Saturated Horizontal Hydraulic Conductivity in an Acid Sulphate Soil

A Minor Field Study in the Vietnamese Mekong Delta

Stefan Uppenberg
Oskar Wallgren
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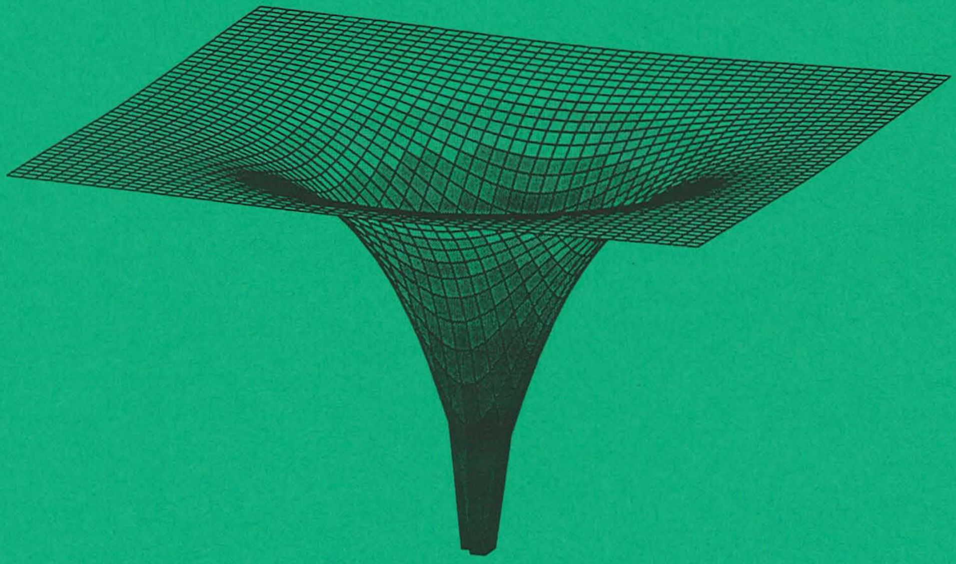

Examensarbete
Handledare: Erik Eriksson, Per-Erik Jansson & Ho Long Phi

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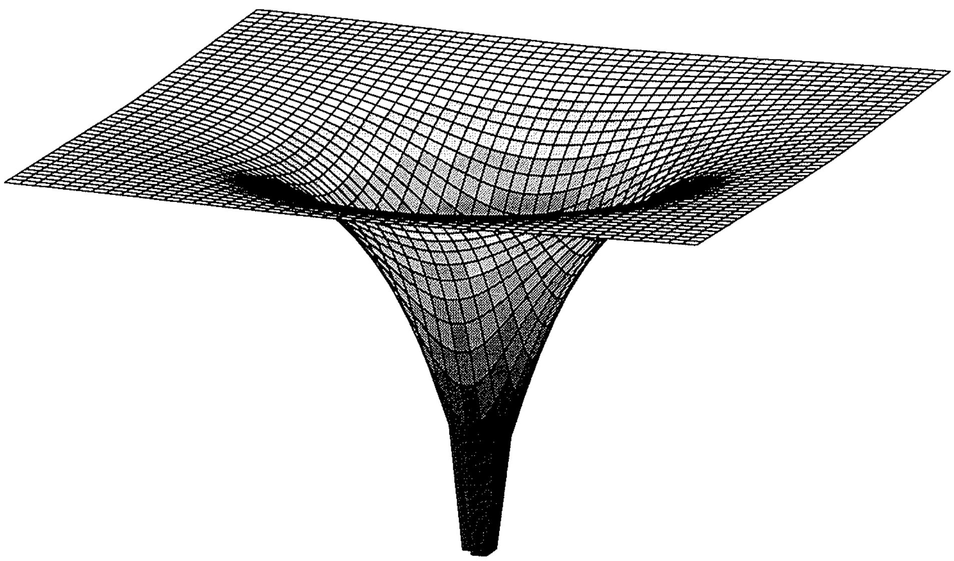

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PREFACE

This paper presents the results from a field study carried out by the three undergraduate students Stefan Uppenberg, Oskar Wallgren and Markus Åhman from April to July 1996. It also presents a theoretical background to groundwater flow and pumping tests as a method for determining the hydraulic properties of the soil and a sensitivity analysis of groundwater flow using the SOIL-model. The overall objective of this project was to increase the knowledge of the hydrological conditions in the acid sulphate soils in the Plain of Reeds, Vietnam, and to provide reliable estimates of the saturated horizontal hydraulic conductivity that could be used in modelling physical and chemical processes in these soils.

The study was carried out within the framework of the Minor Field Study (MFS) Scholarship programme, which is funded by the Swedish International Development Cooperation Agency (Sida). The MFS Scholarship Program offer Swedish university students an opportunity to carry out two months of field work in a Third World country on a basis of a Master's dissertation or a similar in-depth study. These studies are primarily conducted within areas that are important for development co-operation and in countries supported by the Swedish aid programme. The main purpose of the MFS programme is to increase interest in developing countries and to enhance Swedish university students' knowledge and understanding of these countries and their problems. An MFS study should provide the student with initial experience of conditions in such a country. A further purpose is to widen the Swedish personnel resources for recruitment into international development co-operation. The centre for International and Educational Cooperation (CITEC) at the Royal Institute of Technology, KTH, Stockholm, administers the MFS programme for most faculties of engineering and natural sciences in Sweden.[1]

The numerical methods and the QBASIC program used in the transient flow calculations were developed by Prof. Erik Eriksson.

The authors would like to thank all the people that made this study and report possible. CITEC and Sida provided the money necessary for this study to be carried out. We are grateful to Vo Khac Tri and all the others at the Southern Institute for Water Resources Research in Ho Chi Minh City for their help during our stay in Vietnam. The abstract was translated into Vietnamese by Tran Kim Tinh. We especially would like to thank the three people who by their enthusiasm in supervising us and guiding us through the jungle of soil hydrology have made the work both interesting and exciting; Dr. Ho Long Phi, Prof. Erik Eriksson and Prof. Per-Erik Jansson.

February 1997

Stefan Uppenberg, Oskar Wallgren, Markus Åhman

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[1]Information about the MFS Program at CITEC is available through Ms Sigrun Santesson, Programme Officer at

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ABSTRACT
SATURATED HORIZONTAL HYDRAULIC CONDUCTIVITY IN AN ACID SULPHATE SOIL,
A Minor Field Study in the Vietnamese Mekong Delta.

Stefan Uppenberg, Oskar Wallgren, Markus Åhman, Aquatic and Environmental Engineering, Institute of Earth Sciences, Uppsala University, Norbyvägen 18 B, S-752 36 Uppsala, Sweden.

This study was made within the Management of Acid Sulphate Soils Project (MASSP) and was carried out at Tan Thanh Experimental Farm. The Mekong delta, situated in the southern part of Vietnam, is an increasingly important area for agriculture and aquaculture in Vietnam. Approximately half of the area is covered with acid sulphate soils. These soils give rise to problems because of their acidity which effects rice cultivation and water quality negatively. Due to these problems there is a need for better understanding of the water balance and the groundwater movements in these soils. The objective of this study was to study the saturated horizontal hydraulic conductivity, *K*, and the effective porosity, *S*, of the soil, in order to provide data to the physical and chemical models developed by MASSP.

Steady state pumping tests gave *K*-values between 12 and 37 m/day and transient flow pumping tests gave *K*-values between 12 and 41 m/day. Estimated mean *K* was 23 m/day for both methods which is a somewhat higher value than previous measurements have indicated. The estimated effective porosity varied between 0.006 and 0.080. Guyon's and Theis' methods of calculation gave mean values 0.008 and 0.030 respectively. Both methods for calculating *K* are sensitive to variations in depth of the aquifer.

A sensitivity analysis was performed to analyse how sensitive a computer model of the soil can be to variations in *K*, and thereby how important reliable *K*-values are when simulating water flows through the soil.

REFERAT
MÄTTAD HORISONTELL HYDRAULISK KONDUKTIVITET I EN SUR SULFATJORD,
En mindre fältstudie i Mekongdeltat i Vietnam.

Denna studie utfördes vid experimentstationen i Tan Thanh inom ramarna för Management of Acid Sulphate Soils Project (MASSP). Mekongdeltat i södra Vietnam är ett allt mer betydelsefullt område för jordbruk och vattenbruk i Vietnam. Ungefär hälften av området täcks av sura sulfatjordar. Den sura miljön i jordarna påverkar risodling och vattenkvalitet negativt. Därför finns det ett behov av en bättre förståelse för vattenbalans och grundvattenflöden i jordarna. Syftet med studien var att mäta jordens mättade horisontella hydrauliska konduktivitet, *K*, och effektiva porositet, *S*, för att tillhandahålla indata till de fysikaliska och kemiska modeller som utvecklas av MASSP.

Provpumpningar under stationärt tillstånd gav *K*-värden mellan 12 och 37 m/dygn, medan provpumpningar under transient skede gav *K*-värden mellan 12 och 41 m/dygn. Båda metoderna gav ett medelvärde på 23 m/dygn, vilket är ett något högre värde än tidigare utförda mätningar har indikerat. Den uppskattade effektiva porositeten varierade mellan 0.006 och 0.080. Guyons och Theis beräkningsmetoder gav medelvärdena 0.008 respektive 0.030. Båda metoderna för att beräkna *K* är känsliga för variationer i akvifärens uppskattade mäktighet.

En känslighetsanalys genomfördes för att studera hur prediktioner från en datormodell påverkades av variationer i *K*. Detta gjordes för att klarlägga hur viktiga noggrant bestämda *K*-värden är vid simuleringar av vattenflöden genom denna typ av jordar.

ĐỘ DẪN NƯỚC THEO CHIỀU NGANG TRONG ĐIỀU KIỆN ĐẤT BẢO HÒA Ở MỘT BIỂU LOẠI ĐẤT PHÈN

Tiểu luận nghiên cứu tại Đồng Bằng Sông Cửu Long- Việt Nam

Stefan Uppenberg, Oskar Wallgren, Markus Åhman, Aquatic and Environment Engineering, Institute of Earth Sciences, Uppsala University, Norbyvägen 18 B, S-752 36 Uppsala, Sweden.

Tiểu luận này được thực hiện trong khuôn khổ chương trình Quản Lý Đất Chua Phèn (MASSP) và đặt tại trạm thí nghiệm Tân Thạnh. Đồng Bằng Sông Cửu Long nằm ở phía Nam Việt Nam, là một vùng trở nên càng ngày càng quan trọng trong nông nghiệp và thủy sản ở Việt Nam. Khỏang một nửa diện tích của Đồng bằng là đất phèn. Các loại đất này gây nhiều trở ngại cho việc canh tác lúa và làm ô nhiễm nguồn nước do tính chua của chúng. Vì các trở ngại trên, do đó cần hiểu hơn về cân bằng nước và sự di chuyển của nước ngầm trong các loại đất đó. Mục đích của đề tài này là để nghiên cứu về tính thấm theo chiều ngang, K, và độ xốp hửu hiệu của đất để cung cấp thêm số liệu cho mô hình lý và hóa của chương trình MASSP.

Đo tính thấm bằng phương pháp bôm ở trang thái tỉnh (steady state pumping test) cho kết quả thay đổi trong khỏang 12 đến 37 m/ngày và phương pháp bôm chuyển tiếp (transient flovv pumping test) cho kết quả thay đổi từ 12 đến 41 m/day. K trung bình được ước tính là 23 m/ngày cho cả hai phương pháp, kết quả này cho thấy tương đối cao hơn các lần đo trước. Độ xốp hửu hiệu được ước tính trong khỏang 0.008 và 0.030 theo thứ tự. K - tính tóan cho cả hai phương pháp thì nhạy so với độ sâu của thủy cấp.

Phân tích về tính nhạy được thực hiện để phân tích xem độ nhạy của mô hình điện tóan như thế nào khi K thay đổi và từ đó xem tầm quan trọng và thực tế của các giá trị K khi mô phỏng về nước chảy xuyên qua đất.

1. INTRODUCTION

Vietnam stretches over 1600 km along the eastern coast of the Indochinese Peninsula. The country's land surface area is 326,797 km^2. The country's two main cultivated areas are the Red River Delta (15,000 km^2) in the north and the Mekong Delta (49,500 km^2) in the south. The population was 71 million in 1993 (UI 1994).

The Mekong delta is, in a geological perspective, a very young area. This strongly affects the chemical and physical conditions in the soils. Among the older parts of the delta are the Plain of Reeds which were formed in the last 5500 years (Verburg, 1994). As in many other of the areas of the Mekong delta, the Plain of Reeds are dominated by *acid sulphate soils*. These soils often have low pH and they can present agricultural difficulties when cultivated. The Vietnamese government has, together with foreign research institutes, initialised research to develop and improve methods for agricultural management of land and water resources in areas with acid sulphate soils.

