KTH Land and Water
Resources Engineering

SOIL MANAGEMENT STRATEGIES TO ESTABLISH VEGETATION AND GROUNDWATER RECHARGE WHEN RESTORING GRAVEL PITS

Simulation studies and review of actual field practices in Sweden.

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December 2003

TRITA-LWR.LIC 2016

ISSN 1650-8629

ISRN KTH/LWR/LIC 2016-SE

ISBN 91-7283-671-7

PREFACE AND ACKNOWLEDGEMENTS

I have been a PhD student at the Department of Land and Water Resources Engineering for 6 years now. A lot has happened during those years and the way here has sometimes been long and winding. My thoughts go to a lot of special people whose paths I have had the fortune to cross during my time at KTH. You have all contributed in different ways to make this thesis become reality, thanks.

I would like to express my gratitude to my supervisors Professor Per-Erik Jansson and Assistant Professor Bo Olofsson at the Department of Land and Water Resources Engineering, KTH for invaluable support! Sincere thanks also to Professor Emeritus Gert Knutsson, who was the initiator of the project and my supervisor during the first phase of this study. I would like to thank the members of the supervision and reference group for assisting me: Lars Svensson at Jehanders Sand och Grus, Lars Stenlid at Skanska and Sven Wallman at NCC. I gratefully acknowledge Sveriges Bergmaterial Industri (SBMI) and Svenska Byggbranschens Utvecklingsfond (SBUF) for providing the funding for this work. Thanks for contributions from Bertil Nilsson at the Department of Land and Water Resources Engineering, KTH, for valuable assistance in the laboratory and field. I am also grateful to employees at the Löten gravel pit, Ekerö for providing space for my field trial and for their kind reception. Thanks also to personnel at county councils throughout the country and quarry operators at a number of companies in the industry for their hospitality during my visits and for participating in valuable discussions concerning my studies.

A special thanks to all of my family and friends for being who you are and for making me think of life in “essence” so that work could not always puzzle my head. Thanks to my mother and to my beloved husband for being my best support. Last of all I want to send my love to my father who is no longer with us, for being so very important for me in all the ways possible.

Karin Palmqvist Larsson

Stockholm, December 2003

ABSTRACT

The removal of vegetation and overburden changes the natural water purifying processes and thus decreases the groundwater protection in gravel pit areas. The sand and gravel deposits used for aggregate extraction in Sweden are also often valuable for extraction of groundwater as a drinking water resource. The Swedish legislation requires that gravel pits be restored after the cessation of extraction, the aim being to reestablish vegetation and to reinstate groundwater purifying processes.

The objective of this study was to improve our understanding of the processes governing groundwater protection and vegetation establishment so that these could be applied to improving restoration methods for reestablishing natural groundwater protection. The focus was on the importance of soil physical properties of the topsoil for vegetation establishment and groundwater recharge.

Actual field methods for restoration were reviewed. Conflicts between aggregate extraction and groundwater interests were common. In many cases the actual restoration carried out differed from pre-planned specifications in permit documentation.

Commonly available substrates that might be used for restoration of gravel pits were investigated. The soils were described as regards texture, organic content, porosity, water retention and hydraulic conductivity. The way in which a combination of the water retention characteristic and the unsaturated conductivity influenced the behaviour of the soil-plant-atmosphere system was demonstrated using a process-orientated simulation model. Plants with well-developed aboveground characteristics and shallow roots in particular exerted the highest requirements on the soil physical properties.

Key words: groundwater protection, soil physical properties, CoupModel, unsaturated conductivity, water retention, transpiration, soil evaporation

LIST OF PAPERS

This thesis is based on the following papers, which are referred to in the text by their Roman numerals:

I. Palmqvist K (1999) *Efterbehandling av täkter, del 1. Inventering samt utvärdering av efterbehandlingsmetoder*. Report at the Department of Land and Water Resources Engineering, KTH, Stockholm.

II. Palmqvist Larsson K. & Jansson P-E. (2003) *Soil management to establish vegetation and groundwater recharge when restoring gravel pits*. Manuscript.

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INTRODUCTION

Gravel extraction affects the groundwater resource in different ways. The removal of vegetation and topsoil increases the variation in groundwater composition, decreases the transit time for groundwater recharge, reduces the natural water purifying processes and thus decreases the groundwater protection (Rintala, 1997; Sander 1997). After exploitation ceases, the area is restored through soil management and vegetation establishment to reconstruct a water-purifying soil profile and a vegetation cover.

Sand and gravel deposits in Sweden are valuable for extraction of both aggregate and groundwater. While the groundwater resources have been given a high priority during recent years (SGU, 2003), mainly due to the 2002 Environment Act, introduced by the Swedish Government in 1999 (Miljöbalken, 2002) and Environmental Targets (NVV, 2003a), the demands on the extraction industry and the requirements for restoration have also increased.

In Sweden, work is underway to implement fifteen Environmental Targets (NVV, 2003a), which form the main thrust in the implementation of the 2002 Environment Act.

Vegetation establishment forms part of the restoration requirements and the major threats are drought and lack of nutrients (Alapassi et al., 1994; Rintala, 1997). Other requirements include demands on the composition of the topsoil (NVV & GMF, 1995). The major task for the topsoil is to create conditions for vegetation to establish and grow and to diminish the risk for contamination of the groundwater (Alapassi et al., 1994; Rintala, 1997). Studies by Sander (1997) show that the properties of the original soil profile and the restoration method are of great importance in re-establishing vegetation and a soil profile with natural water-purifying properties.

Hydraulic properties of the soil control the ability of soil to store and transmit water and nutrients. They are important when considering soil suitability for crop production and other land uses; the vulnerability of groundwater to pollution; and the soil and plant response to climate.

To increase our understanding of the processes governing reinstatement of a soil with groundwater-purifying processes and a vegetation cover from a bare soil surface, further knowledge is needed concerning the management of restoration. Further studies are desirable concerning the importance of the original soil and the choice of applied soil, the restoration method, the thickness of the organic topsoil and the depth to the groundwater, in order to achieve the resumption of natural water purifying processes and the establishment of a vegetation cover. A major problem is the lack of predictive methods in making a rational choice of management practice to achieve defined goals at specific sites.

