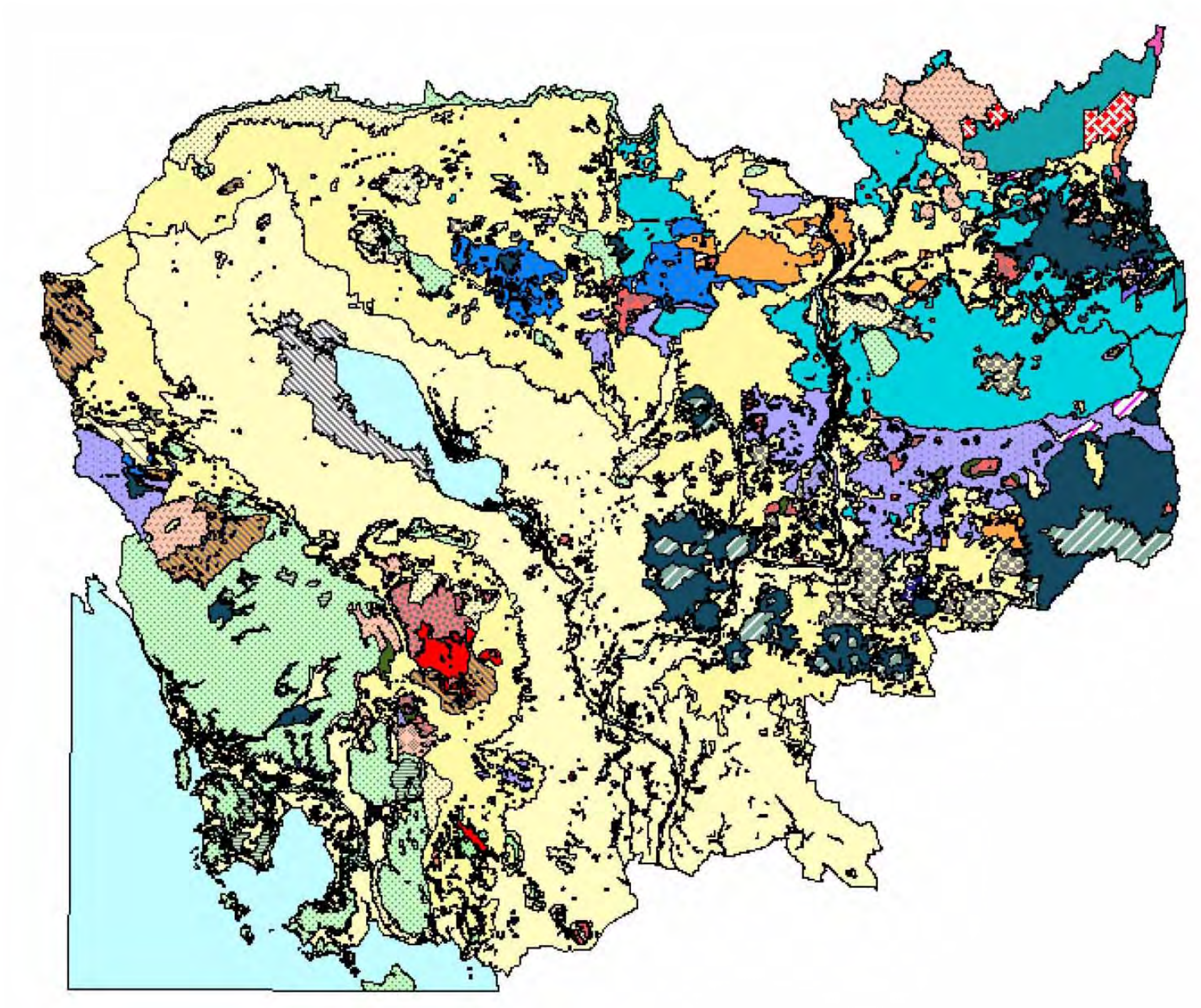
- Carte Miniere du Cambodge
  Scale 1:1,000,000
  Bureau de Recherche Geologiques et Minieres
  D.R.M.E./A.O. Mission, Cambodge, 1970.
- Geological map of Kampuchea, Laos and Viet Nam
  Scale 1:1,000,000
  Compiler-in-Chief: Phan Cu Tien, Hanoi, 1988.


ATLAS OF MINERAL RESOURCES
OF THE ESCAP REGION
GEOLOGICAL MAP OF CAMBODIA
Ministry of Water Resources and Meteorology
Department of Water Supply and Sanitation
GROUNDWATER UNIT
Published by the United Nations Economic and Social Commission for Asia and the Pacific in cooperation with the Department of Geology and Mines of Cambodia
SCALE 1 : 1,500,000
EXPLANATION
STRATIGRAPHIC UNITS
INTRUSIVE UNITS
VOLCANIC ROCKS
OTHER SYMBOLS
MAJOR GEOTECTONIC AND MORPHOTECTONIC UNITS OF CAMBODIA
Battambang
Siem Reap
Kampong Thom
PHNOM PENH
Svay Rieng


ATLAS OF MINERAL RESOURCES
OF THE ESCAP REGION
GEOLOGICAL MAP OF CAMBODIA
Ministry of Water Resources and Meteorology
Department of Water Supply and Sanitation
GROUNDWATER UNIT

4. Geology_Map_04

geo-200k
[Ministry of Industry, Mines, and Energy, Department of Geology]



5. References

Anderson, H.R., 1978: Hydrogeologic Reconnaissance of the Mekong Delta in South Vietnam and Cambodia, Water-Supply Paper 1608-R, United States Geological Survey, Washington DC.

Rasmussen, W.C., and G.M. Bradford, 1977: Ground-Water Resources of Cambodia, Water-Supply Paper 1608-P, United States Geological Survey, Washington DC.

Roberts, M.S., 1998: Groundwater Irrigation in the Mekong Delta of Cambodia, M.Sc. Thesis, Cornell University, August 1998.

APPENDIX B

Limits of the Young Alluvium

Christopher J. Neville
S.S. Papadopulos & Associates, Inc.
Last update: May 1, 2009

Overview

In our conceptualization of groundwater flow in the Prey Veng-Svay Rieng study area, a key element is the extent of the Young Alluvium. The fine-grained sediments of the Young Alluvium act as a "cap" over the permeable sediments of the Old Alluvium. In our conceptualization, where there is recharge to the Old Alluvium from the infiltration of precipitation, it occurs over areas where the Young Alluvium is absent.

As far as we are aware, there is no recent "definite" geologic map of the extent of the Young Alluvium. We have reviewed four maps to infer its limits. In the following notes we present our interpretations developed from these maps.

1. Geology_Map_01

<u>Source:</u>
Geological Map of Cambodia Showing Location of Lithologic Sections [Rasmussen and Bradford, 1978; Plate 1]

Our interpretation of the limits of the Young Alluvium is shown in Figure 1. We have inferred the limits of the Young Alluvium from lines digitized from Rasmussen and Bradford (1978; Plate 1). The following units are identified in Rasmussen and Bradford's map:

- Qya = Young Alluvium is uppermost geologic unit;
- Qoa = Old Alluvium is uppermost geologic unit; and
- b = Basalt is uppermost geologic unit.

Roberts (1998; Figure 2-2) also shows the northern limits of the Young Alluvium, referring to Rasmussen and Bradford (1978). The limits are indicated by the red line, and are roughly consistent with the limits digitized from Rasmussen and Bradford (1978).

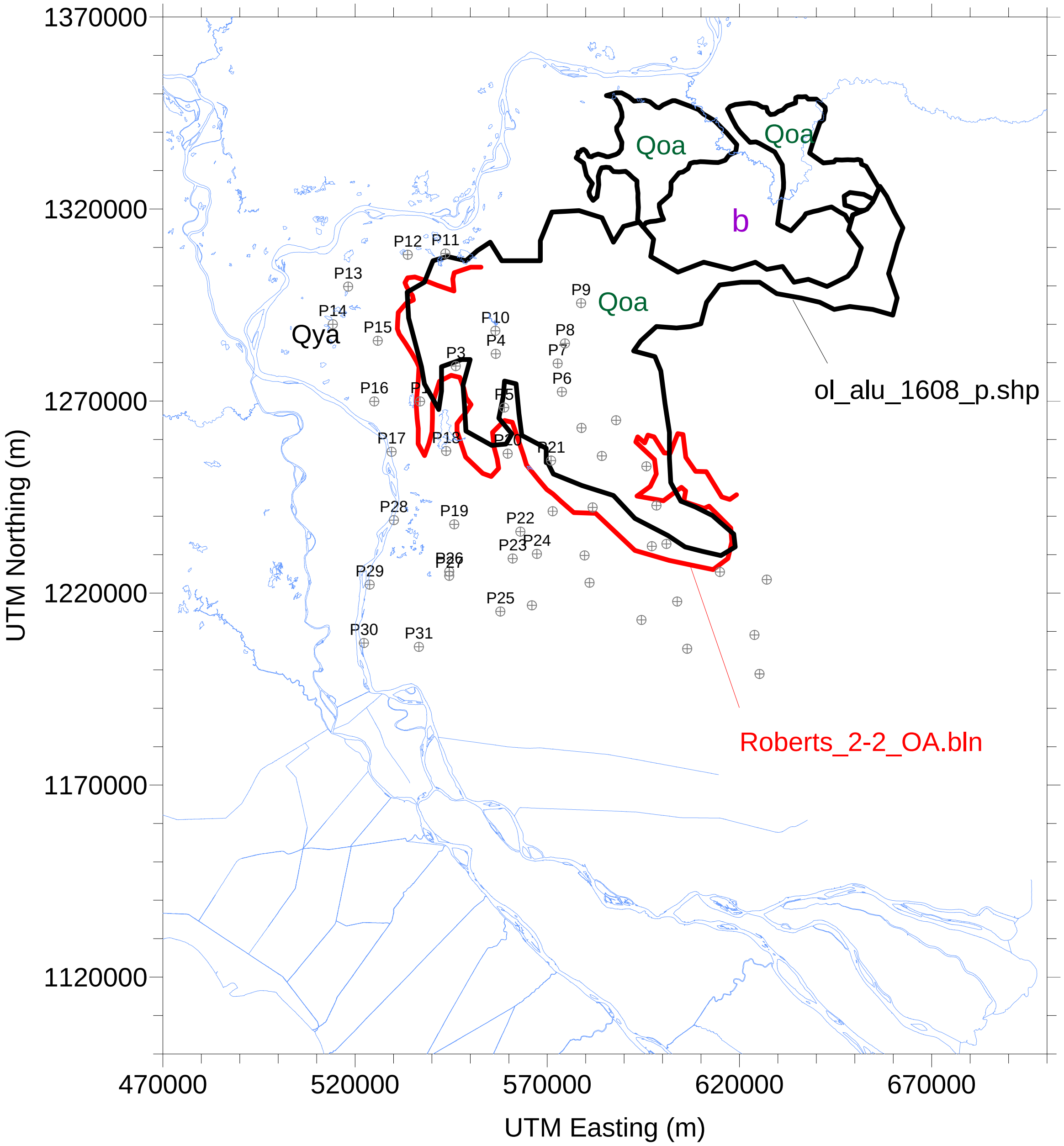


Figure 1. Limits of the Young Alluvium inferred from Rasmussen and Bradford (1978)

2. Geology_Map_02

Source:
Elevation of the Regional Water Table, Mekong River Delta Region, South Vietnam and Cambodia [Anderson, 1978; Plate 2]

Our interpretation of the limits of the Young Alluvium is shown in Figure 2. The limits of the area where the Old Alluvium is the uppermost unit (Young Alluvium is absent) are digitized from Anderson (1978). The limits are truncated on the east by the limits of the groundwater model.

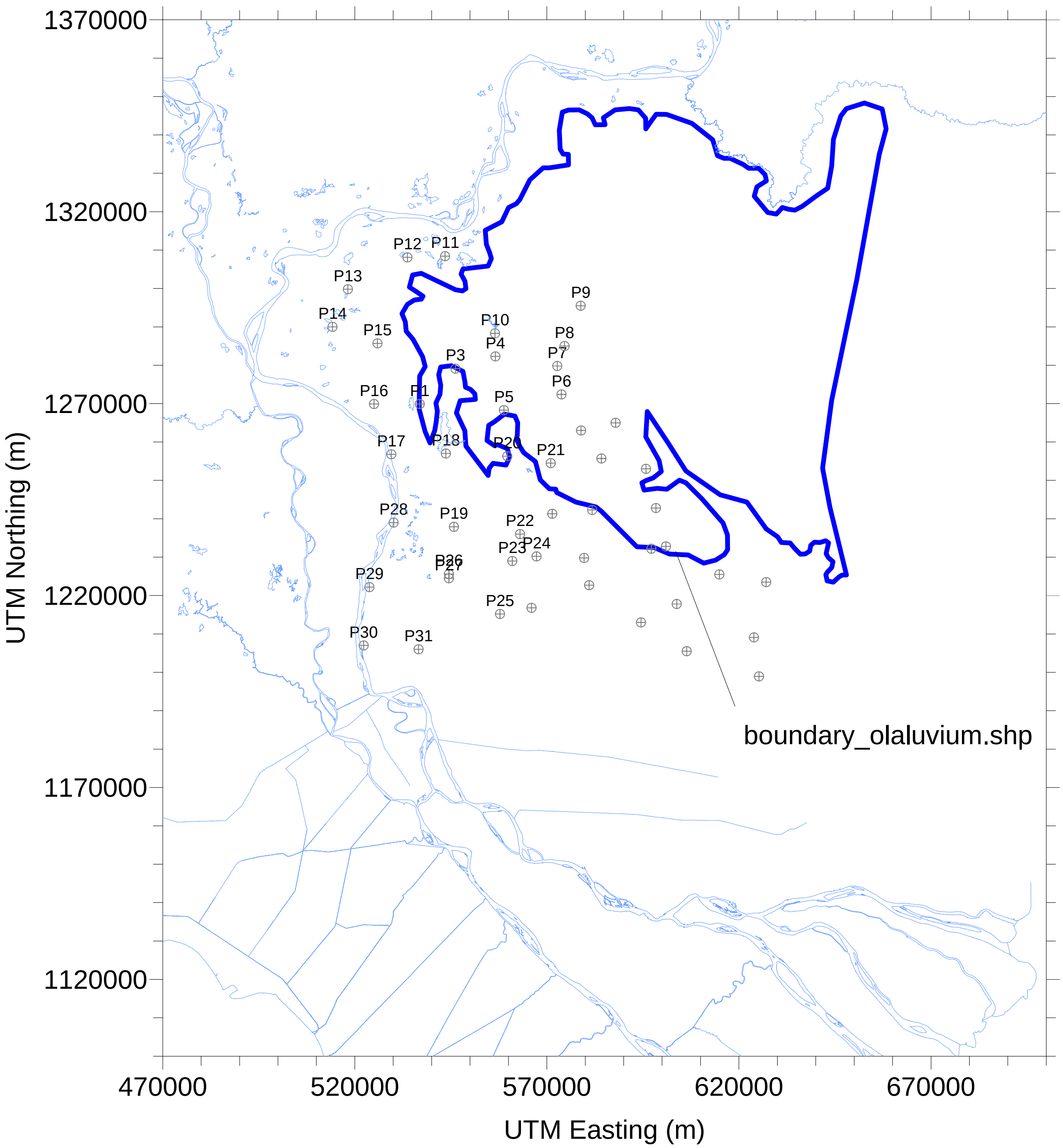


Figure 2. Limits of the Young Alluvium inferred from Anderson (1978)

3. Geology_Map_03

Source:
Geological Map of Cambodia [Ministry of Water Resources and Meteorology, Department of Water Supply and Sanitation, Groundwater Unit]

Our interpretation of the limits of the Young Alluvium is shown in Figure 3. The following units are identified in the geologic map:

- Q4, Holocene: Silts, sands, organic material of Tonlesap Formation;
- Q2-3, Quaternary (Middle-Upper Pleistocene): Fluvial sediments of Battambang Formation;
- N2-Q, Upper Neogene – Quaternary: Mainly Pliocene-Pleistocene sands, silts, gravels, claystone – the Older Alluvium laterite of the top of the Barnieu Formation in eastern Cambodia; and
- QB, Quaternary (Middle) basalts.

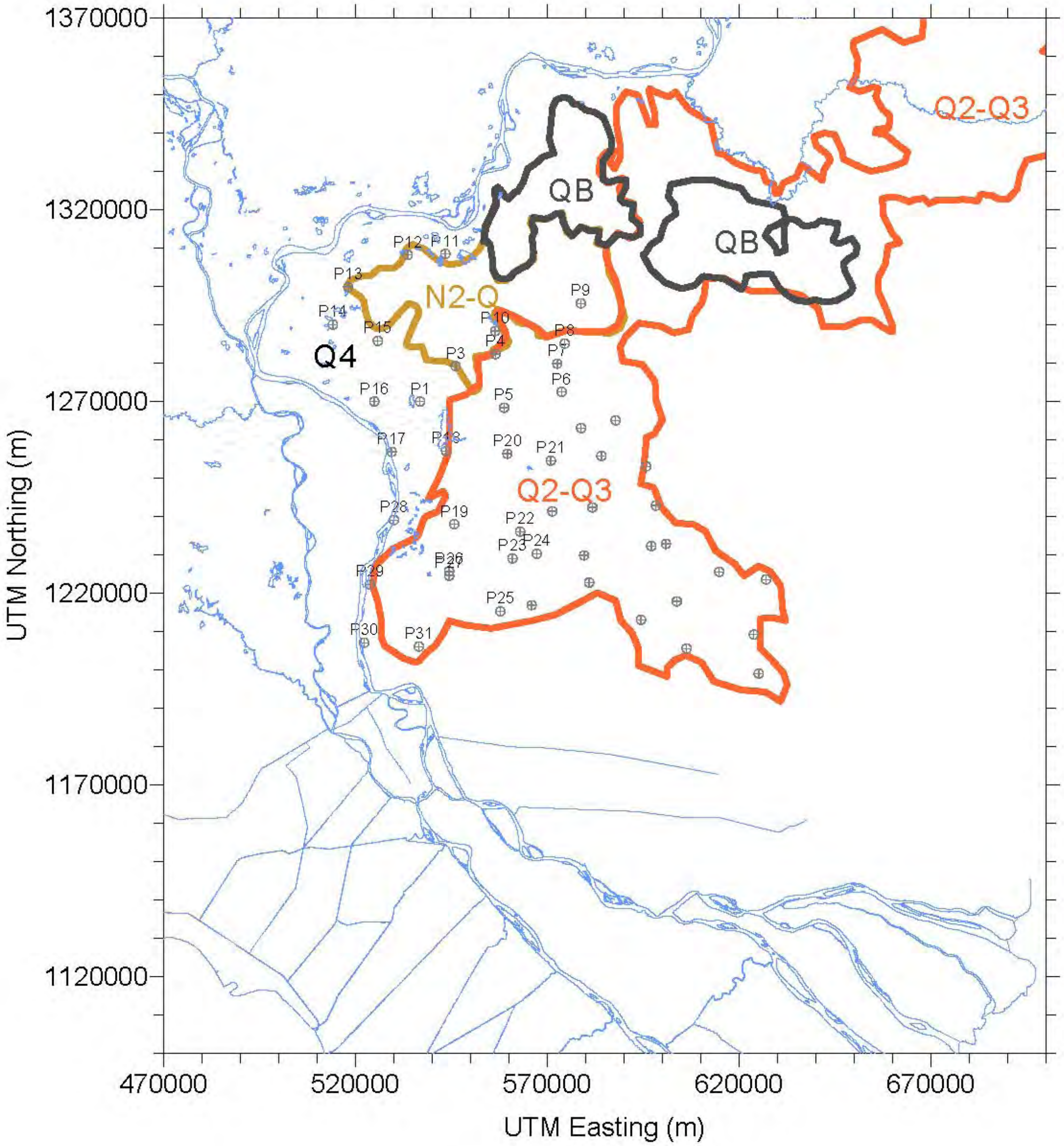


Figure 3. Limits of the Young Alluvium inferred from the *Geological Map of Cambodia*

4. Geology_Map_04

<u>Source:</u>
geo-200k [Ministry of Industry, Mines, and Energy, Department of Geology]

A detail of the map, with the EU-PRASAC wells in Prey Veng and Svay Rieng superimposed is shown in Figure 4. The wells in the northern area are inferred to be located in areas where the Young Alluvium is absent. Several of the wells appear to be located close to the limits of the Young Alluvium.

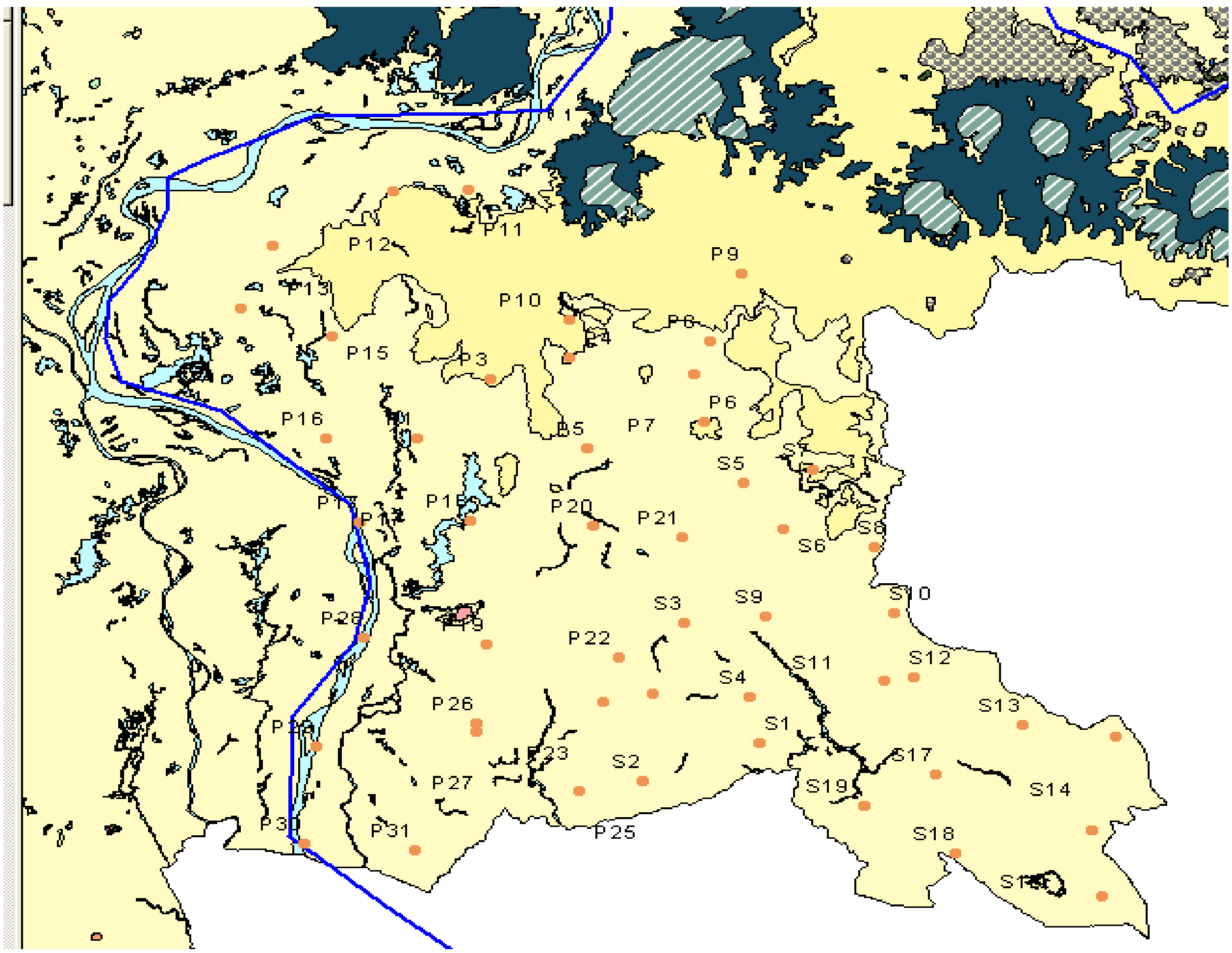


Figure 4. Limits of the Young Alluvium inferred from *geo-200k*

References

Anderson, H.R., 1978: Hydrogeologic Reconnaissance of the Mekong Delta in South Vietnam and Cambodia, Water-Supply Paper 1608-R, United States Geological Survey, Washington DC.

Rasmussen, W.C., and G.M. Bradford, 1977: Ground-Water Resources of Cambodia, Water-Supply Paper 1608-P, United States Geological Survey, Washington DC.

Roberts, M.S., 1998: Groundwater Irrigation in the Mekong Delta of Cambodia, M.Sc. Thesis, Cornell University, August 1998.

APPENDIX C

Mekong River gauging station data

Christopher J. Neville
S.S. Papadopulos & Associates, Inc.
Last update: May 31, 2007

Overview

Information available from the Mekong River Commission (MRC) [http://ffw.mrcmekong.org/south.htm] indicates that there are five gauging stations along the main branch of the Mekong River:

1. Kratie;
2. Kompong Cham;
3. Chroy Changvar [This gauging station is not part of the Mekong River Commission's flood monitoring network; rather, the gauging station is monitored by MoWRAM];
4. Neak Loeung; and
5. Tan Chau.

The locations of the gauging stations are shown in Figure 1.

The Mekong River Commission's network includes five other stations in the model area, but they are not considered here because they are not located on the main channel of the Mekong River. These stations are:

1. Phnom Penh, on the Bassac River;
2. Phnom Penh Port, on the Tonle Sap;
3. Koh Khel, on the Bassac Sap;
4. Preak Kdam, on the Tonle Sap, and
5. Chau Doc, on the Bassac River.

In the following notes, we have assembled the information from the MRC to prepare a cross-section of the river at each gauging station, along with a record of average daily water levels between 1997 and 2006. The thin blue lines on the water level records represent the data for each year. The solid thick red lines represent an envelope of the minimum and maximum average daily levels. The dashed red lines represent averages of the daily averages, and the horizontal dashed red lines represent the average level between 1997 and 2006.