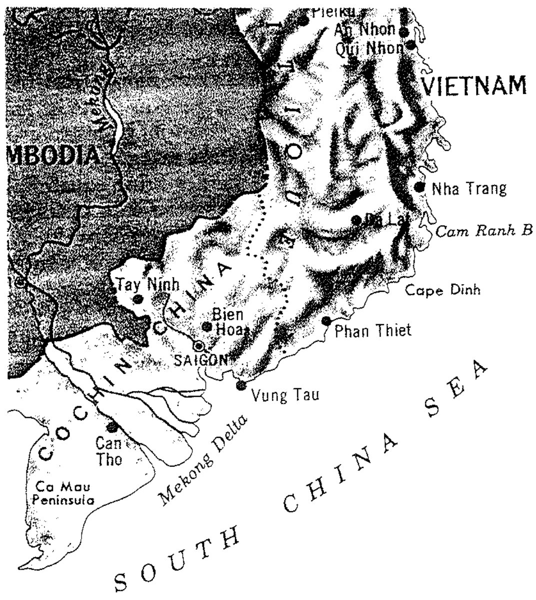


Figure 1.1. Map of the southern part of Vietnam.

The Vietnamese government has identified food and consumer goods for export as its main goals for national economic development up to year 2000. The plan aims to provide enough food and other essential items to meet national needs and provide commodities for export to obtain foreign currencies needed to accelerate the economic development in Vietnam. There are great problems associated with the use of acid sulphate soils for agriculture and there is a great need for proper management strategies to maximise the output e g the rice yield under the given conditions. The Plain of Reeds consists of mainly acid sulphate soils and reclamation of the area has become a priority for the Vietnamese government. This is due to economic, social and political interests. In the mid 80's important works to improve canal systems were initiated and land was given to local farmers and migrants, with the task to reclaim their land within a few years (Husson, 1995). This program has not yet given the desired positive results and the need for a water management program for the acid sulphate soils in the area has become obvious. Different research programs have been initialised to improve strategies for land reclamation and water management. To cope with the difficulties facing farmers trying to increase their rice yields, the Management of Acid Sulphate Soils

Project (MASSP) was initialised in 1987. The project is supported by the Swedish International Development Co-operation Agency (Sida) through the Mekong River Commission Secretariat in Bangkok. The objective of MASSP is to develop and improve methods for agricultural management of land and water resources in areas with acid sulphate soils.

The Management of Acid Sulphate Soil Project (MASSP) has as one of its objectives "...to develop a model for prediction of the consequences of present and alternative water management strategies on soil and water quality in potential actual acid sulphate soils" (MRC, 1995). Models for water quality have been well developed and successfully applied to different areas in the Mekong Delta (Nguyen T D). Within MASSP a water management model for acid sulphate soils is being developed. It consists of both physical and chemical sub models. For the calibration and validation of these sub models, knowledge of the values of a large number of parameters is necessary. The hydraulic conductivity has been identified as a key parameter to the flows of water and the leaching of substances from the soils to the surrounding canals (Eriksson, 1996). The data available on the horizontal hydraulic conductivity are uncertain and a need for complementary measurements is obvious.

To more fully understand the role of the hydraulic conductivity for the magnitude of groundwater flows, a computer based sensitivity analysis was performed at the Swedish University for Agricultural Sciences during spring 1996. The design of the simulations and the results will be presented in Appendix 1. The field work part of the project was carried out during June 1996. The experiments were made to determine the saturated horizontal hydraulic conductivity in the soils of the experimental station in Tan Thanh, Long An province, Vietnam.

2. THE ACID SULPHATE SOILS OF VIETNAM; GEOGRAPHY AND GEOLOGY

In this report, the term *acid sulphate soils* will be used to mean "...materials and soils in which as a result of processes of soil formation, sulphuric acids either will be produced, are being produced or have been produced in amounts that have a lasting effect on main soil characteristics" (Pons, 1972). These soils are formed when normally waterlogged and reduced parent material containing large amounts of sulphides, mainly pyrites, is drained and aerated. The sulphides in the material which come in contact with the oxygen of the air is oxidized and transformed into sulphates. The sulphates attack the clay mineral, causing liberation of aluminium ions in amounts toxic to plant roots and micro-organisms. The pH also decreases and can reach values as low as 1.5 in severe cases. Potential toxic substances like Fe and Al ions are also released when the soil is saturated with water (during flood) and there are reducing conditions. For further details on the chemistry see section 3.

Because of the low pH and toxic substances in the soil water, acid sulphate soils are considered poor soils for farming and cultivation. Traditionally farming practices on these soils have not been very intensive, but with increasing population and new demands for agricultural land the interest for acid sulphate soils has increased. Acid sulphate soils are found in all climate zones of the world. The majority of the soils are found in low coastal areas and are developing in recent marine sediments (Kawalec, 1972). Not many acid sulphate soils are found in continental environments. This can be explained by the fact that these areas are comparatively old and that the formation of acid sulphate soils is associated with recent deposits. Many inland soils of sedimentary origin have been acid sulphate soils in their "early years". Despite this, acid sulphate soils can occur in inland areas where pyritic rocks are found, but this is rare.

The Mekong delta covers a total area of 4.95 million ha, 3.9 million ha of which is located in Vietnam. Of these, 2.9 million ha is used for agriculture and aquaculture. For Vietnam, the delta is an important region as it provides 10-11 million tons of paddy, or 50% of the national harvest and accommodates 14.6 million people. Rice and fisheries from the delta account for 27% of the Gross Domestic Product (data from Nguyen D L 1995). The area is supplied with fresh water through the Mekong river and rainfall. Both are subject to seasonal variations which result in the north part of the delta being flooded from August to November. In the poorly drained depressional areas the land can be flooded for up to 6 months. During the 19th and the 20th centuries a large canal system was built in the delta to open areas for settlement and land development and for transportation. Approximately 45% of the Vietnamese part of the delta is covered with acid sulphate soils (Nguyen T D). Two kinds of problems occur:

(1) When the soil is exposed to oxygen, chemical substances harmful to plants are formed. This makes the soil less suitable for agricultural use.

(2) When the area is flooded, the acid water from the fields is leached to the canal system causing problems in areas not normally affected. The acidic conditions can be harmful to aquatic life. Problems may occur if the acidified water is used for irrigation for long periods.

3. OVERVIEW OF CHEMICAL PROCESSES IN ACID SULPHATE SOILS (after Verburg, 1994 & Dent, 1986)

3.1 Introduction

In order to understand the genesis, characteristics and associated agronomic limitations of acid sulphate soils, the chemical processes that are involved in the sedimentation, formation and seasonal dynamics of acid sulphate soil should be mentioned. The essential chemical processes in acid sulphate soils are, firstly, the formation of potential acidity (predominantly pyrite) in a waterlogged environment, and subsequently, the oxidation of this pyrite following natural or artificial drainage.

3.2 Formation of potential acidity

Pyrite (FeS_2) is quantitatively the most important mineral for acidity in acid sulphate soils. The formation of pyrite involves:

-Reduction of sulphate ions to sulphides by sulphate-reducing bacteria, during decomposition of organic matter.

-Partial oxidation of sulphides to elemental sulphur or polysulphidic ions.

-Formation of iron monosulphide (FeS) by combination of dissolved sulphides with iron. The iron originates mostly from iron III oxides and silicates in the sediment, but is reduced to iron II by bacterial action.

-Formation of pyrite by combination of iron monosulphide and elemental sulphur. Alternatively pyrite may precipitate directly from dissolved iron II and polysulphide ions.

The formation of pyrite with iron III oxide as a source of iron may be represented by:

$$Fe_2O_{3,(s)} + 4SO_4^{2-} + 8CH_2O + \frac{1}{2}O_{2,(aq)} \Rightarrow 2FeS_{2,(s)} + 8HCO_{3\ (aq)}^{-} + 4H_2O \qquad (3.1)$$

The iron III oxide originates from the sediment and the sulphate ions from seawater. There are some important conditions which have to be fulfilled to make pyrite formation possible. First, the environment has to be anaerobic. The sulphate reduction takes place only under severely reducing conditions, and no oxygen must be available. This is the situation in waterlogged sediments that are rich in organic matter. Decomposition of this organic matter by anaerobic bacteria produces a reducing environment. Second, there has to be a source of dissolved sulphate present. Usually this source will be sea water or brackish tidal water. Third, there has to be enough organic matter to provide energy for the sulphate-reducing bacteria. The sulphate is used by the organisms according to the following equation:

$$SO_4^{2-} + 2CH_2O \Rightarrow H_2S + 2HCO_3^- \qquad (3.2)$$

Sulphate ions serve as the electron sink for the micro-organisms and are thereby reduced to sulphide. In addition to the conditions mentioned above, there has to be a source of iron for the reaction to take place. Most soils and sediments contain abundant iron oxides and hydroxides. In an anaerobic environment they are reduced to Fe^{2+}, which is soluble within the normal pH range and may also be mobilised by soluble organic products. The time necessary for the formation of pyrite by these processes ranges from a couple of days to several years, depending on the situation. Saline and brackish water tidal swamps and marshes constitute by far the most extensive potential acid sulphate soil environment. The Mekong delta has formed over the last 5500 years and during this time the conditions for forming pyrite have been ideal. Dense mangrove vegetation has covered the area which has been regularly flooded.

3.3 Oxidation of potential acidity; harmful products

If the conditions change from strongly reducing to a less reducing environment pyrite can initially react with oxygen dissolved in the water. This is a two step process, the second of which is very slow. The net reaction is:

$$2FeS_2 + 7O_2 + 2H_2O \Rightarrow 2Fe^{2+} + 4SO_4^{2-} + 4H^+ \qquad (3.3)$$

This reaction will lower pH. If pH is brought below 4, Fe^{3+} becomes soluble and enables a rapid two step oxidation of pyrite:

$$FeS_2 + 14Fe^{3+} + 8H_2O \Rightarrow 15Fe^{2+} + 2SO_4^{2-} + 16H^+ \qquad (3.4)$$

In the presence of oxygen a bacterial catalysed reaction can bring Fe^{3+} back to the system by:

$$Fe^{2+} + \tfrac{1}{4}O_2 + H^+ \Rightarrow Fe^{3+} + \tfrac{1}{2}H_2O \qquad (3.5)$$

Most of the acidity generated by the oxidation of pyrite by iron III is spent in the oxidation of iron II back to iron III. The net result, which is the most interesting for our further discussion, may be expressed as:

$$FeS_2 + \tfrac{15}{4}O_2 + \tfrac{7}{2}H_2O \Rightarrow Fe(OH)_3 + 2SO_4^{2-} + 4H^+ \qquad (3.6)$$

This reaction indicates that each mole of pyrite oxidised results in 4 moles of acidity. The rate of pyrite oxidation increases with decreasing pH. At very low pH (<4) the supply of oxygen is the limiting factor. This is why the pyritic material exposed to air acidifies much faster than the material constantly covered with water (van Breemen, 1972). The oxidation of pyrite and the resulting lowered pH can present severe toxicity problems to crops. Buffering the acidity at a low pH is attributed to acid hydrolysis of aluminosilicate clays. High contents of dissolved silica and Al^{3+} in the groundwater are striking characteristics of acid sulphate soils. The high concentration of dissolved Al^{3+} produces the most harmful effects on living plants, but ferrous-iron and H_2S toxicity can also give negative effects

4. THEORY OF PUMPING TESTS

4.1 General

In this section a brief overview of the basic theory of groundwater flow in unconfined aquifers is given. Both steady-state and transient flow situations are studied. The main focus is on the theories behind pumping tests used to determine the horizontal hydraulic conductivity. The equations governing groundwater flow in confined aquifers are in many cases similar but are not dealt with in this report.

The basic law of flow is Darcy's law, formulated in 1856 by the French hydraulic engineer Henry Darcy. It states that the velocity of groundwater flow can be described as

$$v = -K\frac{d\varphi}{dx} \tag{4.1}$$

where the velocity v is defined as the specific discharge Q/A, where Q is the discharge and A is the area involved in the transport of water, φ is the hydraulic head, $d\varphi/dx$ is the hydraulic gradient and K is the hydraulic conductivity. Darcy´s law is applicable in all situations of normal flow where the water can be viewed as a continuum and where groundwater flow is laminar. For all cases discussed in this paper Darcy's law is assumed to be valid.

The Dupuit-Forcheimer theory of free surface flow can be used to greatly simplify the analysis of groundwater flow in an unconfined system bounded by a free surface. It was first presented by Dupuit in 1863 and later developed by Forcheimer in 1930. The theory is based on two assumptions: (1) all flowlines in a system of gravity flow towards a shallow sink are horizontal and (2) the hydraulic gradient is assumed to be equal to the slope of the free surface and to be invariant with depth. In recent years the Dupuit-Forcheimer theory has been developed and used by other scientists, e.g. Guyon, to describe and calculate groundwater flow in a number of different situations and systems.

