Water and Agriculture

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Water and Agriculture

Report from the international conference in Falkenberg, Sweden, 14-16 May 2006
Chairman was professor Piotr Kowalik (Poland) Bertebos Prize Winner 2005.

The Royal Swedish Academy of Agriculture and Forestry
in cooperation with the Bertebos Foundation

Contents

Water means life and life means water. Nothing can live without water - plant, animal or human. Fresh water resources are diminishing and in many areas there is competition for water by sectors including industry, agriculture, cities and nature. Water productivity studies indicate that to obtain 1 tonne of biomass it is necessary to use at least 1 000 tonnes of water. One consequence of this is that in Southern Europe more than 70 % of all water resources are dedicated to agriculture. The water in rivers, the ground and the soil must be studied, understood and managed. One of the most important issues is water quality but salinity and water re-use are also pressing questions. Both conservation of water resources and desalinisation and wastewater treatment should be given priority in many urban and rural regions.

The main focus of this report from the Bertebos conference 2006, is on the problem of water use by agriculture - including agricultural productivity, the environment, how computer models can support decision-making, the main priorities during the process of handling the water and how to implement and evaluate the Scandinavian and Baltic dimension of the European Water Framework Directive.

THE BERTEBOS FOUNDATION was established 1994 by Olof and Brita Stenström to promote training and scientific research within the food sector. The Bertebos Prize is awarded every second year for research of distinguished quality and practical use in Food, Agriculture, Ecology and Animal Health.

Water and agriculture - a general overview

PIOTR KOWALIK, GDANSK UNIVERSITY OF TECHNOLOGY, POLAND

Professor Piotr Kowalik (Poland), Bertebos Prize Winner 2005 and chairman of the Falkenberg conference Water and Agriculture 2006.

Leonardo da Vinci, constructor of the drainage system of a swamp area north of Rome, said that "water is the blood of the soil". When you talk about water, you refer not only to the pure medium, but also to the function of water. Just like the blood in our bodies, water is a transporter of chemicals and microbes in the ecosystems.

Agrohydrology is a science dealing with the water in agricultural fields, grasslands, wetlands and forests, focusing on the role of vegetation in the circulation of water in the environment *(green hydrology* or *ecohydrology)*.

The most important problems agrohydrology deals with are:

- The sun as a driving force of water movement on the Earth, and its part in evaporation, photosynthesis and transpiration.
- Evaporation
- Photosynthesis and transpiration
- Relations between solar radiation and yield
- Relation between water use and yield.

All these factors can of course be studied and discussed on different spatial scales. Here we will stick to the single field as the geographical unit.

The concept of evaporation can be illustrated by water in an open bowl or pot, in which the water surface is exposed to the sun and the wind in the same way as the surrounding surface of the soil. Evaporation is related to air temperature, air humidity and wind speed. This simple device, completed with some method to measure the water level, is also an instrument that measures evaporation – an evaporimeter. The evaporimeter is very useful in connection with irrigation, because the level of water needed to keep different types of soil from drying out can easily be measured, thus defining the point when it is necessary to start irrigation.

This concept was the starting point of the theories for evaporation, and one of the founders of the theory of how water is evaporating was Howard Penman from the UK. During the Second World War he was working for the army and had the task to predict when in the spring the soil was dry enough to support the heavy military traffic. He was obliged to keep his methods secret, so it wasn't until eleven years later he gave lectures on the technique he used.

Incidentally, the evaporation from grassland is about the same as from an open water surface (ratio 1:1). However, other types of plant cover or vegetation perform differently in this respect. Thus, crops like wheat or rye have 0.7 of the evaporation of open water, while pine has

SOLAR RADIATION AND YIELD

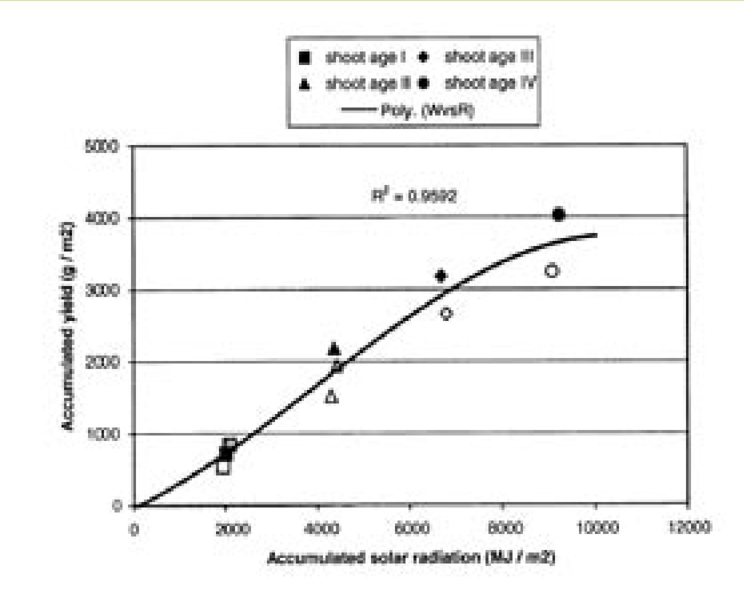


Figure 1. The accumulated yield as a function of accumulated solar radiation. The graph shows the efficiency of the crop to transform solar radiation into biomass. This efficiency is typically only about 1 %. Some plants, like for example the sugar beet, perform a little better – up to 3 %.