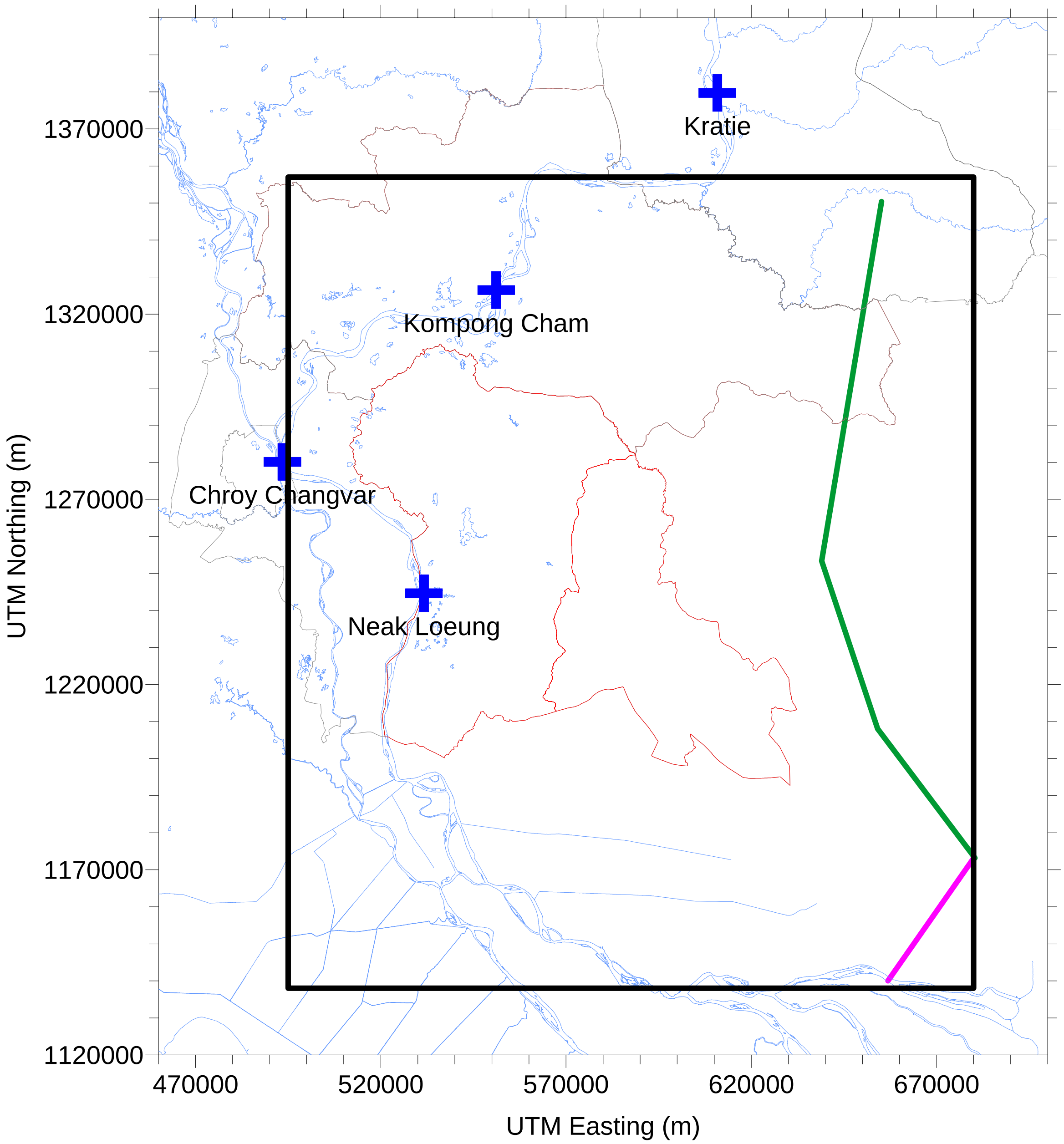
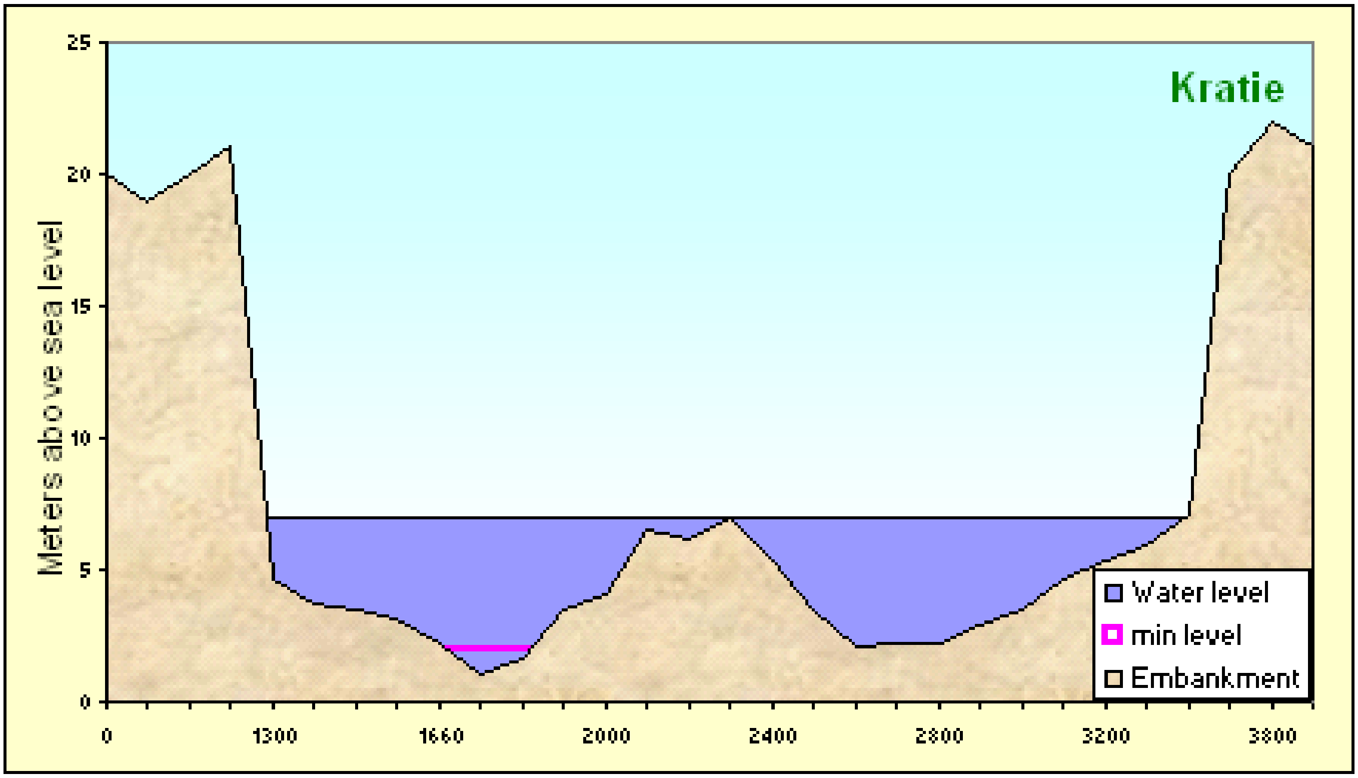


Figure 1. Locations of Mekong River gauging stations

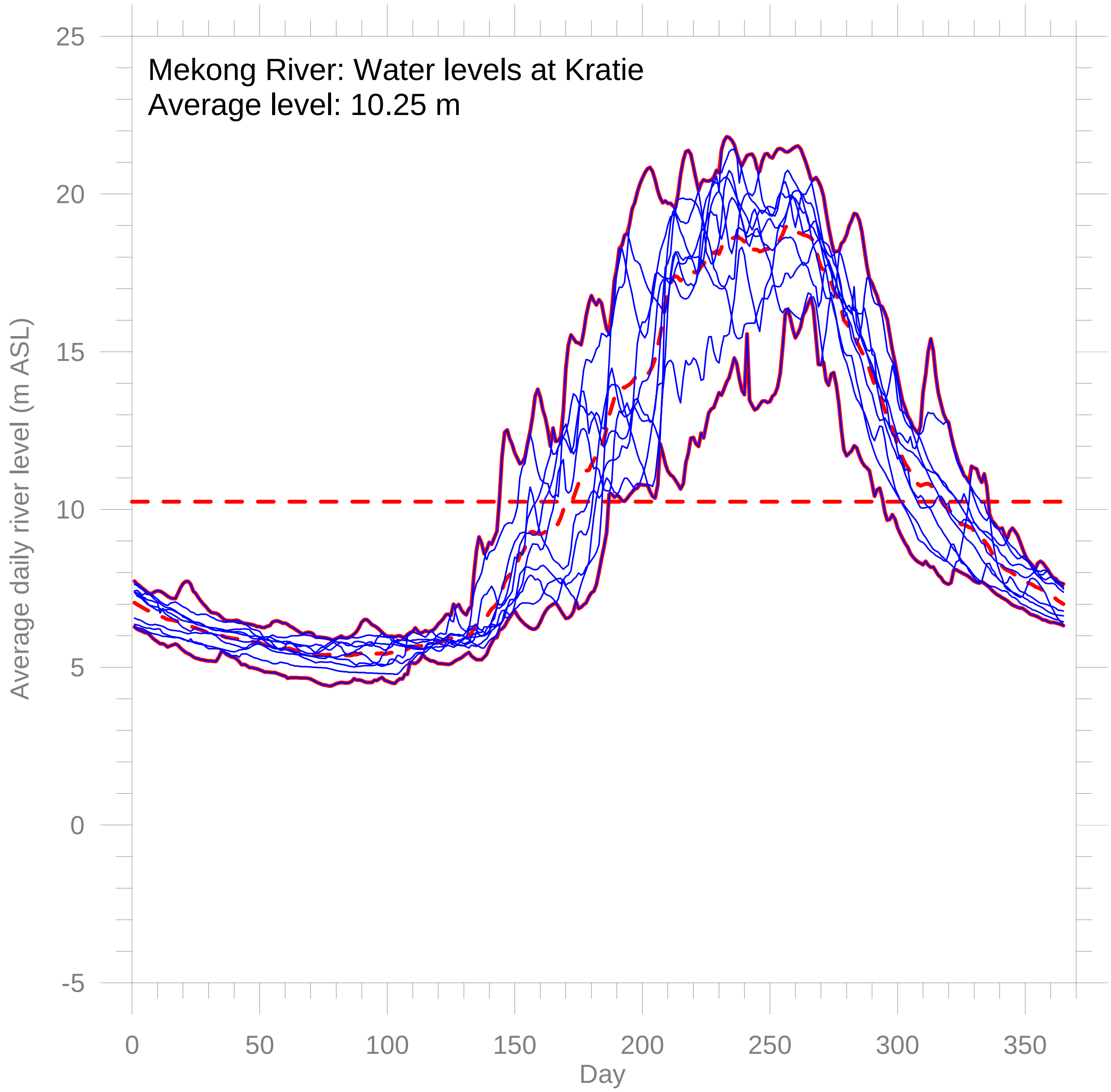
1. Kratie

Zero gauge Kratie = -1.08 m above MSL
All levels are above zero gauge
Minimum level = 3.06 m

<u>Cross-section</u>



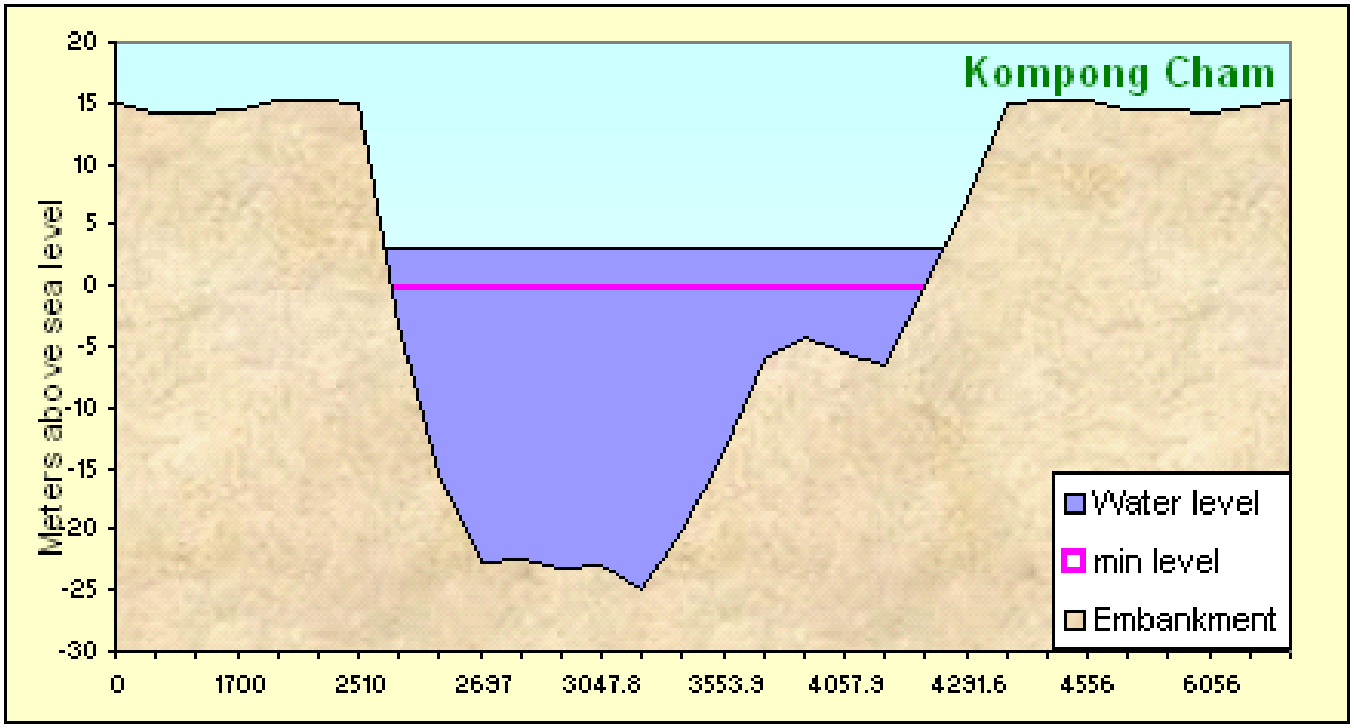
Water level record



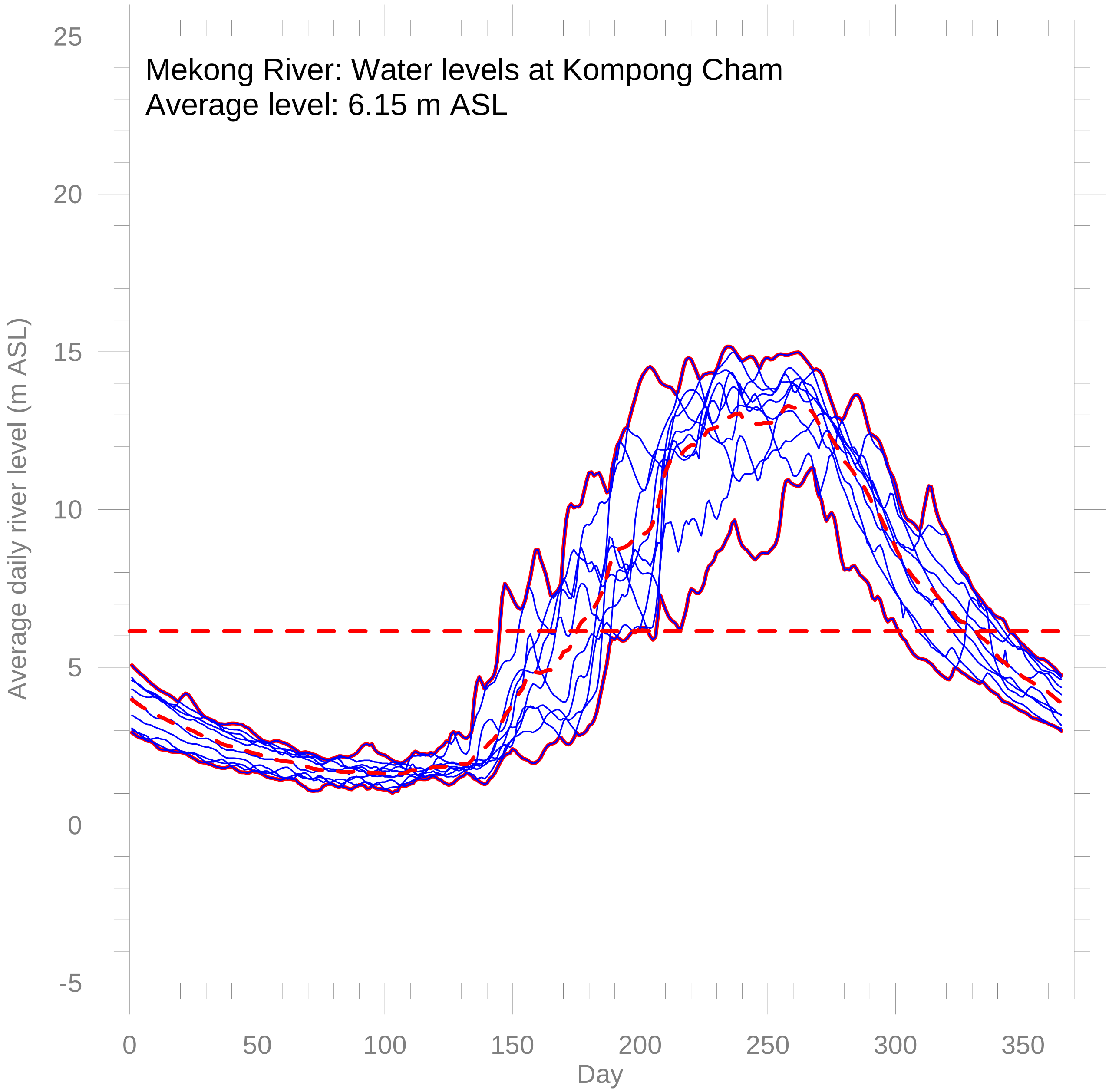
2. Kompong Cham

Zero gauge Kompong Cham = -0.93 m above MSL
Minimum level = 0.65 m
All levels are above zero gauge

<u>Cross-section</u>



Water level record

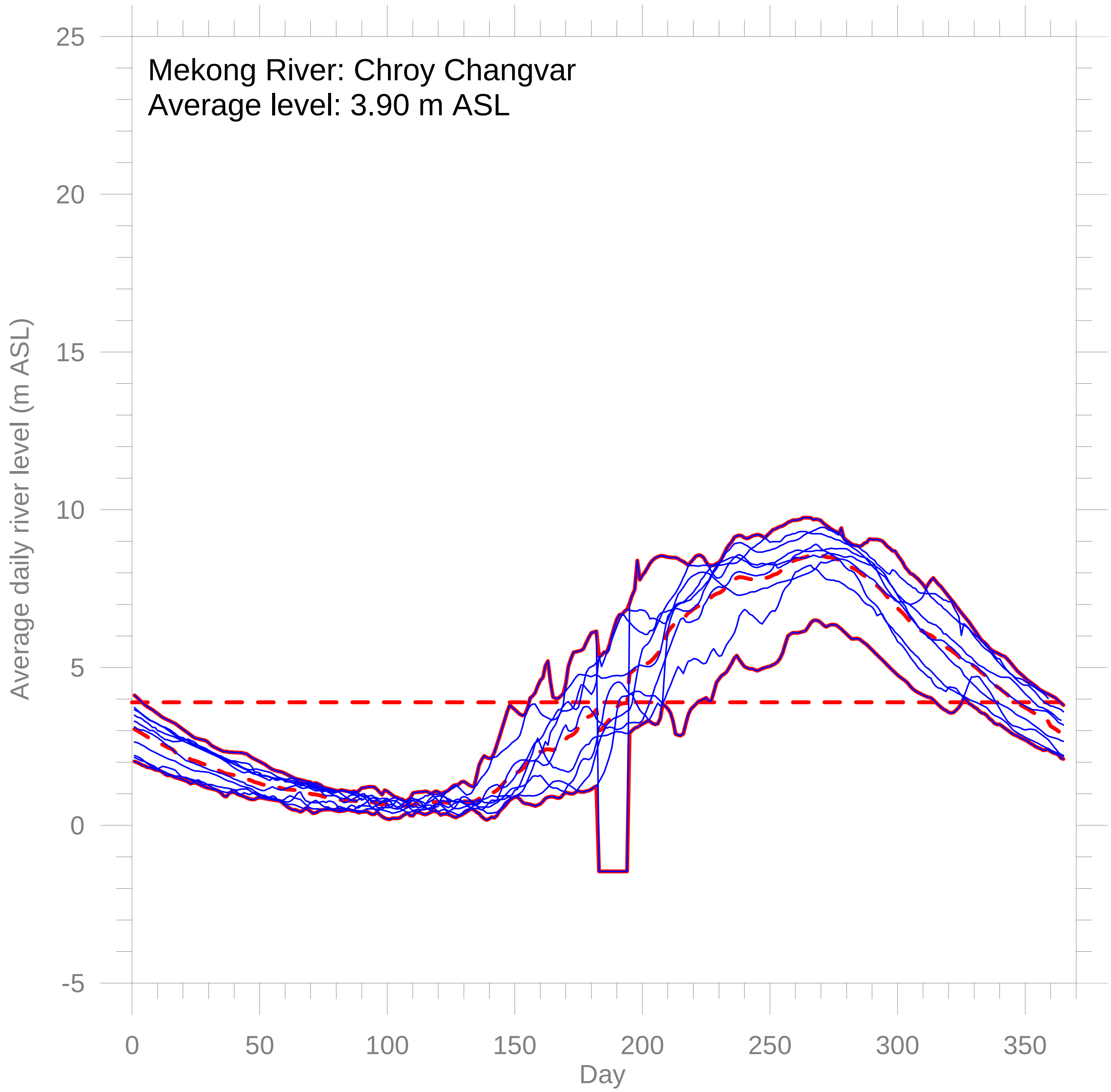


3. Chroy Changvar (close to Phnom Penh)

Cross-section

We have not been able to locate a cross-section for this gauging station.