OBJECTIVES

The overall objective of this thesis was to improve the understanding of processes governing groundwater protection and vegetation establishment that might be applicable in improving restoration methods for reestablishing natural groundwater protection. Secondary objectives were to describe the environmental impact, particularly on the groundwater, of gravel extraction and the restoration methods commonly used in Sweden; to physically describe the properties of different potential topsoils; and to identify and quantify the relationship between the different physical properties of the soil and the impact on vegetation establishment and groundwater recharge.

The main focus was on the importance of soil physical properties of the topsoil for vegetation establishment and groundwater recharge and to apply a method for selecting topsoil characteristics.

BACKGROUND

Environmental impact due to gravel extraction

The groundwater is protected to different degrees by the overlying soil profile. The thickness of the unsaturated zone is of great importance for the reduction of contamination (including bacteria and viruses). Substances are adsorbed (e.g. organic substances) on the soil particles and sometimes decomposed (e.g. organic matter), especially in the organic topsoil. The adsorption capacity of the soil can be used as a measure of the groundwater protection against contamination that can be adsorbed or decomposed in the soil profile. A measure of the vulnerability of the groundwater resource that can be used are the combination of the specific area of the soil in the unsaturated zone and information of whether a soil profile is developed (Maxe & Johansson, 1998).

In a natural soil profile with vegetation cover, the combined effect of water, minerals and microorganisms leads to an effective buffer against changes in the groundwater quality. The composition of chemical components in the soil water is balanced by ion exchange, weathering and the adsorption of e.g. organic substances onto organic material (Allard et al., 1997). Decreased ion exchange leads to decreased buffering against acid precipitation, decreased pH values and thereby enhanced leakage of several ions to the groundwater (Sander, 1997). Removal of vegetation reduces the production of carbon dioxide and thus carbonic acid that would otherwise enhance the weathering. Thus the soil-forming processes are reduced when vegetation cover is removed.

Groundwater quality and level are affected by gravel extraction. When vegetation and the upper soil profile (often a podsol) are removed, the number of biochemical reactions in the soil water is reduced significantly, evapotranspiration decreases and groundwater recharge increases. During spring, the watertable is largely elevated compared to in natural areas. The quantity of dissolved salts, the amount of soil water and the variation in groundwater quality increases. Gravel extraction increases the risk for pollution of groundwater and may cause difficulties in treatment of the water in drinking water production (Hatva, 1994).

Research in Finland during the 1990s showed that the quality of groundwater is a result of the processes taking place in the upper soil layers. The zone where these chemical changes take place is at least 2 m thick and thus important for the groundwater protection. The natural soil profile functions as a biological and geochemical filter that neutralizes and buffers variations in the precipitation; decomposes organic matter; absorbs metal ions; enhances decay of minerals in the root zone and increases input of metal ions to the water. These layers are removed prior to excavation and the natural water purifying processes disappear (Sandborg, 1992a, b; Kuusinen, 1992; Hyyppä & Penttinen, 1992; Hatva et al., 1993a, b).

Vegetation takes up water and nutrients, which are stored in the biomass, and therefore prevents leaching to groundwater. Clear felling and removal of vegetation interrupts the water and nutrient uptake, thereby increasing direct throughfall of precipitation, surface runoff, water content of the soil, drainage and leaching of nutrients to the groundwater. A vegetation cover provides protection against surface erosion, increases the transit time for groundwater recharge and supplies the soil with organic material, which increases the microbiological activity and storage capacity of nutrients. The groundwater protection is thus strongly dependent on the vegetation cover.

Environmental goals and legislation

In Sweden, work is underway to implement fifteen Environmental Targets (NVV, 2003a), which form the main thrust in the implementation of the 2002 Environment Act (Miljöbalken, 2002). Two of these targets are "Groundwater of Good Quality" and "Good Environment in Built-up Areas". The main objective for the Groundwater target is to ensure that sufficient groundwater resources are available for drinking water extraction now and in the future. The quality of the groundwater must not be negatively affected by human activities such as land use, extraction of gravel, contamination by pollutants, etc. The "Good Environment in Built-up Areas" target has the sub-targets of reducing the use of natural gravel as aggregate and to increase the use of recycled material. This is important since gravel extraction quarries in Sweden are often located in geological formations that are important for present and future groundwater extraction and thus limit the possibilities for groundwater based drinking water production (SGU, 2003). When assessing permit applications for gravel quarries, the local county council weighs the need for aggregate against damages that the quarry might cause on animal and vegetation habitats and the surrounding environment (Section 12 §2 of the Act). Local authorities are very restrictive with permits for new extraction sites in water-bearing geological formations (Länsstyrelsen, 2003).

Since the quality of natural groundwater can limit its use as drinking water, it is important to preserve groundwater formations with good quality. In Sweden, 85% of the inhabitants are dependent on municipal drinking water and 49% of all municipal drinking water production is dependent on gravel deposits for equal parts of direct groundwater extraction and artificial groundwater recharge. Good quality of groundwater is of great importance on a local, regional and national level (SGU, 2003).

The Swedish Geological Survey (SGU) has the main responsibility for the environmental target "Groundwater of Good Quality". It is divided into four sub-targets, the first of which is that groundwater-bearing geological formations of importance for the present or future drinking water maintenance must be provided with long-term protection against exploitation that limits the use of the water. The possibility of using groundwater for drinking water production in a long-term perspective is already limited since protection of the groundwater formation cannot be guaranteed due to the fact that the geological formations have already been extracted or affected by other human activities. The protection of geological formations of importance for drinking water production, today and in the future, is therefore of the greatest importance. Mapping of important groundwater reservoirs and classification of water-bearing geological formations, essential for enabling sufficient protection to be provided against e.g. exploitation, are conducted by the Swedish Geological Survey. Physical planning on a regional and local level and environmental impact assessment are important tools in achieving this goal (SGU, 2003).