1.2, alfalfa 1.6 and spruce or willow 2.2. This is something to keep in mind when discussing water need. Development of plant cover of vegetation using a lot of water can be detrimental to the water balance.

Transpiration

Transpiration is the uptake of water by plants and transpiring of water into the atmosphere. This is coupled with the uptake of carbon dioxide in the photosynthesis, producing biomass and oxygen. The photosynthesis needs heat and light to run, but it is also true that it cannot run without water. Figure 1 shows the accumulated yield as a function of accumulated solar radiation. One way to put it is that the graph shows the efficiency of the crop to transform solar radiation into biomass. This efficiency is typically only about 1 %. Some plants, like for example the sugar beet, perform a little better – up to 3 %.

Looking at transpiration, the efficiency is even lower. For 1 kg yield, we need 1 000 kg water. In other words, the efficiency in terms of water use is 0.1 %. This relation is linear, meaning that if the water supply is 50 % of maximum, also the yield will be only 50 % of maximum. Taking yield as Y, transpiration as T and the coefficient of water productivity as α, we can write: $Y = \alpha \cdot T$. One ton of biomass (Y) needs one thousand tons of water (T). The coefficient α is crop-dependent. Some plants are using more water to produce a certain amount of biomass than others. A lot of water is used by spruce and willow, much less

YIELD AND GROUNDWATER

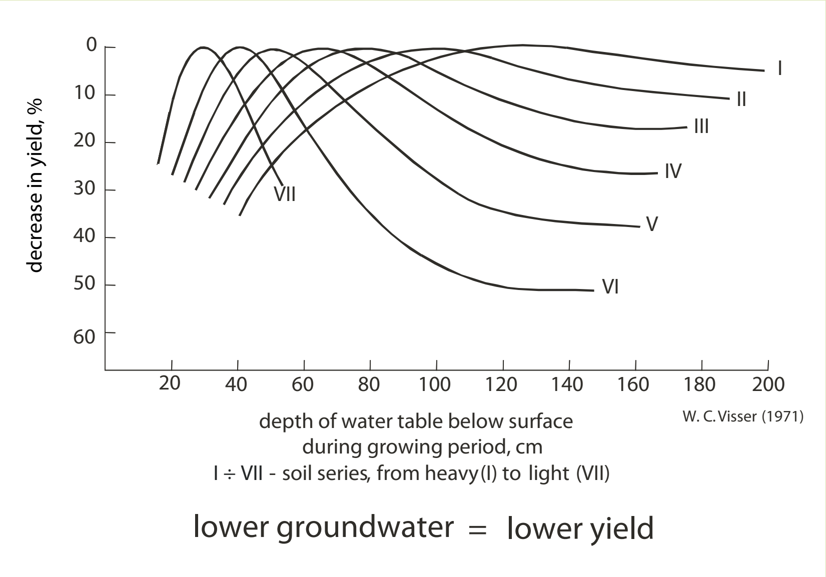


Figure 2. How transpiration is related to the groundwater levels. In general, a lower groundwater level reduces transpiration, which means that also the yield will be reduced.

by grasses (half) and the smallest amount by some agricultural crops like barley (less than half).

Water resources

Looking at water resources we have to consider not only the exchange of water between the soil