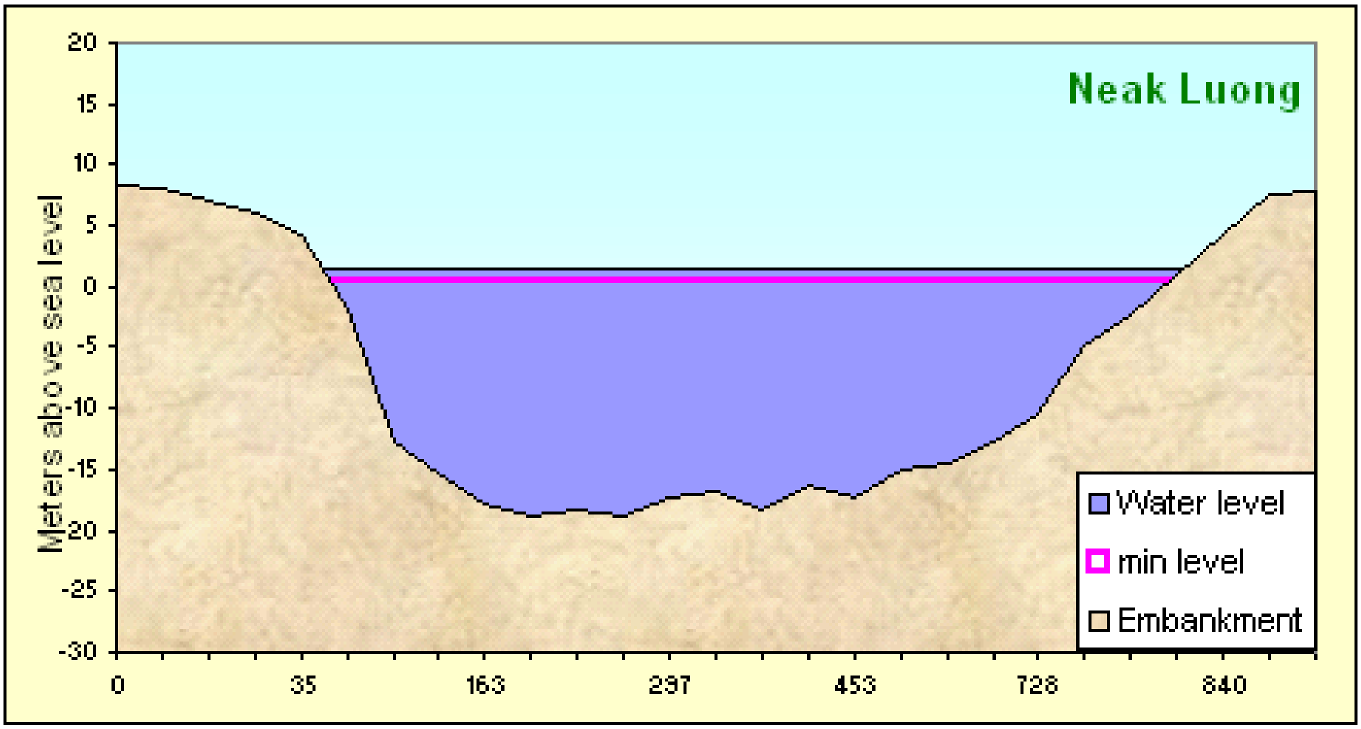
Water level record



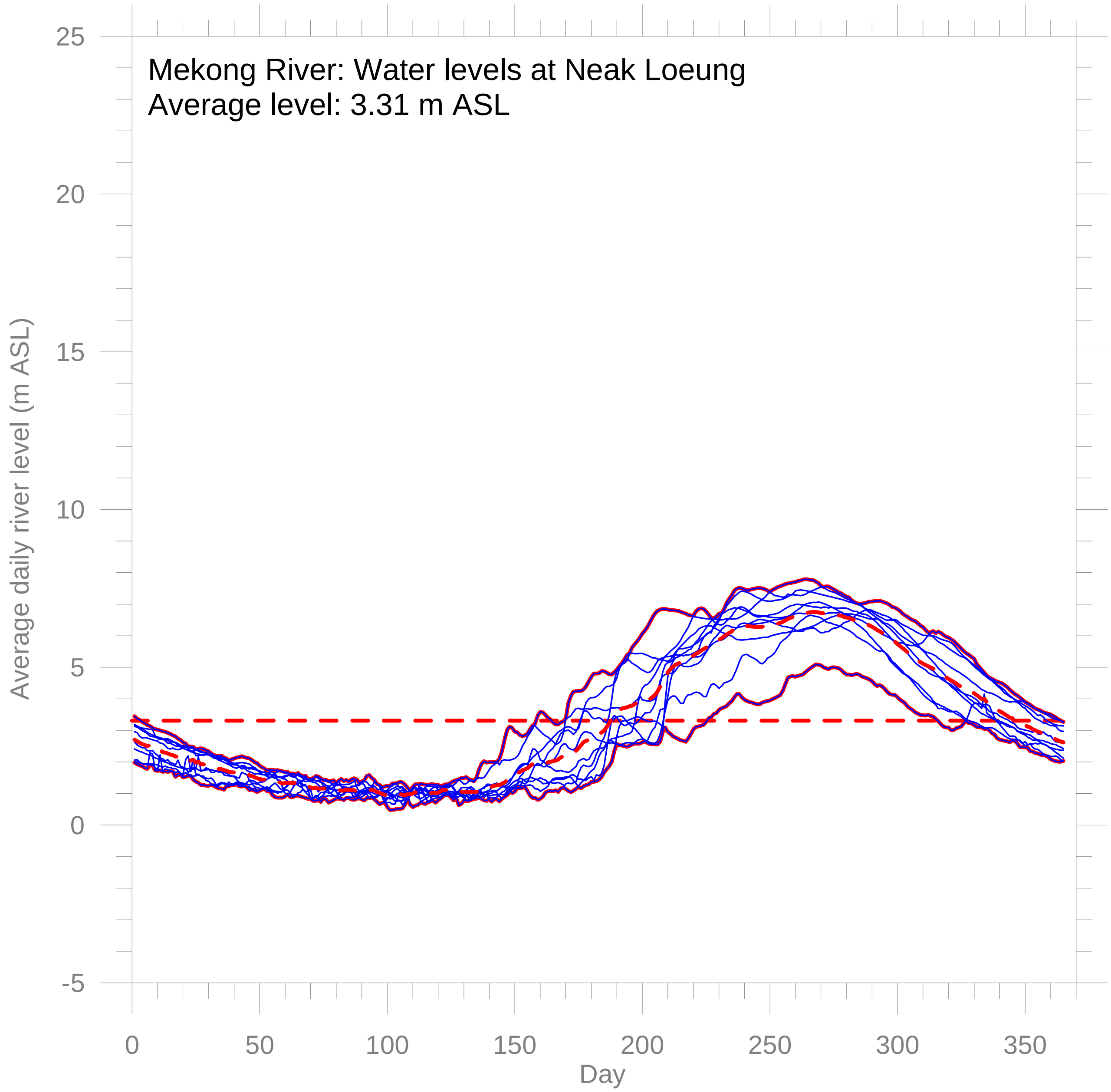
4. Neak Loeung

Zero gauge Neak Loeung = -0.33 m above MSL
Minimum level = 0.81 m
All levels are above zero gauge

<u>Cross-section</u>



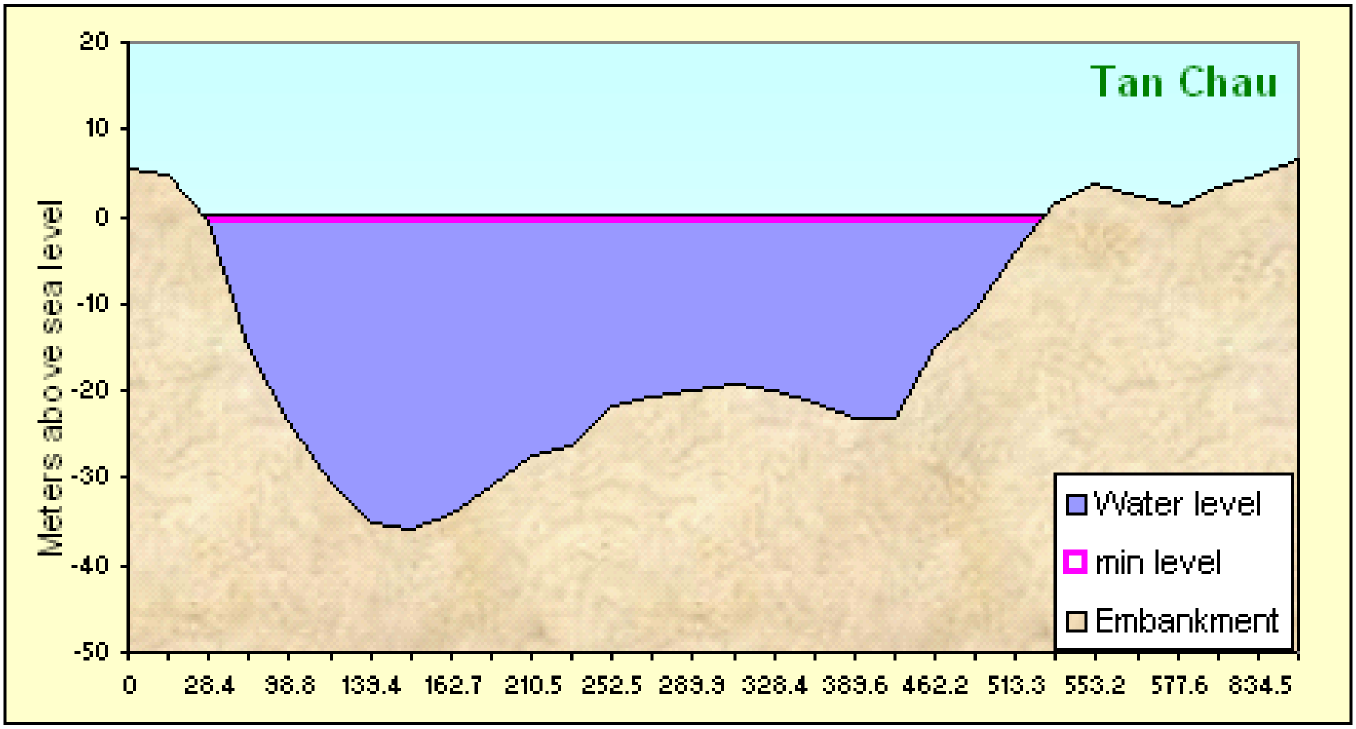
Water level record



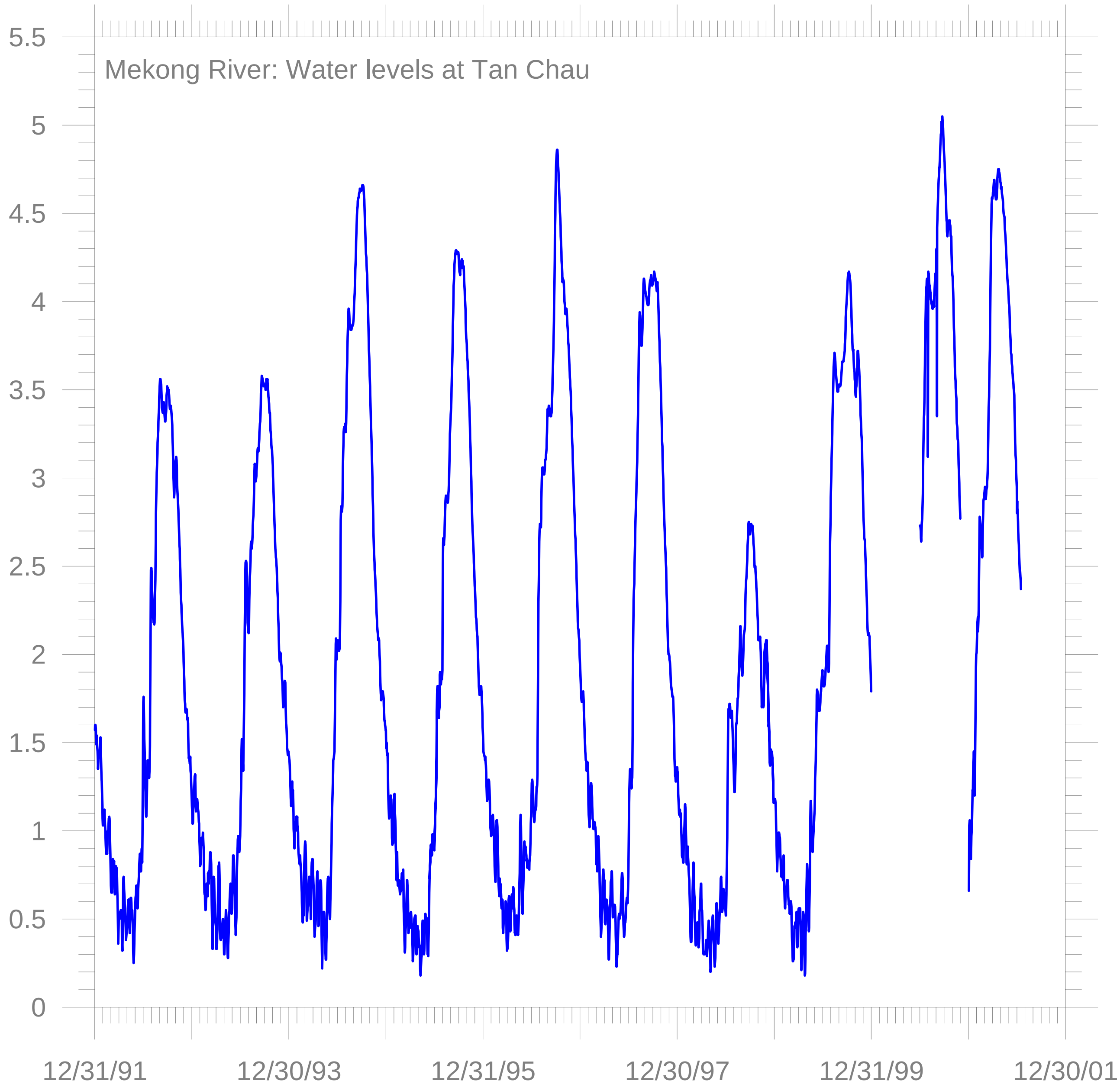
5. Tan Chau

Zero gauge Tan Chau = 0.001 m above MSL
Minimum level = -0.37 m
All levels are above zero gauge

<u>Cross-section</u>

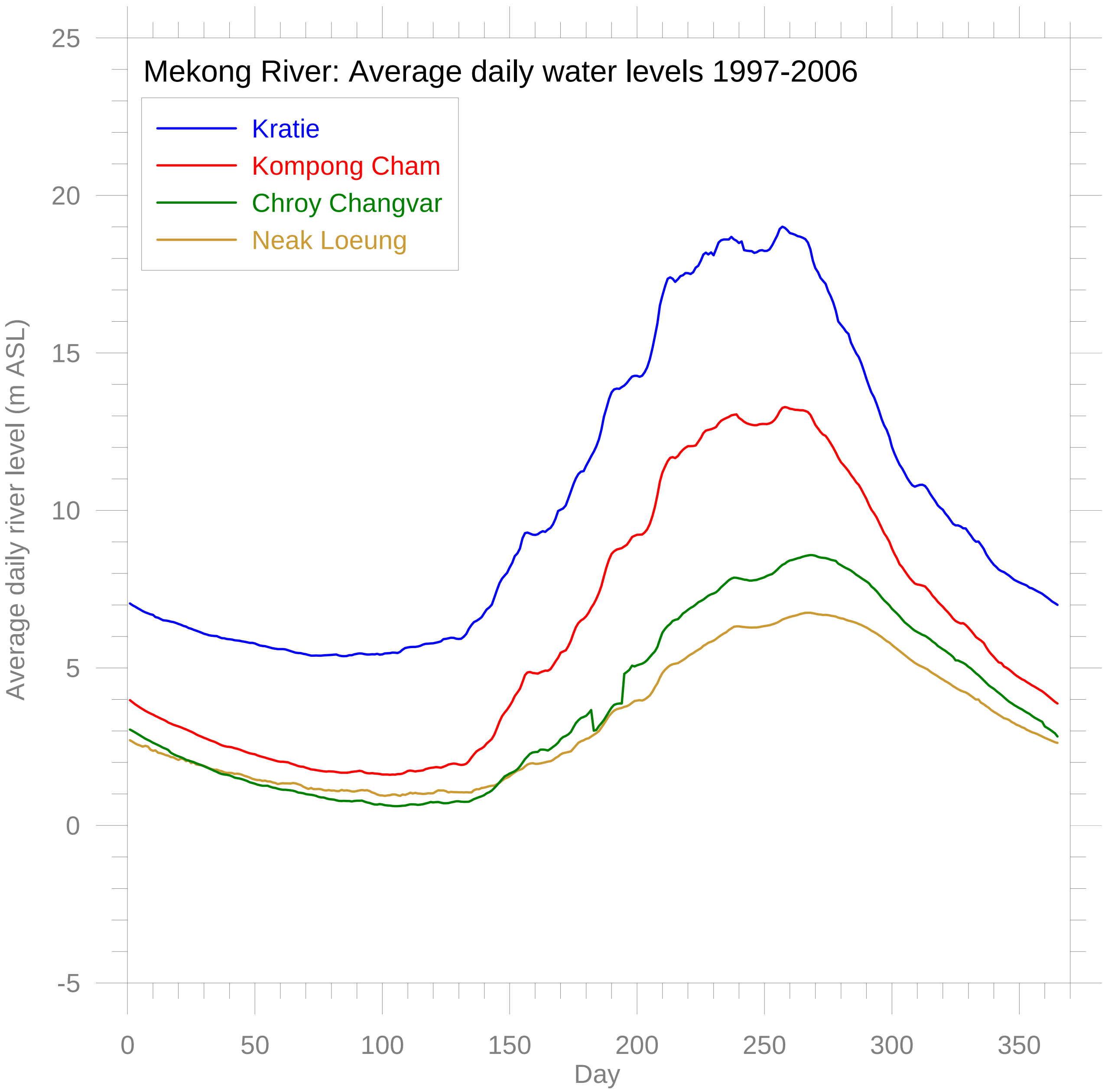


Water level record



6. Average water levels along the Mekong River

The averages between 1997 and 2006 of the average daily levels at each gauging station along the Mekong River are plotted below. These represent an idealized annual cycle of the river. As expected the average river levels decline progressing south along the river. The magnitude of the annual flood also diminishes progressing south.



The time-averaged levels are tabulated below.

Station	**Time-averaged water level (m ASL)**
Kratie	10.25
Kompong Cham	6.15
Chroy Changvar	3.90
Neak Loeung	3.31

Annex E: First Workshop Presentation

Prey Veng-Svay Rieng Groundwater Modeling Project

Kingdom of Cambodia
Ministry of Water Resources and Meteorology
Phnom Penh
February 28, 2007

Workshop Overview

- Study objectives
- Study team
- Study schedule
- Overview of groundwater modeling
- Discussion

Study Objectives

Final objective:

Develop a groundwater model to evaluate the feasibility and potential consequences of additional groundwater withdrawals for irrigation in Prey Veng and Svay Rieng provinces.

Study Goals

1. Understand, on a quantitative basis, regional groundwater flow in Prey Veng and Svay Rieng.

2. To build capabilities for analysis of groundwater systems in Cambodia, by Cambodians.

Study Team

- Michael Roberts, IDE (Cambodia)
- Christopher Neville, SSP&A (Canada)
- So Im Monichoth, CADTIS (Cambodia)
- Chiep Piseth, CADTIS (Cambodia)
- Pang Peng, MOWRAM (Cambodia)
- Preap Sameng, MOWRAM (Cambodia)

Study Schedule

- Project inception report: Nov. 2006
- Mission #1: Feb. 2007
- Development of the model: Feb.- March 2007
- Mission #2: April 2007
- Completion and reporting: Aug. 2007

What is groundwater modeling?

- Interpretation and synthesis of hydrogeologic data
- Development of regional and local water budgets
- Prediction of the effects of changes to a hydrologic system

Why is groundwater modeling important? (1)

- Formalize the understanding of regional hydrology
- Provide a context for historical and ongoing data collection
- Guide the design of monitoring programs

Why is groundwater modeling important? (2)

- Inform management decisions regarding water resources
- Provide rational basis for decisions regarding increased groundwater withdrawals at existing facilities
- Provide rational basis for the search for additional water supplies
- Inform land-use decisions

The Groundwater Modeling Process

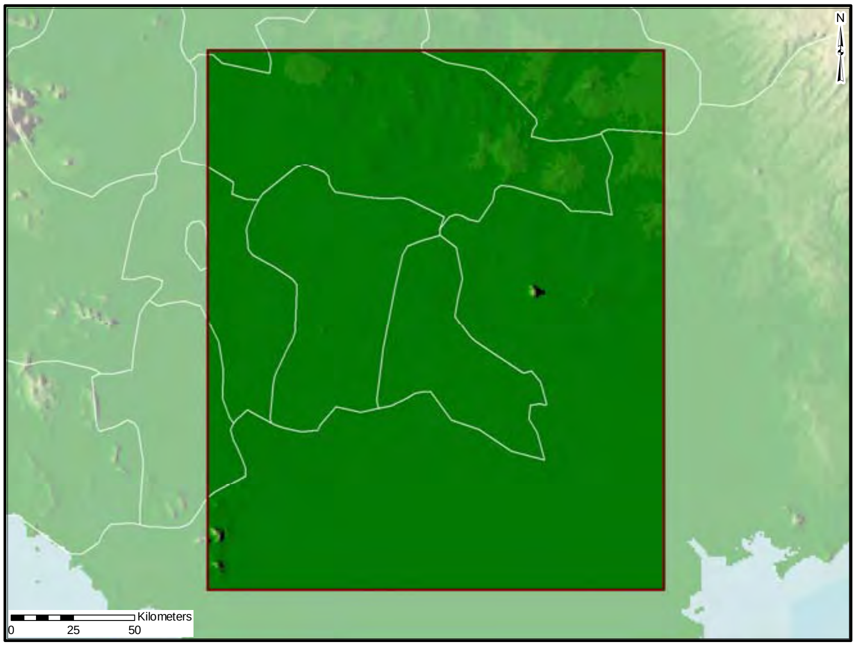
- Data compilation and review
- Conceptual model development
- Numerical model development
- Model calibration
- Model application
- Reporting

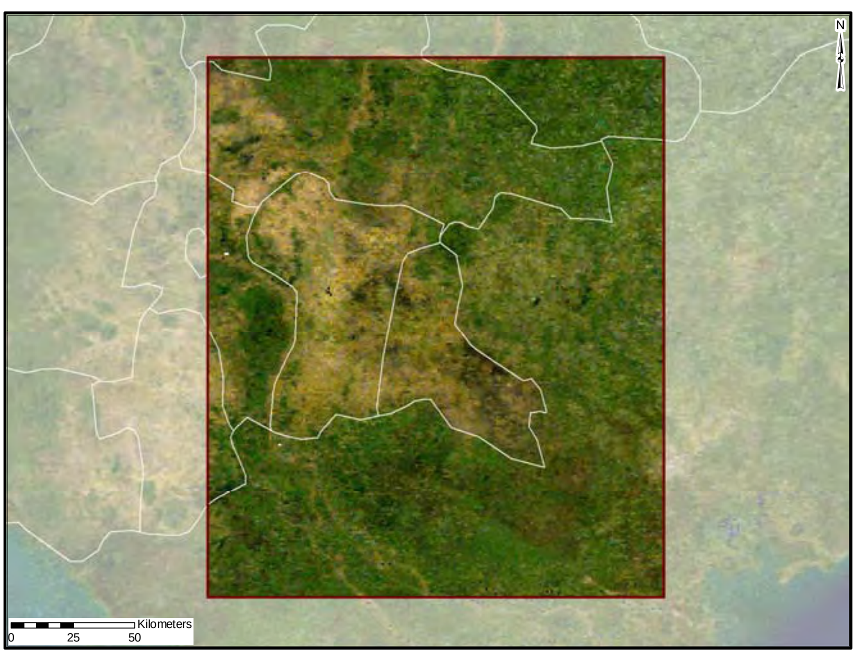
Data Compilation and Review

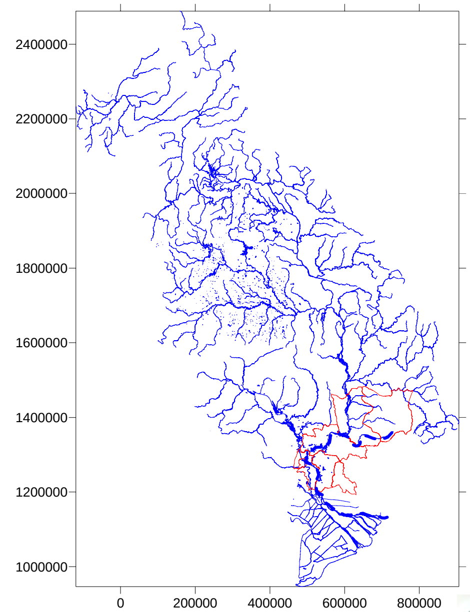
- Identification of data needs
- Compilation of data
- Plotting and review of data

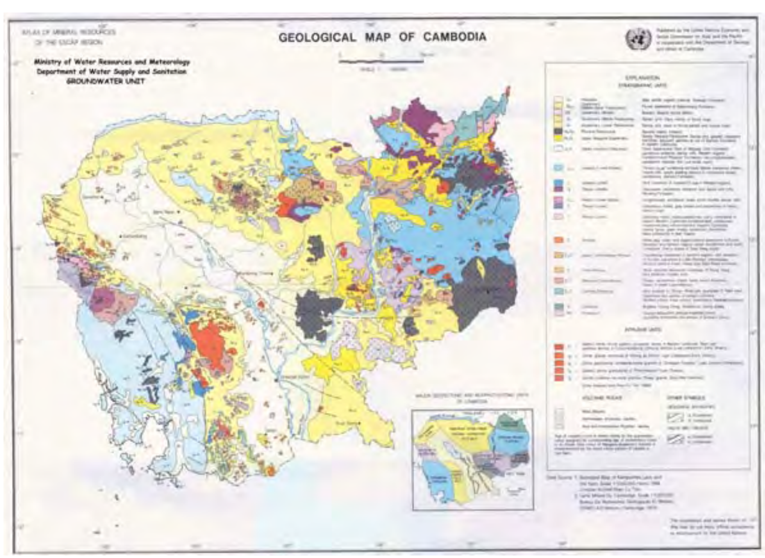
Data Compilation: Mapping

- Topography
- Land use
- Hydrography
- Geology


N
Kilometers
0 25 50

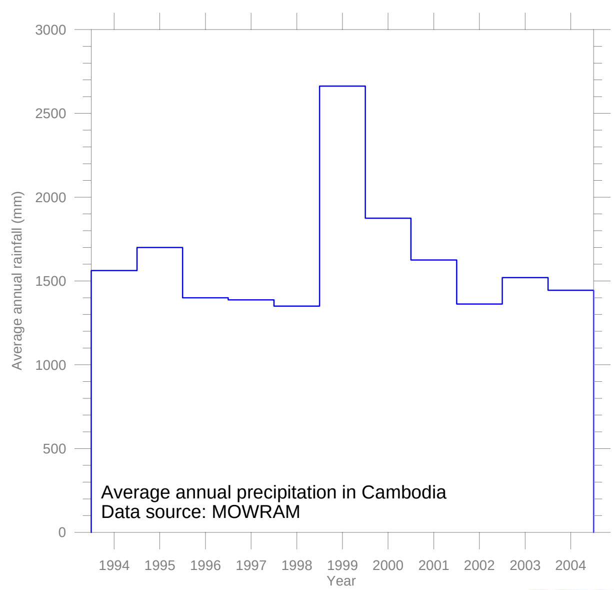

N
Kilometers
0 25 50

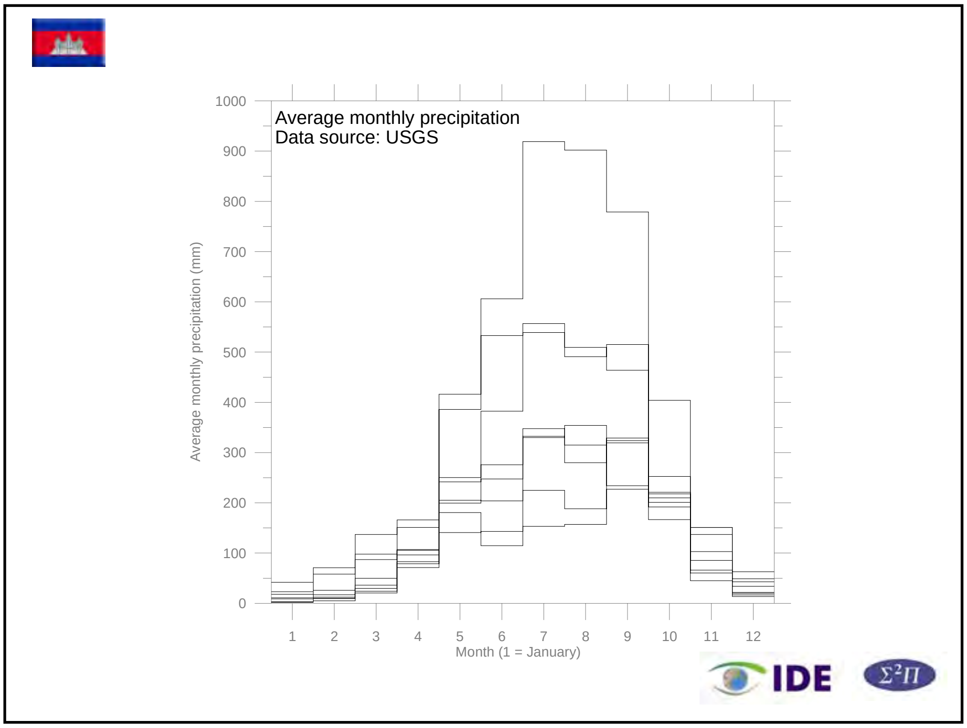

2400000
2200000
2000000
1800000
1600000
1400000
1200000
1000000
0
200000
400000
600000
800000