Sand and gravel extraction is regulated in the legislation by the 2002 Environment Act and permission is granted by the local authorities according to section 12 §1 of the 2002 Environmental Act. The quarry operator is responsible for restoration and a restoration plan must be submitted with the permit application documentation (NVV, 2003b). Requirements on the restoration can be specified in the permit documentation and recommendations regarding the execution of the restoration are available from the Swedish Environmental Protection Agency (NVV & GMF, 1995).

Requirements on restoration contain guidelines regarding the thickness of the topsoil layer applied, the composition of the topsoil (e.g. organic content) and the depth to the watertable (NVV & GMF, 1995): Gravel pits inside the inner zone of groundwater protection area should not be excavated deeper than 3 metres above the highest groundwater level. Successive restoration should be practised and vegetation should be established as soon as possible after cessation of extraction. A topsoil of 0.5 m consisting of former overburden or other organic soil should be reconstructed. Permits for new gravel pits are not allowed. For gravel pits inside the outer zone of groundwater protection area, the same restrictions apply except that such pits may be excavated to 2 metres above highest groundwater level (NVV & GMF, 1995). According to SGU (2003) these recommendations ought to be updated.

According to one of the overall aims of the 2002 Environment Act (Section 1, §1), the legislation should be enforced in such a way that sustainability is achieved in the long-term perspective. The sustainability aspects are of great importance in modern legislation (Section 2, §5) and preference is given to land use that leads to sustainability (Section 3 §1 of the 2002 Environment Act).

According to guidelines regarding permits for gravel extraction, sand and gravel deposits of importance for future groundwater supply should if possible be preserved due to the fact that the groundwater interest is of greater importance for society in a long-term perspective (Miljövårdsenheten, 1995). If regulations for a groundwater protection area (Section 7, §22) coincide with a permit application for a gravel pit (Section 12, §1) the permit application must not be assessed until the groundwater protection issue is decided (Regulation (1998:904) §4, 2002 Environment Act).

In regulations for groundwater protection areas, gravel pits should not be allowed in inner and outer zones since groundwater protection is decreased by the removal of topsoil, vegetation and excavation. When reviewing an application for a renewed permit, for example, the possibility of performing a good restoration should be taken into account (NVV, 2003c).

Methods used for restoration

The aim of restoration is to protect the groundwater from contamination; to increase the transit time for groundwater recharge and to decrease changes in the quality of groundwater (SGU, 2003; NVV, 2003c).

Due to the importance of vegetation for groundwater protection and soil-forming processes, it is important to establish vegetation on ceased gravel extraction sites as soon as possible after cessation of operations. Topsoil used when restoring gravel pits should function as a good vegetation substrate without affecting the groundwater quality negatively and the transit time for groundwater should be increased. Deficits of nutrients and water are the biggest threats to rapid vegetation establishment (Alapassi et al., 1994; Rintala, 1997). Consequently, the most important property for vegetation establishment is the capacity of the soil to hold water and nutrients. This capacity increases with content of organic matter, clay and Al- and Fe-oxides (Bradshaw & Chadwick, 1980; NVV, 1989; Rintala 1997). However the organic material on the one hand improves nutrient and water supply to vegetation and on the other hand may be a source of pollution for the groundwater.

Studies during 1992-1994 in Finland (Rintala 1997) concerning the use of different types of topsoil showed that all organic topsoils studied increased the leachate of nutrient and organic substances to the groundwater compared to a bare surface. All organic topsoils also improved the nutrient content, biological activity, water-holding capacity and therefore the possibilities for vegetation establishment. The best topsoil found in the study was a mixture of sand and decomposed peat or sand and original topsoil (Rintala, 1997). Studies by Petrov et al. (1995) also showed that the water-holding properties of the soil could be improved by adding fine material in the form of crushed rock fine aggregate.

In Sweden, Sander (1997) showed that the properties of the original material, such as texture and content of clay and organic matter, played an important role in the reconstruction of a water-purifying topsoil and vegetation. The organic content of the soil profile was higher in vegetated areas. According to that study, the original overburden made the least change to groundwater quality (Sander, 1997).

MATERIALS AND METHODS

Literature regarding the environmental impact due to gravel pits was reviewed. Different restoration methods were studied through interviews with personal at local county councils, archive studies and studies of both ongoing and ceased extraction sites.

A number of different possible topsoils were physically described through laboratory studies of textural analysis, organic matter content, porosity, water retention characteristics and hydraulic conductivity.

Five soils that can be of interest for use as topsoils when restoring gravel pits and quarries were selected for detailed studies. A field site was established at Löten gravel pit (Lat 59.5º N, Long 17.5º E) which is located 20 km west of Stockholm (Figure 1). Three different soils (A-C) were taken from the surrounding area and applied at a thickness of 10 cm to the surface at the gravel pit in Löten. Soil samples were taken to a depth of 1m (measured from the soil surface) in the centre of each plot. Two additional soils (D-E) were taken from the stone quarry of Rydbo in Täby and were also measured in the laboratory, similarly to the first three soils.

Soils analysed in the laboratory:

Sandy gravelly till from excavation along a nearby dirt road at Ekerö, (till).

Sand as a by-product from washing gravel in the Löten gravel pit, Ekerö, (sand).

Gravelly sand from removal of topsoil in the Löten gravel pit, Ekerö, (gravelly sand).

Sandy gravel from excavation in the Rydbo stone quarry, Täby (crushed rock aggregate 0-8 mm)

Gravelly sand from excavation in the Rydbo stone quarry, Täby (crushed rock fine aggr. 0-4mm)

Figure 1. Field site at Löten gravel pit, Ekerö (June 2003). There was a substantial difference between the vegetation in the applied till and the surrounding area.

In order to identify and quantify the relationship between soil physical properties, vegetation establishment, groundwater recharge and climate conditions, a physically based modelling tool was used. The model describes the behaviour of the soil-plant-atmosphere system and it was used to simulate plant water uptake (transpiration), groundwater recharge (deep percolation), evaporation from soil surface and decrease of potential water uptake due to water deficit during a period of 18 years between 1961.01.01-1978.12.31. The base for the simulation study was climate conditions at Ystad, but data from Falun and Kiruna were also used. The five soils from the laboratory measurements were complemented with additional soils from profile 102:1 in the database of the CoupModel.