SOIL WATER DYNAMICS

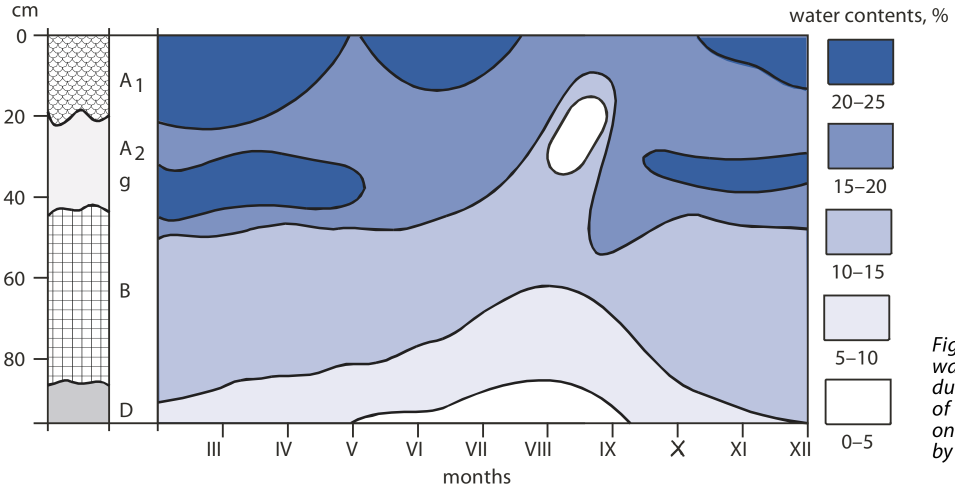


Figure 3. The soil water dynamics during most part of the year (based on measurements by Hjalmar Uggla).

and the atmosphere, but also the flow of water in the soil itself. One issue of particular interest is how transpiration is related to the groundwater levels. In general, a lower groundwater level reduces transpiration, which means that also the yield will be reduced. Figure 2 shows an example of this. In light soils the effect of lower groundwater table on the yield is dramatic. One of the strategies to prevent this is to stop the outflow from the fields.

Figure 3 gives a picture of the soil water dynamics during most part of the year. As can be seen the groundwater level has dropped below one metre. The upper part of the profile is mainly supplied by the rain. There are also certain water reserves in the middle part, especially in the spring and fall. In this case, the subsoil was very dense due to heavy machinery compaction, and because of this water is stored in the middle. The drop of water content in the middle of the profile has nothing to do with the upper or lower boundary conditions. It is simply a consequence of the water uptake through the roots of the vegetation.

Vegetation

The vegetation still adds another dimension to the soil water dynamics. Through the transpiration of the plants, water leaves the ground and goes into the atmosphere during the day. During the night, respiration is small or closed down, and the water storage in the ground is replaced. This slow, solar-driven day-and-night pulse is so to speak the heartbeat of the plants.

Summary

- Actual problems of agrohydrology are related to water in terrestrial ecosystems (agricultural lands, grasslands, wetlands and forest).
- The flow of water through the vegetation is of the same magnitude as the flow of water in the rivers.
- To produce 1 kg of biomass about 1 000 kg of water are needed.
- There is an increasing risk for conflicts among different water users; for example water is needed for the industry and for human and agricultural use as well as for the natural environment as a whole.

Water and achievement of the millennium goal

MALIN FALKENMARK, PROFESSOR, STOCKHOLM INTERNATIONAL WATER INSTITUTE, SWEDEN

In the past, water and future food production has been addressed as an issue of irrigation needs and related water demands. A recent overview has however made clear that the result of the green revolution is a large scale overappropriation of stream flow in irrigation dependent regions at the expense of water requirements for healthy aquatic ecosystems (an area corresponding to 15 % of the continents, hosting 1.4 billion people). The consequence is visible in many large rivers now being more or less severely depleted. Examples of this can be found in most parts of Asia, Northern Africa and Mexico.

The fact that an increasing number of river basins are thus becoming closed means that the irrigation option is being increasingly constrained for expanded food production to a rapidly growing world population. Analysis of the hydrological consequences of an increased food production will therefore have to switch focus from irrigation water needs to overall requirements for consumptive water use, irrespective of the origin of the water available to the roots, whether it is infiltrated rain (green water resource/soil moisture) or infiltrated irrigation water (blue water resource).

Stockholm International Water Institute and Stockholm Environment Institute, have made a water balance-based study of the water requirements involved in alleviating world hunger. The focus is on water requirements and from what sources these requirements may be met. The starting point are the Millennium Development Goals (MDG). The first goal is the hunger goal, which combines hunger and poverty, because most poor people are also hungry. The poor and hungry are at present to a large extent concentrated to rural areas, and therefore agriculture is the entry point for both poverty eradication and hunger alleviation.

A primary target of the first Millennium Development Goal is to halve the number of poor and hungry until 2015. The study included not only this target, but also the water requirements to feed humanity beyond that target on an acceptable nutritional level by 2030, including the growing world population till 2050, when the population growth is believed to have stabilised. The study is a country-by-country-based analysis for 92 developing countries. The population of the rural areas is not believed to grow over these years, but the population of urban areas will, and this will of course influence the diet.

Globally the problem with undernourishment is most severe in sub-saharan Africa and southern Asia, which make the environmental conditions in these areas particularly interesting. Furthermore, the countries with the lowest human development index are found in the same areas. Human development index takes into account life expectancy at birth, literacy level and the purchasing power of the poor.