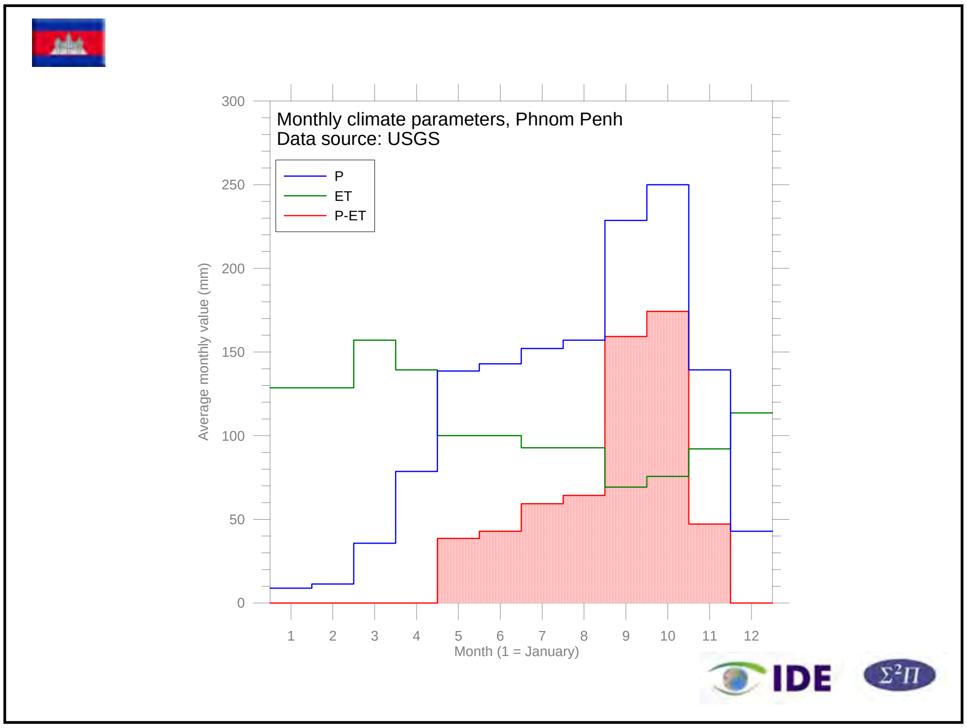

GEOLOGICAL MAP OF CAMBODIA
Ministry of Water Resources and Meteorology
Department of Water Supply and Sanitation
GROUNDWATER UNIT

Climate Data

- Annual precipitation
- Monthly precipitation
- Estimates of evaporation and plant transpiration

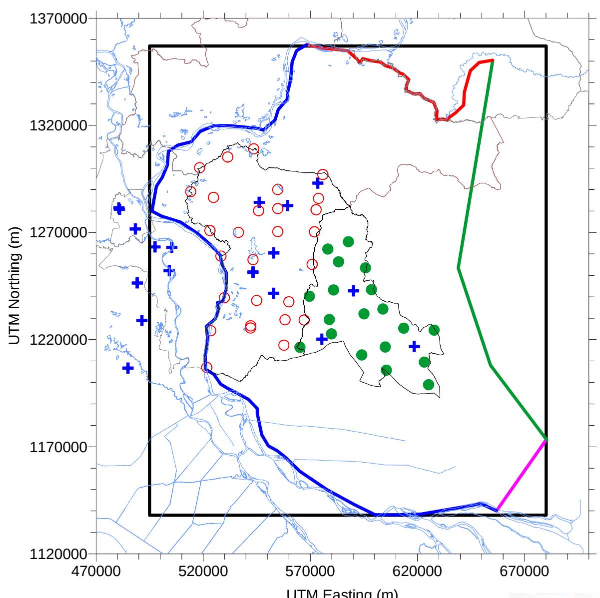



Average monthly precipitation
Data source: USGS
Average monthly precipitation (mm)
Month (1 = January)
IDE

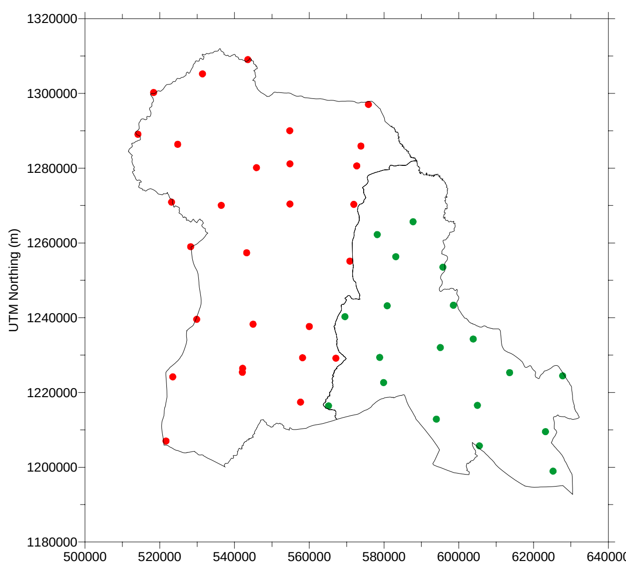

Monthly climate parameters, Phnom Penh
Data source: USGS
P
ET
P-ET
Average monthly value (mm)
Month (1 = January)
IDE

Hydrogeologic Data

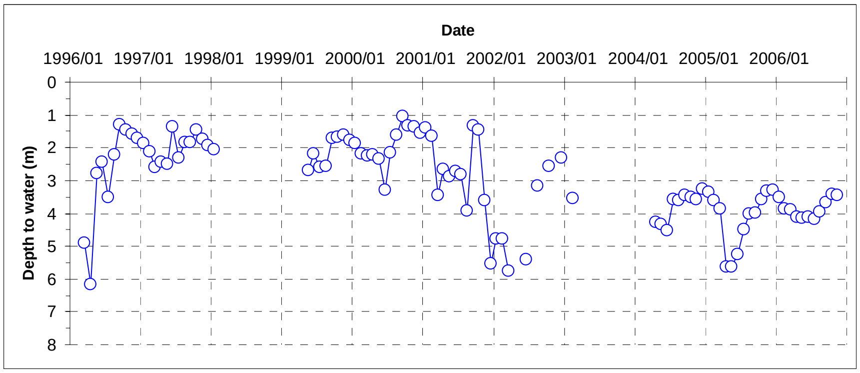
- Groundwater level data from observation wells
- "Point" water level data
- Existing interpretations of regional groundwater levels and flow directions
- Estimates of material properties from hydraulic testing



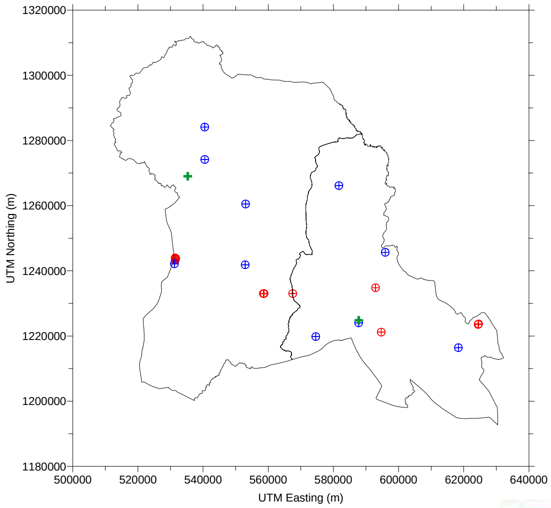
PRASAC Monitoring Program



PRASAC Svay Rieng: S2

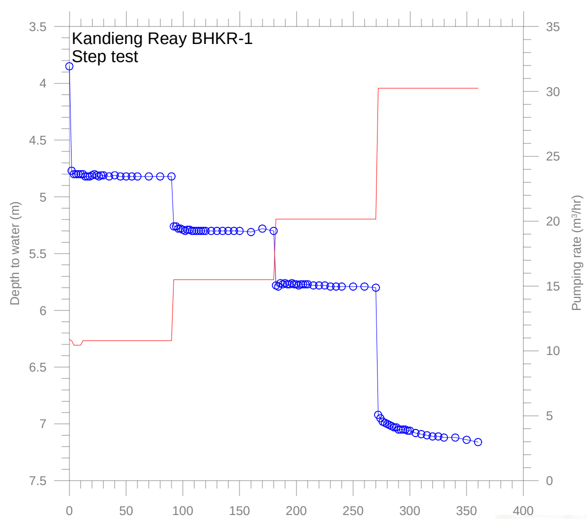


Hydraulic testing

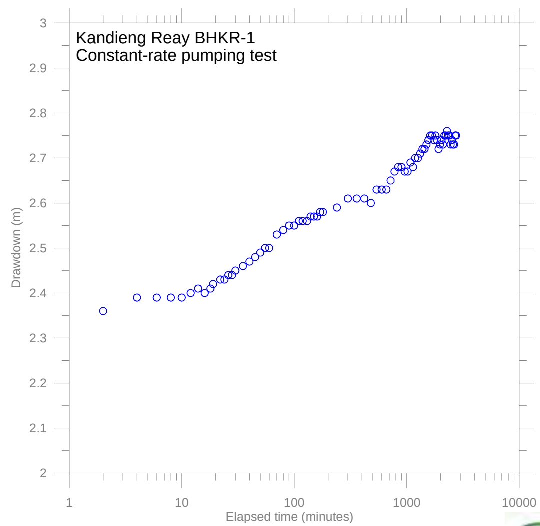


CUPPWSP Wells

Hydraulic testing (1)



Hydraulic testing (2)



Numerical Model Development

- Overall approach
- Simulation approach and modeling environment
- Model limits
- Finite-difference grid

Overall Modeling Approach

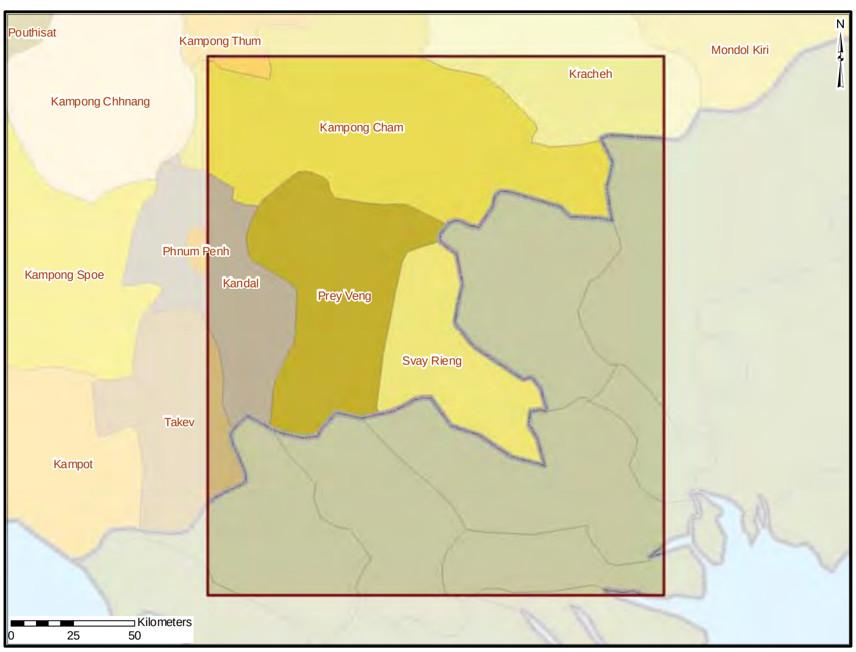
- General framework for understanding groundwater flow and assisting in management decisions
- Regional in scope, with the potential for eventual refinement to address local issues
- Phased approach

Simulation Techniques

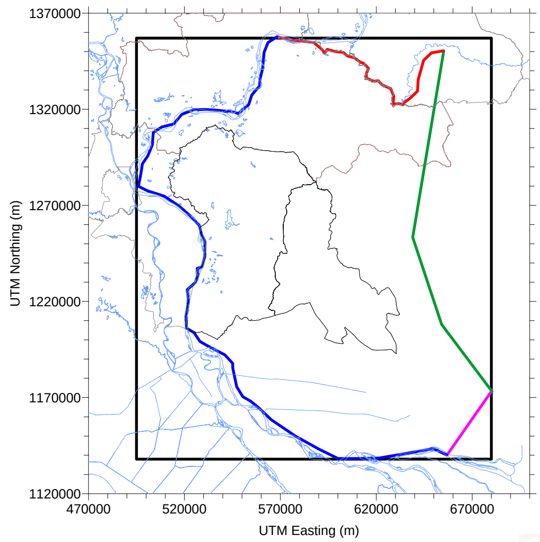
- MODFLOW (Finite-difference)
- Groundwater Vistas (Graphical User Interface)
- Techniques and application consistent with the state-of-the-art-practice in North America

Model Development

- Model limits
- Finite-difference grid

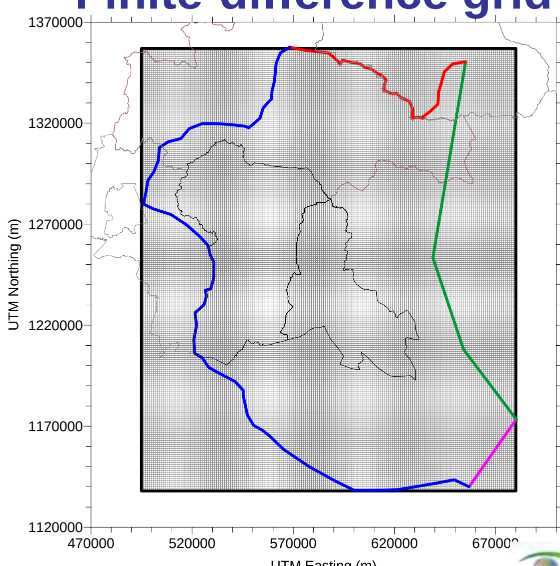


Model limits



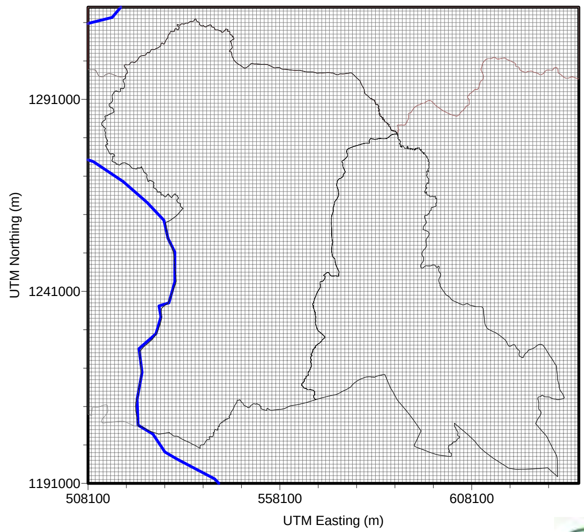
IDE

Finite-difference grid

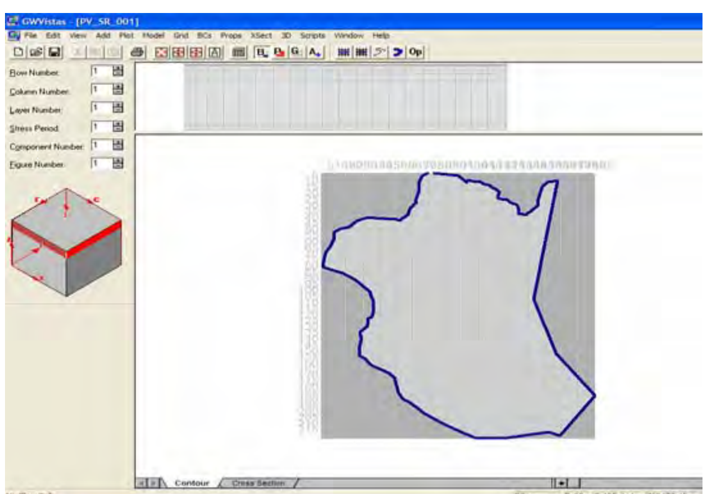


IDE

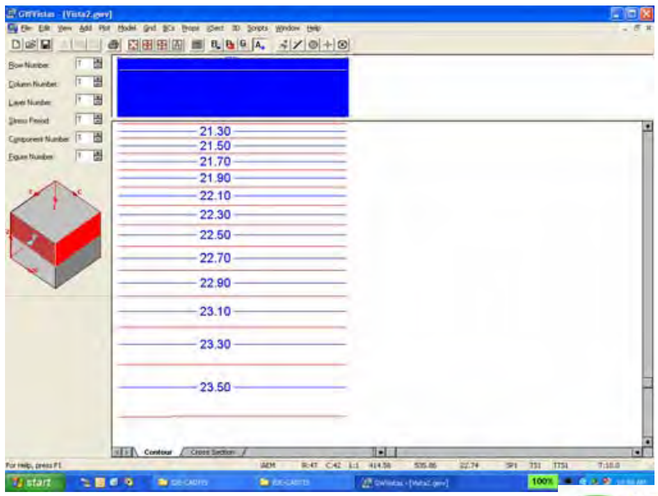
Finite-difference grid (detail)



Modeling environment (1)



Modeling environment (2)



Model Development (1)

- Development of the regional hydrostratigraphic model
- Mapping of surfaces to define model layers
- Specification of boundary conditions along the Mekong River and the southern discharge boundary

Model Development (2)

- Development of preliminary distributions of hydraulic conductivity
- Development of preliminary distribution of recharge
- Preliminary simulation of long-term average conditions

Model Calibration

- Why is calibration necessary?
- What conditions will we consider?
- What parameters will we adjust?
- What targets will we use to constrain the analyses?

Model Application

- Development of irrigation scenarios
- Model set-up for each irrigation scenario
- Numerical simulation
- Review and documentation of model results

Model Reporting

- A clear, complete and self-contained report on the model is essential.
- Documentation is simplified by preparation of regular, brief internal technical reports.
- Final reporting will follow state-of-the practice guidelines.
- Communication of key findings and understanding to all stakeholders is vital.

Next steps

- Ongoing data compilation and review
- Refinement of the conceptual model
- Completion of the initial development of the numerical model
- Model calibration
- Model application for evaluation of alternative irrigation scenarios

Challenges

- Language?
- Experience
- Lack of a central repository for hydrologic and hydrogeologic data
- Quality assurance of data
- Scale of analysis
- Complexity of the processes that control groundwater flow

Conclusions

- Models are important tools for management of groundwater resources.
- Modeling of Prey Veng and Svay Rieng will yield a physically-based, quantitative technique for evaluating the feasibility and potential impact of developing groundwater supplies for irrigation.

Questions or Comments?

GROUNDWATER MODEL IN PREY VENG AND SVAY REANG PROVINCES

Questionnaire from workshop
at MOWRAM Place

សំនួរពិភាក្សាសិក្ខាសាលានៅក្រសួងធនធានទឹកនិងឧតុនិយម
ស្តីពី ម៉ូឌែលទឹកក្រោមដី

សំនួរពិភាក្សាសំរាប់ក្រុមទី ១:

១.តើម៉ូឌែល មួយអាចប្រើប្រាស់បានរយៈពេលប៉ុន្មាន? តើមានការកែលំអរវាដែរឬទេ?
២.តើស្រទាប់ទឹកក្រោមដីមានជំរៅប៉ុន្មាន? តើគេអាចប្រើវាបានក្នុងជំរៅណាខ្លះ?
៣.តើម៉ូឌែល អាចប្រាប់ពេលកំណត់នៃការប្រើប្រាស់ទឹកបានឬទេ? តើមានការប៉ះពាល់យ៉ាងដូចម្តេចដែរ?
៤.តើម៉ូឌែល អាចប្រាប់សារធាតុបំពុលទឹកក្រោមដីឬទេ?តើវាមានកំរិតណាដែរ?
៥.តើម៉ូឌែល អាចដឹងពីជំរាបទឹកក្រោមដីមកពីតំបន់ផ្សេងៗឬទេ?
៦.តើម៉ូឌែល អាចគណនាគុណភាពទឹកសំរាប់ប្រភេទដំណាំបានដែរឬទេ?

សំនួរពិភាក្សាសំរាប់ក្រុមទី ២:

១. តើម៉ូឌែល សិក្សាដូចម្តេចទើបដឹងពីបរិមាណទឹកក្រោមដី?
២.តើការសិក្សាទឹកក្រោមដីមានសារៈប្រយោជន៍អ្វីខ្លះសំរាប់អនាគត់? ឧទា.នៅខេត្តស្វាយរៀងមានចំនួន៧ស្រុក ដែលទឹកមានរសជាតិជូរ។
៣.តើការយកទឹកក្រោមដីសំរាប់ស្រោចស្រពដំណាំកសិកម្ម មានផលប៉ះពាល់ដល់អ្វីខ្លះទៅថ្ងៃអនាគត់?
៤.តើប្រភពទឹកក្រោមដីមានសណ្ឋាននិងលក្ខណៈខុសគ្នាដូចម្តេច? តើម៉ូឌែលនេះអាចប្រាប់បានឬទេ?
៥.តើយើងសិក្សាដូចម្តេចទើបដឹងថា ការប្រើប្រាស់ទឹកជាមធ្យមប្រចាំថ្ងៃ?

៦. តើម៉ូឌែល អាចកំណត់ព្រំដែននៃសារធាតុគីមីក្នុងទឹកក្រោមដីបានឬទេ?

៧. តើម៉ូឌែលអាចប្រាប់បានទេ បើសិនជាអណ្តូងទឹកជ្រៅៗ បូមទឹកប្រើច្រើន ហើយមានការប៉ះពាល់ដល់អណ្តូងរាក់ៗ ដែលនៅជិតវា ដូចម្តេចដែរ?

៨. តើពាក្យម៉ូឌែល មានន័យដូចម្តេចដែរ? ហេតុអ្វីត្រូវធ្វើម៉ូឌែលទឹកក្រោមដី?

<u>សំនួរពិភាក្សាសំរាប់ក្រុមទី.៣:</u>

១.តើម៉ូឌែល អាចបញ្ជាក់ថាតើបរិមាណធនធានទឹកដែលមាននៅខេត្តព្រៃវែងនិងស្វាយរៀងប៉ុន្មាន បើសិនជាគេយកវាទៅស្រោចស្រពដំណាំស្រូវ នៅខែប្រាំងនិងខែវស្សា? តើវាមានលទ្ធភាពអាចស្រោចស្រពបាននៅតំបន់អភិវឌ្ឍន៍ណាខ្លះ?

២.តើម៉ូឌែល អាចដឹងពីបរិមាណសារធាតុអាសេនីក និងអាចកំណត់តំបន់ដែលមានជាតិអាសេនិក, ជាតិជូរ និងជាតិផ្សេងៗទៀតដែរឬទេ?

៣.តើអាចកំណត់ជំរៅអណ្តូងដែលជីកសំរាប់ទាញយកទឹកប្រើប្រាស់នៅរដូវប្រាំងដោយមិនចេះរីងស្ងួត បានឬទេ?

៤.តើម៉ូឌែល អាចដឹងនិងកំណត់ពីប្រភេទដំណាំអ្វីខ្លះដែលអាចដាំបាន បើសិនជាគេយកទឹកដែលមានគុណភាពធម្មជាតិនៅតំបន់នោះ យកមកប្រើប្រាស់ស្រោចស្រព?

៥. តើម៉ូឌែល អាចដឹងនិងប្រាប់ពីរយៈពេល នៃផលប៉ះពាល់គុណភាពដី ដោយសារការប្រើប្រាស់ធនធានទឹកក្រោមដីដែរឬទេ?

៦. តើម៉ូឌែល អាចប្រាប់ពីបំរែបំរួលទឹកក្រោមដីពីតំបន់មួយទៅតំបន់មួយបានដែរឬទេ?

៧. តើម៉ូឌែល អាចដឹងពីកំរិតនៃការស្រុតដី ដោយសារការទាញយកទឹកក្រោមដីមកប្រើច្រើនទៅតាមតំរូវការចាំបាច់នោះ?

<u>សំនួរពិភាក្សាសំរាប់ក្រុមទី.៤:</u>

១.តើ ម៉ូឌែល ផ្តល់អនុសាសន៍បែបណាដើម្បីអោយអណ្តូងមានទឹកឡើងវិញ?

២.តើខេត្តទាំង២ " **ព្រៃវែង និងស្វាយរៀង** " អាចជីកអណ្តូងបានប៉ុន្មានបន្ថែមទៀតលើអណ្តូងចាស់ ហើយនៅតំបន់ណា?

៣.តើម៉ូឌែល អាចប្រាប់ពីតំបន់ណាដែលអាចយកទឹកអណ្តូងទៅប្រើប្រាស់សំរាប់ការងារដាំស្រូវ ដាំបន្លែ និងសំរាប់ហូប ហើយនៅពេលណា?

៤.តើក្នុង១ខែអាចបូមទឹកបានប៉ុន្មានម៉ែតគីប?

៥.តើកំណត់នីវ៉ូទឹកសមុទ្រទៅនិងកន្លែងអណ្តូងដែលយើងវាស់ យ៉ាងដូចម្តេច?

៦.តើការប្រើប្រាស់ទឹកក្រោមដីច្រើន វាប្រែប្រួលយ៉ាងដូចម្តេចដែរ? ចុះបើប្រើតាមការកំណត់ នោះវាប្រែប្រួលដែរឬទេ?

៧.តើម៉ូឌែល អាចធ្វើការកំណត់ពីគុណភាពទឹកក្រោមដីបានដែរឬទេ?