Added to the study were:

Clayey soil from the database of the CoupModel.

Organic clayey soil from the database of the CoupModel.

The reason for choosing a modelling tool to study these relationships is that such a large, complex and interactive system can be studied as an integrated system with well-defined changes of different specific components. Modelling is also cheap compared to extensive field experiments and can be used as a predictive tool for management techniques.

The model describes the flow of water and energy through the soil-plant-atmosphere system (Jansson & Karlberg, 2001). The model was used to simulate plant water uptake (transpiration), groundwater recharge, evaporation and degree of potential water uptake due to water deficit. The basic structure is a one dimensional depth profile of a layered soil profile, with user-specified thicknesses and soil properties, covered with vegetation. Two coupled differential equations for water and heat flow represent the central part of the model.

The required information on soil properties is extensive compared to what is normally available from standard field investigations. However submodels enable the user to estimate a reasonable range for such soil properties from commonly available information such as soil texture (Jansson & Karlberg, 2001).

Infiltration of water takes place at the soil surface and no surface runoff is accounted for, while if there is an excess of water in the soil, water percolates to groundwater (Figure 2).

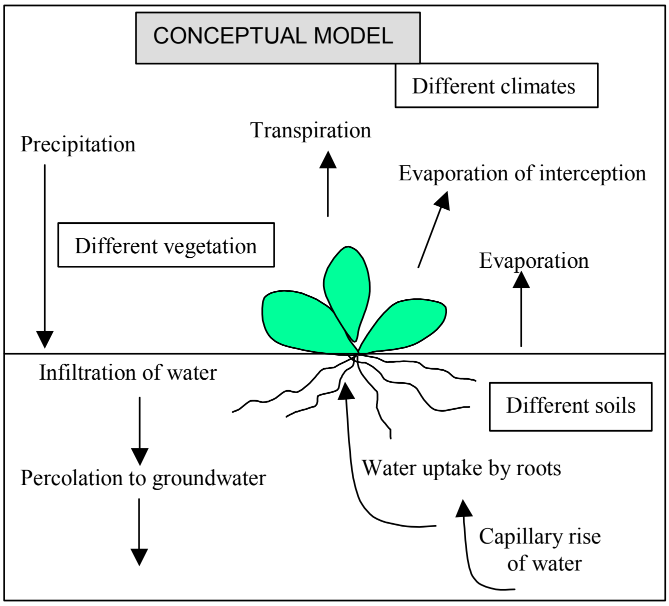

Figure 2. Conceptual model of the simulated soil-plant-atmosphere system (II).

The amount of groundwater recharge is calculated according to the water balance. Evaporation from the soil surface is driven by meteorological conditions and calculated by an empirical approach based on the Penman-Monteith formula according to eq. (1).

$$L_v E_s = \frac{\Delta(R_{ns} - q_h) + \rho_a c_p \dfrac{(e_s - e)}{r_{as}}}{\Delta + \gamma\left(1 + \dfrac{r_{ss}}{r_{as}}\right)} \qquad \text{(eq.1)}$$

Where E_s = soil surface evaporation, L_v = latent heat of vaporisation, R_{ns} = net radiation at the soil surface, q_h = soil surface heat flux from the previous time step, r_{as} = aerodynamic resistance above soil surface, r_{ss} = surface resistance at the soil surface, e_s =vapour pressure at saturation in the air, e = actual vapour pressure in the air, Δ = slope of saturated vapour pressure versus temperature curve, ϱ_a = density of air, c_p = heat capacity of air, γ = psychrometer constant.

Actual transpiration equals the water uptake by roots. Potential transpiration is defined as a potential rate when neither soil water deficits nor low soil temperatures influence the water uptake and is calculated from Penman´s combination equation in the form given by Monteith (1965). Capillary rise of water is dependent on the unsaturated conductivity of the soil. In the present study, vegetation was parameterized to represent 4 different stages of vegetation establishment, from an almost bare soil surface to an established vegetation cover.

Inputs to the model are measured soil properties in parameter tables, meteorological data used as driving variables and parameter values in tables (e.g. plant characteristics).

Measured retention points were fitted to the water retention function expressed by Brooks & Corey (1964) according to eq. (2).

$$\frac{(\theta-\theta_r)}{(\theta_s-\theta_r)}=\left(\frac{\psi}{\psi_a}\right)^{\lambda} \quad \text{(eq.2)}$$

Where θ = actual water content, θ_r = residual water content, θ_s = water content (volume wetness) at saturation, ψ = actual pressure head, ψ_a = pressure head at air entry, λ = pore size distribution index.

The unsaturated conductivity was determined using parameters describing the water retention curve in eq. (3) according to Mualem (1976).

$$k_w{}^* = k_{mat}\left(\frac{\psi_a}{\psi}\right)^{2+(2+n)\lambda} \quad \text{(eq.3)}$$

Where $k_w{}^*$ = unsaturated conductivity, k_{mat} = saturated matrix conductivity, ψ_a = pressure head at air entry, n = parameter accounting for pore correlation and flow path tortuosity, λ = pore size distribution index, ψ = actual pressure head.

RESULTS AND DISCUSSION

Restoration methods

Interviews with personal at local county councils in 16 of 21 counties in Sweden, archive studies and studies of extraction sites (in 7 counties) concerning restoration methods and management, conflicting interests and environmental impact were conducted. Different restoration methods were studied and some examples reported (I).

Depending on the local circumstances, different aspects of the restoration were evaluated and the focus was found to vary between: water protection, nature conservation, biological diversity, security and landscaping (aesthetic aspects). However, requirements were often poorly adjusted to local conditions. Conflicts between groundwater interests and aggregate extraction were found in almost all counties studied. In general, dumping is not allowed in ceased gravel pits (I).