The well theory developed by scientists like Darcy, Forcheimer, Guyon and Theis provides an excellent means to analyse groundwater flow problems, such as pumping tests. One should, however, be aware of some of the limitations of well theory in the cases presented in this report:

1. The Dupuit assumptions are of an approximate nature. With these assumptions it can even be shown that there would be no flow at all (Shaw,1988).
2. The soil is assumed to be uniform and isotropic.
3. The thickness of the aquifer is assumed to be constant.
4. The initial piezometric level is assumed to be level.
5. Only laminar flow is assumed to exist in the region of the well.
6. The aquifer from which the water is drawn must be infinite for the theory to hold true.

Nevertheless, for the cases studied in this paper the Dupuit-Forcheimer theory is applicable and the errors created by the simplification of the flow theory are acceptable.

4.2 Steady-state situations

During a pumping test, a steady-state situation is present when the system does not change with time, i.e. the drawdown of the groundwater surface does not change with time. It is important to be aware that in almost every case only a pseudo steady-state can be obtained. Even though changes occur very slowly, they are still continuing. However, for calculations of soil parameters a pseudo-steady-state is enough in most cases. In this paper, no difference will be made between real steady-state and pseudo steady-state situations.

4.3 Guyon's pumping test

According to LeSaffre (1989) the saturated horizontal hydraulic conductivity can be measured using Guyon's pumping test. A well is drilled and the water pumped out until a steady-state situation is reached. Then the water levels in the well and in an observation tube, located at a known distance from the well, are measured (Figure 4.1). The theory is based upon Darcy's law and the Dupuit assumptions.

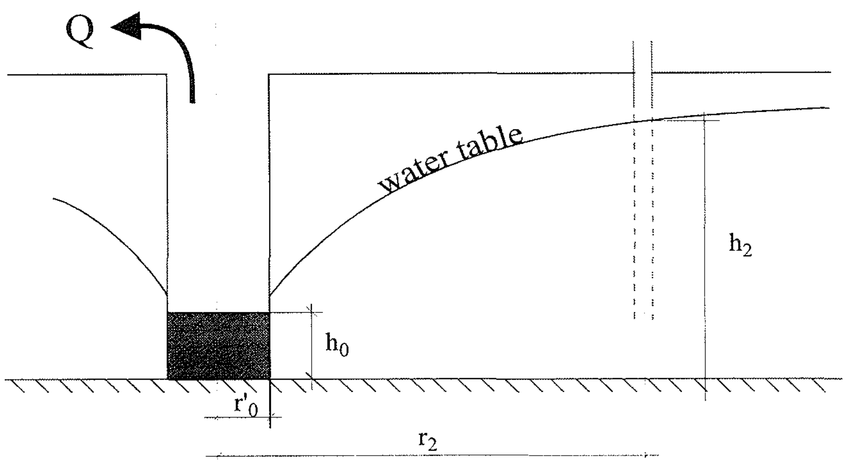


Figure 4.1. Guyon's pumping test, the well reaching the impermeable layer.

The theory of Guyon requires steady-state and assumes radial symmetry of soil properties. It also requires a well defined thickness of the aquifer. The aquifer is bounded by the groundwater surface and an impermeable layer. Two cases can be distinguished: a) the well does not reach the impermeable layer and b) the well reaches the impermeable layer. The case studied in this report is of type b) (Figure 4.1).

For the type b) case the hydraulic conductivity can be calculated in the following way, introduced by Guyon and Wolsack in 1978 (LeSaffre, 1989):

The radial component of the saturated flow rate *q(r)*, per unit width through any vertical section can be written using Darcy's law

$$q(r) = -\int_{0}^{h(r)} K(z)\frac{\partial\varphi(r,z)}{\partial r}dz \tag{4.2}$$

where r is the radial co-ordinate from the well axis, z is the elevation above the impermeable layer, $\varphi(r,z)$ [also denoted φ], is the hydraulic head above the impermeable layer, $h(r)$ [also denoted h] is the water table height above the impermeable layer and $K(z)$ is the horizontal component of the depth-dependent hydraulic conductivity. Equation (4.2) can be transformed using the unit discharge function $F(r)$ as follows:

$$q(r) = -\frac{dF(r)}{dr} \tag{4.3}$$

$$F(r) = \int_0^h K(z)(\varphi - z)dz \tag{4.4}$$

Substituting Dupuit's assumption $[\varphi(\mathrm{r,z}) = \mathrm{h(r)}]$ in equation (4.3) yields

$$F(r) = K(h)\frac{h^2}{2} \tag{4.5}$$

$$K(h) = \frac{2}{h^2}\int_0^h K(z)(h - z)dz \tag{4.6}$$

The total flow rate through any vertical cylindrical section is equal to the discharge Q pumped out of the well:

$$Q = 2\pi r q(r) \tag{4.7}$$

Combining equation (4.3) and equation (4.7) and then integrating after r, using the expression of $F(r)$ in equation (4.5) yields

$$\frac{Q}{\pi}\ln\left(\frac{r_2}{r_0^{'}}\right) = h_2^2 K(h_2) - h_0^2 K(h_0) \tag{4.8}$$

where h_0 and h_2 are the respective water heights inside the well and inside the farther observation tube. $r_0^{'}$ is the outer radius of the well and r_2 is the distance from the well axis to the farther observation tube. If the soil is homogeneous this equation provides the average hydraulic conductivity K for the soil

$$K = \frac{\frac{Q}{\pi}\ln\left(\frac{r_2}{r_0^{'}}\right)}{h_2^2 - h_0^2} \tag{4.9}$$

4.4 Transient flow

To be able to understand the equations used when working with transient flow situations it is necessary to do a more thorough penetration of the underlying theory than was made in the steady-state case. Here the treatment of the theory is presented after Freeze & Cherry, 1979.

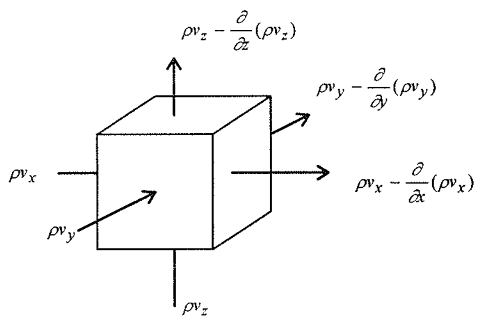


Figure 4.2 Elemental control volume for flow through porous media.

For transient flow the net flow into any given elemental control volume must be equal to the time rate of change of fluid mass storage within the element. With reference to Figure 4.2, the equation of continuity takes the form:

$$-\frac{\partial(\rho v_x)}{\partial x} - \frac{\partial(\rho v_y)}{\partial y} - \frac{\partial(\rho v_z)}{\partial z} = \frac{\partial(\rho n)}{\partial t} \qquad (4.10)$$

where n is the porosity of the medium. The change in ρ and the change in n are both produced by a change in hydraulic head h, and the volume of water produced by the two mechanisms for a unit decline in head is S_S , where S_S is the specific storage. The mass rate of water produced (time rate of change of fluid mass storage) is $\rho S_S \frac{\partial h}{\partial t}$ and equation 4.10 becomes

$$-\frac{\partial(\rho v_x)}{\partial x} - \frac{\partial(\rho v_y)}{\partial y} - \frac{\partial(\rho v_z)}{\partial z} = S_s \frac{\partial h}{\partial t} \qquad (4.11)$$

Expanding the terms on the left hand side and recognizing that the terms of the form $\rho \partial v_x / \partial x$ are much greater than terms of the form $v_x \, \partial \rho / \partial x$ allows us to eliminate ρ from both sides. Inserting Darcy's law, we obtain

$$\frac{\partial}{\partial x}\left(K_x \frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_y \frac{\partial h}{\partial y}\right) + \frac{\partial}{\partial z}\left(Kz \frac{\partial h}{\partial z}\right) = S_s \frac{\partial h}{\partial t} \qquad (4.12)$$

If the medium is homogenous and isotropic, equation (4.12) reduces to

$$\frac{\partial^2 h}{\partial x^2}+\frac{\partial^2 h}{\partial y^2}+\frac{\partial^2 h}{\partial z^2}=\frac{S_s}{K}\frac{\partial h}{\partial t} \tag{4.13}$$

Equation (4.13) is known as the diffusion equation. The solution *h(x,y,z,t)* describes the value of the hydraulic head at any point in a flow field at any time. For the special case of a horizontal unconfined aquifer with the original thickness *b*, $S=S_S b$ where *S* is the effective porosity, and $T=Kb$ where *T* is the transmissivity, the two-dimensional form of eq. (4.13) becomes

$$\frac{\partial^2 h}{\partial x^2}+\frac{\partial^2 h}{\partial y^2}=\frac{S_s}{K}\frac{\partial h}{\partial t} \tag{4.14}$$

4.5 Theis' method

In 1935 Theis, using an analogy to heat flow theory, presented an analytical solution to eq (4.14):

$$s(t)=\frac{Q\times W(u(t))}{4\times\pi\times T} \tag{4.15}$$

were *t* is the time of the observation, *s* is the drawdown, *Q* the pump rate, *T* the transmissivity and

$$u(t)=\frac{{r^2}/{4t}\times S}{T} \tag{4.16}$$

S is the effective porosity and *r* is the distance between the pumping well and observation well. *W(a)* is the infinite integral for $e^{-a}a^{-1}$ and is called the exponential integral or the well function. *S* and *u* are non-dimensional. Solutions to these equations are implicit and must be found with a trial-and-error method. The transmissivity *T* is then calculated with drawdowns dd_1 and dd_2 at two different times from start t_1 and t_2 by finding the solution *T* to the equation

$$\frac{dd_1}{dd_2}=\frac{W(u(t_1,T))}{W(u(t_2,T))} \tag{4.17}$$

The relationship between T and the hydraulic conductivity K is

$$K = \frac{T}{d} \tag{4.18}$$

were d is the depth of the aquifer.

As can be seen in the equations above, the drawdown at any point at a given time is directly proportional to the pumping rate and inversely proportional to aquifer transmissivity and effective porosity. Aquifers of low transmissivity develop tight, deep drawdown cones, whereas aquifers of high transmissivity develop wide, shallow cones.

4.6 Effective porosity

The effective porosity can be calculated in several ways using transient flow theory. When solving the Theis equations, one obtains both the effective porosity S and the transmissivity T. Another way of finding the effective porosity is to use the first stage of a pumping test, when the water table is slowly depressed and the soil desaturated (after LeSaffre, 1989). The method uses the same set-up as described in Figure 4.1 but with an additional observation tube between the well and the observation tube seen in figure 4.1. Practice shows that during the first stage of the pumping test, the flow reaching the well is supplied only by the depression cone. As a result, the effective porosity S is computed by the ratio between the volume of water extracted from the soil v, and the cone volume, V:

$$S = \frac{v}{V} \tag{4.19}$$

The volume of water extracted from the soil is

$$v = v_p - \pi r_0^2 d_o \tag{4.20}$$

where v_p is the pumped volume since the beginning of the test, r_0 is the radius of the well and d is the water drawdown in the well. Assuming that the water table drawdown d since the beginning of the test is a logarithmic function of the distance to the well axis, the depression cone volume can be expressed as

$$V = \pi \frac{d_1 - d_2}{\ln\left(\frac{r_2}{r_1}\right)} \left[\frac{R^2 - r_0^2}{2} - r_0^2 \ln\left(\frac{R}{r_0}\right) \right] \tag{4.21}$$

where r_0 is the radius of the well, r_1 and r_2 are, respectively, the distances to the nearer and farther observation tubes from the well axis, d_1 and d_2 are, respectively, the drawdowns inside the nearer and farther observation tubes and R is the radius of influence of the well:

$$\ln R = \frac{d_1 \ln r_2 - d_2 \ln r_1}{d_1 - d_2} \qquad (4.22)$$

By substituting eq. (4.22) into eq. (4.21) and then substituting eq. (4.20) and (4.21) into eq. (4.19) the effective porosity S can be calculated.

5. METHODS

5.1 Geographical facts. Objective of the study

The experiments were carried out at the Management of Acid Sulfate Soils Project (MASSP) experimental station, Tan Thanh Farm, Long An province, Vietnam. The field work lasted between the 14th and the 26th June 1996 and the experiments were done in the second half of this period. The measurements were part of the MASSP supplementary measurement program at Tan Thanh Farm, carried out at the beginning of the rainy season of 1996.

In cooperation with the MASSP coordinator, plot P4 was chosen as the experimental site. This plot is already used for continuos monitoring of for example groundwater level and soil temperature with equipment installed in April 1996. A map of the Tan Thanh Farm area is shown in Figure 5.1.