The correlation of areas with a high level of undernourishment and savannah agro-ecosystem is interesting. Kofi Annan, Secretary-General of the United Nations, brought special attention to Africa when he called for a "uniquely African green revolution in the 21st century to end the continent's plague of hunger".

In the savannah zone, there are particular

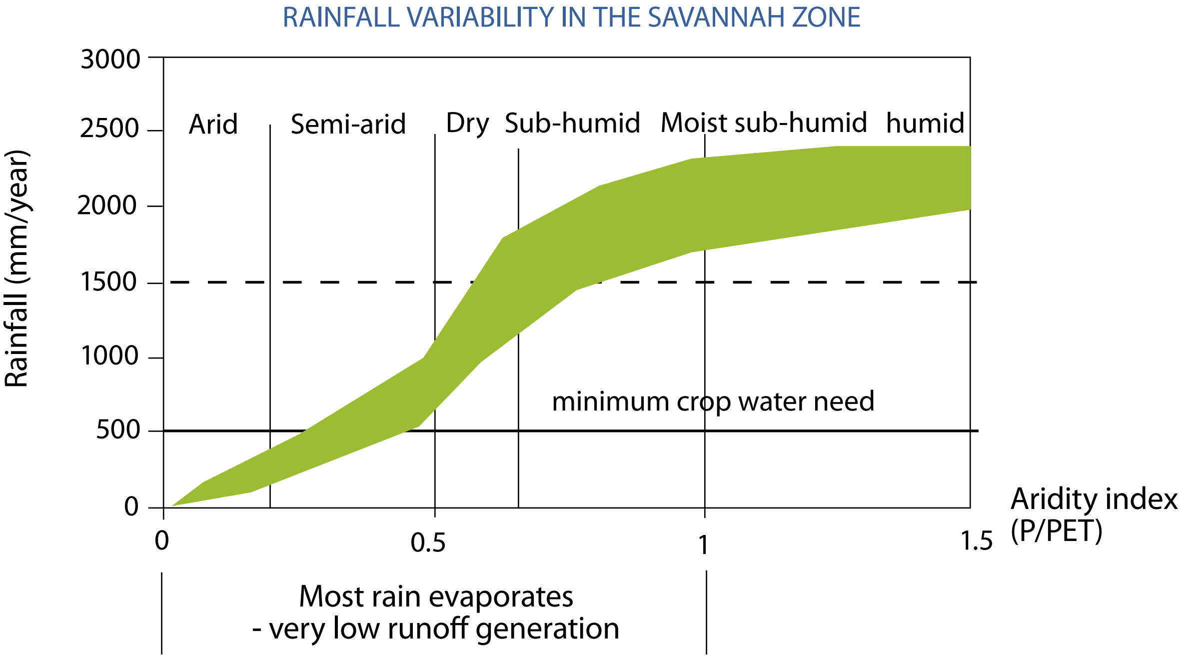


Figure 1. In the zone below aridity index 1.0 most rain evaporates, which means that there is very little runoff generation. The main problems in the savannah zone are therefore water shortage and unreliability.

key water problems to address. The main problem is the great rainfall variability across a zone reaching from arid to sub-humid conditions (figure 1). The growing season is short. Dry spells are typical for the wet season, which has major implications for the productivity. There are also inter-annual droughts that are linked to the El Niño-phenomenon in the Pacific Ocean. The atmosphere is also very ’thirsty’ with high evaporative demands. As can be seen in figure 1, in the zone below aridity index 1.0 most rain evaporates, which means that there is very little runoff generation. The main problems in the savannah zone are therefore water shortage and unreliability. The conditions also influence the solutions. Irrigation is not a solution, because of high evaporation and the very limited access to ’blue’ water (see below).

The question asked in the study was how much water will be required to produce the additional food needed to alleviate world hunger. We assume that the daily per capita demand is 3 000 kilocalories (which is consistent with the FAO projection for 2030 for the developing world) and that the diet consists of 20 % animal protein. This is because there is a trend towards more meat in the diet, as more people live in urban areas.

Current water productivity is 0.5 m^3/1 000 kilocalories for grain and 4 m^3/1000 kilocalories for livestock. The big difference is due to the low energy efficiency in producing animal protein. This means a per capita water requirement of 1 300 m^3/year. This is 70 times more than the basic household needs – which is the usual starting point in international discussions on future water needs.