៨.តើម៉ូឌែល អាចបញ្ជាក់ពីបរិមាណទឹកក្រោមដី នៅពេលទឹកជំនន់និងពេលរាំងស្ងួតដែរឬទេ?

៩.តើម៉ូឌែល អាចបញ្ជាក់ពីនិតិវិធីក្នុងការទាញយកទឹកក្រោមដីមកប្រើ "បរិមាណទឹក" បានទេ?

Annex F: Second Workshop Agenda and Minutes

Groundwater Modeling Scenarios Meeting
June 8, 2007

Agenda

1. Meeting objectives
2. Potential modeling scenarios
3. Recommended modeling scenarios

Attachments

1. Map of installed and proposed CPPUWSP municipal production wells
2. Questions from the February 2007 Groundwater Model Workshop

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1- Meeting objectives

This meeting has been organized to discuss applications of the groundwater model of Prey Veng and Svay Rieng that is currently being developed. These applications are referred to as *modeling scenarios*.

The meeting is intended to be an informal discussion to identify the first set of questions that can be addressed by the model. The desired outcome of the meeting will be a list of specific scenarios that will be the first analyses with the model.

2- Potential modeling scenarios

During the February 2007 Groundwater Model Workshop, the group sessions identified a comprehensive list of questions that are of interest. In an attachment to these notes we have grouped these questions into those for which the model is presently being developed to address, and those which the model may in the future be extended to address. The initial applications of the groundwater model will be related to questions concerning groundwater quantity and specifically to estimating groundwater supplies that may be available for irrigation.

After the groundwater model has been calibrated, it can potentially be used to address a wide range of questions. We have identified several categories for scenario development:

1- Maximum yield;
2- Groundwater withdrawal for irrigation in targeted areas;
3- Development of large-capacity municipal supply wells;
4- Long-term climate change; and
5- Man-made changes in the Mekong River.

Maximum yield

What are the sustainable groundwater yields of Prey Veng and Svay Rieng as a whole?

Regional irrigation projects

What are the potential effects of developing groundwater supplies for irrigation in targeted areas?

Development of large-capacity municipal supply wells

What are the potential effects of pumping from large-capacity municipal supply wells that have already been installed or are planned under the *Cambodia Provincial and Peri-Urban Water and Sanitation Project* (CPPUWSP) program?

What are the potential effects of developing additional local groundwater supplies to meet projected population growth?

Long-term climate change

How might the magnitude of available groundwater supplies be affected by long-term climate change?

Man-made changes in the Mekong River

How might the magnitude of available groundwater supplies be affected by construction of major hydraulic structures (dams, dykes, reservoirs, canals) along the Mekong River and its tributaries?

3- Recommended modeling scenarios

Potential long-term changes in climate and the construction of major hydraulic structures may have profound implications with respect to the availability of groundwater supplies for irrigation in Prey Veng and Svay Rieng. The groundwater model will provide a general framework within which these changes can be assessed. Although the long-term changes may be significant, for this study we recommend that the first model scenarios be developed to analyze the potential effects of developments within the next five years.

<u>Recommended Scenario 1: Province-wide sustainable yield assessment</u>

This scenario will be developed to predict the sustainable groundwater yield of Prey Veng and Svay Rieng provinces as a whole. A maximum allowable decline in water levels will be specified for the entire area of both provinces, and the groundwater model will be used to predict the groundwater yield.

<u>Recommended Scenario 2: Regional irrigation projects</u>

This scenario will be developed to predict the effects of groundwater developments in targeted areas.

What areas are priorities for irrigation with groundwater?
How much water may be required to achieve the irrigation objectives?

<u>Recommended Scenario 3: Development of large-capacity municipal supply wells</u>

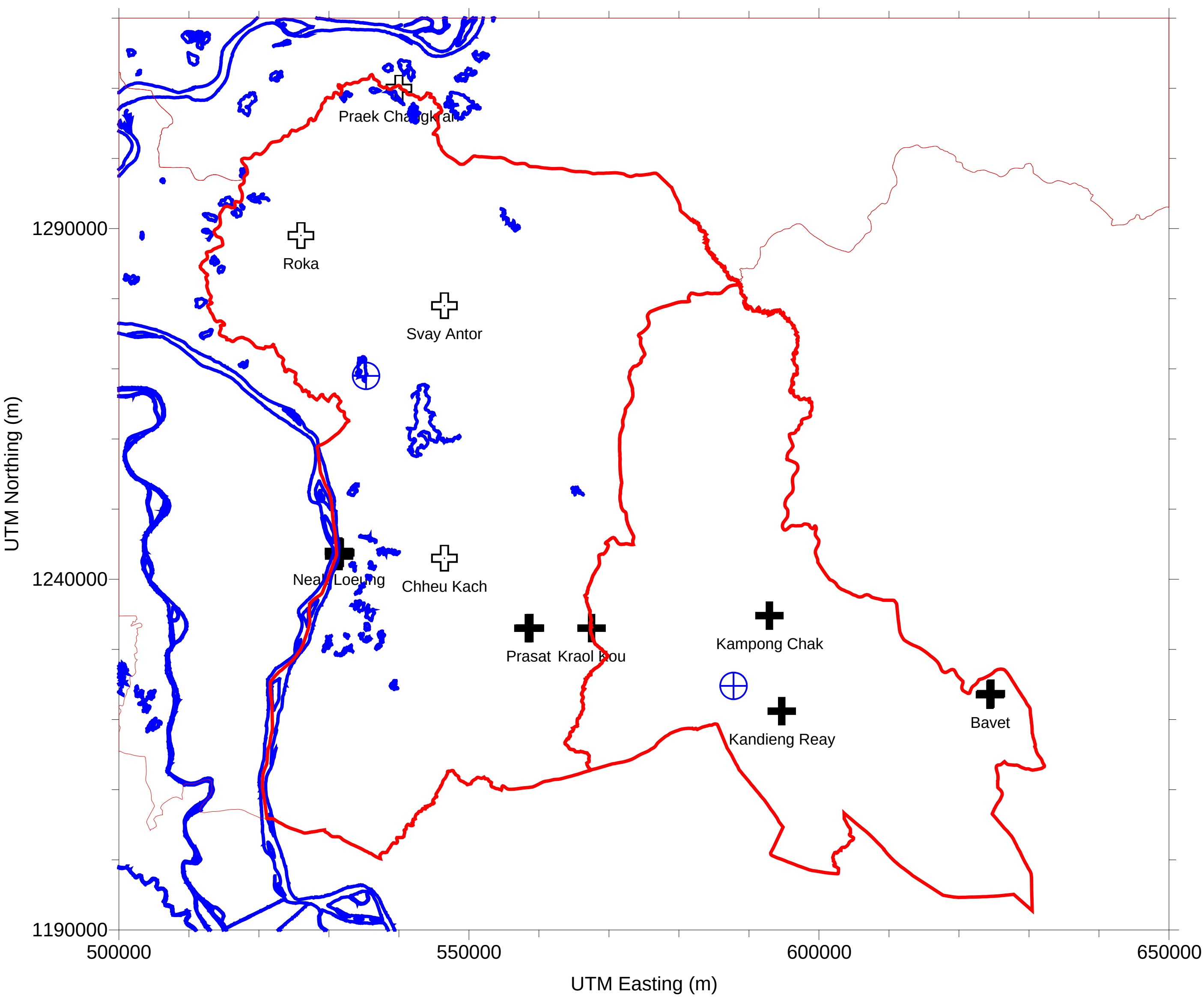
A total of nine (9) large-capacity municipal supply wells have already been installed under the *Cambodia Provincial and Peri-Urban Water and Sanitation Project* (CPPUWSP) program. According to the World Bank Environmental Assessment for the CPPUWSP program, an additional four (4) locations are planned for development in Prey Veng and Svay Rieng. The locations of the wells are shown in Figure 1.

We recommend that a scenario be developed to simulate the potential regional effects of the combined installed and planned wells.

What are the expected yields for the four proposed locations?

We anticipate that additional groundwater supplies may be developed to meet growing populations in the towns in Prey Veng and Svay Rieng. Has anyone made projections of population growth and expected municipal water requirements?

Figure 1
Locations of installed and proposed CPPUWSP wells
with Prey Veng and Svay Rieng municipal wells



Questions from the February 2007 Groundwater Model Workshop

1. Questions that the Prey Veng-Svay Rieng groundwater model is being developed to address

<u>Group 1:</u>

1- How long can the groundwater model be used? Can the model be updated?

3- Can the groundwater model be used to evaluate the maximum safe groundwater yield?

5- Can the groundwater model be used to identify recharge areas for the groundwater system?

<u>Group 2:</u>

1- Can the groundwater model be used to estimate the quantities of groundwater that are available?

3- Can the groundwater model be used to predict the impacts of developing groundwater supplies for vegetable cultivation?

7- Can the groundwater model be used to assess the potential impacts to shallow wells from excessive pumping of deep wells?

<u>Group 3:</u>

1- Can the groundwater model be used to estimate the amount of groundwater that is available for irrigation of rice paddies during the dry and rainy seasons? Can the model be used to identify which zones to irrigate?

3- Can the model be used to predict whether a well will go dry due to pumping during the dry season?

5- Can the model be used to assess variations in groundwater from one region to another?

<u>Group 4:</u>

1- Will the model be used to make recommendations regarding wells drying up?

2- How many additional wells can be installed in Prey Veng and Svay Rieng provinces? Where will the new wells be located?

4- How many cubic meters of water can be pumped each month in Prey Veng and Svay Rieng?

6- What will be the impacts of large-scale groundwater withdrawals? What are the potential impacts if a mandated pumping schedule is followed?

8- Can the model be used to evaluate the quantity of groundwater that is available during the dry and flood seasons?

9- Can the model be used to develop groundwater extraction strategies [and the quantity of groundwater that is available]?

2. Questions that the Prey Veng-Svay Rieng groundwater model may eventually be extended to address

<u>Group 1:</u>

4- Can the groundwater model be used to identify areas of groundwater contamination?

6- Can the groundwater model be used to assess the quality of water available for agricultural use?

<u>Group 2:</u>

2- Can the groundwater model be used to predict changes in water quality? [There are 7 districts in Svay Rieng province in which groundwater supplies have become sour. Can the model be used to identify the cause?]

6- Can the groundwater model be used to map the distribution of dissolved mineral species (for example, arsenic and iron)?

<u>Group 3:</u>

2- Can the model be used to identify areas where arsenic concentrations are elevated, and the limits of the areas with high arsenic?

5- Can the model be used to assess changes in soil quality due to groundwater use [i.e., due to the application of irrigation water]?

7- Can the model be used to predict the amount of land subsidence that may occur due to heavy pumping for irrigation?

<u>Group 4:</u>

7- Can the groundwater model be used to assess water quality?

STRATEGIC STUDY OF GROUNDWATER RESOURCES
IN PREY VENG AND SVAY RIENG (PHASE 2)

Workshop for the Discussion of Modeling Scenarios
Friday, June 8, 2007
MoWRAM Tuk Thla office

Present

- Meng Sakphouseth, PSDD
- Hir Samnang, MoI
- Pang Peng, MoWRAM
- Preap Sameng, MoWRAM
- _________, MoWRAM
- Christopher Neville, SSP&A
- So Im Monichoth, CADTIS
- Chiep Piseth, CADTIS
- Michael Roberts, IDE

Purpose

- Present and discuss recommendations for the scenarios to be modeled in the groundwater study.

Meeting began with a brief description of the groundwater modeling project and a description of what a *scenario* is.

This was followed by a presentation of three proposed scenarios. The scenarios are described in the meeting handout (attached). Below are the comments arising out of the discussion.

Scenario 1: (calculate withdrawal rate that will draw down the water level to 6m)

- Why choose 6 m as the maximum drawdown depth? Because this represents an important threshold. Groundwater above 6m can be easily accessed by many people using simple and inexpensive pumps. If the water depth drops below 6m, many existing pumps will become ineffective resulting in a significant increase in the cost of accessing water.
- The withdrawal rates should be calculated for other depths as well to develop a relationship curve.

Scenario 2: (modeling agricultural water use)

- Should model projected water needs (+10 years?) in existing agricultural areas determined from land use maps
- Should calculate limits to agricultural use

Scenario 3: (modeling town water supplies)

- Should also model significant private well users, e.g., casinos and hotels. But where is information on these users available?

General discussion

- A fourth scenario should be created combining Scenarios 2 and 3

- In looking at climate change questions or Mekong River level changes we should not look very far into the future (25+ years), the emphasis should be on near term uses of the model.
- The immediate needs are for information and recommendations related to the design and implementation of development projects by government and NGOs:
    - What areas can be developed for groundwater use and what areas should be left alone?
    - What types of development (agriculture, domestic, municipal) are feasible in each area?
- Can the model estimate required well depths in an area (useful in project costing)? Could give mean depths over large areas but not very detailed.

Next steps:
Scenario descriptions to be revised and circulated for comment

Annex G: Final Workshop Presentation

Strategic Study of Groundwater Resources in Prey Veng and Svay Rieng (Phase 2)

Final Stakeholder Workshop

Kingdom of Cambodia
National Committee for Sub-National Level Democratic Development
Ministry of Water Resources and Meteorology
Phnom Penh, August 28, 2009

Study Team

- Michael Roberts, IDE (Cambodia)
- Christopher Neville, SSP&A (Canada)
- So Im Monichoth, CADTIS (Cambodia)
- Chiep Piseth, CADTIS (Cambodia)
- Pang Peng, MOWRAM (Cambodia)
- Preap Sameng, MOWRAM (Cambodia)
- Jinhui Zhang, SSP&A (Canada)

Objectives of this Workshop

1. Understand what a groundwater model is and what it can and cannot be used for
2. Understand the results from the PVG-SVG groundwater model that was developed during this project
3. Understand the potential uses of the PVG-SVG groundwater model in the future

Workshop Overview

- Study Objectives
- Groundwater Level Records
- Building the Groundwater Model
- Sustainable Groundwater Withdrawals
- Questions and Discussion
- Future Uses of the Model
- Integrating Planning and Modeling
- Questions and Discussion

Workshop Overview

- Study Objectives
- Groundwater Level Records
- Building the Groundwater Model
- Sustainable Groundwater Withdrawals
- Questions and Discussion
- Future Uses of the Model
- Integrating Planning and Modeling
- Questions and Discussion

Study Objective

Develop a groundwater model to evaluate the effect of additional groundwater withdrawals for irrigation in Prey Veng and Svay Rieng provinces.

Workshop Overview

- Study Objectives
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- Sustainable Groundwater Withdrawals
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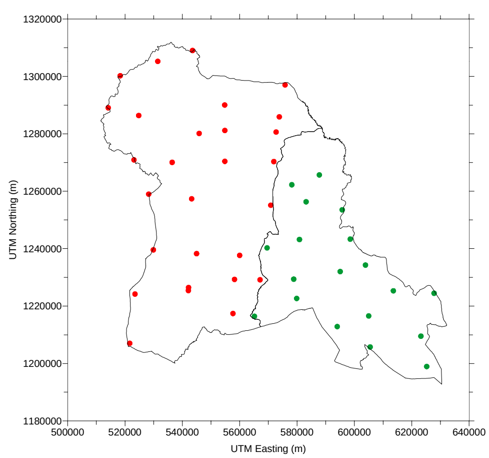
- Future Uses of the Model
- Integrating Planning and Modeling
- Questions and Discussion

IDE ΣΠ

Groundwater Monitoring



- Network of 49 monitoring wells
- Installed in 1996 by EU-PRASAC

IDE ΣΠ

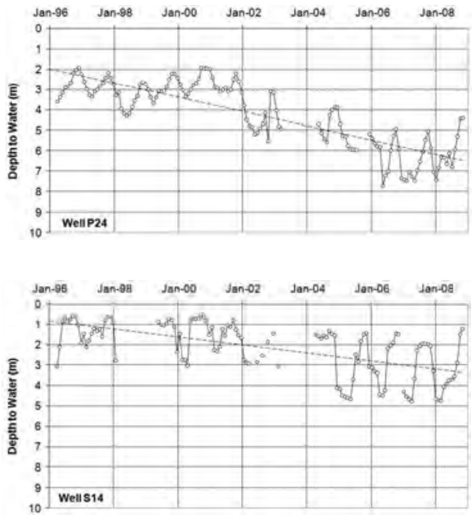
Groundwater Monitoring

- Monthly water levels collected by PDoWRAM in PVG and SVG
- Such a long-term record from so many wells is a ***remarkable achievement***

Groundwater Monitoring

- Water level in many monitoring wells show decreasing water levels
- There is concern that overuse of the groundwater for irrigation may be causing the decline

Groundwater Monitoring

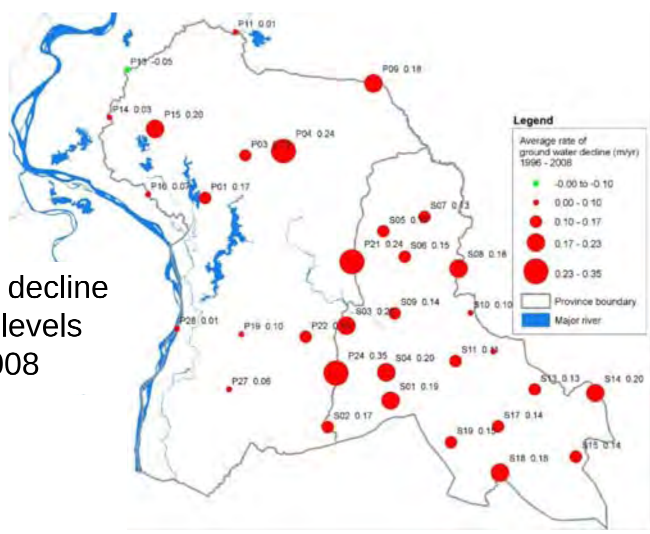


These plots are typical of the 49 groundwater monitoring wells in PVG and SVG

Overall trend of declining groundwater levels from 1996 through 2008

IDE

Groundwater Monitoring



Average rate of decline in groundwater levels from 1996 to 2008

IDE

Workshop Overview

- Study Objectives
- Groundwater Level Records
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- Questions and Discussion

What is a groundwater model?

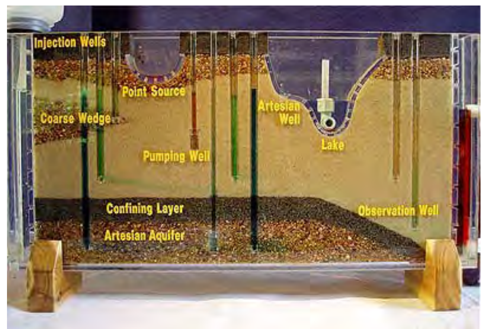
A simplified version of a real-world groundwater flow system that…

- simulates certain aspects of the real-world system
- can be used to predict how the real-world system will react to certain changes

What is a groundwater model?

One type of model is a small-scale physical model

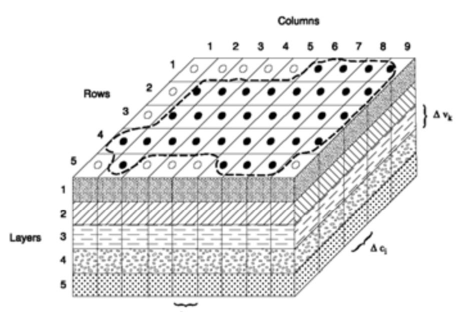
Uses real gravel, sand, clay and colored dyes to observe how water flows.



What is a groundwater model?

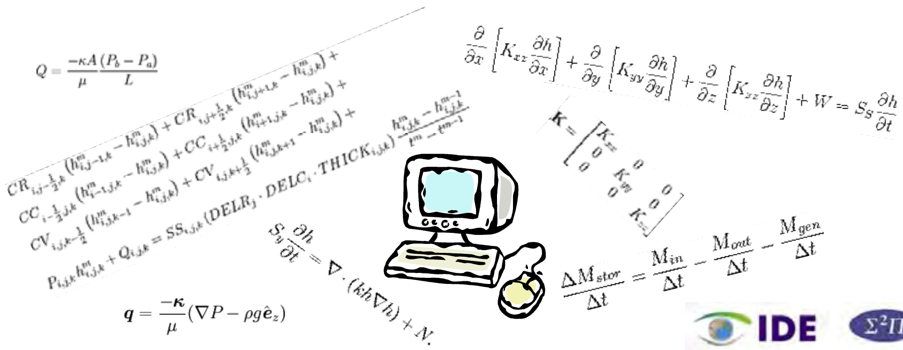
Another type is a numerical groundwater model

Divides the study area up into a grid of small cells and…



What is a groundwater model?

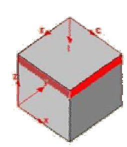
…uses a computer to calculate the water level in each cell and the flow between cells using mathematical equations.



Groundwater modeling software

This study used two software packages to create a mathematical groundwater model:

Groundwater Vistas was used to define the characteristics of the grid cells



MODFLOW was used to solve the model equations

$$Q = \frac{-\kappa A}{\mu} \frac{(P_b - P_a)}{L}$$

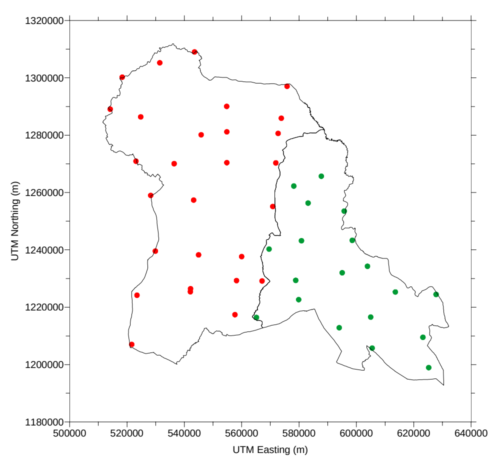
Building the Groundwater Model

1. Data compilation	Gather relevant information on topography, geology, hydrology, climate, and aquifer parameters
2. Conceptual model	Develop an understanding of how the real-world groundwater system works
3. Numerical model	Determine the model boundaries, grid spacing, and parameters for each grid cell
4. Model calibration	Adjust key parameters in the numerical model until the results match real-world observations as closely as possible

Data Compilation

Key data sources:

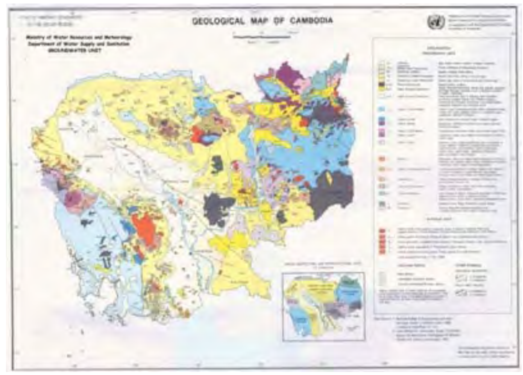
PDoWRAM groundwater monitoring wells



Data Compilation

Key data sources:

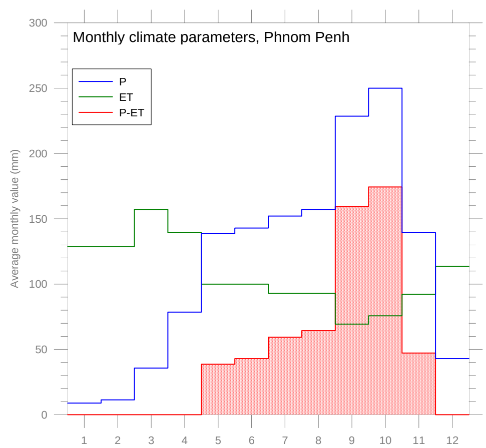
Geologic maps



Data Compilation

Key data sources:

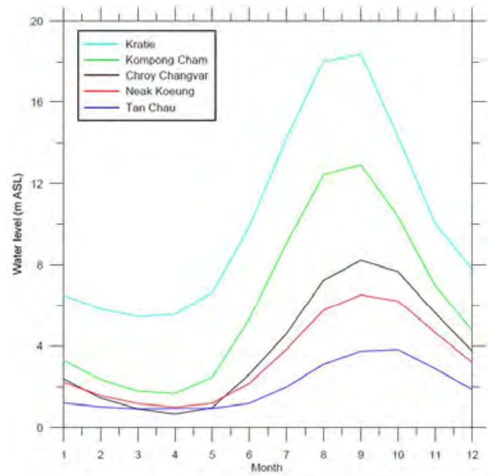
Climate data



Data Compilation

Key data sources:

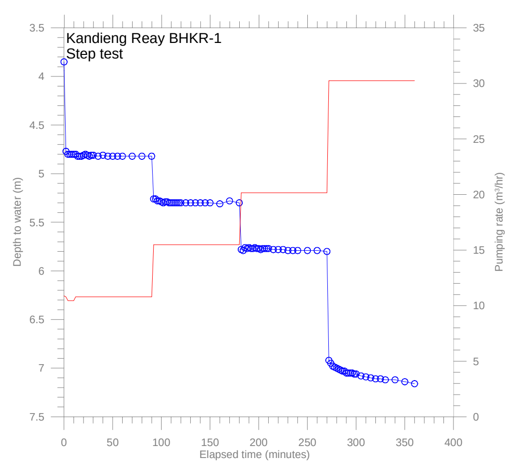
Mekong River levels



Data Compilation

Key data sources:

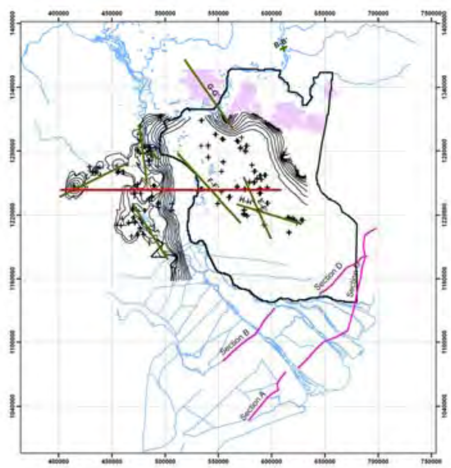
Well pumping tests at CUPPWSP wells to determine hydraulic conductivity of the aquifer