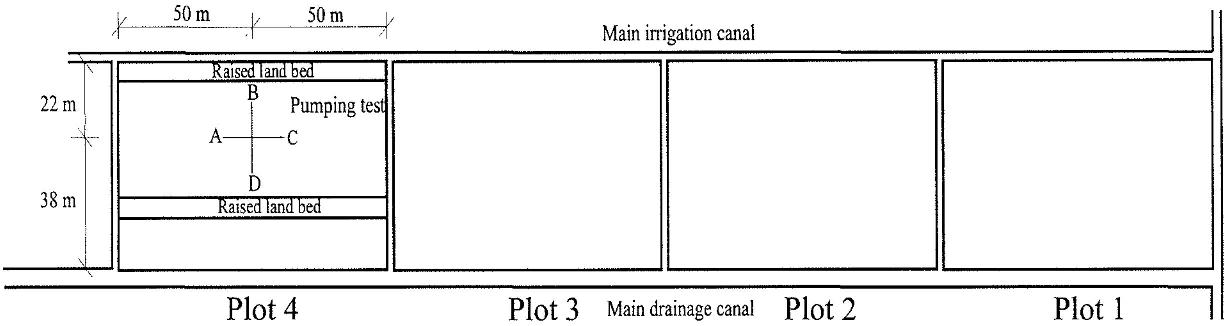


Figure 5.1. Map of the Tan Thanh Farm area.

The objective of the study was to determine the saturated horizontal hydraulic conductivity of the field and the effective porosity of the soil. A first test using the auger hole method indicated high conductivities (>10 m/day) and a decision was made to use the pumping test method. With the equipment available, it was not possible to obtain reliable results from auger tests. Another reason for choosing a pumping test rather than using the auger hole method was the higher accuracy of the pumping test (LeSaffre, 1990). In the auger test, the diameter of the soil column involved is about 30-50 cm whereas the radius of influence of the pumping test well is several meters. 5 to 10 auger hole tests are necessary to obtain the hydraulic conductivity with the same precision provided by one steady-state pumping test (LeSaffre, 1990)

5.2 Description of the experimental setup

The well was drilled in the center of the field to minimize boundary effects as much as possible (Figure 5.2). The closest small canal was then 22 meters away. At the start of the experiments, the well reached 130 cm below the soil surface. The well was later deepened to 140 cm.

The outer diameter of the well was 22 cm. From the well, four perpendicular transects were drawn, labeled A-D. On transect A, seven groundwater observation tubes were placed at 0.25, 0.5, 1.0, 1.5, 2.0, 3.0 and 4.5 meters distance from the center of the well. The diameter of the observation tubes was 34 mm. On the other transects, observation tubes were put down at 1.0 and 3.0 meters distance.

The observation tubes and the well were placed with their upper ends in the same horizontal plane, defining a reference level against which all water levels during the experiments were measured. The transducers connected to the logger were placed in the observation tubes A0.25, A0.5, A1.0, A1.5 and A3.0 and in the well. A list of the equipment used is given in Appendix A.

In the first four pumping tests, a perforated tube with the same diameter as the well was placed inside the well to prevent the walls from falling in because of the flow of water. This proved to be a mistake since the resistance of the tube was large compared to the resistance in the soil, so that the groundwater surface did not follow the normal funnel form. The tube was therefore removed. The walls of the well were surprisingly stable during the following 8 tests and there was almost no sign of material falling in from the walls. By the end of test nº 3 a small cavity (approx. 5 cm deep) was observed in the well in the transect D direction. This cavity was considered too small to affect the total groundwater flow to the well.

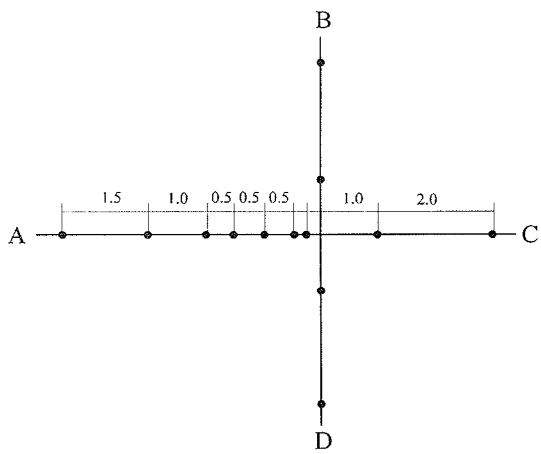


Figure 5.2. The experimental site with the well in the centre and the observation tubes on transect A-D.

5.3 Tests

A total of 8 steady-state pumping tests without the tube in the well were carried out, with the flows varying between 1.74 and 3.07 (*10^{-4}) m^3s^{-1} (Table 5.1). The drawdowns in the well varied between -44 and -117 cm relative to the soil surface. Each test was run so that a stable steady-state was reached. This was obtained by placing the pump inlet at a specific level in the well and then adjusting the flow so that the pumping rate was slightly higher than the steady-state flow into the well. The waterlevel in the well would then oscillate around the chosen level of drawdown, the pump altering between pumping air and pumping water. The period and the amplitude of the oscillation was relatively small (5 to 20 seconds and up to 5 cm respectively) and has not been considered in the calculations. The running time of the test varied between 1 and 5 hours. One 12 hour test was also done to determine if any changes in the steady-state levels would occur. In all tests, the groundwater level in the observation tubes and in the well was recorded by a data logger every 30 seconds.

Table 5.1. Steady-state pumping tests performed at Tan Thanh Farm 19-24/6 1996

Pumping test	Start time (date, time)	Running time (hrs)	Flow ($10^{-4}m^3/s$)	Water level in well (cm)	Maximum difference in grw. level during test. (cm)
s1	19/6, 16.55	1	3.07	-101.0	0.5
s2	21/6, 10.08	5	2.67	-102.5	0.8
s3	21/6, 16.38	1.5	2.54	-78.5	0.8
s4	22/6, 09.06	1	2.56	-80.0	0.4
s5	22/6, 10.13	1.5	2.30	-62.6	1.9
s6a	22/6, 11.43	1.5	1.74	-44.0	2.1
s6b	22/6, 13.16	1.5	1.94	-44.0	0.4
s7	23/6, 18.06	12	2.86	-117.0	7.8
s8	24/6, 11.12	3.5	2.44	-117.0	1.5

Transient flow tests were carried out in addition to the conventional steady-state pumping tests. Starting from an unaffected groundwater surface a steady flow out of the well was arranged and the drawdown in the observation tubes was recorded. When steady-state was reached or when the well was emptied, the experiment was stopped. A total of 8 experiments with different flows were carried out, the flow varying between 2.69 and 5.26 (10^{-4}) m^3s^{-1}. The drawdowns in the tubes were recorded every second by a data logger. After every test there was sufficient time for recovery of the groundwater level before the next test was started.

During the whole experimental period, the groundwater level in the canals and in an unaffected part of the field was measured. The groundwater level variations were small; the maximum change during a single test was 8 cm.

5.4 Calculations

For steady-state pumping tests, the hydraulic conductivity *K* was calculated according to equation 9 given in the theoretical background above. In the cases where transient flow methods were used, an analytical solution is not possible.

Theis method calculations are sensitive to the choice of drawdown pairs and to stochastic variations in the recorded values. One way to prevent this sensitivity having too much influence on the results is to make many calculations for the chosen observation tube and then average the K values obtained. When calculating K values from the data from the transient flow experiments the observation times t and $5*t$ were chosen, with t varying from 10 seconds up to a fifth of the maximum time recording in the data series.

In the experiments conducted at Tan Thanh farm, 20 to 40 different pairs of drawdowns were used for each calculation of the K value.

6. RESULTS

6.1 Steady-state tests

The water table responded very quickly when the pumping started (Figure 6.1). Steady-state was reached in approximately 30 minutes depending on discharge rate. An example of the resulting shape of the water table is shown in Figure 6.2.

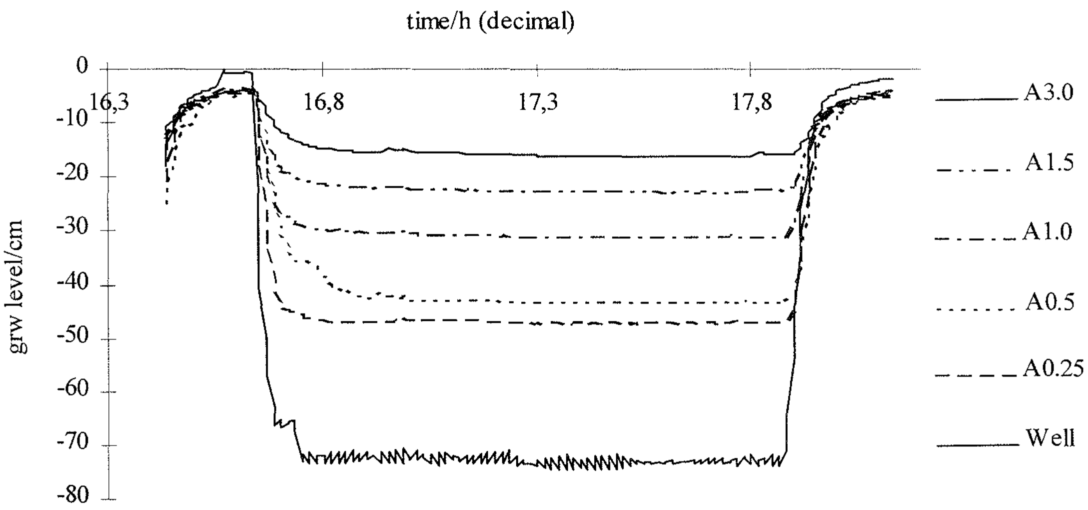


Figure 6.1. Water levels, pumping test no. s3.

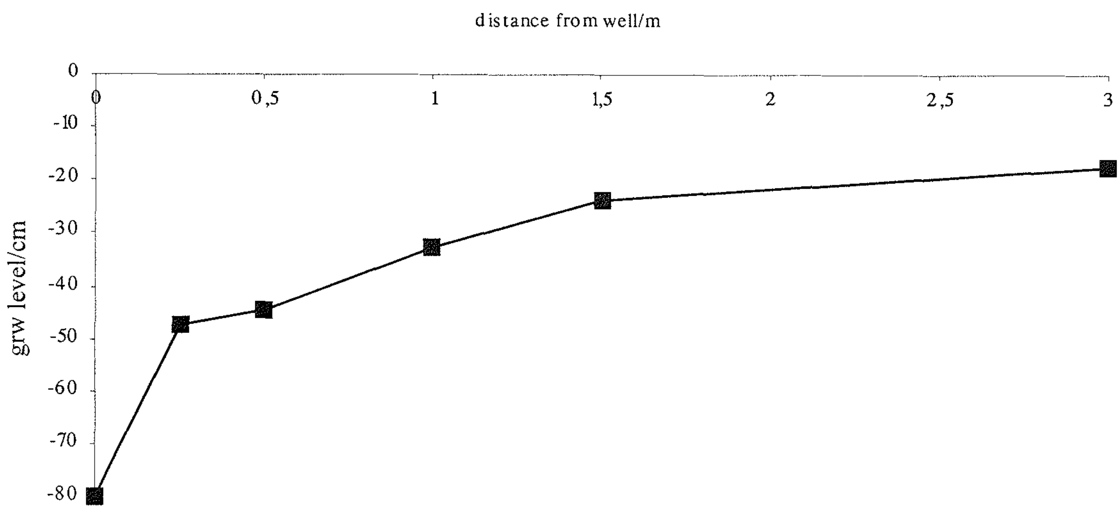


Figure 6.2. Shape of water table at steady-state, pumping test no. s3. Original groundwater level -1 cm.

The calculations of hydraulic conductivity according to Guyon's method are based on the assumption of symmetric drawdown of the water table. In the case studied, this assumption was validated by using automatic as well as manual observations in the observation tubes on transects A-D and then comparing the corresponding drawdowns. The water levels in the observation tubes at 1 m and 3 m were analyzed for symmetry. The coefficient of variance was never greater than 0.06 (Table 6.1).