CONSUMPTIVE WATER USE FOR AGRICULTURE PRODUCTS

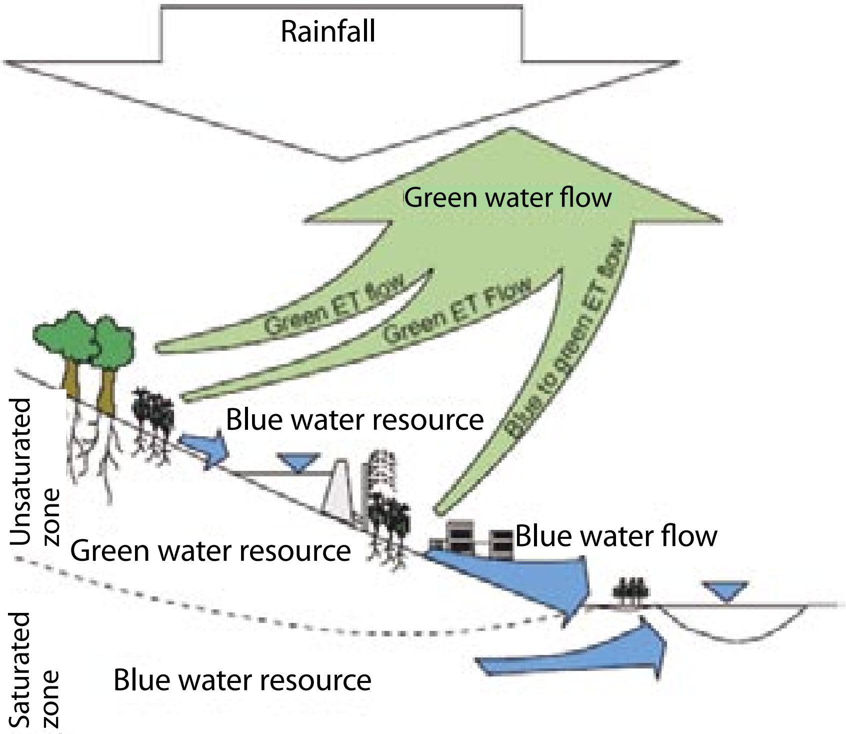


Figure 2. The green-blue water paradigm. The water availability is the rainfall, the water need is the crop water requirement and the water resource is the soil moisture – the green water in the soil – regardless of if it originates from infiltrated rain or from infiltrated irrigation water.

The focus of the study was the water required, which is the consumptive water use for agriculture products, and where to find it. Due to the aridity, soil water has to be incorporated in the analysis, and therefore the new green-blue water paradigm (figure 2), where rainfall is divided into two main flows – 'blue' and 'green' water - was developed. In this respect the study involves a shift of thinking: The water availability is the rainfall, the water need is the crop water requirement and the water resource is the soil moisture – the green water in the soil – regardless of if it originates from infiltrated rain or from infiltrated irrigation water.

To estimate the amount of water required for hunger alleviation the consumptive water requirements for food production in the 92 developing countries were summed up. The results showed that by 2015 another 50 % of water is needed to fulfil the hunger goal (figure 3). By 2030 another 4 200 km^3 of water will be needed annually. The overall water requirements in other words imply almost a doubling in the coming decades of the vapour flow linked to food production.

Because of the low level of blue water in the savannah zone irrigation has already drained rivers and reservoirs, and therefore blue water irrigation can provide only about 15 % of the water needed. The remaining 85 % must be green water. To handle this we have to improve water productivity. If that is not sufficient, horizontal expansion is the only remaining possibility.

The second step of the study was to examine the water productivity to find out what gains are possible. There are two types of water loss to exploit; the green water losses (evaporation) and