Data Compilation

Key data sources:

Depth-to-bedrock and geologic cross sections from various reports



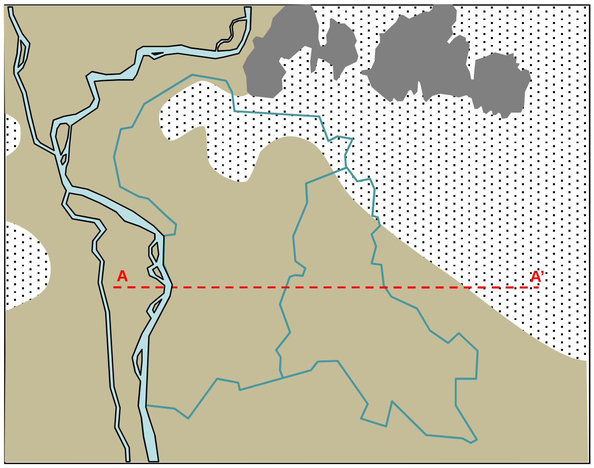
IDE

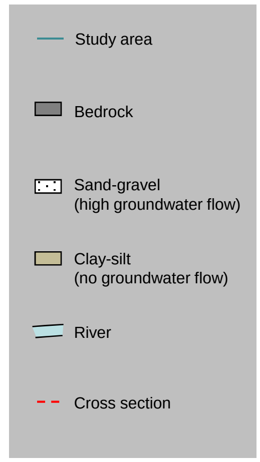
Conceptual Model

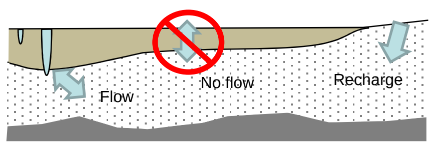
All data are reviewed and studied to develop an understanding of how the real-world groundwater system works

IDE

Conceptual Model



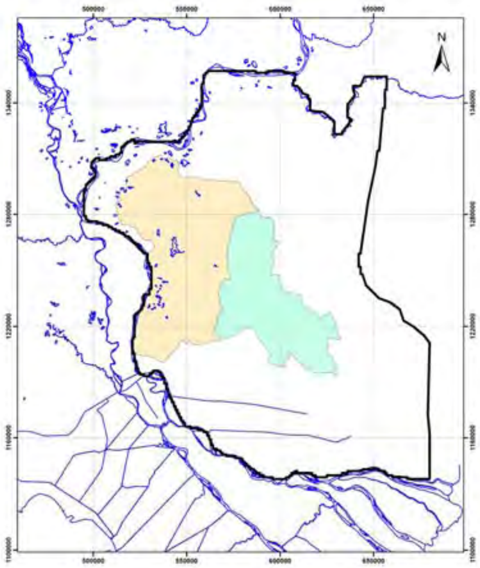




Numerical Model

Determine the model boundaries, grid spacing, and parameters for each grid cell

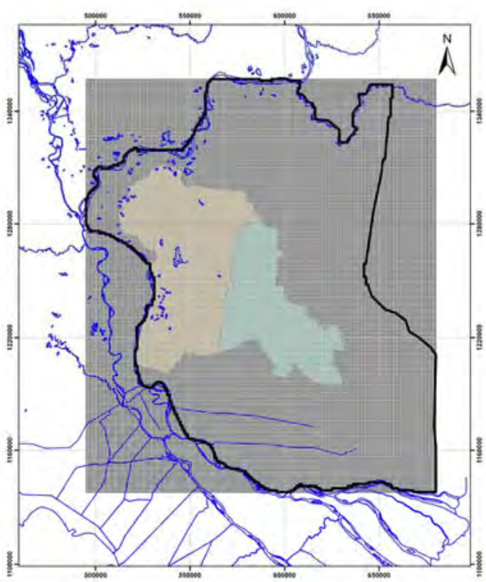
Numerical Model



Define model boundaries based on hydrological features such as:

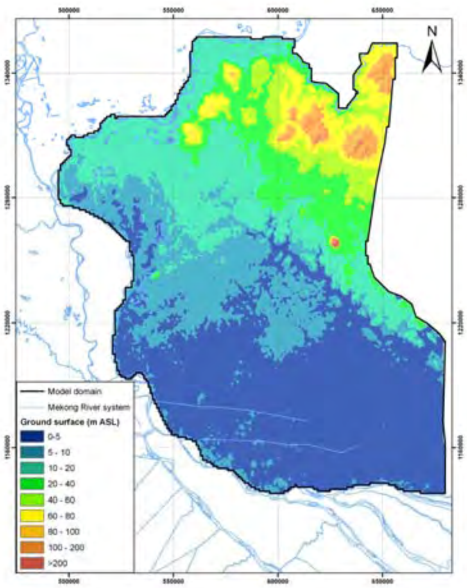
- Rivers
- Flow divides

Numerical Model



Define grid spacing: 1 km x 1 km

Numerical Model



Ground surface elevation

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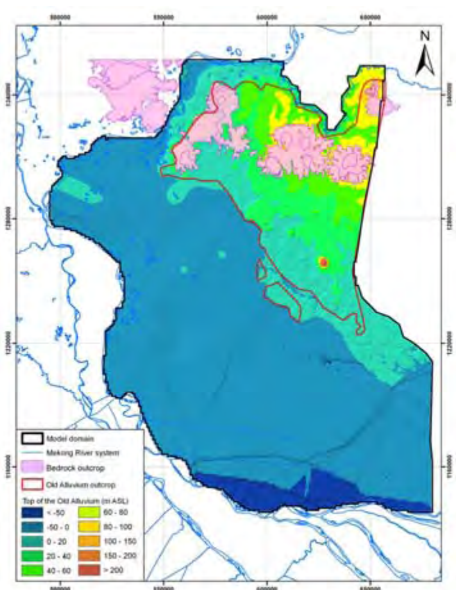
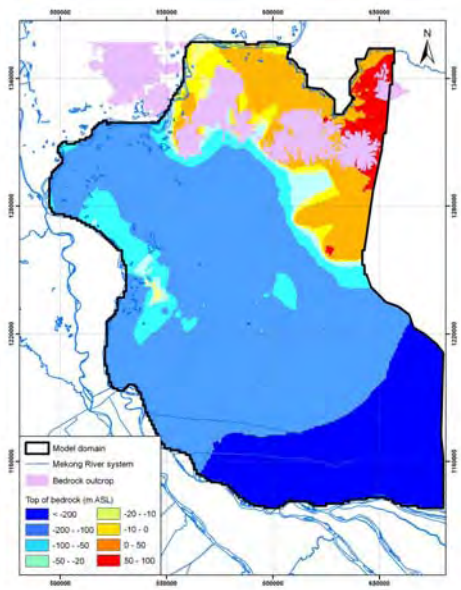
Numerical Model



Top of aquifer elevations

IDE

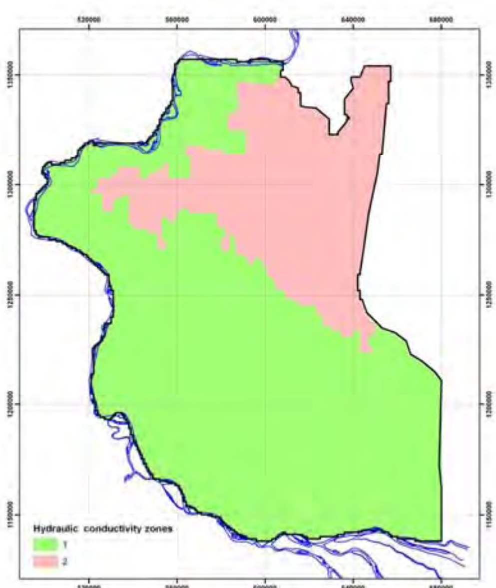
Numerical Model



Bedrock elevation

IDE

Numerical Model



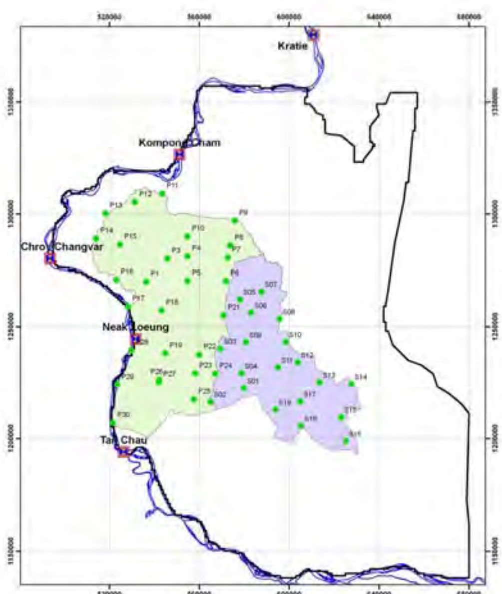
Hydraulic conductivity

IDE

Model Calibration

Adjust key parameters in the numerical model until the results match real-world observations as closely as possible

Model Calibration



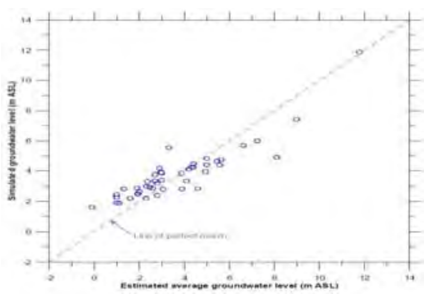
Steady-sate calibration

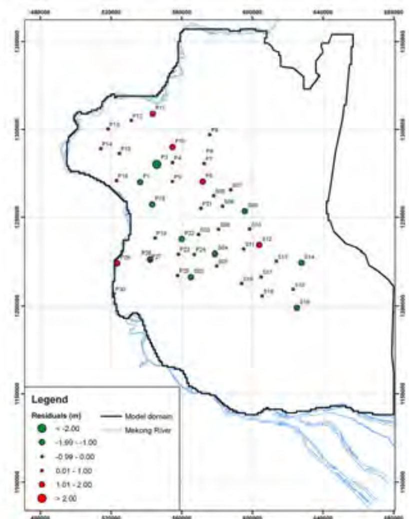
Run the model with historical averages for river levels and rainfall

Compare calculated water levels with average historical water levels observed in PDoWRAM monitoring wells

Model Calibration

Differences between calculated and observed water levels are within accepted standards for accuracy





Workshop Overview

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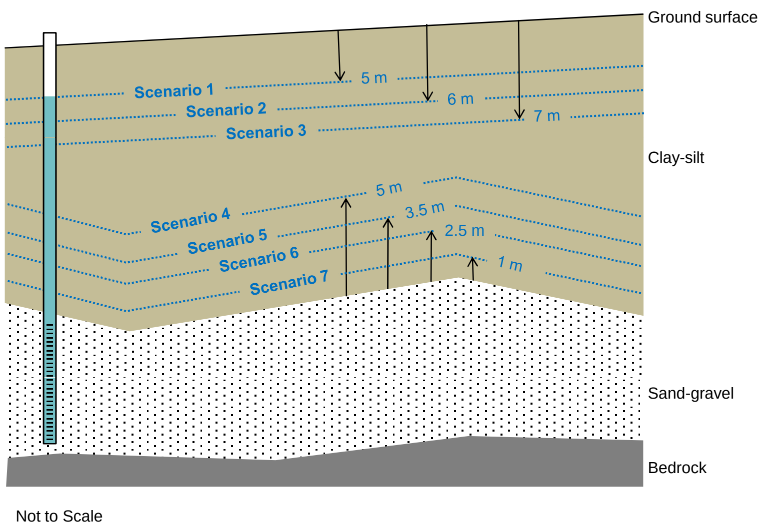
Sustainable Withdrawals

The completed model was applied to estimate the total sustainable withdrawals under various conditions

Scenarios Modeled



Sustainable Withdrawals

Scenario	Criteria	Sustainable Withdrawal Rate
	Maximum depth of water table below the ground surface	
1	5.0 m	0.23 mm/day
2	6.0 m	0.29 mm/day
3	7.0 m	0.33 mm/day
	Minimum height of water table above the top of the sand-gravel layer	
4	5.0 m	1.01 mm/day
5	3.5 m	1.11 mm/day
6	2.5 m	1.15 mm/day
7	1.0 m	1.24 mm/day

IDE

Sustainable Withdrawals

Sustainable Withdrawal values…

- …are the maximum amount of water that can be withdrawn from the aquifer without exceeding the specified water-level drawdown limits.
- …assume a uniform rate of water withdrawals across the study area.
- …are averaged over a year-long period.

IDE

Sustainable Withdrawals

The drawdown criteria of 6 m below the ground surface is an important limit.

If the water level drops below 6 m, more than 130,000 domestic hand-pumps in PVG and SVR will no longer be able to pump water.

Sustainable Withdrawals

For a maximum groundwater depth of 6 m, the maximum sustainable withdrawal is 0.29 mm/day

By comparison, groundwater usage in 2005 is estimated as:

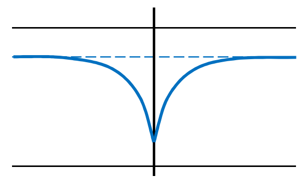
- Agricultural = 0.14 mm/day or about 50% of sustainable withdrawal
- Domestic = 0.008 mm/day or about 3% of sustainable withdrawal

Another comparison: dry season rice

- Water requirement = 10 mm/day.
- About 45,000 ha could be irrigated using all of the sustainable withdrawal

Some Limitations

The groundwater model does not model the drawdown of water around individual wells.



Instead, it models the large-scale effects of pumping from many wells

Some Limitations

The use of the word “sustainable” means that the specified groundwater level (e.g., 6 m below ground surface) can be “sustainably” maintained while withdrawing water at the “sustainable withdrawal” rate

It does <u>not</u> mean that these withdrawals will cause no other impacts on the environment. For example, less water may be available for water users and ecosystems that are located downstream of the study area.

Workshop Overview

- Study Objectives
- Groundwater Level Records
- Building the Groundwater Model
- Sustainable Groundwater Withdrawals
- Questions and Discussion
- Future Uses of the Model
- Integrating Planning and Modeling
- Questions and Discussion

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Future Model Uses

In this project, the groundwater model that has been built is like an airplane. It is a high-investment, high-technology vehicle that can take you many places.

But it has only been used to go on one trip so far.

What Are Models Good For?

Modeling is an important method for improving our understanding of complex natural systems (like groundwater systems)

What Are Models Good For?

Models are useful tools for:

- Providing a rational basis for water resource management and planning
- Predicting impacts of future development scenarios
- Comparing different development options
- Conducting “what if” analyses
- Linking with other models (hydrological, ecological, economic, social, etc.)
- Guiding the design of data collection programs

Future Model Uses

Potential scenarios that could be modeled with the PVG-SVG groundwater model in the future include:

- Effects of new agricultural developments
- Effects of the increase in rural domestic water use due to population growth
- Effects of developing new urban domestic water supply systems

Future Model Uses

- Effects of potential groundwater management policies (e.g., groundwater regulation)
- Effects of community-based groundwater management strategies
- Effects of variations in annual rainfall and Mekong River levels due to climate change
- Effects of reservoir developments in the Mekong River basin upstream of the study area

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Planning and Modeling

As a tool for natural resource management, modeling works best when there are:

- Strong modeling skills
- Good communication between modelers, development planners, and other stakeholders
- Modeling teams that include other important (non-hydrogeologic) skills
- Lots of good quality data

Planning and Modeling

- Strong modeling skills

It is not possible to build strong modeling capacity in a single modeling project (just as it is not possible to learn how to fly in a single airplane trip)

Extensive and continuous practice with many modeling projects is needed to develop the necessary experience

Planning and Modeling

➢ Good communication between modelers, development planners, and other stakeholders

Frequent and meaningful communication leads to:

- Improved understanding of each party's priorities and constraints
- Models that are designed to answer relevant questions
- Models with an appropriate level of precision
- Shared expectations (no surprises)

IDE

Planning and Modeling

➢ Teams with diverse skills

Groundwater effects do not exist in isolation.

Results from groundwater models are more useful when linked to ecological, social, economic, and policy implications

Modelers and development planners should have access to expertise in biological sciences, sociology, economics, and policy analysis.

IDE

Planning and Modeling

- Good quality data

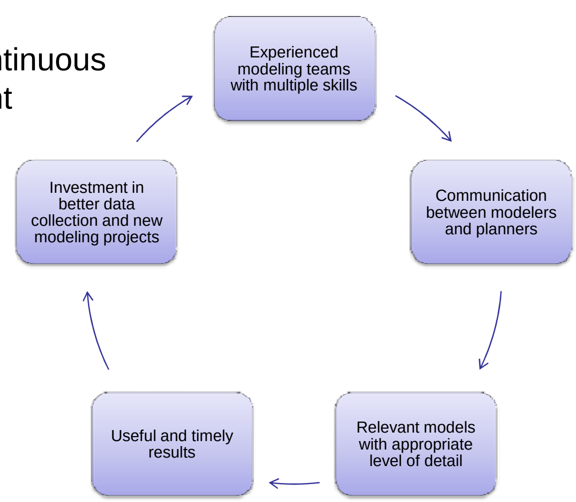
Modeling quality depends of availability and quality of data

Long-term historical data are important for determining trends, establishing baseline conditions, and calibrating models

Need careful, consistent collection and open access to this information

Planning and Modeling

Cycle of continuous improvement



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Thank You

យុទ្ធសាស្ត្រសិក្សាទឹកក្រោមដី នៅក្នុងខេត្តព្រៃវែង និងស្វាយរៀង
(ដំណាក់កាលទី២)

សិក្ខាសាលាបញ្ចប់

ព្រះរាជាណាចក្រកម្ពុជា

គណៈកម្មការជាតិសម្រាប់ការអភិវឌ្ឍន៍តាមបែបប្រជាធិបតេយ្យនៅថ្នាក់ក្រោមជាតិ

ក្រសួងធនធានទឹក និងឧតុនិយម

ភ្នំពេញ ២៨សីហា ២០០៩

IDE

ក្រុមសិក្សា

- Michael Roberts, IDE (Cambodia)
- Christopher Neville, SSP&A (Canada)
- So Im Monichoth, CADTIS (Cambodia)
- Chiep Piseth, CADTIS (Cambodia)
- Pang Peng, MOWRAM (Cambodia)
- Preap Sameng, MOWRAM (Cambodia)
- Jinhui Zhang, SSP&A (Canada)

IDE

គោលបំណងនៃសិក្ខាសាលា

១. យល់ដឹងពីអ្វីជាម៉ូដែលទឹកក្រោមដី និងការដែលអាច និងមិនអាចប្រើប្រាស់វា

២. យល់ដឹងពីលទ្ធផលរបស់ម៉ូដែលទឹកក្រោមដីនៃខេត្តព្រៃវែង និងស្វាយរៀងដែលបានអភិវឌ្ឍនក្នុងគំរោងនេះ

៣. យល់ដឹងពីសក្តានុពលនៃការប្រើប្រាស់ម៉ូដែលទឹកក្រោមដីក្នុងខេត្តព្រៃវែងនិងស្វាយរៀង នៅពេលអនាគត

សេចក្តីសង្ខេបសិក្ខាសាលា

- គោលបំណងនៃការសិក្សា
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គោលបំណងនៃការសិក្ខាទឹកក្រោមដី

ការបង្កើតម៉ូដែលទឹកក្រោមដីគឺដើម្បីប៉ាន់ប្រមាណផល ប៉ះពាល់ក្នុងការទាញយកទឹកក្រោមដីសម្រាប់ប្រព័ន្ធ ស្រោចស្រពក្នុងខេត្តព្រៃវែង និងស្វាយរៀង

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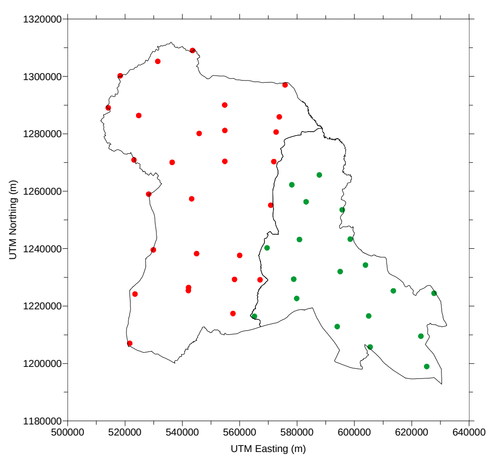
ការតាមដានទឹកក្រោមដី



- ប្រព័ន្ធតាមដានលើ៤៩អណ្តូង
- បានតំឡើងក្នុងឆ្នាំ១៩៩៦ដោយ អ៊ីយូ-ប្រាសាក់

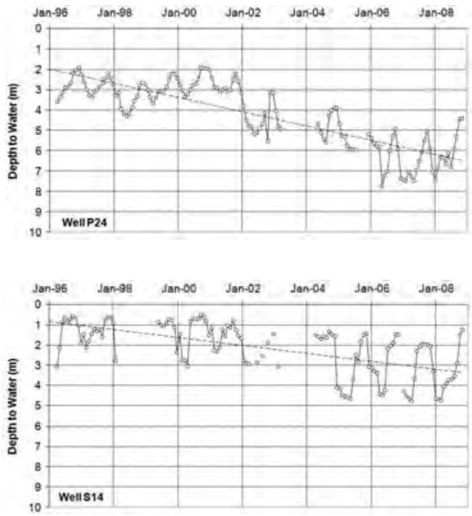
ការតាមដានទឹកក្រោមដី

- ប្រមូលកំរិតទឹកប្រចាំខែដោយមន្ទីរធនធានទឹក និងឧតុនិយមខេត្ត (PDoWRAM) ខេត្តព្រៃវែង និងស្វាយរៀង
- ការដែលកំណត់យកបានគឺជាកំណត់ត្រារយៈពេលវែង ទៅលើអណ្តូងជាច្រើន

ការតាមដានទឹកក្រោមដី

- យោងតាមកំពស់ទឹកក្នុងអណ្តូងដែលបានកត់ត្រាទុកបង្ហាញថាកំរិតទឹកក្រោមដីកំពុងថយចុះ
- មានការព្រួយបារម្ភថាការប្រើប្រាស់ទឹកក្រោមដីលើសលប់សម្រាប់ប្រព័ន្ធស្រោចស្រព គឺជាហេតុបណ្តាលឱ្យមានភាពខ្វះខាតទឹក

ការតាមដានទឹកក្រោមដី



ក្រាហ្វិកនេះបង្ហាញពីកំពស់ទឹកក្រោមដីនៃ

អណ្តូង៤៩ក្នុងខេត្តព្រៃវែង និងស្វាយរៀង

ឃើញថានិន្នាការជារួមនៃទឹកក្រោមដីថយចុះ

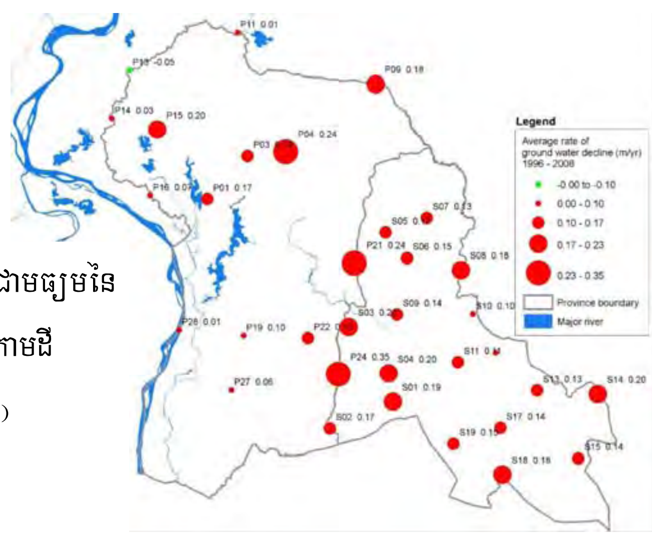
(១៩៩៦ដល់ ២០០៨)

ការតាមដានទឹកក្រោមដី

ផែនទីបង្ហាញពីអត្រាជាមធ្យមនៃ

ការថយចុះកំរិតទឹកក្រោមដី

(១៩៩៦ ដល់ ២០០៨)



សេចក្តីសង្ខេបសិក្ខាសាលា

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IDE Σ²Π

តើអ្វីជាម៉ូដែលទឹកក្រោមដី?

គឺជាចក្ខុវិស័យមួយដែលធ្វើឱ្យងាយស្រួលក្នុងការតាមដានប្រពន្ធ័លំហូរទឹកក្រោមដីដែលមានលក្ខណៈជាសាកលគឺថា...

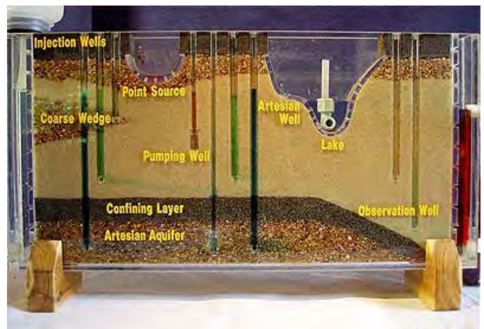
- បង្កើតសារឡើងវិញនូវទ្រង់ទ្រាយជាក់លាក់មួយនៃប្រពន្ធ័ដែលមានលក្ខណៈជាសាកល
- អាចត្រូវបានប្រើប្រាស់សម្រាប់ព្យាករណ៍ពីរបៀបនៃប្រពន្ធ័ដែលមានលក្ខណៈជាសាកល ឬទូទៅដែលនឹងត្រូវប្រតិកម្មទៅនឹងការផ្លាស់ប្តូរមួយជាក់លាក់

IDE Σ²Π

តើអ្វីជាម៉ូដែលទឹកក្រោមដី?