Table 6.1. Means, standard deviations and coefficients of variance of six pumping tests for observation tubes at the same distance from the well

Pumping test	r = 1 m			r = 3 m		
	mean water level	s	c_v	mean water level	s	c_v
s1	-22.18	3.10	0.059	---	---	---
s2	-27.50	3.14	0.055	-14.30	0.36	0.0081
s3	-29.08	3.15	0.053	-15.45	0.47	0.010
s4	-30.63	3.24	0.053	-17.21	0.44	0.0093
s5	-29.10	2.80	0.047	-17.25	0.65	0.014
s6	-19.89	2.34	0.047	-10.96	0.73	0.018

The distance from the soil surface to the impermeable layer was assumed to be 1.2 m (Phi 1996; Eriksson, 1996). The calculated mean saturated horizontal hydraulic conductivity of the field was 26 m/day when all the pumping tests were considered. An averaging of the conductivities where pumping test no. 5, 6a and 6b were excluded was also made with a resulting mean conductivity of 23 m/day (Table 6.2). The drawdown in the well during the excluded tests was considered insufficient to provide reliable values of the hydraulic conductivity. The conductivity values (Table 6.2) were calculated from an average of 10 level measurements during a period of steady-state with stable flow. During pumping test no. 6 it started to rain and hence the discharge rate changed. Conductivity values were calculated for the time before and during rainfall with different flow rates (tests no 6a and 6b respectively).

Table 6.2. Calculated saturated horizontal hydraulic conductivities, steady-state situations

Pumping test	*K* calculated for A0.25 (m/day)	*K* calculated for A0.5 (m/day)	*K* calculated for A1.0 (m/day)	*K* calculated for A1.5 (m/day)	*K* calculated for A3.0 (m/day)
s1	---	17.8	20.5	20.4	23.4
s2	11.4	18.2	20.3	20.1	22.3
s3	15.9	25.3	24.7	23.4	25.4
s4	15.8	26.3	25.8	24.1	26.2
s5	20.1	35.7	29.9	26.9	28.8
s6a	19.6	37.5	30.8	28.1	29.9
s6b	19.3	36.6	30.0	27.6	29.6
s7	13.4	22.8	23.1	22.6	25.3
s8	13.1	21.1	22.2	21.9	24.4

6. 2 Transient flow tests

The calculated mean saturated horizontal hydraulic conductivity for the transient flow pumping tests was 23 m/day. Mean values were calculated for the water levels recorded in A0.5, A1.0, A1.5 and A3.0 (Table 6.3). In Figure 6.3 an example of drawdowns in the observation tubes during a transient flow test is shown. Figure 6.4 shows an example of how calculated *K*-values vary, depending on which start time for the calculations that is chosen.

A comparison between the results obtained from steady-state pumping tests and the results from the calculations based on transient flow shows that they give similar results.

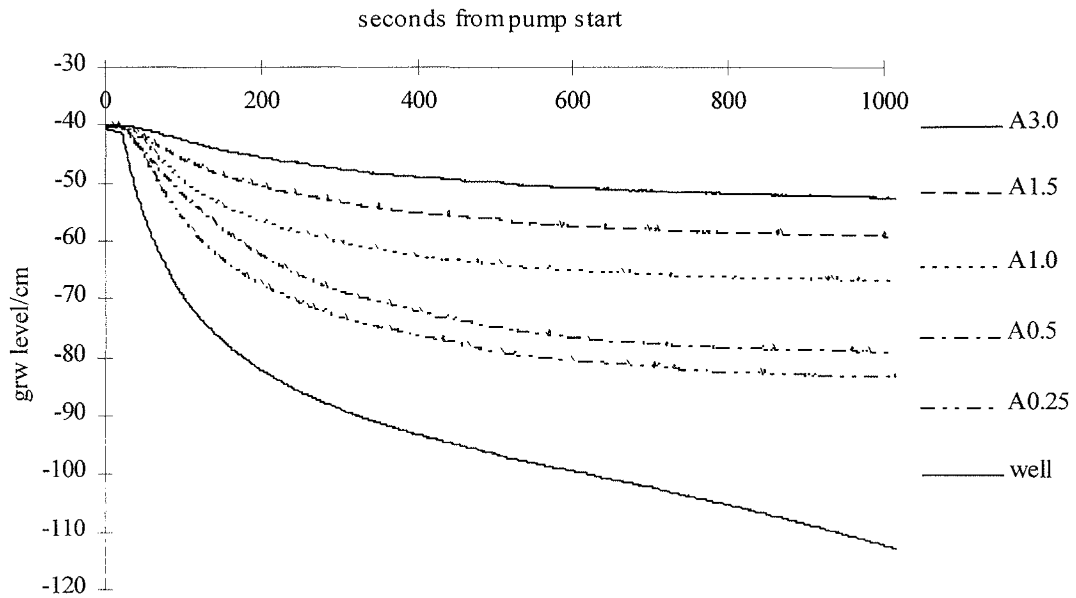


Figure 6.3. Drawdowns in well and observation tubes, test t8.

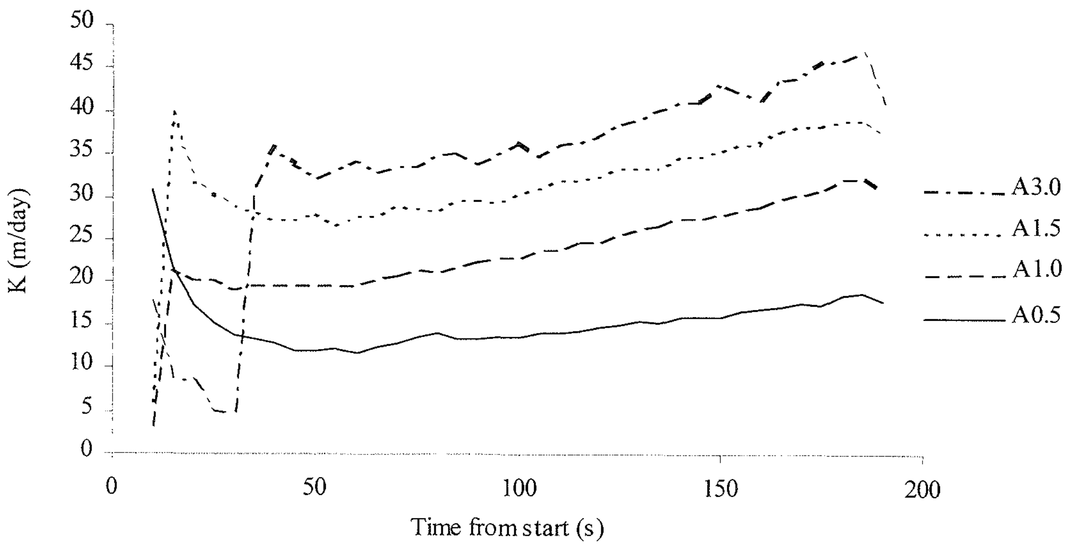


Figure 6.4. Calculated hydraulic conductivities test no t2, Theis method.

The effective porosity S was calculated on the same set of data, both by using the theory developed by Guyon and by using the equations presented by Theis, and the results were 0.008 and 0.030 respectively (Table 6.4). The reason for this difference is unknown but the delayed yield in the transient flow tests could affect the calculated effective porosities.

Table 6.3. Calculated mean conductivities from pumping tests, transient situation

Pumping test	K calculated for A0.5 (m/day)	K calculated for A1.0 (m/day)	K calculated for A1.5 (m/day)	K calculated for A3.0 (m/day)	Flow (10^{-4} m^3s^{-1})
t1	14.0	16.1	24.3	29.5	3.6
t2	12.8	19.8	26.4	28.4	2.9
t3	20.4	21.6	33.6	8.2	5.3
t4	11.6	19.0	26.0	38.1	2.8
t5	15.6	16.8	27.9	16.7	4.0
t6	16.5	21.1	30.6	40.6	4.4
t7	15.5	22.9	30.9	31.9	3.2
t8	10.5	17.0	23.7	28.7	2.7

Table 6.4. Calculated mean effective porosities from pumping tests, transient situation. Mean values

Pumping test	S calculated for A0.5	S calculated for A1.0	S calculated for A1.5	S calculated for A3.0	S (Guyon eq.)	Flow (10^{-4} m^3s^{-1})
t1	0.08	0.02	0.02	0.010	0.010	3.57
t2	0.06	0.04	0.02	0.009	0.005	2.85
t3	0.08	0.02	0.02	0.008	0.007	5.26
t4	0.07	0.02	0.02	0.008	0.007	2.83
t5	0.08	0.02	0.02	0.008	0.006	4.00
t6	0.06	0.02	0.02	0.009	0.006	4.44
t7	0.05	0.02	0.01	0.009	0.006	3.23
t8	0.03	0.10	0.01	0.007	0.014	2.69

7. DISCUSSION

7.1 Soil characteristics

The equations used in this report for calculating the horizontal hydraulic conductivity assume a) radial symmetry and b) a homogeneous soil. Dong et al. (1991) has shown that the soil studied consists of three main layers: the A-horizon to 15 cm depth is rich in organic matter and in macropores, the B-horizon from 15 cm to 90-120 cm depth is a ripe structureless type soil. Below the B-horizon the C-horizon is found which can be regarded as impermeable. According to Dong et al. (1991) the soil is largely homogenous below 15 cm down to the impermeable layer. Plot 4 lacks the plough sole often found in rice fields that have been under cultivation for a longer period of time.

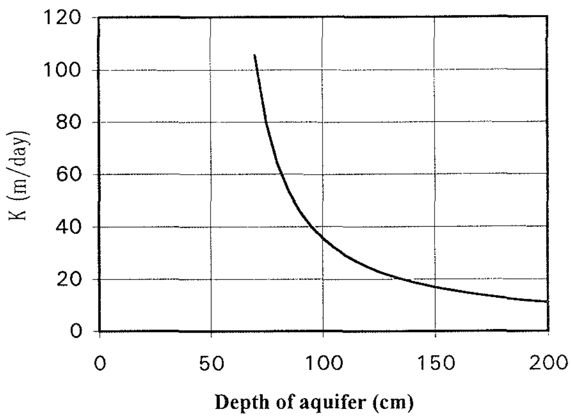


Figure 7.1. Calculated K-values for different assumed distances d to the impermeable layer. Calculations are based on pumping test no. s3, observation tube A1.0.

In this study, the distance to the impermeable layer was generally assumed to be 120 cm (Eriksson, 1996; Phi, 1996). However, one should be aware of the great importance of this distance when calculating the horizontal hydraulic conductivity. The estimated value of K may be adjusted in accordance with the relationship obtained for a specific set of data for different distances to the impermeable layer (Figure 7.1). For transient flow methods the conductivity linearly decreases with increasing aquifer depth and thus the water bearing layer's thickness will still be of great importance.

To ensure radial symmetry the drawdowns in observation tubes at corresponding distances from the well were compared. The result of the comparison showed that the soil can be viewed as radially symmetric, even though the indicating variable used in this case, the coefficient of variance, is a rather coarse one. If possible, it would be desirable to perform a more extensive statistical analysis of the symmetry using a hypothesis test. In this case, however, the collected number of data is too small and too unevenly distributed to make such a test reliable.

7.2 Soil properties

A shift towards higher estimated values of the calculated hydraulic conductivity can be observed as one uses observation tubes at greater distances from the well in the steady-state equation to obtain the K-value. This might well emanate from the influence of macropores at shallow depths in the soil. In the surface layer of the soil the number of macropores is much greater than in deeper horizons. The reason is the greater biological activity at shallow depths. During the dry season there are also many cracks in the surface layer due to soil shrinkage. The groundwater level is closer to the soil surface further away from the well as the drawdown of the groundwater level decreases at greater distances from the well. Thus, the influence of macropores will increase correspondingly. In this situation, one of the conditions upon which the flow theory relies, soil homogeneity, is no longer valid. Because of the heterogeneity in the soil, the drawdown of the groundwater level in the farther observation tubes, where the drawdown is small and the influence of macropores may be substantial, was greater and the calculated conductivity higher than would be expected for a homogenous soil.

When the transient flow method was used to calculate the hydraulic conductivity, the same pattern of increasing calculated values of K with increasing distances from the well could be seen. The reasons for this are partly as described above, but also due to the effect of delayed yield. Immediately after a lowering of the water table there is still water left in the zone above the water table because of capillary forces. This water will "leak" downwards to the water table resulting in a higher water level in the observation tubes, and thereby a higher calculated conductivity, than would have been the case if this delayed yield had not existed. The effect of delayed yield is larger when the drawdown is small, which gives higher K for observation tubes farther away from the well. Delayed yield is only significant for the beginning of a pumping test and does not affect the steady-state tests.

Tube A0.25 was excluded when calculations of the average horizontal hydraulic conductivity were conducted. The reason for this was the short distance between tube A0.25 and the well, causing significant boundary effects.

In pumping test no 7, an increase in the calculated K-values with time was obtained. One explanation could be tidal effects which can be seen as far as into the middle of the field according to Larsson, 1996. During the pumping test the groundwater level in the field 10 m from a drainage canal decreased approximately 8 cm due to tidal movements. The calculated K-value increased with time because of this phenomena. The reason for this is simply that when calculating the K-values the average value of the flow rate during the whole pumping test was used. When drawdowns in the observation tubes increase because of tidal effects, the calculated K-value will increase if one does not take into account the decreased discharge flow. As no measurements of the flow rate were carried out during the night when the test was performed, there was no possibility of knowing the exact decrease in water discharge rate. As mentioned above, a mean value of the water discharge rate for the whole pumping test was used instead, causing the described effects when calculating the K-value. An obvious way to avoid these unwanted effects is to carry out more frequent flow measurements.