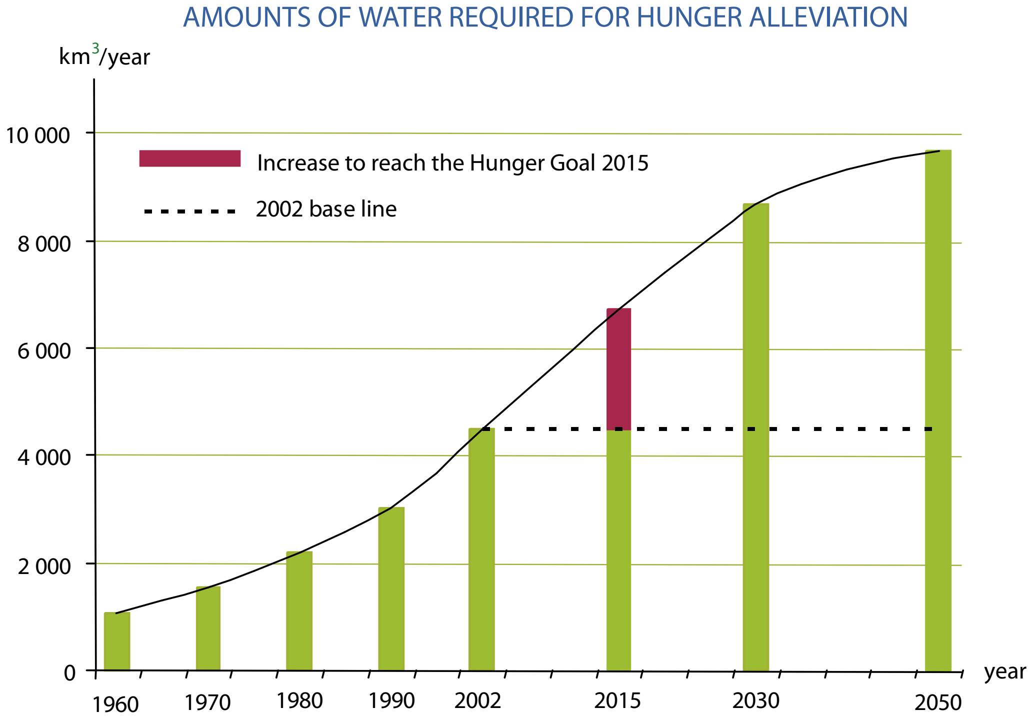


Figure 3. To estimate the amount of water required for hunger alleviation the consumptive water requirements for food production in the 92 developing countries were summed up. The results showed that by 2015 another 50 % of water is needed to fulfil the hunger goal. By 2030 another 4 200 km^3 of water will be needed annually.

the blue water losses (run-off, drainage and percolation) on the crop fields. The problem is not water availability in terms of rainfall, but the accessibility of that water in the root zone, because only a part of the rain infiltrates. Because of the low water holding capacity of the soil only part of the infiltrated water stays in the root zone. Furthermore, the roots are only capable of taking up part of the water that stays, because of the great evaporation losses and because they have been damaged by the dry spells.

There is a great potential in agriculture if the water losses can be reduced (figure 4). The techniques available for reducing blue water losses are soil and water conservation to maximise infiltration, and soil conservation to increase the water holding capacity. The green water losses can be diminished by minimising naked soil and dry spell mitigation, based on protective irrigation to improve the water uptake.

The third step in the study was to look at the options and to try to quantify them.

- The first option is **irrigation**, which cannot contribute very much to meet the water requirements. The assumption was to start with the current level of irrigation, assuming 70 % efficiency, and increasing proportionally with the population increase. These are very optimistic assumptions. Still, as can be seen from table 1 irrigation cannot contribute very much.
- The second option is **improved water productivity** by reducing the green water losses, by striving for a denser foliage, reducing evaporation from plants.

COVERING THE WATER REQUIREMENTS

Relative to comsumptive water use 2002 (km^3/year)

	2015	2030	2050
Additional consumptive use requirement (current water productivity)	2200	4200	5200
Options:			
- Irrigation	270	520	725
- Reduced green water losses	350	1150	2300
- Reduced blue water losses *("making better use of local rain")*	1580	2500	2100
- Expansion of cropland			

Table 1. Water requirements for the decades to come and options to cover them.

- The rest of the additional water needed has to come from **reduced blue water losses** and **expansion of cropland**.

Conclusions

The hunger alleviation is a core component of the Millennium Development Goals, since most other goals will not be possible to reach unless hunger is alleviated. The goal involves a tremendous water challenge. In sub-saharan Africa the water usage has to be four times higher than today, and in south Asia it needs to double. These calculations are based on the diet assumptions mentioned, which of course can be discussed. A factor that could influence the development may be better food distribution, which will allow lower per capita energy supply. Another possibility is bringing down losses in post harvest handling and distribution of food. There are studies indicating that this could bring down the daily per capita need to 2 200 kilocalories. A third option is to bring down the consumption of red meat.

SITUATION OF TYPICAL SMALLHOLDER FARMER IN SUB-SAHARAN AFRICA

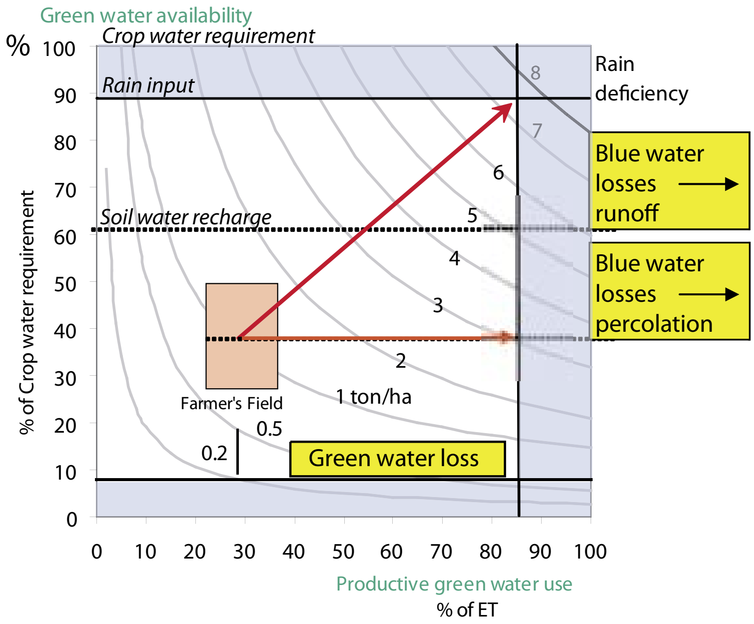


Figure 4. There is a great potential in agriculture if the water losses can be reduced. The techniques available for reducing blue water losses are soil/water conservation to maximise infiltration, and soil conservation to increase the water holding capacity. The green water losses can be diminished by minimising naked soil and dry spell mitigation, based on protective irrigation to improve the water uptake.