In the demands for restoration, organic topsoil is often required. The overburden is unfortunately often not used for restoration and even if it is saved, it is seldom enough to cover the extraction area. This might be due to several causes but often the soil is not appropriately taken care of. Vegetation establishment was found to be enhanced by the use of organic topsoil. Areas where overburden was applied showed enhanced vegetation establishment compared to areas without any kind of organic topsoil, where vegetation was scarce and surface erosion considerable. According to Alapassi et al. (1994) the lack of vegetation delayed the soil-forming processes. If the soil surface after cessation of extraction is coarse (see e. g. Figure 3), it is even more important to apply overburden or other organic topsoil (Buttleman, 1992). The only suitable vegetation in these sites is vegetation with a deep rooting system that extracts water from deeper levels below the coarse surface (Bradshaw & Chadwick, 1980). At some sites, excavation spoil has been used as organic topsoil and backfill with good results (I).

Figure 3. Barksjöberget gravel pit in the county of Norrbotten, Sweden. Gravel extraction has ceased but no overburden or other organic topsoil has been applied during restoration despite a very coarse soil surface (I).

Impacts on the groundwater or surface water were recorded in less than one quarter of the gravel pits and in less than half of the stone quarries. For the gravel pits, the impact was mainly reduced levels of iron and manganese in groundwater downstream of the gravel pit lake. For the stone quarries, the impact was mainly increased levels of nitrate in surface water and decreases in groundwater level in the vicinity of the site (I).

Successive restoration, when overburden from one part of the pit is successively applied to ceased areas, thereby minimising the open pit area, enhancing vegetation establishment and increasing groundwater protection, forms part of the recommendations from the Swedish Environmental Protection Agency (NVV & GMF, 1995) and was required in all counties studied. In practice, however, it was only working satisfactory in about 50% of the counties. In order to restrict the active extraction area, extraction was divided into stages in 100% of the studied gravel pits and in more than 80% of the stone quarries studied (I).

The requirements on restoration varied substantially between different locations in Sweden (Figure 4). In 50% of the counties studied, the requirements on restoration were classified as “minor demands” since the only requirements were to smoothen the slopes out and to apply overburden. In less than 50% of the counties, the requirements also included vegetation establishment, which is classified as a “moderate demand”. In only one of the counties studied, the requirements in addition included either some kind of preparation of the ground (e.g. loosening up of the compacted soil surface or manuring) or follow-up, which is classified as an “extensive demand” (I).

The restoration carried out differed substantially from pre-planned specifications in permit documentation (Figure 5). "Small restoration" involves smoothing the slopes out and applying overburden; "Moderate restoration" in addition includes vegetation establishment; "Extensive restoration" furthermore includes follow up and eventually some kind of preparation of the ground to facilitate vegetation establishment and in addition successive restoration practice. At most of the sites, the restoration carried out was less extensive than that required. Successive restoration was not practised, the regulation on vegetation establishment was disregarded or the overburden was not applied as pre-planned (I).

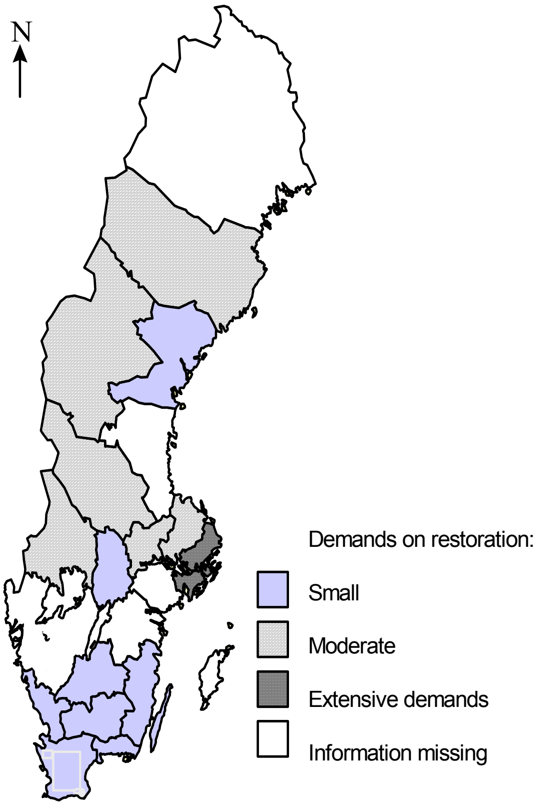

Figure 4. Restoration requirements in different counties in Sweden (I).

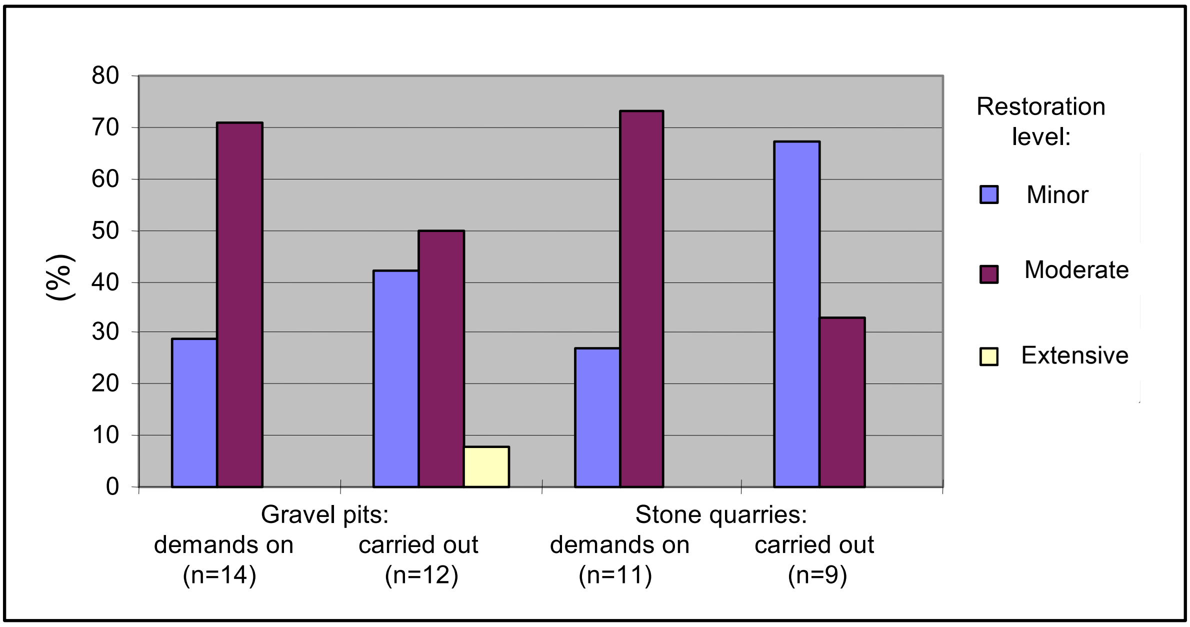

Figure 5. Restoration carried out compared to pre-planned specifications in permit documentation for gravel pits and stone quarries (I).