The steady-state method included a larger soil volume than the transient flow methods. Therefore, results obtained from steady the state pumping tests should be less sensitive to spatial variations in the field and also less sensitive to macropores. On the other hand, the calculations based on steady-state theory were more sensitive to the depth of the water-bearing layer than the transient flow methods.

7.3 Sensitivity analysis

The field measurements of the saturated hydraulic conductivity were performed during two weeks in the middle of June. The rainy season had started some weeks earlier and the ground was completely saturated. The sensitivity analysis in Appendix 1 showed that these conditions makes a SOIL simulation of groundwater level, bypass flow and water content insensitive to variations in total hydraulic conductivity, *K*. It also showed that variations in total drainage flow and vertical flow at 20 cm depth are proportional to variations in *K*. From a SOIL-modelling point of view this means that the hydraulic conductivity is not an important parameter when simulating for example groundwater levels during such conditions. Therefore it would not be worth making efforts to get very accurate values for *K* for that period.

The end of the dry season (March) and the beginning of the rainy season (May) were periods when the SOIL-simulation was more sensitive to variations in *K* (Appendix 1, Table 1). Consequently very careful measurements of *K* on many locations may be necessary to achieve reliable simulation results. However, the sensitivity during these periods varied depending on the order of magnitude of *K*. For response types A and B (Appendix 1, Figure 5) the model was sensitive to variations if *K* was low and insensitive to variations for high values. For response type D (Appendix 1, Figure 5) the model was sensitive to variations when *K* values was within a specific interval and insensitive for both lower and higher values of *K*. Hence, simulated flows and levels can be insensitive to variations also during these periods, if the order of magnitude of *K* lies outside the sensitive interval.

In the sensitivity analysis the highest value of *K* used was 16 m/day, whereas the average *K* from the field experiments was more than 20 m/day. All response curves except C in Figure 5 (Appendix 1) showed no changes in variable values for the highest values of *K*. Therefore, one can also assume constant variable values for *K*-values up to 22 m/day and above. In the same way, the variable values for response type C can be assumed to continue to increase linearly for increasing *K*. The result from the sensitivity analysis suggests that all the target variables considered in the SOIL simulation, except vertical flow at 20 cm in June and total drainage flow in June, should be insensitive to variations in *K* during March, May and June (Appendix 1, Table 1) due to the high *K* value. Both vertical flow at 20 cm and total drainage flow in June would respond linearly to variations in *K*. If *K* varies over the year, field measurements of *K* must be made during periods of high sensitivity if they are to be used to predict and explain field behaviour.

The sorption properties (Appendix 1) generally had a small influence on the simulation results compared to saturated *K*. However, the bypass flow was affected by variations in sorptivity during the first rainfalls of the rainy season. The results from the sensitivity analysis do not mean that it is not important in reality. If much of the acidity in the soil is assumed to be formed at the walls of cracks and other macropores, then bypass flow can greatly affect how much of the acidity is washed out of the soil to the canals. Therefore it may be very important to make thorough studies of the soil matrix properties if one wants to increase the understanding of exchange processes within the soil.

7.4 Future research

None of the pumping tests described in this report give any information about the exchange rate of water between the field and the surrounding canals. To get more knowledge about these processes one should perform tests of the hydraulic conductivity of the dikes bordering the canals and the soil underneath them. One way of doing this could be to carry out a pumping test closer to a canal. The shape of the drawdown cone of such a pumping test would be asymmetric and provide information about the effects of canal dikes on groundwater flow. In addition it is also desirable to consider *where* the acidification processes take place in the soil. If much of the acidity is formed at the walls of cracks and other macropores, bypass flow can greatly affect how much of the acidity is washed out of the soil to the canals. If this is proven to be the case, the properties of the soil matrix would be of interest as the bypass flow is dependent on the sorptivity of the soil aggregates.

8. CONCLUSIONS

The results of the pumping tests indicated a somewhat higher value of the horizontal hydraulic conductivity than reported earlier. This implies that water flow through the soil could be larger than one has believed previously and that the leaching from the soil may also be more effective. The effective porosity of the soil seems to be lower than indicated by measurements carried out by Larsson (1996). It should be noted that the methods used for determining S could be less accurate than the methods used by Larsson.

When using the Guyon method for determining K at steady-state, the estimated depth d of the aquifer greatly influences the results (K is proportional to d^{-2}). In the transient flow calculations, K has a linear response to d which for small values of d makes the method less sensitive to uncertainties in d.

9. REFERENCES

van Breemen, N. 1972. Environmental aspects of acid sulphate soils. I Introductory papers and bibliography. Proceedings of the international symposium on acid sulphate soils 13-20 august 1972, Wageningen, Netherlands (edited by H. Dost) (publication 18 vol. 1)

Dent, D.L. 1986. Acid Sulphate soils: a base line for Research and Development. ILRI-publ. 39. ILRI, Wageningen

Follin, S. 1992. Numerical Calculations on Heterogeneity of Groundwater Flow. Stockholm: Royal Institute of Technology.

Freeze, A & Cherry, J. 1979. Groundwater. New Jersey: Prentice-Hall

Husson, O et al. 1995. Land reclamation on severely acid sulphate soil in the Plain of Reeds. The experience of the IOS/FOS FSR project.

Jansson, P-E. 1996. Simulation Model for Soil Water and Heat Conditions. Uppsala: Swedish University for Agricultural Sciences.

Kawalec A. 1972. World distribution of acid sulphate soils. References and map. I Introductory papers and bibliography. Proceedings of the international symposium on acid sulphate soils 13-20 august 1972, Wageningen, Netherlands (edited by H. Dost) (publication 18 vol. 1)

Kutilek, M & Nielsen, D R . 1994. Soil Hydrology. Cremlingen: Catena Verlag..

Larsson, C. 1996. Infiltration capacity and tidal Influence on Groundwater Motion in Acid Sulphate Soils. Undergraduate thesis 10 p. Uppsala: Institute of Earth Sciences, Hydrology. Uppsala University.

Miller, D R. 1974. Sensitivity Analysis and Validation of Simulation Models. Journal of Theoretical Biology vol 48. pp 345-360.

MRC, The Mekong River Commission Secretariat. 1995. The Management of acid sulphate soils project (MASSP) in the Mekong Delta, Viet Nam: Phase II. Project Proposal.

Nguyen, Duc Lien. 1995. Water resources development on acid sulphate soil and it's environmental effects. Workshop on acid sulphate soil: Development and management Ho Chi Minh City, 18-20 October 1995

Nguyen, Tat Dac. Simulation of acid water in canals and possible linkage to acid sulphate soil model. (source and year unknown)

Pons, L.J. 1972. Outline of the genesis, characteristics, classification and improvement of acid sulphate soils. I Introductory papers and bibliography. Proceedings of the international symposium on acid sulphate soils 13-20 august 1972, Wageningen, Netherlands (ed. H. Dost) (publication 18 vol. 1)

Shaw, E. 1988. Hydrology In Practice. London: Van Nostrand Reinhold.

van Shilfgaarde, J. 1957. Theory of Land Drainage. Drainage of Agricultural Lands. (ed. Luthin, J). American Society of Agronomy. pp 79-113.

UI (Utrikespolitiska Institutet). 1994. Vietnam. Länder i fickformat 807.

Verburg, P. 1994. Morphology and Genesis of Soils & Evaluation of the Side Effects of a New Canal in an Acid Sulphate Soil Area. Plain of Reeds, Viet Nam. Netherlands: Department of Soil Science and Geology, Wageningen Agricultural University.

Personal communication: Eriksson, Erik. 1996. Hydroconsult AB, Uppsala.
Phi, Ho Long. 1996. Polytechnic University, Ho Chi Minh City.

APPENDIX 1. SENSITIVITY ANALYSIS

BACKGROUND

The saturated hydraulic conductivity is an important parameter when studying the hydrological conditions in an area. It is necessary to get reliable values for this soil property to be able to calculate soil water flows in the area.

There are many commonly practised laboratory and field methods to determine saturated hydraulic conductivity. However, the natural spatial heterogeneity of the soil results in variations of well above 100% in units of just a few ha or less (Kutilek & Nielsen, 1994). Since time, labour and computer capacity is often limited, one is often restricted to the use of some mean value when modelling. In order to decide what effects this reduction of the variations has on the modelling results, a sensitivity analysis can be performed. Sensitivity analysis is the process of introducing planned perturbations into a model and observing their effect (Miller, 1974). The method is used to identify important parameters and interactions (Hermann, 1967, in Miller) and to decide on the relative worth of improving various parts of a data base (Meyer, 1971, in Miller). For example, if sensitivity analysis shows that variations in a parameter are of little importance, large gains can be made in computer efficiency through making the model coarser and allowing smaller parameter contrasts (Follin, 1992).

The objective of the sensitivity analysis presented in this paper is to decide what effects variations in total saturated hydraulic conductivity and saturated conductivity of soil matrix could have when modelling the hydrological conditions for Tan Thanh Farm. The justification for this is to see how important the measurement accuracy is and if an averaging of measured values of saturated conductivities gives sufficient information to correctly estimate the variables of interest in a simulation.

METHODS

The SOIL 9.31 model (Jansson, 1996) has been used to simulate a crop season from January to August 1992 at the Tan Thanh Farm. Input files for climate and soil properties in the area were available.

Calculation of water flow

The model is one-dimensional and water flow through the profile is calculated as described in Figure 1. Bypass flow, q_{bypass}, is the rapid flow in macropores (in this case mainly cracks) during conditions when smaller pores are only partially filled with water. q_{bypass} is zero as long as inflow, q_{in}, doesn't exceed the sorptivity of the soil. Sorptivity, S_{mat}, is the capacity of aggregates to absorb water and is defined as

$$S_{mat} = a_{scale} \cdot a_r \cdot k_{mat} \cdot pF$$

a_{scale}= scaling coefficient accounting for geometry of aggregates
a_r= ratio compartment thickness/unit horizontal area
k_{mat}= maximum conductivity of matrix pores
pF= ^{10}log of water tension

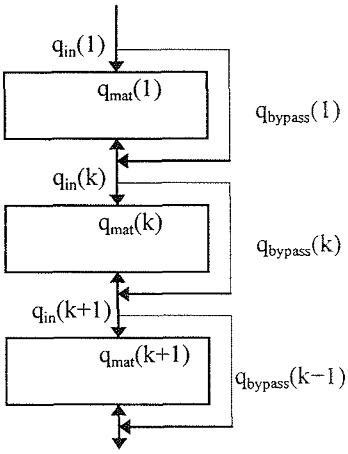


Figure 1. Water flow paths with bypass flows (Jansson, 1996).

When $q_{in} \geq S_{mat}$ matrix flow, q_{mat}, equals S_{mat} and $q_{bypass} = q_{in} - q_{mat}$. Bypass flow is zero for saturated conditions and can thus never reach layers below groundwater level.
The unsaturated conductivity as a function of water content is described by a graph similar to Figure 2. Up to a water content of θ_S - θ_m (porosity - macropore volume) the conductivity is determined by the matrix pores. When water content exceeds θ_S - θ_m the contribution of macropores to the conductivity is considered with the linear and steeper part of the graph. k_{sat} is the saturated hydraulic conductivity including the macropores.

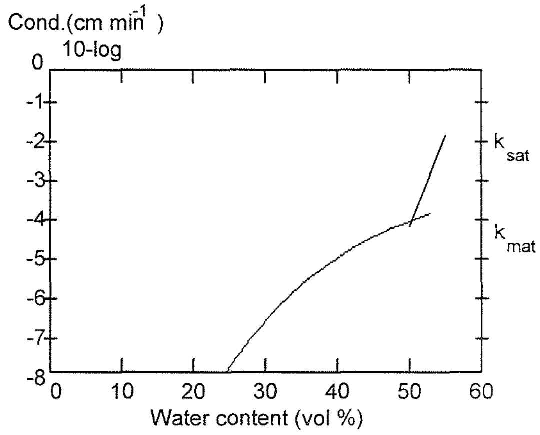


Figure 2. Example of unsaturated conductivity as a function of water content for a clay soil (Jansson, 1996).

The groundwater flows are considered as a sink term in the one-dimensional structure of the model and the physical base-approaches can conceptually be compared with a drainage system. Water flow to drainage pipes (canals) occurs when the simulated groundwater table is above the level of the pipes, i.e., flow occurs horizontally from a layer to drainage pipes when the soil in the layer is saturated.