Water and agriculture in the European Union

MAREK NAWALANY, PROFESSOR, WARSAW UNIVERSITY OF TECHNOLOGY, POLAND

Governing of water in Europe with respect to food production is a complex issue involving a number of spatial and temporal scales, two essentially distinct climatic zones and a multitude of organisations interlinked by complex dependencies. The water actors are competing for the resource, using economic and political means.

Averaged results for the EU25-countries show that when Europeans are asked to list the five main environmental issues that they are worried about, nearly half of the respondents answer that they are worried about water pollution (with figures for individual countries as high as 71 %). The highest figures are found in southern Europe, which is already facing the effects of climate change and increased water needs for agricultural purposes.

The Water Framework Directive

The Water Framework Directive (WFD) was adopted by the European Union in 2000 as a response to the concerns expressed by the citizens of Europe. The overall objective of the directive and the new European water policy is to make polluted waters clean again and to ensure that clean waters are kept clean.

More specifically, the Water Framework Directive demands that all waters should achieve *good ecological status*. The meaning of good ecological status is only outlined in the directive, and must be defined further in each member country, taking into account the present situation, the natural conditions and the resources available for water management and restoration. All kinds of water bodies, including surface waters, groundwater and coastal waters, are included in the directive.

Tools and mechanisms to achieve the goal include:

- Water management based on river basins.
- 'Combined approach' comprising of emission limit values and quality standards.
- Getting the water price right.
- Making the citizens more closely involved.
- Streamlining national legislation.

The Water Framework Directive defines a number of steps to be taken in each member state, with one fixed deadline, to reach the objective. The first step was to identify all water bodies on river basin basis and identify the pressures upon each water body. Next, good ecological status for each water body should be defined and monitoring programmes developed. The two steps should be completed no later than December 2006.

The steps to follow over the coming years are:

- Establishing and implementing a river basin management plan and a programme of measures to achieve and maintain good status (December 2009).
- The programme of measures is getting operational (December 2012).
- Reviewing and updating the river basin management plan and the programme of measures to take into account any change of circumstances (December 2013).
- Achieving environmental objectives (December 2015).

Already, some countries have reported that they will not be able to reach the goal of good ecological status in all waters regardless of the measures taken, either for physical or economical reasons.

Water use and water demand in Europe

Table 1 shows the agricultural water use in the EU 25-countries. In total, agriculture accounts for 50 % of the water use in Europe, but as can be seen from the table the conditions differ widely between countries. In the south, agriculture accounts for a much higher than average proportion of the total water use (mostly for irrigation), while the opposite is true for northern countries like for example Sweden and Poland. This means that when discussing water and agriculture in a European perspective we need to keep in mind that we are actually talking about two sub-continents – a southern and a northern one – with profoundly different conditions.

From an environmental perspective, agriculture is not only one of the major consumers of water but it is also a polluter, emitting a considerable flux of liquid and solid waste into the environment.

The major European policy tools for issues related to water and agriculture are the Water Framework Directive and the Common Agricultural Policy (CAP). However, these two tools are not consistent and difficult to conciliate. The subsidies under CAP diffuse the water problems and clearly contradict the Water Framework Directive requirement of full cost recovery in the water sector.

The Integrated Water Resources Management (IWRM) concept is expected to encapsulate all complexities of water-agriculture issues and guide decision-makers and water-users towards sustainable coexistence of agriculture and water resources. However, there is a factor of economic and political risk in implementing IWRM, as this concept has never been tried on the large scale of a region or a state.

Water issues of agriculture are also strongly linked with the use of water by other sectors which in many instances have their own water problems unresolved, for example the old and leaking European sanitary infrastructure. There is a competition over water. Urban areas presently extracts more water from the sources than is replaced, which of course is not sustainable in the long run.