The handling of the overburden was classified at different sites (Figure 6). “Good handling” implies that the overburden was used for restoration with a limited storage period; “Moderate handling” implies that the overburden was stored for long periods (leading to transformation of soil properties and seed composition); “Poor handling” implies that the overburden was used for purposes other than restoration. The handling was better in stone quarries than in gravel pits which may be due to that some gravel pits were used occasionally over long periods of time and not restored in between extraction events (I).

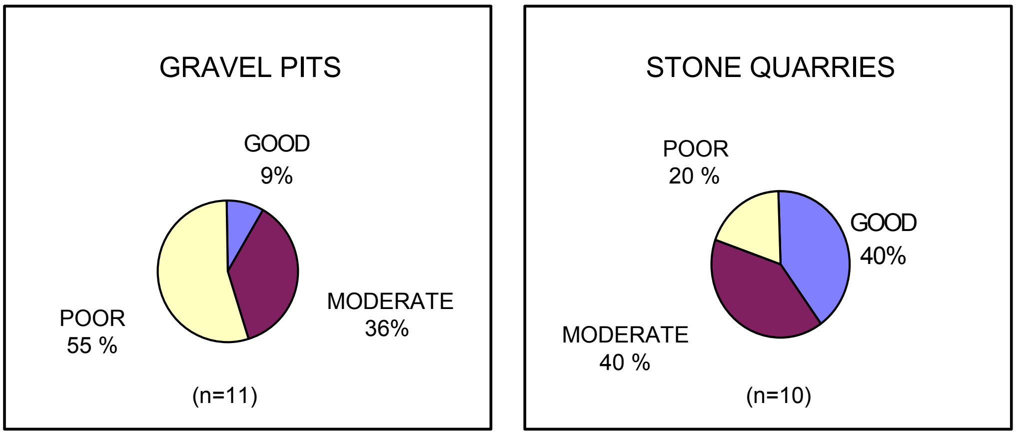

Figure 6. Handling of overburden in gravel pits and stone quarries (I).

Depending on location in Sweden, there are different requirements regarding the distance between pit floor and groundwater level. However in general the recommendations from the Swedish Environmental Protection Agency (NVV & GMF,1995) regarding the depth from pit floor to groundwater level inside and outside groundwater protection areas respectively are included as requirements in the permits. The recommendations regarding applied organic topsoil are, however, not generally observed (I).

Pre-planned land use after cessation of extraction in gravel pits is dominated by forest (60%), recreation (25%), farming (10%) and industrial activities (10%). In stone quarries the pre-planned land use is dominated by forest (50%), industrial activity (20%) and recreation (20%). The location of the site influences the land use possibilities for the site (e.g. in sparsely or densely populated areas) (I).

Importance of soil physical properties

A modelling tool can be useful as a tool to predict the impact from different soil physical properties, for management techniques under various environmental conditions (II).

The combination of the properties of unsaturated conductivity and water retention regulates the transport and storage of water in the soil (Figures 7 & 8). When studying a 10 cm thick layer of applied soil, the differences between the soils were mostly due to the transport properties (unsaturated conductivity) and not so much to the water storage properties (water retention of the applied soil). The underlying soil layers and the specific combination of applied topsoil and underlying soil influenced the results. When studying applied soil with a thickness of 40 cm, the water storage properties were also of importance in addition to transport properties and these properties compensated each other, since soils with high unsaturated conductivity had low water storage properties (II).

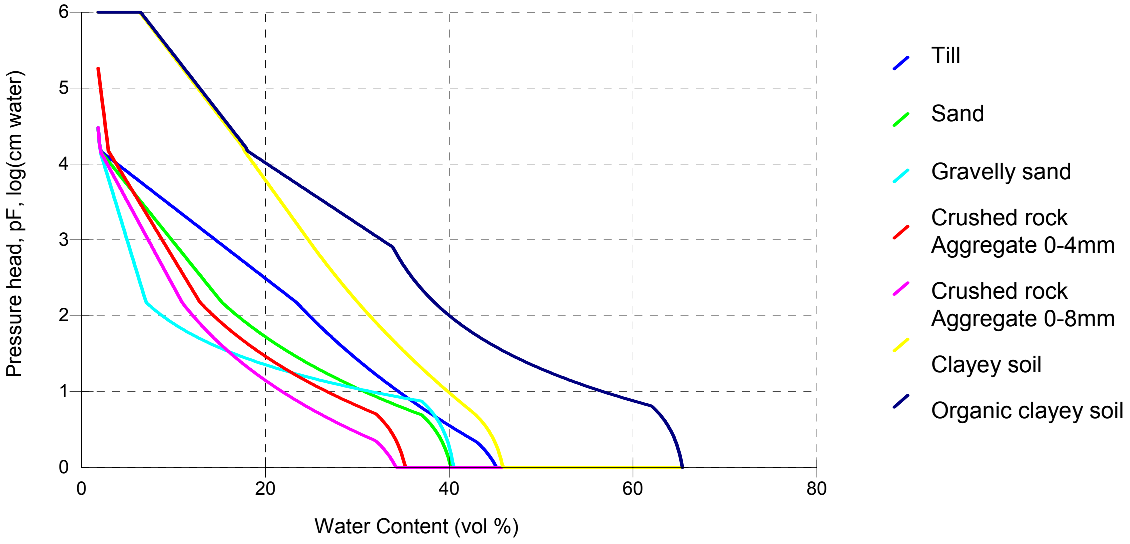

Figure 7. Water retention characteristics for applied soils (II).