នេះជារូបរាងម៉ូដែលមួយតូចដែលគេធ្វើពិសោធន៍ពីលំហូរទឹកក្រោមដី

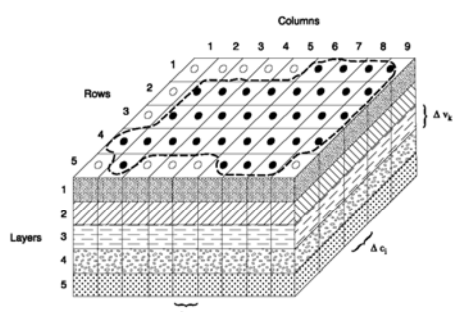
គេប្រើគ្រួសល្អិតសុទ្ធ ខ្សាច់ ដីឥដ្ឋ និងពណ៌ទឹកដើម្បីសង្កេតពី របៀបទឹកហូរ



តើអ្វីជាមួយដែលទឹកក្រោមដី?

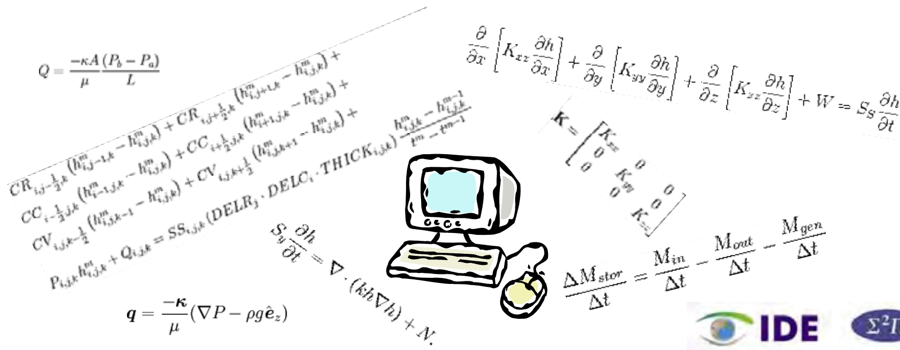
ប្រភេទមួយផ្សេងទៀតគឺគណិតវិទ្យាម៉ូដែលទឹកក្រោមដី

បែងចែកផ្នែកសិក្សាឱ្យក្លាយជា ក្រឡាតូចៗ និង...



តើអ្វីជាមួយដែលទឹកក្រោមដី?

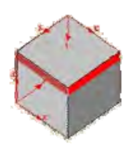
...ប្រើប្រាស់កុំព្យូរទ័រដើម្បីគណនាកំរិតកំពស់ទឹកក្រោមដីនៅក្នុងក្រឡានីមួយៗ និងលំហូររវាងក្រឡាមួយៗដោយប្រើប្រាស់សមីការគណិតវិទ្យា



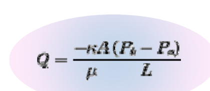
Softwareរបស់ម៉ូដែលទឹកក្រោមដី

ការសិក្សានេះគឺប្រើកញ្ចប់សុសវ៉ារពីរដើម្បីបង្កើតម៉ូដែលទឹកក្រោមដីដែលទាក់ទងនឹងគណិតវិទ្យា:

Groundwater Vistas គឺប្រើសម្រាប់កំណត់ចំណាំពីលក្ខណៈរបស់ក្រឡានីមួយៗ



MODFLOW គឺត្រូវបានប្រើសំរាប់ដោះស្រាយនូវសមីការម៉ូដែល



ការបង្កើតម៉ូដែលទឹកក្រោមដី

1. ការចងក្រងទិន្នន័យ	ប្រមូលពតិមាន ដែលជាប់ទាក់ទងភូគព្ភសាស្ត្រ ជលសាស្ត្រ ឧតុនិយម និងប៉ារ៉ាម៉ែត្រមួយចំនួនរបស់ទឹកក្រោមដី
2. ការចាប់ផ្តើមនៃម៉ូដែល	ត្រូវបង្កើតម៉ូដេល និងស្វែងយល់ពីប្រពន្ធ័ដំណើរការរបស់ទឹកក្រោមដីដែលមានលក្ខណ:ជាសាកល ឬទូទៅ
3. គណិតវិទ្យាម៉ូដែល	កំណត់ព្រំប្រទល់ម៉ូដែល វង្វាស់ប្រវែង និងប៉ារ៉ាម៉ែត្រសម្រាប់ក្រឡានីមួយៗ
4. ការកែសំរួលតំលៃប៉ារ៉ាមែត្រម៉ូដែល	កែសម្រួលតំលៃប៉ារ៉ាម៉ែត្រដែលជាគន្លឹះនៅក្នុងម៉ូដែលគណិតវិទ្យារហូតទទួលបានលទ្ធផលដែលតំលៃស្មើ ឬប្រហាក់ប្រហែលនឹងតំលៃដែលគេធ្វើការវាស់វែង

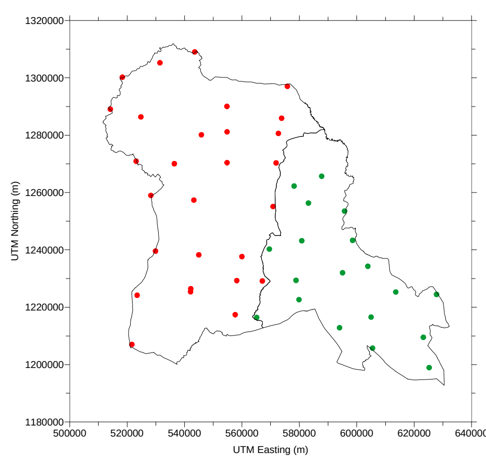
IDE Σ²Π

ការចងក្រងទិន្នន័យ

ការប្រមូលទិន្ន័យ:

PDoWRAM តាមដាន

និងកត់ត្រាកំពស់ទឹកក្រោមដីនៃអណ្តូង

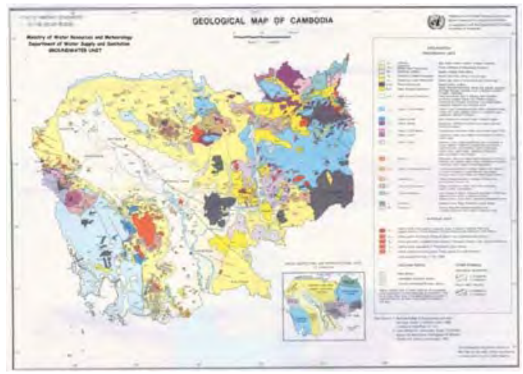


IDE Σ²Π

ការចងក្រងទិន្នន័យ

ប្រភព និងគន្លឹះសំរាប់ប្រមូលទិន្ន័យ:

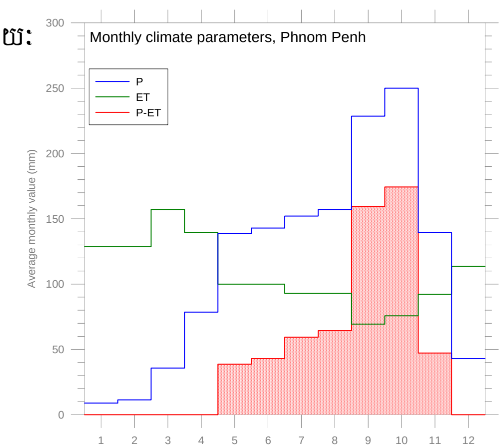
ផែនទីភូមិសាស្ត្រ



ការចងក្រងទិន្នន័យ

ប្រភព និងគន្លឹះសំរាប់ប្រមូលទិន្នន័យ:

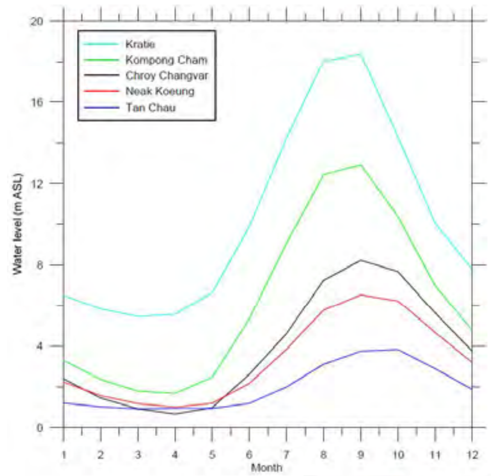
ទិន្នន័យឧតុនិយម



ការចងក្រងទិន្នន័យ

ប្រភព និងគន្លឹះសំរាប់ប្រមូលទិន្នន័យ:

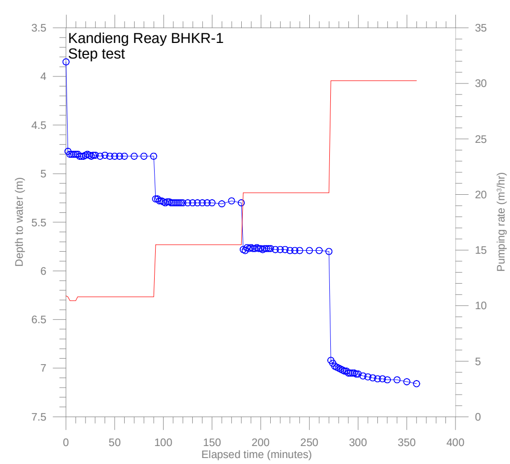
កំពស់ទឹកទន្លេមេគង្គនៅតាមស្ថានីយជលសាស្រ្ត



ការចងក្រងទិន្នន័យ

ប្រភព និងគន្លឹះសំរាប់ប្រមូលទិន្នន័យ:

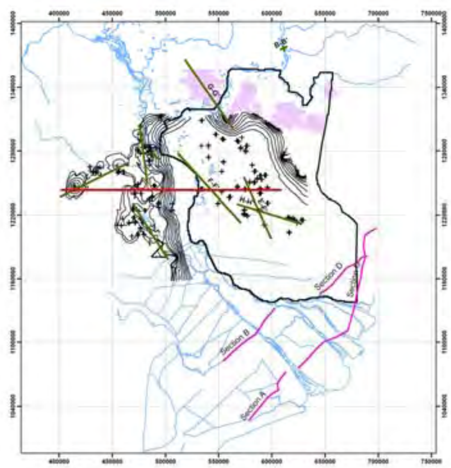
ការសាកល្បងបូមទឹកអណ្តូងនៅ CUPPWSP ដើម្បីកំណត់មេគុណលំហូរទឹកក្រោមដី



ការចងក្រងទិន្នន័យ

ប្រភព និងគន្លឹះសំរាប់ប្រមូលទិន្នន័យ:

យើងមានទិន្នន័យដល់ជំរៅដល់ស្រទាប់ថ្មក្រោមដី និងការធ្វើមុខកាត់ភូមិសាស្ត្រពីអកស្រាវជ្រាវជាច្រើនដែលបានចងក្រងជារបាយការណ៍



Model domain
Mekong River system
WSP 1608-P: Plate 01 (Rasmussen and Bradford, 1977)
WSP 1608-R: Plate 02 (Anderson, 1987)
Contours from Appendix 11 (Kokusai-Kogyo Co., Ltd., 2002)
Cross section from Appendix 11 (Kokusai-Kogyo Co., Ltd., 2002)
\+ Resistivity Soundings (Kokusai Kogyo Co., Ltd., 2002)
Bedrock outcrop

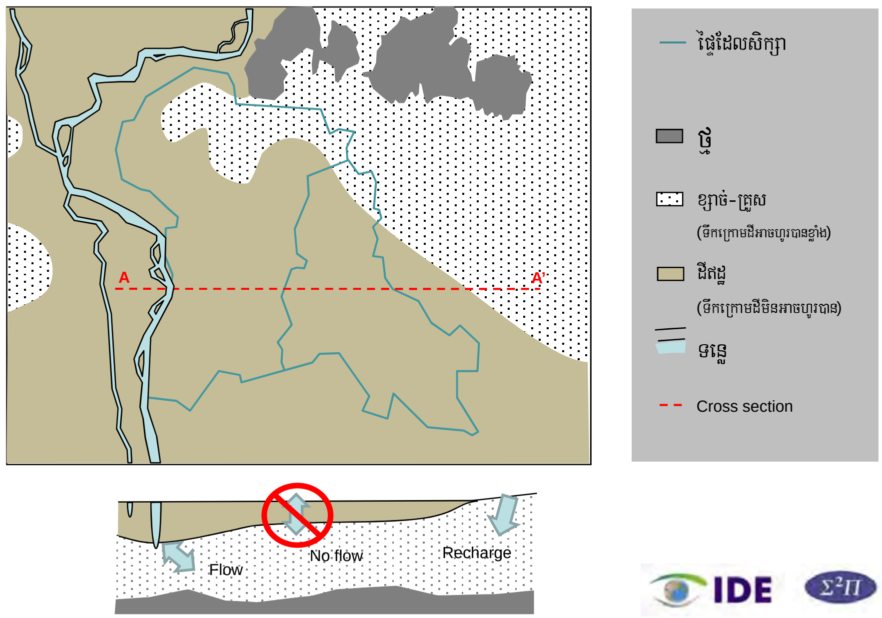
IDE Σ²Π

ការចាប់ផ្តើមនៃម៉ូដែល

គ្រប់ទិន្នន័យគឺត្រូវបានពិនិត្យសារឡើង និងបានសិក្សាដើម្បីធ្វើការស្វែងយល់ពីរបៀបដំណើរការប្រពន្ធ័ទឹកក្រោមដីដែលមានលក្ខណៈជាសាកល ឬទូទៅ ។

IDE Σ²Π

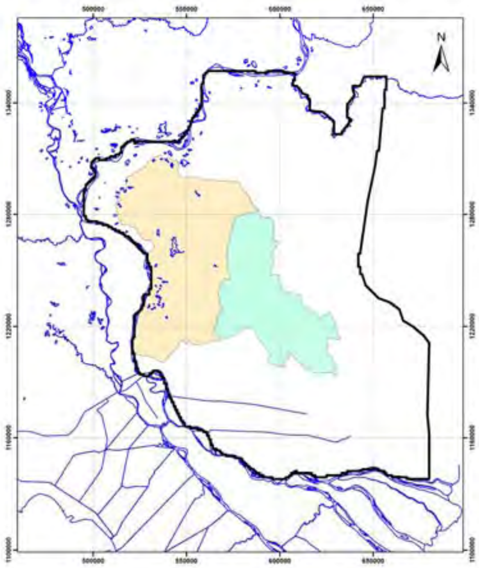
ការចាប់ផ្តើមនៃម៉ូដែល



ចំនួនម៉ូដែល

កំណត់ព្រំប្រទល់របស់ម៉ូដែល វង្វាស់ប្រវែងក្រឡានិងតំលៃប៉ារ៉ាម៉ែត្ររបស់ក្រឡានីមួយៗ

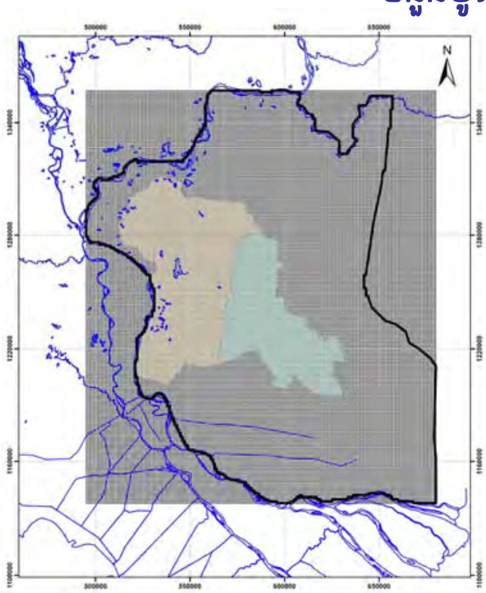
ចំនួនម៉ូដែល



កំណត់ប្រទល់របស់ម៉ូដែលដោយ ផ្អែកលើជលសាស្ត្រដូចជា:

- ទន្លេ
- ការបែងចែកលំហូរ

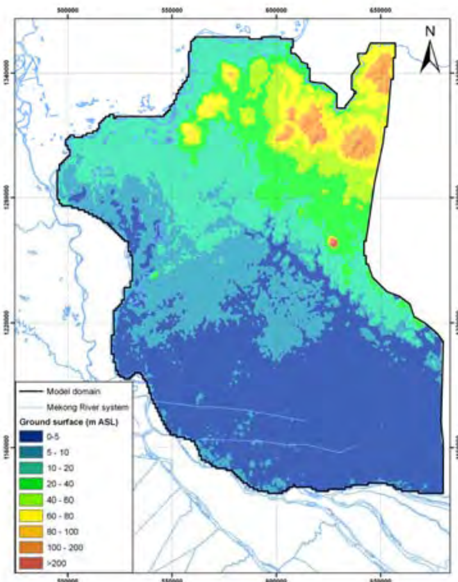
ចំនួនម៉ូដែល



កំណត់ចន្លោះពីក្រឡាមួយទៅក្រឡាមួយ:

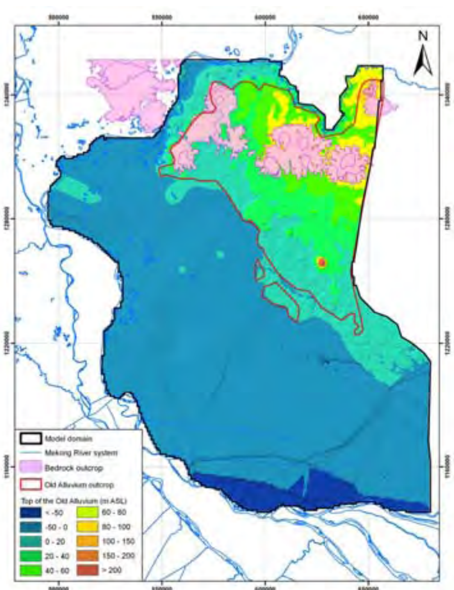
•1 km x 1 km

ចំនួនម៉ូដែល



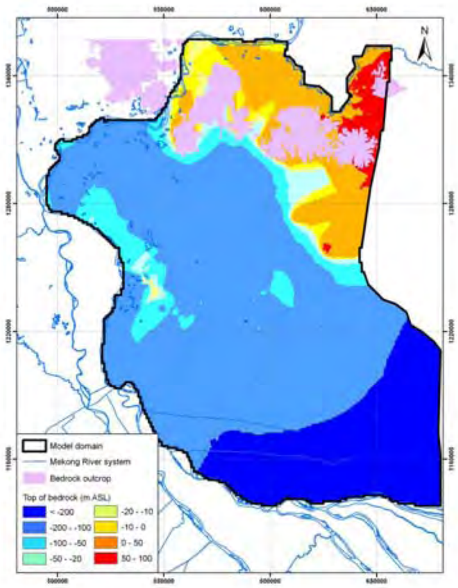
កំពស់ផ្ទៃដី

ចំនួនម៉ូដែល



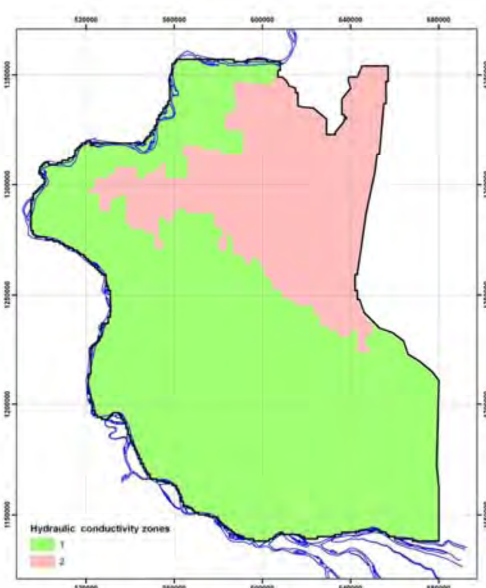
កំពស់ទឹកក្រោមដីផ្នែកខាងលើ

ចំនួនម៉ូដែល



កំពស់ស្រទាប់ថ្មនៅក្រោមដី

ចំនួនម៉ូដែល

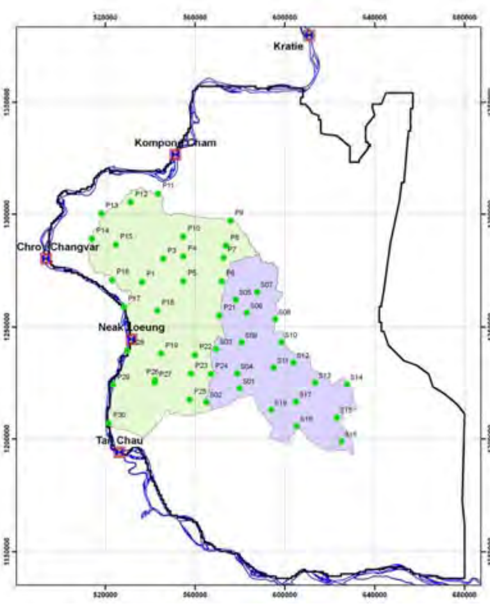


មេគុណលំហូរទឹក

ការកែសំរួលតំលៃប៉ារ៉ាមែត្រម៉ូដែល

កែសម្រួលតំលៃប៉ារ៉ាម៉ែត្រដែលជាគន្លឹះនៅក្នុងម៉ូដែលគណិតវិទ្យារហូតទទួលបានលទ្ធផលដែលតំលៃស្មើ ឬប្រហាក់ប្រហែលនឹងតំលៃដែលគេធ្វើការវាស់វែង

ការកែសំរលតំលៃប៉ារ៉ាមែត្រម៉ូដែល



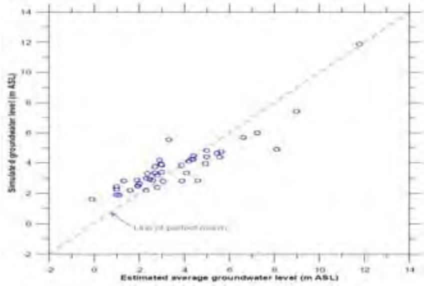
ការកែសម្រួលប៉ារ៉ាម៉ែត្រដោយស្ថាឌីស្តេត (Steady-state)

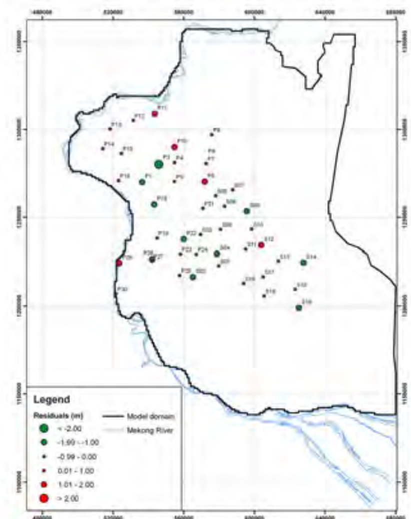
គឺម៉ូដែលធ្វើការជាមួយកំពស់ទឹកទន្លេ និងទឹកភ្លៀងក្នុងមធ្យមភាគច្រើនឆ្នាំ

ម៉ូដែលចាប់ផ្តើមគណនាកំពស់ទឹកមធ្យមភាគច្រើនឆ្នាំ ហើយប្រៀបធៀបទៅនឹងមធ្យមភាគកំពស់ទឹកអណ្តូងច្រើនឆ្នាំដែលគេកត់ត្រាទុកដោយ PDoWRAM

ការកែសំរួលតំលៃប៉ារ៉ាមែត្រម៉ូដែល

ក្រាហ្វិកបង្ហាញភាពខុសគ្នារវាងលទ្ធផលពីម៉ូដែល និងទិន្នន័យដែលគេកត់ត្រាទុក ដែលលទ្ធផលនេះឋិតនៅក្នុងស្តង់ដារមួយអាចទទួលយកបាន





សេចក្តីសង្ខេបសិក្ខាសាលា

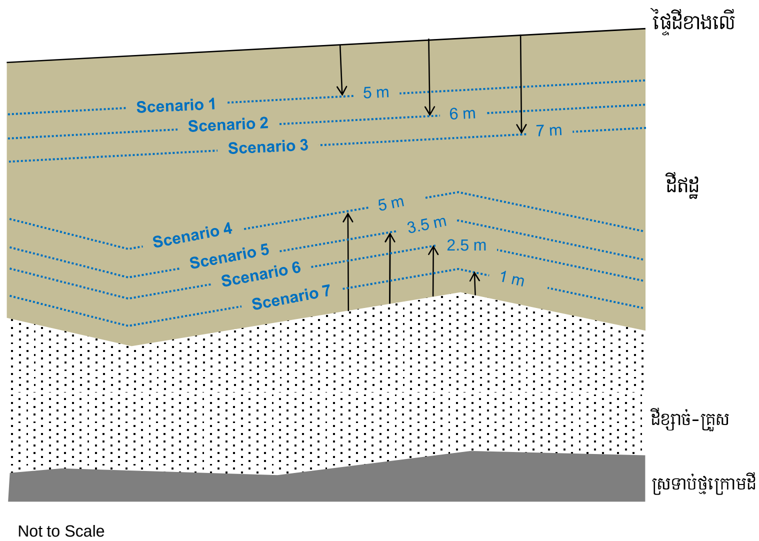
- គោលបំណងនៃការសិក្សា
- ការកត់ត្រាកំរិតកំពស់ទឹកក្រោមដី
- ការបង្កើតម៉ូដែលទឹកក្រោមដី
- និរន្តភាពនៃការទាញយកមកប្រើប្រាស់ទឹកក្រោមដី
- សំនួរ និងការពិភាក្សា
- ការប្រើប្រាស់ម៉ូដែលក្នុងពេលអនាគត
- សមាហរណកម្មគំរោង និងម៉ូដេល
- សំនួរនិងការពិភាក្សា

និរន្តភាពនៃការទាញយកទឹកក្រោមដីសម្រាប់ប្រើប្រាស់

ម៉ូដែលពេញលេញមួយត្រូវបានអនុវត្ត ដើម្បីប៉ាន់ប្រមាណនៃការប្រើប្រាស់ទឹកឱ្យមាន និរន្តភាពក្រោមលក្ខខណ្ឌខុសៗគ្នា

IDE

សេនារីយ៉ូម៉ូដែល



IDE

និរន្តភាពនៃការទាញយកទឹកក្រោមដីសម្រាប់ប្រើប្រាស់

សេនារីយ៉ូ	លក្ខណៈវិនិច្ឆ័យ	អត្រានៃការទាញយកមកប្រើប្រាស់
	ជំរៅទឹកអតិបរិមានៃទឹកក្រោមដី	
1	5.0 m	0.23 mm/ថ្ងៃ
2	6.0 m	0.29 mm/ថ្ងៃ
3	7.0 m	0.33 mm/ថ្ងៃ
	កំពស់ទឹកអប្បបរិមាខាងលើបំផុតនៃស្រទាប់ខ្សាច់-គ្រួស	
4	5.0 m	1.01 mm/ថ្ងៃ
5	3.5 m	1.11 mm/ថ្ងៃ
6	2.5 m	1.15 mm/ថ្ងៃ
7	1.0 m	1.24 mm/ថ្ងៃ

និរន្តភាពនៃការទាញយកទឹកក្រោមដីមកប្រើប្រាស់

តម្លៃនិរន្តភាពនៃការទាញយកទឹកក្រោមដីប្រើប្រាស់......