The calculations of groundwater flow in the simulations were based on the theories presented by Hooghoudt (1940) and Ernst (1956). The basic idea is that one can approximate a pipe drainage system underlain with an impermeable layer by an open drainage system with the impermeable layer at a reduced depth (Figure 3). Thus one can use the theory of horizontal flow to approximate the combination of horizontal and radial flow.

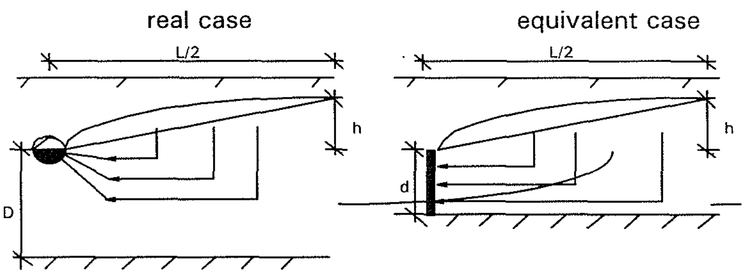


Figure 3. The Hooghoudt idea of transformation.

The equations developed by Hooghoudt can be presented as follows:

Real flow (horizontal+radial):

$$h = h_h + h_r = \frac{qL_h^2}{8KD_h} + \frac{qL}{pK}\ln\frac{aD_r}{u}$$

Here h is the total head loss, D_h is the conceptual average thickness of the horizontal flow zone *(D+h/2)*, aD_r is an indicative geometric parameter often with the same value as *D,* and u is the wet entry parameter of the drain.

Equivalent flow (horizontal):

$$h = h_h^* = \frac{qL_h^2}{8KD_h^*}$$

where * means "equivalent". The average thickness of the equivalent horizontal flow zone, D_h^*, may be approximated as $d + h/2$. One can divide the flow zone in two layers: one above the drainage base and one below. With different hydraulic conductivities, K_1 above and K_2 below the drainage base, one can readily derive the following expression for the discharge q:

$$q = \frac{4K_1h^2}{L^2} + \frac{8K_2dh}{L^2}$$

In the model, the groundwater flows were calculated using Ernst equation which is very much similar to the one derived by Hooghoudt but is better at handling vertical heterogeneity in the soil.

Simulations

The SOIL-parameters SCALECOND and ASCALEL, here α_{cond} and α_{sorp} respectively, were used to perform the sensitivity analysis. α_{cond} scales the conductivity function in Figure 2 (moves the entire curve up or down). α_{sorp} scales the coefficient a_{scale} in the sorptivity equation. That gives the same result for sorptivity as changing the matrix conductivity, but it will not have any influence on the vertical matrix flow calculations since k_{mat} does not change.

First, a reference simulation with default values for total (≈0.5 m/day) and matrix (=0.1 mm/day) saturated hydraulic conductivities was performed. Then a set of simulations were run where both α_{sorp} and α_{cond} varied from $10^{-1.5}$ to $10^{1.5}$ in 31 equidistant logarithmic steps. This resulted in a total number of 961 simulations. Each simulation was compared with the reference simulation and mean difference (ME = $mean_{sim}$ - $mean_{ref}$) was calculated for five variables of interest during March, May and June. The reason for choosing these months is that the soil water conditions at these times are crucial to the formation of acidity in the acid sulphate soil. March is the end of the dry season with the lowest groundwater levels and the highest pyrite oxidation potential. May and June are the beginning of the rain period when the groundwater level rises and the acidity is washed out from the soil.

The variables of interest are:

- Groundwater level
- Water content in 10-20 cm horizon
- Total water flow at 20 cm
- Bypass water flow at 20 cm
- Total water flow in drainage pipes (canals)

The fluctuations of groundwater level give direct visual information on the oxidation potential in the soil and thereby on the formation of acidity. The water flows are variables sensitive for variations in K and the total and bypass flows at 20 cm together give information on matrix flow. Water content was also chosen as a more conservative variable.

Evaluation of variances in the variables were made qualitatively:

- Graphs from simulations showing real variable values during the season gave direct visual information on what really happened, and if variations had any effect at all.
- Plots of ME against different α_{cond} and α_{sorp} during the three different periods gave information on when and how much mean values were affected.

RESULTS

Variations in α_{sorp}, governing the matrix water flow, generally don't affect the variables of interest at all, even for very high values of α_{sorp}. However, variations in bypass flow depending on different sorption properties appear during heavy rainfall when the soil is very dry. The reason is that the aggregates have a low sorptivity owing to a low pF-value, so that a greater part of the water flow becomes bypass flow. For the other target variables, the independence of sorption scaling coefficient can be explained by the fact that it doesn't matter which pathway the water takes. For example the water content reaches the same value whether the water flows directly into the pores or flows upwards by capillary rise from the groundwater (Figure 4). The conclusion is that if the importance of matrix conductivity is to be studied more thoroughly, target variables and time periods should be chosen very carefully.

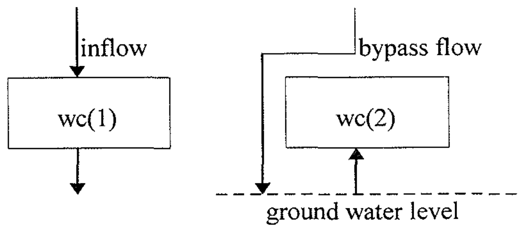


Figure 4. Water content in horizons gets the same value in both cases. wc(1)=wc(2)

When plotting ME for the target variables towards linearly increasing α_{cond}, which increases the total conductivity, five different types of response behaviour are recognised depending on variable type and time of season. Four of the response patterns are shown in Figure 5. The fifth alternative, E, is no response at all. Different responses for groundwater level and water flow at 20 cm are discussed here in more detail and a characterisation of all the target variables is given in Table 1.

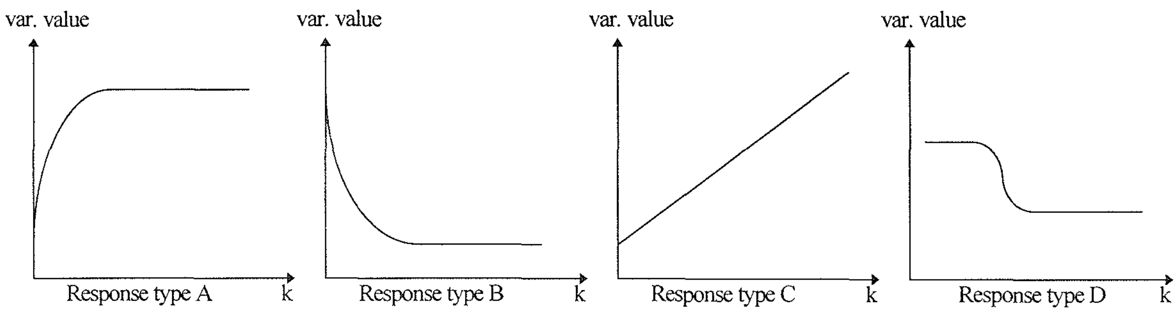


Figure 5. Different types of target variable responses to linearly increased values of total hydraulic conductivity

Table 1. Summary of response types for the target variables in different time periods

Period	Groundwater level	Flow at 20 cm depth	Bypass flow at 20 cm depth	Total pipeflow	Water content at 10-20 cm
March	A	D	D	B	A
May	B	D	E	D	B
June	E	C	E	C	E

Groundwater level

The simulated responses of groundwater levels, during March, May and June, to linearly increasing hydraulic conductivity is shown in Figure 6.

During March, the groundwater level shows a response similar to A. The temperature is high (as always) with high evaporation. There is little precipitation since it is at the end of the dry season. When the conductivity is low (less than 0.4 m/day), the limiting factor for the level is flow from the drainage canals back into the field. This results in a lowering of the groundwater level if conductivity decreases, since evaporation becomes larger than flow from the canals. When the conductivities are large the groundwater level is totally controlled by the drainage level in the canals.

It starts to rain in May. For low conductivities, the water flow through the soil to drainage canals is slow. Therefore, the thickness of the aquifer must be large in order to be able to transport the water to the canals. This results in a high groundwater level. As conductivity increases, the higher flow rates through the soil lower the groundwater level. For very high conductivity values, the groundwater level is determined by the drainage level in the canals. The result is a type B response.

During June, the soil is completely saturated and the groundwater level is not affected by changes in conductivity. A type E response is observed.

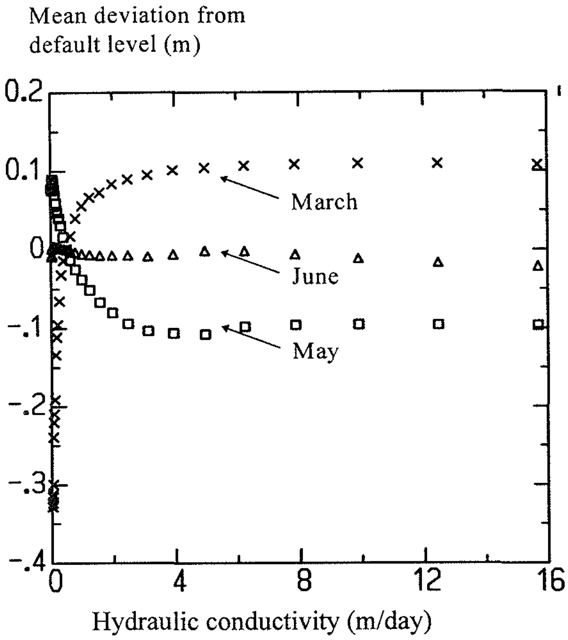


Figure 6. Mean deviation from default groundwater level for March, May and June calculated from simulations using different values on hydraulic conductivity.

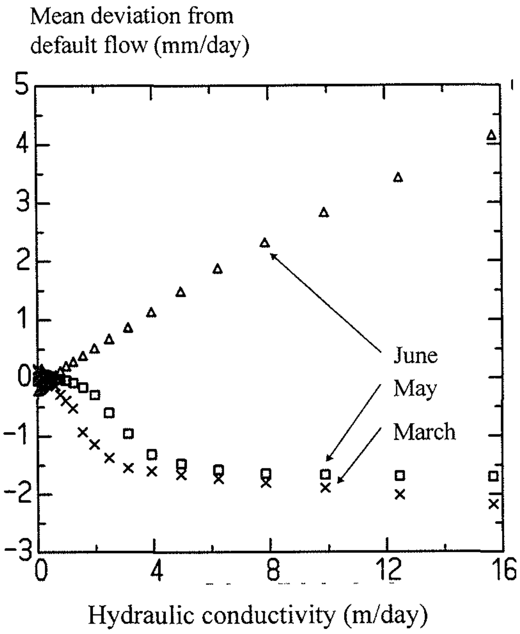


Figure 7. Mean deviation from default water flow at 20 cm depth for March, May and June calculated from simulations using different values on hydraulic conductivity.

Water flow at 20 cm

The simulated responses of water flow at 20 cm depth, during March, May and June, to linearly increasing hydraulic conductivity are shown in Figure 7.

During March and May the responses are of type D. There is little precipitation and evaporation is very high during this period. This gives an upward net flow (negative flow) through the profile. But low conductivities results in a deeper groundwater level (below 20 cm), as described earlier, and therefore no upward water flow through the horizon. As conductivity increases, the groundwater level rises, and for a certain *K*-value reaches a level high enough to give upward flow at 20 cm depth. The negative flow rate increases with conductivity up to a conductivity value above which the flow is limited by the evaporation capacity.

The saturated conditions in June give a linear type C response for water flow at 20 cm to increased conductivity values. This follows from Darcy's law (equation 4.1 in section 4), in which flow rate for a specific hydraulic gradient is proportional to hydraulic conductivity.