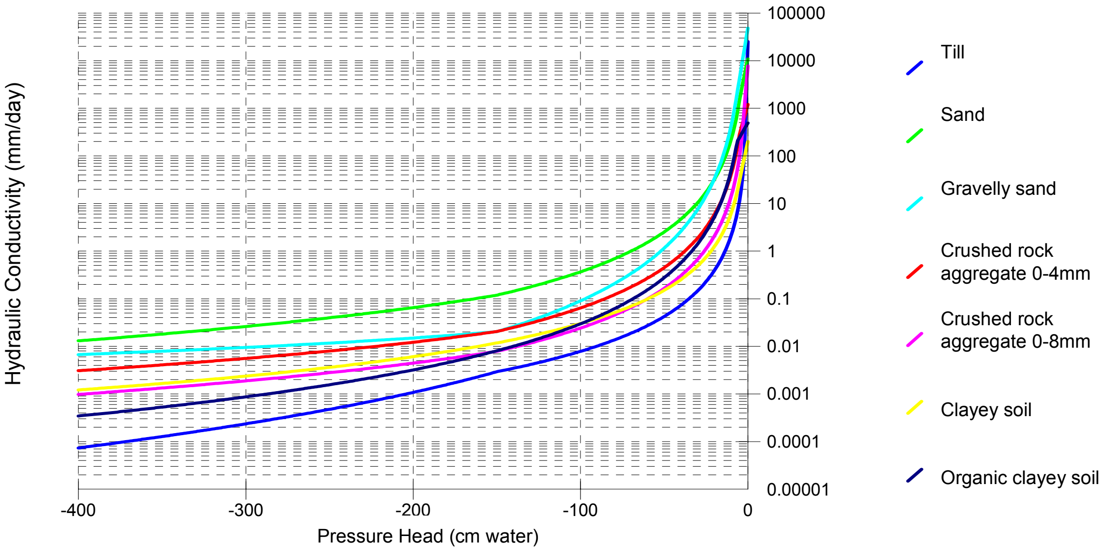

Figure 8. Unsaturated conductivity characteristics for applied soils (II).

All of the topsoils studied contained more plant-available water than the underlying soil layers. The gravelly sand (original topsoil from the Löten gravel pit) was very similar to the underlying soil profile with respect to both unsaturated conductivity and water retention. The till and the organic clayey soil contained most water available to plants (II).

The organic content increased the porosity and thereby the water content of the soil. A high content of clay increased the water content but the water was not available to plants due to high retention. Therefore both the till and the sand contained more plant-available water than the clayey soil.

However, the plant water supply was not only related to the plant-available water storage of the soil, but was to a high degree also dependent on the capillary rise of water from deeper soil layers for the water supply. The combination of water retention and unsaturated conductivity was of the greatest importance for the water supply. When the water flow was directed upwards, towards the dry surface, the soils with a higher unsaturated conductivity were more efficient at providing a flow towards the surface (II).

All soils except for the sand had lower unsaturated conductivity and thus lower capillarity than the underlying soil layers and thereby the evaporation decreased (for 10 cm applied sand) compared to gravelly sand (Figure 9). The sand instead increased the evaporation compared to the gravelly sand. The smallest soil evaporation was obtained for the two clayey soils, despite high water storage capacity, due to low unsaturated conductivity. The evaporation was thus dependent on the capillary rise of water and therefore the unsaturated conductivity was of the utmost importance. When the thickness of the topsoil layer applied was increased, the evaporation increased due to enlarged water storage capacity, except for the sand. The higher unsaturated conductivity in the sand made the evaporation decrease when soil thickness was increased due to the increased drainage of the soil. With 40 cm of applied soil, without vegetation cover, there was little difference in evaporation between the different soils due to the compensation of the soil properties (II).