- ......គឺជាចំនួនអតិបរិមានៃទឹកដែលអាចយកមកប្រើប្រាស់ពីទឹកក្រោមដីដោយគ្មានភាពលើសលុប ដែលកំណត់ការបន្ថយកំរិតទឹកជាក់លាក់
- ......ការប៉ាន់ប្រមាណដោយទាញយកទឹក និងបរិមាណមួយដូចគានៅក្នុងតំបន់សិក្សា
- ....តំលៃជាមធ្យមលើរយៈពេលលើសពីមួយឆ្នាំ

និរន្តភាពនៃការប្រើប្រាស់ទឹកក្រោមដី

និរន្តភាពនៃការទាញយកទឹកក្នុងជំរៅអតិបរិមា៦ម៉ គឺជាតំលៃមួយដ៏សំខាន់

ប្រសិនបើកំរិតទឹកធ្លាក់ក្រោម៦ម៉នោះអណ្តូងស្នប់ដែលមានចំនួនច្រើនជាង១៣០.០០០សំរាប់ប្រើប្រាស់តាមផ្ទះនៅក្នុងខេត្តព្រៃវែងនិងស្វាយរៀងនឹងមិនយូរប៉ុន្មានពុំមានទឹកប្រើប្រាស់ ។

និរន្តភាពនៃការប្រើប្រាស់ទឹកក្រោមដី

សម្រាប់ជម្រៅទឹកជ្រៅបំផុត៦ម នោះនិរន្តភាពនៃការទាញយកទឹកមកក្នុងតំលៃអតិបរិមាគឺ0.២៩មម ក្នុងមួយថ្ងៃ

ដោយមានការប្រៀបធៀប ការប្រើប្រាស់ទឹកក្នុងឆ្នាំ២00៥គឺត្រូវបានប៉ាន់ប្រមាណដូចខាងក្រោមៈ

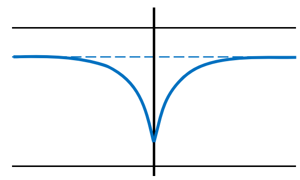
- កសិកម្ម = 0.១៤មម/ថ្ងៃ ឬប្រហែល៥0%សម្រាប់និរន្តរភាពនៃការទាញយកទឹកក្រោមដី
- ប្រើប្រាស់ក្នុងគ្រួសារ = 0.00៨មម/ថ្ងៃ ឬប្រហែល៣%សម្រាប់និរន្តរភាពនៃការទាញយកទឹកក្រោមដីប្រើប្រាស់

ការប្រៀបធៀបផ្សេងៗទៀតៈ នៅរដូវស្រែប្រាំង

- តម្រូវការទឹក = ១0មម/ថ្ងៃ
- ប្រហែល៤៥.000 ហិកតាអាចធ្វើការស្រោចស្រពប្រកបដោយនិរន្តភាពនៃការទាញយកទឹកក្រោមដីប្រើប្រាស់

ការកំណត់ខ្លះៗទៀត

ម៉ូដែលទឹកក្រោមដីគឺមិនមែនជាម៉ូដែលសម្រាប់ការកាត់បន្ថយនៃទឹកជុំវិញអណ្តូងដែលប្រើប្រាស់ជាលក្ខណៈគ្រួសារទេ



ផ្ទុយទៅវិញ ម៉ូដែលគឺជាវង្វាស់ដ៏ធំដែលគណនាអំពីឥទ្ធិពលនៃការទាញយកទឹកពីអណ្តូងជាច្រើនមកប្រើប្រាស់

ការកំណត់ខ្លះៗទៀត

ការប្រើពាក្យ "និរន្តភាព" មានន័យថាជាកំរិតទឹកក្រោមដីជាក់លាក់មួយ (ឧ. ៦ម៉ខាងក្រោមផ្ទៃដី) អាចមាន "និរន្តភាព" ដែលត្រូវបានថែរក្សាខណៈពេលដែលការប្រើប្រាស់ទឹកក្រោមដីគឺស្ថិតនៅត្រង់អត្រាការប្រើប្រាស់ដែលមាននិរន្តភាព។

វាមិនមានន័យថាការប្រើប្រាស់ទឹកទាំងនេះនឹងមិនបណ្តាលឱ្យមានផលប៉ះពាល់ដល់បរិស្ថានដ៏ទៃទៀតនោះទេ។ ឧទាហរណ៍ ការប្រើប្រាស់ទឹកតិចគឺអាចជាប្រយោជន៍សម្រាប់អ្នកប្រើប្រាស់ទឹក និងប្រពន្ធ័អេកូឡូស៊ីដែលស្ថិតនៅតាមខ្សែទឹកនៃតំបន់សិក្សា។

សេចក្តីសង្ខេបសិក្សាសាលា

- គោលបំណងនៃការសិក្សា
- ការកត់ត្រាកំរិតកំពស់ទឹកក្រោមដី
- ការបង្កើតម៉ូដែលទឹកក្រោមដី
- និរន្តភាពនៃការទាញយកមកប្រើប្រាស់ទឹកក្រោមដី
- សំនួរ និងការពិភាក្សា
- ការប្រើប្រាស់ម៉ូដែលក្នុងពេលអនាគត
- សមាហរណកម្មគំរោង និងម៉ូដែល
- សំនួរនិងការពិភាក្សា

សេចក្តីសង្ខេបសិក្សាសាលានេះ

- គោលបំណងនៃការសិក្សា
- ការកត់ត្រាកំរិតកំពស់ទឹកក្រោមដី
- ការបង្កើតម៉ូដែលទឹកក្រោមដី
- និរន្តភាពនៃការទាញយកមកប្រើប្រាស់ទឹកក្រោមដី
- សំនួរ និងការពិភាក្សា
- ការប្រើប្រាស់ម៉ូដែលក្នុងពេលអនាគត
- សមាហរណកម្មគំរោង និងម៉ូដែល
- សំនួរនិងការពិភាក្សា

ការប្រើប្រាស់ម៉ូដែលនៅពេលអនាគត

នៅក្នុងគម្រោងនេះ ម៉ូដែលទឹកក្រោមដីគឺត្រូវបាន ស្ថាបនាឡើងដូចជាយន្តហោះមួយ ។ វាមាន ការវិនិយោគខ្ពស់ មានបច្ចេកវិទ្យាខ្ពស់ដែលជាយាន្ត ជំនិះមួយដែលអាចនាំអ្នកទៅកាន់កន្លែងជាច្រើន

ប៉ុន្តែវាគ្រាន់តែអាចប្រើប្រាស់សម្រាប់ ការធ្វើដំណើរ<u>មួយជើង</u>តែប៉ុណ្ណោះ

IDE Σ²Π

តើម៉ូដែលមានសារៈសំខាន់ដូចម្តេច?

ម៉ូដែលគឺជាវិធីដ៏មានសារៈសំខាន់សម្រាប់បង្កើនការយល់ដឹងរបស់យើង នៃប្រពន្ធ័ដ៏ស្មុគស្មាញរបស់ធម្មជាតិ (ដូចជាប្រពន្ធ័ទឹកក្រោមដី)

IDE Σ²Π

តើម៉ូដែលមានសារៈសំខាន់ដូចម្តេច?

ម៉ូដែលគឺជាឧបករណ៍ដែលមានប្រយោជន៏សម្រាប់:

- ផ្តល់នូវមូលដ្ឋានសមស្របមួយសម្រាប់ការគ្រប់គ្រងធនធានទឹក និងធ្វើផែនការធនធានទឹក
- ព្យាករណ៏ផលប៉ះពាល់ក្នុងការអភិវឌ្ឍនសេនារីយ៉ូនៅពេលអនាគត
- ប្រៀបធៀបភាពខុសគ្នានៃជម្រើសក្នុងការអភិវឌ្ឍន៏
- បង្កើតការវិភាគ " ប្រសិនបើ "
- ភ្ជាប់ជាមួយម៉ូដែលដទៃទៀត (ជលសាស្ត្រ អេកូឡូស៊ី សេដ្ឋកិច្ច សង្គម ។ល។)
- ដឹកនាំការបង្ហាញពីកម្មវិធីប្រមូលទិន្នន័យ

ការប្រើម៉ូដែលក្នុងពេលអនាគត

ម៉ូដែលទឹកក្រោមដីក្នុងខេត្តព្រៃវែងនិងស្វាយរៀងមានសក្តានុពលភាពអាចធ្វើសេនារីយ៉ូនៅពេលអនាគតដោយរួមបញ្ចូល:

- វិភាគផលប៉ះពាល់នៃការអភិវឌ្ឍកសិកម្មថ្មី
- វិភាគផលប៉ះពាល់នៃការបង្កើនការប្រើប្រាស់ទឹកជាលក្ខណៈគ្រួសារនៅតាមជនបទដោយ

សំអាងទៅលើកំនើនប្រជាជន

- វិភាគផលប៉ះពាល់នៃការអភិវឌ្ឍប្រពន្ធ័ផ្គត់ផ្គង់ទឹកជាលក្ខណៈគ្រួសារនៅតាមទីក្រុង

ការប្រើម៉ូដែលក្នុងពេលអនាគត

- វិភាគផលប៉ះពាល់នៃគោលនយោបាយគ្រប់គ្រងសក្តានុពលទឹកក្រោមដី (ឧ. ច្បាប់ទាក់ទងនឹងការប្រើប្រាស់ទឹកក្រោមដី)
- វិភាគផលប៉ះពាល់នៃយុទ្ធសាស្ត្រគ្រប់គ្រងទឹកក្រោមដីក្នុងសហគមន៍
- វិភាគផលប៉ះពាល់នៃការផ្លាស់ប្តូរកំពស់ទឹកភ្លៀងប្រចាំឆ្នាំនិងកំពស់ទឹកទន្លេមេគង្គ ដោយផ្អែកទៅលើបម្រែបម្រួលអាកាសធាតុ
- វិភាគផលប៉ះពាល់នៃការសង់អាងទឹកនៅក្នុងអាងទឹកទន្លេមេគង្គផែកខាងលើ

សេចក្តីសង្ខេបសិក្ខាសាលា

- គោលបំណងនៃការសិក្សា
- ការកត់ត្រាកំរិតកំពស់ទឹកក្រោមដី
- ការបង្កើតម៉ូដែលទឹកក្រោមដី
- និរន្តភាពនៃការទាញយកមកប្រើប្រាស់ទឹកក្រោមដី
- សំនួរ និងការពិភាក្សា
- ការប្រើប្រាស់ម៉ូដែលក្នុងពេលអនាគត
- សមាហរណកម្មគំរោង និងម៉ូដែល
- សំនួរនិងការពិភាក្សា

គំរោង និងម៉ូដែល

ដើម្បីឱ្យម៉ូដែលធ្វើការបានដ៏ល្អបំផុតក្នុងការគ្រប់គ្រងធនធានធម្មជាតិគឺនៅពេលដែល:

- មានជំនាញការម៉ូដែលខ្លាំង
- មានការប្រាស្រ័យទាក់ទងល្អរវាងអ្នកម៉ូដែល អ្នកធ្វើផែនការអភិវឌ្ឍ និងអ្នកចូលរួមដទៃទៀត
- ក្រុមម៉ូដែលគឺត្រូវមានជំនាញសំខាន់ដទៃ (មិនមែនជលសាស្ត្រភគុវិទ្យា)
- មានទិន្នន័យច្រើន ហើយមានគុណភាព

គំរោង និងម៉ូដែល

- ជំនាញការម៉ូដែលខ្លាំង

វាមិនមែនជាការងាយស្រួលក្នុងការបង្កើតសមត្ថភាពអ្នកម៉ូដែលឱ្យខ្លាំងក្លាក្នុងករណីអ្នកធ្វើម៉ូដែល ឬអ្នកប្រើប្រាស់នៅមានសមត្ថភាពទាប និងមិនទំលំទូលាយ

(វាដូចជាការដែលមិនងាយស្រួលក្នុងការរៀនបើកបរយន្តហោះតែមួយនោះដែរ)

ដូចនេះ ដើម្បីឱ្យមានសមត្ថភាពលក្នុងការធ្វើម៉ូដែល គឺចាំបាច់ត្រូវមានសមត្ថភាព និងចំណេះដឹងទូលំទូលាយជាមួយការអនុវត្តផ្ទាល់យ៉ាងច្រើនជាមួយកម្មវិធីម៉ូដែល ហើយត្រូវការកសាងបទពិសោធនប្រសិនបើអាចធ្វើបាន

គំរោង និងម៉ូដែល

- មានការប្រាស្រ័យទាក់ទងល្អរវាងអ្នកម៉ូដែល អ្នកធ្វើផែនការអភិវឌ្ឍ និងអ្នកចូលរួមដទៃទៀត

ជាញឹកញាប់ និងពោរពេញដោយអត្ថន័យសម្រាប់ការប្រាស្រ័យទាក់ទងគឺនាំឱ្យៈ

- បង្កើនការយល់ដឹងឱ្យបានច្បាស់នូវផ្នែកណាមួយសំខាន់
និងលក្ខណៈផ្សេងទៀតដែលនឹងសមហេតុផល
- ម៉ូដែលគឺត្រូវបានរៀបចំដើម្បីឆ្លើយតបទៅនឹងសំនួរដែលមានជាប់ទាក់ទង
- ម៉ូដែលជាកម្រិតមួយដែលមានភាពត្រឹមត្រូវ និងច្បាស់លាស់
- ជាការចែករំលែកក្នុងការរំពឹងទុក (ដោយពុំមានភាពភ្ញាក់ផ្អើល)

គំរោង និងម៉ូដែល

- ក្រុមការងារដែលមានជំនាញផ្សេងៗគ្នា

ទឹកក្រោមដីដែលកើតមានមិនអាចស្ថិតនៅដាច់តែឯងនោះទេ

លទ្ធផលដែលបានមកពីម៉ូដែលទឹកក្រោមដីគឺមានសារៈប្រយោជន៏បាននៅពេលភ្ជាប់ជាមួយអេកូឡូស៊ី សង្គម សេដ្ឋកិច្ច និងការជាប់ទាក់ទងនឹងគោលនយោបាយ

អ្នកម៉ូដែល និងអ្នកធ្វើផែនការអភិវឌ្ឍន៏គួរតែមានជំនាញក្នុងវិទ្យាសាស្ត្រនៃជីវសាស្ត្រ ជីវសង្គម សេដ្ឋកិច្ច និងការវិភាគគោលនយោបាយ

គំរោង និងម៉ូដែល

➤ ទិន្នន័យដែលមានគុណភាពល្អ

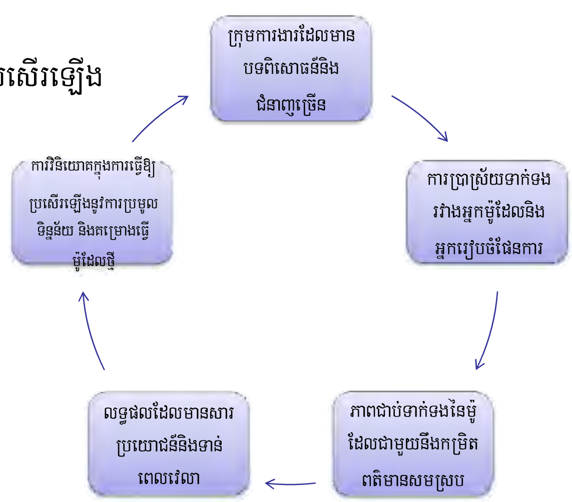
គុណភាពម៉ូដែលគឺអាស្រ័យលើគុណភាពរបស់ទិន្នន័យ

ទិន្នន័យដែលបានសិក្សារយៈពេលវែងកន្លងរួចមកហើយគឺមានសារៈសំខាន់សម្រាប់កំណត់ទិសដៅ បង្កើតលក្ខខណ្ឌមូលដ្ឋាន និង ការកែសម្រួលតំលៃប៉ារ៉ាម៉ែត្ររបស់ម៉ូដែល

ត្រូវមានការយកចិត្តទុកដាក់ខ្ពស់ ការប្រមូលទិន្នន័យជាប្រចាំ និងអាចទទួលយកពិមាននេះបាន

គំរោង និងម៉ូដែល

វដ្តនៃការធ្វើបន្តប្រសើរឡើង



សេចក្តីសង្ខេបសិក្ខាសាលា

- គោលបំណងនៃការសិក្សា
- ការកត់ត្រាកំរិតកំពស់ទឹកក្រោមដី
- ការបង្កើតម៉ូដែលទឹកក្រោមដី
- និរន្តភាពនៃការទាញយកមកប្រើប្រាស់ទឹកក្រោមដី
- សំនួរ និងការពិភាក្សា
- ការប្រើប្រាស់ម៉ូដែលក្នុងពេលអនាគត
- សមាហរណកម្មគំរោង និងម៉ូដែល
- សំនួរនិងការពិភាក្សា

អរគុណ

Strategic Study of Groundwater Resources in Prey Veng and Svay Rieng
Final Stakeholder Workshop
28 Aug 2009

Questions and Answers

Q1: Confusion about the Sustainable Withdrawal values being presented in units of mm/day.

A: The final report will include both mm/day and m3/day

Q2: The Scenarios are defined by a maximum water level drawdown relative to either the ground surface or the top of the old alluvium aquifer. The Scenarios are therefore based on a groundwater table surface that is not flat (i.e., not a uniform elevation at all points). Is a non-uniform groundwater table like this possible, given that water will always seek to form a flat surface?

A flat surface only exists where there is no flow in the aquifer. The model includes the influences of inflow-outflow from rivers, infiltration form recharge areas, and pumping from each of the model grid cells. An uneven groundwater table is possible—and indeed inevitable—due to the influence of these flows.

Q3: Can a typical control well be set up to monitor and warn about excessive drawdown?

A: In reality, the groundwater table is unlikely to decrease uniformly as assumed in the model. Thus, one monitoring well is not enough. The network of 49 PRASAC wells already exists and should continue to be used to monitor future groundwater levels.

Q4: Are the three-dimensional surfaces for the top-of-bedrock, top-of-aquifer, and ground surface exact or are they based on assumptions?

A: The surfaces that represent the top-of-bedrock, top-of-aquifer, and ground surface were generated for this study by interpolating between known points. We have limited ability to observe the situation under the ground. Data from borehole logs, geophysical investigations, and observations of the underground layers where they come to the surface (outcroppings). The spaces between these known points are filled in using our knowledge of the geological processes (e.g., sedimentation) that have created the various layers.

Q5: For the sustainable withdrawal scenarios, does the model assume that water is withdrawn from the entire modeled area or just from the study area of Prey Veng and Svay Rieng.

A: Just the study area of Prey Veng and Svay Rieng.

Q6: For the sustainable withdrawal scenarios, is the target water level (e.g., 5 m, 6 m, 7 m from the ground surface) a static water level or a dynamic water level?

A: It is a mean annual static water level.

Q7: The sustainable withdrawal values are given as averages over the two provinces. Is it possible to break this down to know what withdrawals are sustainable within smaller areas, say districts?

A: Yes, it is possible to break down the reported discharge rates into smaller areas and this could be done as one of the follow-up applications of the model. When the MODFLOW model is run for a scenario, a large binary file is created called the cell-by-cell flow file. A post-processing program can extracts the results from this file by specifying the grid blocks over which the summation is made. Since the grid for the Prey Veng-Svay Rieng model is composed of uniform 1kmx1km cells it is straightforward to identify those grid blocks that correspond to a particular part of the model area.

Q8: Is there a sustainable withdrawal value that will result in no annual depletion of the groundwater table, i.e., a withdrawal that is exactly replaced by annual recharge?

A: If there are groundwater withdrawals, then groundwater levels must be lowered in some places and at some time. There is an abundant literature that demonstrates that it is a fallacy to conceive of the recharge as the sustainable yield of an aquifer. The correct interpretation of the sustainable yield is the amount of groundwater that can be diverted from its present discharge without causing unacceptable changes (to existing users, to ecosystems).

Q9: How long will this model last before it needs to be updated?

A: Historical data from 1996 through 2005 was used in developing and calibrating the model but the use of the model is not limited to those years. The model itself is a representation of those parts of the groundwater system that are more-or-less permanent and unchanging, e.g., the ground elevation, bedrock elevation, top-of-aquifer elevation, hydraulic conductivity of the clayey, sandy, and bedrock, layers, and location of major rivers. Thus, the basic structure of the model will not need to be updated unless a large-scale change happened to these features (e.g., if the Mekong River switched channels). Still, it is possible to improve the model by describing the permanent features more accurately (e.g., more detailed data about the bedrock elevations across the study area).

Q10: Does the water level in a well depend on how deep the well has been drilled?

A: If two adjacent wells tap into the same aquifer, the static water level in both wells will be equal even if they have been drilled to different depths.

បញ្ជីវត្តមាន

(List Of Participant)

ស្តីពី : Strategic Study of Groundwater Resources in Prey Veng and Svay Rieng Woprkshop (Phase 2)

កន្លែងប្រជុំ : General Department of Administration Meeting Room

កាលបរិច្ឆេទ : 28 August 2008

ល.រ NO.	នាម និងគោត្តនាម (Full Name)	ភេទ (Sex)	ក្រសួង-ស្ថាប័ន (Ministry/Con.)	តួនាទី (Position)	ទូរស័ព្ទដៃ (Telephone)	ហត្ថលេខា (Signature)
1	[illegible]	[illegible]	SVR	P.M	099712336	[illegible]
2	[illegible]	"	[illegible]	[illegible]	011 ~~711703~~	[illegible]
3	[illegible]	[illegible]	[illegible]	[illegible]	012/011 711944	[illegible]
4	[illegible]	[illegible]	Exlom-PVG	[illegible] M&E	089702466	[illegible]
5	[illegible]	[illegible]	PSDD	PIA	012722896	[illegible]
6	[illegible]	"	PVG	P.M	0124575	[illegible]
7	[illegible]	[illegible]	[illegible]	[illegible]	011977255	[illegible]
8	[illegible]	[illegible]	[illegible]	PTST/Agro	016763623	[illegible]
9	[illegible]	—	—	PTST/Planning	011-999237	[illegible]
10	[illegible]	"	"	[illegible]	016344-857	[illegible]
11	[illegible]	[illegible]	PVG	[illegible]	012965668	[illegible]
12	[illegible]	[illegible]	PV.G.DDA	[illegible]	012929774	[illegible]
13	[illegible]	[illegible]	PVG.PDA	M.E	012764911	[illegible]
14	[illegible]	"	PSDD/PVG	PMESA	012829376	[illegible]
15	[illegible]	[illegible]	PSDD/PVG	SPPA	012729854	[illegible]
16	[illegible]	[illegible]	[illegible]	[illegible]	011746018	[illegible]
17	[illegible]	[illegible]	"	[illegible]	01241827	[illegible]
18	[illegible]	[illegible]	[illegible]	[illegible]	099812142	[illegible]
19	[illegible]	[illegible]	[illegible]	[illegible]	016 580912	[illegible]
20	[illegible]	[illegible]	PVK	TSV		[illegible]
21	[illegible]	"	[illegible]	CAU	011973054	[illegible]
22	[illegible]	"	[illegible]	[illegible]	017-255727	[illegible]

បញ្ជីវត្តមាន

(List Of Participant)

ស្តីពី : Strategic Study of Groundwater Resources in Prey Veng and Svay Rieng

កន្លែងប្រជុំ : General Department of Administration Meeting Room

កាលបរិច្ឆេទ : 28 August 2008

ល.រ NO.	នាម និងគោត្តនាម (Full Name)	ភេទ (Sex)	ក្រសួង-ស្ថាប័ន (Ministry/Con.)	តួនាទី (Position)	ទូរស័ព្ទទាក់ទង (Telephone)	ហត្ថលេខា (Signature)
23	[illegible]	[illegible]	GRET	[illegible]	089 585868	Kol Yi
24	[illegible]	-"-	CNMC	Modeler	012744058	
25	[illegible]	"	MAFF. PSU	M&E	017 462 600	
26	[illegible]	-"-	PSDD/SVR	LAA	016645922	
27	[illegible]	-"-	PSDD/SVR	PIA	017790342	
28	TIM GRAYLING	M	NCDD/PST	IIA	012 985864	
29	Heng Sophat	M	PADEK	PME	012961036	
30	Uy Sakun	M	PSD/NCDD	[illegible]	01251107	
31	Seth Saman	M	MRD	Deputy Director	016950276	
32	[illegible]	[illegible]	Svay Rieng	TSU	011934190	
33	[illegible]	M	MOWRAM	Direct. Depa.	012.213999	
34	[illegible]	[illegible]	MOWRAM	[illegible]	092253941	
35	[illegible]	[illegible]	MEF	Division chief	012957930	
36	[illegible]	[illegible]	PSDD/SVR	SPPA	012 894656	
37	[illegible]	[illegible]	WSP	WSS Analyst	016940852	
38	[illegible]	[illegible]	PSDD	NAPA	092518866	
39	MICHAEL ROBERTS	M	IDE	COUNTRY DIRECTOR	012 629 069	
40	HIR SAMNANG	M	PSDD/NCDD	NEA	012604400	

Annex H: Training Materials

Training Materials are bound under separate cover in a companion volume to this report.