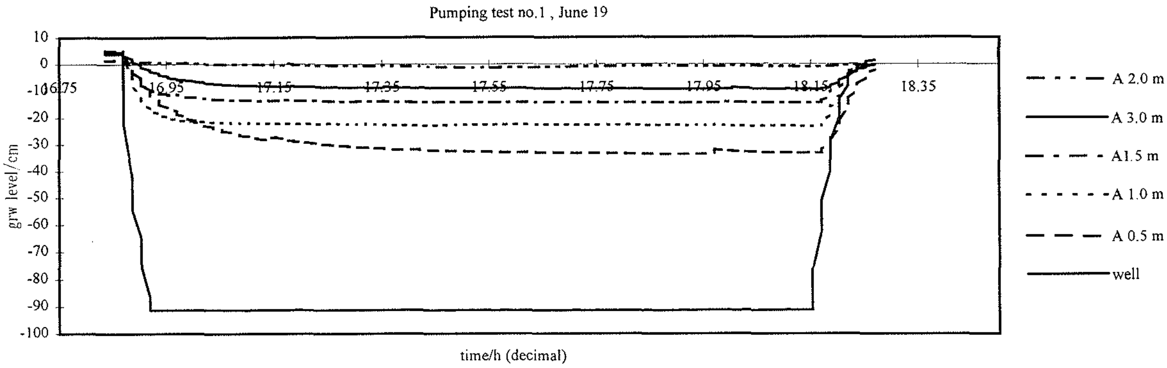
Summary of the results

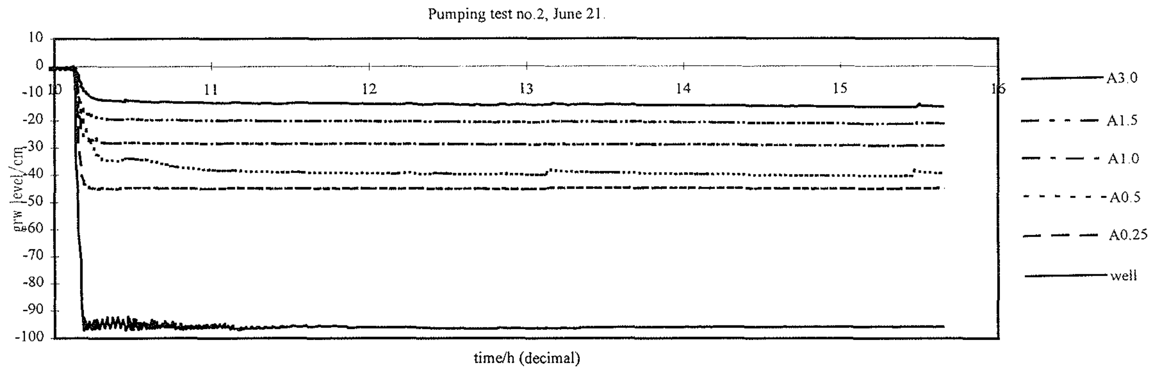
The conclusion of this sensitivity analysis is that the response of a target variable to variations in total hydraulic conductivity is entirely dependent on the weather conditions present. No target variable gives the same type of response at all time periods. To be able to determine the sensitivity of a target variable, it is important to know the response type and the approximate hydraulic conductivity of the soil.

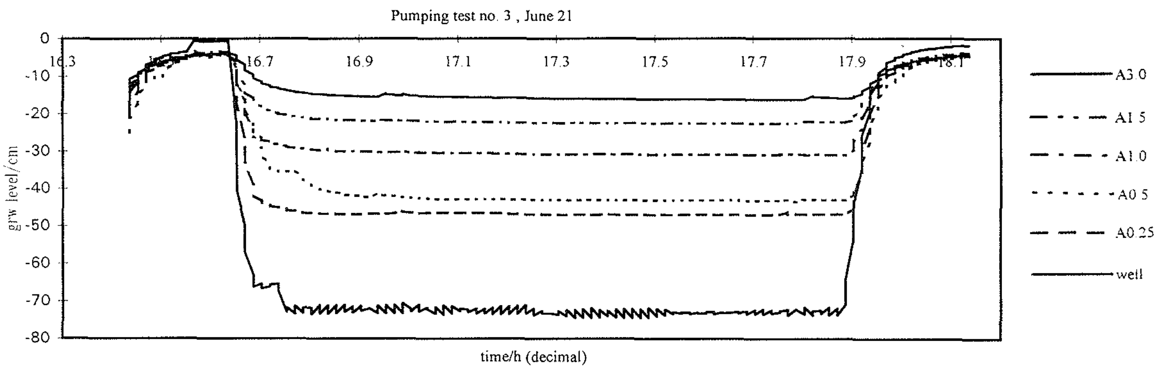
The results also shows that the model is more sensitive to variations in total saturated hydraulic conductivity than to variations in sorptivity of the matrix pores, when studying the selected variables of interest during March, May and June. It is therefore more important to know the total
saturated hydraulic conductivity than it is to know the sorptivity, in order to get reliable simulation results.

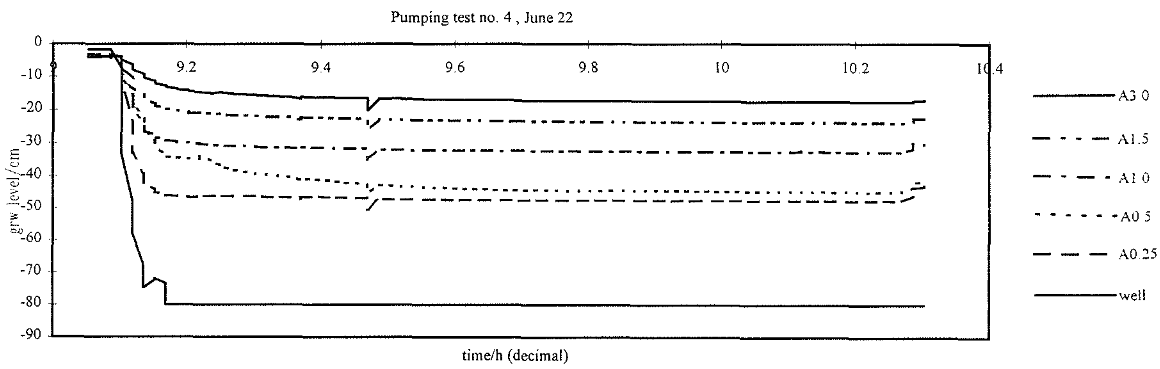
APPENDIX 2. STEADY-STATE PUMPING TESTS

Performed at Tan Than farm, June 19 - June 24 1996









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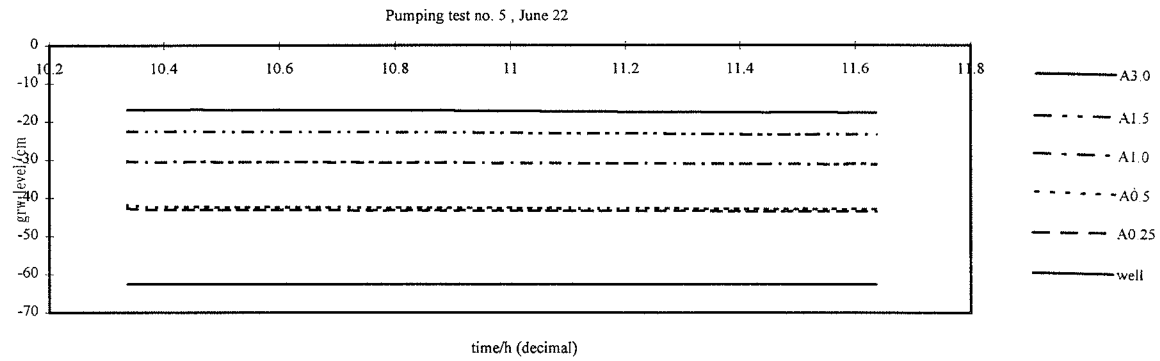
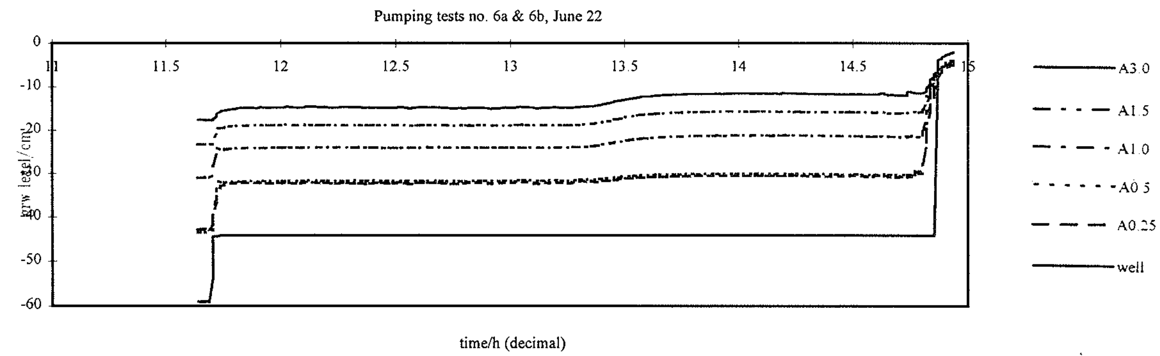
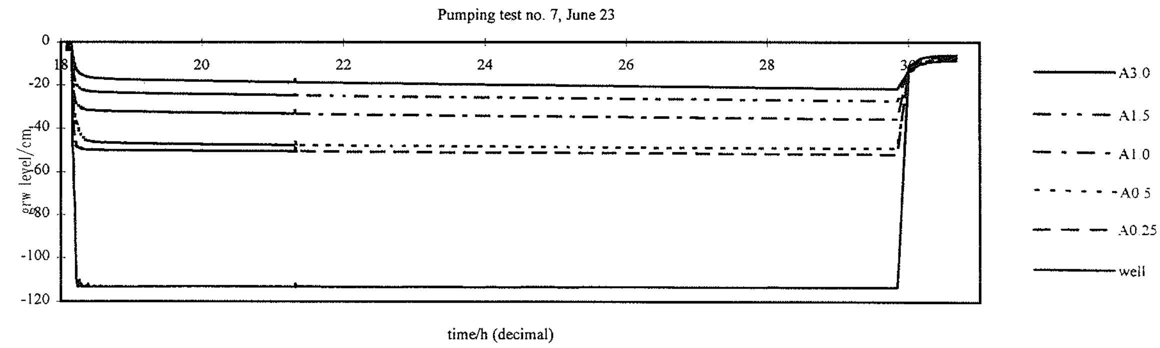
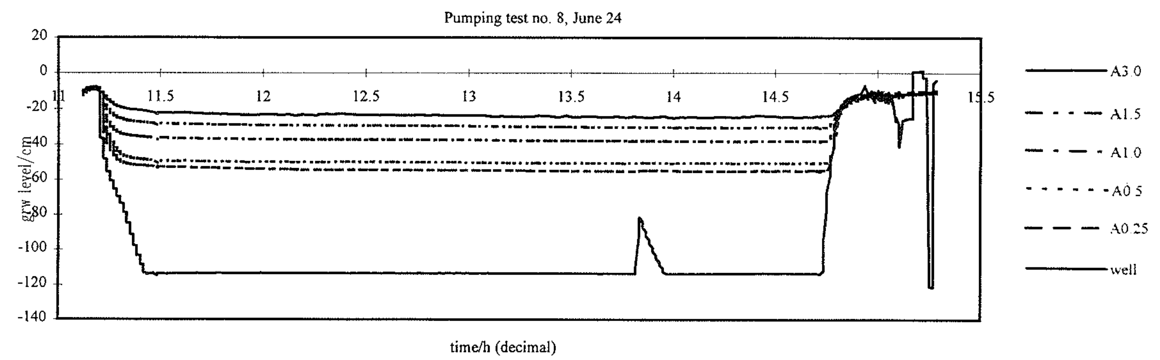

Pumping test no. 5 , June 22
0
-10
-20
-30
-40
-50
-60
-70
10.2
10.4
10.6
10.8
11
11.2
11.4
11.6
11.8
grw level/cm
time/h (decimal)
A3.0
A1.5
A1.0
A0.5
A0.25
well


Pumping tests no. 6a & 6b, June 22
0
-10
-20
-30
-40
-50
-60
11
11.5
12
12.5
13
13.5
14
14.5
15
grw level/cm
time/h (decimal)
A3.0
A1.5
A1.0
A0.5
A0.25
well


Pumping test no. 7, June 23
0
-20
-40
-60
-80
-100
-120
18
20
22
24
26
28
30
grw level/cm
time/h (decimal)
A3.0
A1.5
A1.0
A0.5
A0.25
well


Pumping test no. 8, June 24
20
0
-20
-40
-60
-80
-100
-120
-140
11
11.5
12
12.5
13
13.5
14
14.5
15
15.5
grw level/cm
time/h (decimal)
A3.0
A1.5
A1.0
A0.5
A0.25
well

APPENDIX 3. EQUIPMENT

The pump used was a "Golden Dragon dz50" with a pumping capacity of 2.5 m^3/h. The hose was a reinforced PVC plastic type, diameter 20 mm. To be able to control the water flow rate, a plastic ball valve was used.

The tube used in the well during the first pumping tests was a PVC tube, diameter 220 mm. There were small holes drilled in the tube to allow water to flow freely into it.

PVC plastic tubes were used for the groundwater observation tubes, with small holes drilled in them.

A thin perforated cloth, of the same type as is used for mosquito nets, was wrapped outside both the well tube and the observation tubes, in order to prevent mud and silt entering the tubes through the small holes.

A Campbell data logger CR-10 was used to collect data throughout the experiments. The water levels in the observation tubes were measured both manually and with electronic transducers connected to the data logger.

A theodolite was used to measure the elevation of tubes and to establish a reference level for the measurements.

All water flow rates were measured using a stop watch and a bucket with a well defined volume.

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96:3 Carlsson, H., Larsson, K. & Linnér, H. Växtnäringsstyrning i potatis. 69 s.

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