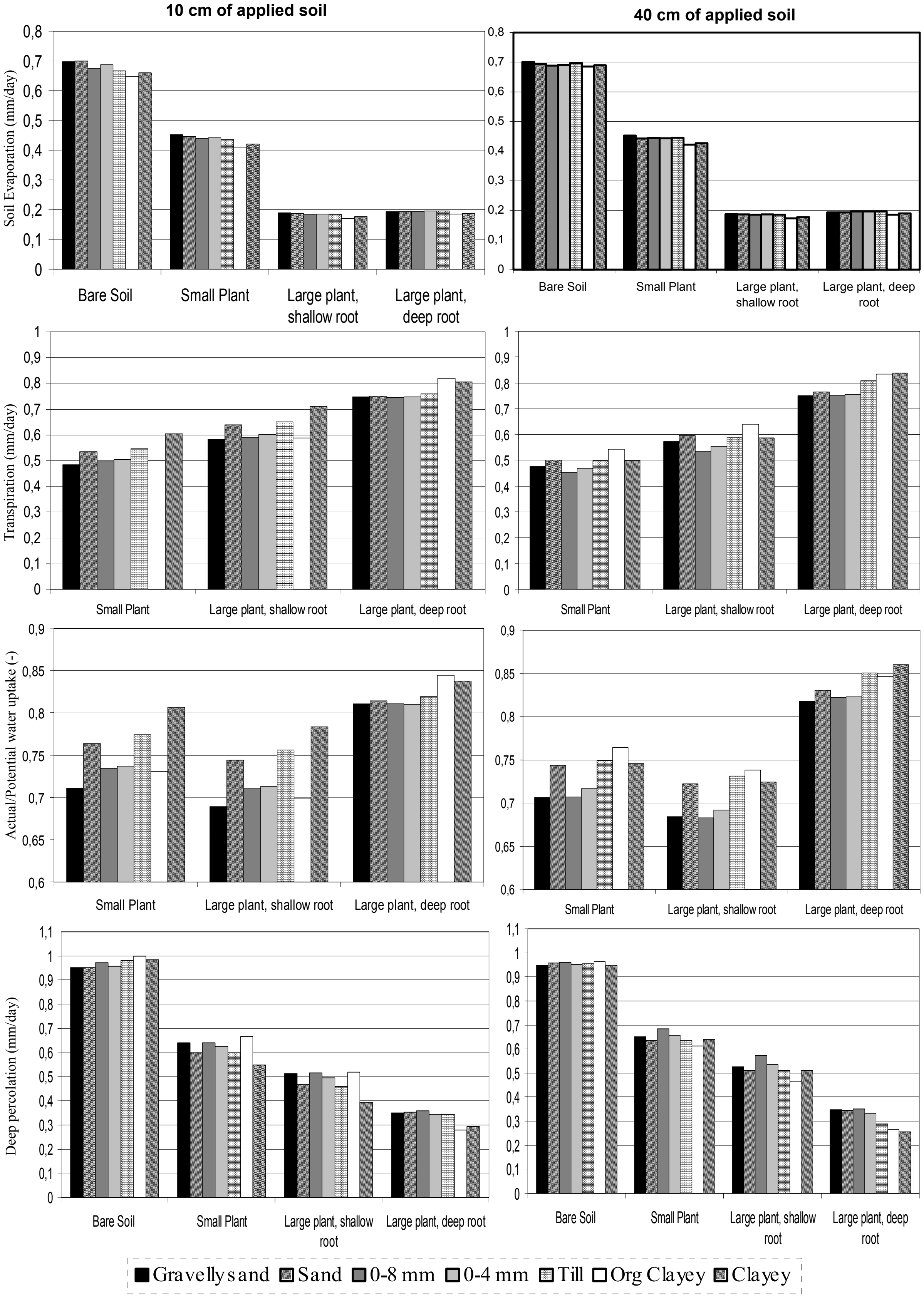

Figure 9. Simulated mean values of soil evaporation, transpiration, degree of potential water uptake and deep percolation during 18 years between 1961-1978 in Ystad (II).

Due to the higher water retention, the transpiration and the degree of potential water uptake increased for plants with deep roots when the applied soil thickness was increased from 10 to 40 cm. However due to the low unsaturated conductivity of the applied soils, the transpiration and degree of potential water uptake for the plants with shallow root systems decreased as the applied soil thickness was increased to 40 cm as a result of decreased capillary rise of water from deeper levels up to the roots. Only the organic clayey soil achieved high capillarity due to high water content and thus high transpiration. Thus the plant water supply in the top 10 cm was dependent on the capillary rise of water and thereby on the unsaturated conductivity. The degree of potential water uptake was higher for large plants with deep roots than for small plants with shallow roots, which illustrates that the plant is more sensitive to water deficit during establishment than later (II).

Depending on the perspective, the choice of applied soil and thickness of the applied soil differ. A 40 cm layer of applied soil with low unsaturated conductivity decreased the transpiration and degree of potential water uptake for a plant with shallow roots compared to a 10 cm layer. However while the unsaturated conductivity was low, the water storage capacity was high and thus the transpiration and degree of potential water uptake for a plant with deep roots increased compared to 10 cm. In the long-term perspective, the higher transpiration and thus growth for a large plant is more profitable, while in the short-term perspective, when focusing on plant establishment, the decreased transpiration and degree of water uptake is also important to consider. The fact that an applied layer of 40 of soil with high water retention increases the transit time for groundwater recharge must also be taken into consideration (II).

The vegetation cover, the choice of applied soil and the groundwater level influence the transit time for groundwater recharge. While a longer transit time allows water purifying processes to act for a longer period of time, different soils provide different degrees of protection to groundwater quality. A vegetation cover thus increases the transit time due to decreased amount of deep percolation. Choosing a topsoil with high water storage capacity increased the transit time without decreasing the groundwater recharge, due to increased soil water content. The transit time for groundwater at 1 m depth was notably increased on addition of 40 cm of topsoil with high water retention compared to a topsoil with low water retention (II).

For large plants with a high potential transpiration, the amount of precipitation seems to be of greater importance for transpiration than the temperature while large plants had a higher transpiration rate in Falun, with a higher precipitation and lower temperature, than in Ystad. In northern Sweden, the effect due to frozen soil highly influenced the transpiration. Therefore the transpiration in the organic clayey soil with high water retention was decreased in Kiruna compared with the other locations, due to the long time needed for thawing in the spring (II).

CONCLUSIONS

Conflicts between aggregate extraction and groundwater interests were found to be common in the Swedish cases studied here. Successive restoration to enhance groundwater protection, which forms part of the recommendations from the Swedish Environmental Protection Agency, was often required but seldom carried out. The recommendations regarding thickness of applied organic topsoil were generally not observed in the permit documentation. Overburden was often used for purposes other than restoration, leading to a shortage of organic topsoil for restoration purposes after cessation of extraction. The restoration carried out often deviated from pre-planned restoration and was most often less extensive.

The model used for simulation of the soil-plant-atmosphere system was useful as a tool to predict the impact from different soil choices and to quantify the influence of different soil properties such as water retention and unsaturated conductivity on vegetation establishment and transit time for groundwater recharge. Therefore a modelling tool might be useful for management of gravel pit restoration.

A combination of properties, transport and storage capacity, influenced the behaviour of the soil-plant-atmosphere system. Results were in accordance with our expectations but some exceptions were noted where the combination of different factors could not be foreseen without the use of the mathematical model.

A high content of clay resulted in decreased transpiration in a cold climate due to delayed thawing during the spring as a result of high ice content.

The unsaturated conductivity played an important role for the plant water supply when the root system was shallow and thus the combination of physical properties of the applied topsoil and of the underlying soil profile was important for the plant water supply.

The degree of potential water uptake was lower for small plants with shallow roots than for large plants with deep roots, thus making small plants more sensitive for water stress. However, developed large plants with shallow roots were most susceptible to water stress.

FUTURE STUDIES

Further simulation experiments of different soil properties and different vegetation cover and its effects on groundwater are of high interest. On the other hand it is also desirable to extend future studies. Simulation experiments should be integrated with chemical/biological aspects. Connections to field/laboratory studies are always of high importance.

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