External challenges

There are also, as professor Falkenmark showed, challenges on the global scale that generate a political dilemma of choosing priorities. The European Water Initiative (EWI) supporting the Millennium Development Goals (MDG) is oriented towards economically unprivileged countries which are in urgent need to improve their water and sanitary situation. European involvement in the initiative clearly compete with solving the continent's own unresolved water problems, especially when agricultural and water interests of new member states are taken into account. The future course of water and agriculture in Europe is difficult to predict as the European policies, like CAP and EWI, are not only conditioned on the internal European situation. On the global arena they meet similar initiatives of the USA, Japan and China.

On top of this, climate change must be taken into account. The number of droughts and flood events in Europe are likely to increase. Differences in water resources between northern and southern Europe will be widened. Northern Europe is likely to have increasing water abundance, whereas southern Europe may face growing water shortage or even water scarcity.

Still, structuring and implementing water

WATER USE OF AGRICULTURE IN EUROPE

COUNTRY	TOTAL WATER USE (km³/ year)	AGRICULTURAL WATER USE (km³/year)	AGRICULTURAL WATER USE (as % of total water use)	IRRIGATED LAND (ha)	YEAR OF IRRIGATION DATA	ANNUAL RAINFALL (mm/year)
EU-25	**241**	**123**	**51**	**12 792 628**		
Austria	2.1	0.021	0.99	4000	1998	1110
Belgium	-	-	-	-	-	847
Cyprus	0.24	0.17	71	39 938	1994	498
Czech Republic	2.6	0.055	2.1	24 000	1998	677
Denmark	1.3	0.54	42	476 000	1998	703
Estonia	0.16	0.0080	4.9	3 680	1995	626
Finland	2.5	0.066	2.7	64 000	1998	537
France	40	3.9	10	2 000 000	1998	867
Germany	47	9.3	20	485 000	1998	700
Greece	7.8	6.2	81	1 422 000	1998	652
Hungary	7.6	2.5	32	210 000	1998	589
Ireland	1.1	0.00020	0.018	-	-	1118
Italy	44	20	45	2 698 000	1998	832
Latvia	0.29	0.036	12	20 000	1995	641
Lithuania	0.27	0.018	6.6	9 247	1995	656
Luxemburg	-	-	-	-	-	934
Malta	0.06	0.014	25	763	1990	383
Netherlands	7.9	2.7	34	565 000	1998	778
Poland	16	1.4	8.3	100 000	1998	600
Portugal	11	8.8	78	632 000	1998	855
Slovakia	-	-	-	174 000	1998	824
Slovenia	-	-	-	2 000	1998	1162
Spain	36	24	68	3 640 000	1998	636
Sweden	3.0	0.26	8.9	115 000	1998	624
United Kingdom	9.5	0.28	2.9	108 000	1998	1220

Table 1. The agricultural water use in the EU 25-countries. In total, agriculture accounts for 50 % of the water use in Europe, but as can be seen from the table the conditions differ widely between countries. (Source: Aquastat 2003)

policy within the agricultural sector will definitely remain an important factor in European politics for the next decades in spite of its complex links with externalities, like global trade and global politics.

The Water Supply and Sanitation Technology Platform (WSSTP)

The Water Supply and Sanitation Technology Platform (WSSTP) is one of the technology platforms that are set up within the European

Environmental Technology Action Plan (ETAP) that was adopted by the European Commission in 2004. It is a European initiative, open to all stakeholders involved in European water supply and sanitation and major end-user groups. The participants in the platform will together produce a common vision document for the whole European water industry together with a strategic research agenda and an implementation plan for the short (2010), medium (2020) and long term (2030). The WSSTP will contribute to:

- The competitiveness of the European water industry (Lisbon Strategy).
- Solving the European water problems.
- Reaching the Millennium Development Goals (Johannesburg).

Water in agriculture is one of the major chapters of the WSSTP. It is expected that solutions found in food production technologies will result in savings of water in terms of its quantity as well as in protecting water resources from agricultural pollution.

The Water in agriculture-chapter of WSSTP contains justification and definitions of research needs, priorities and research goals for the years 2010, 2020 and 2030 corresponding to five subsectors of the European agriculture:

- Rain-fed agriculture
- Irrigated agriculture
- Livestock production
- Aquaculture
- Greenhouses

A vision for each of these sectors has been formulated in consistence with the overall vision of agriculture: *Agriculture – as an important water user – will be economically viable and competitive in the world market. The sector will become more flexible to accommodate the new demands of the market (including environmental demands) and will improve its sustainability.*

WSSTP also have identified priorites for water related technologies. The selected top priorities can be summarised in three clusters:

- **Technology and tool development for increasing water use efficiency and related savings.** This includes use of non-conventional resources (safe and reliable use of wastewater, cascading systems, exploiting brackish water and other marginal water resources), intelligent irrigation systems (leakage detection systems, real time water monitoring sensors to control water quality), improved integrated water management methods and introduction of crops tolerant to salinity and drought.
- **Technology and tool development for optimal use of inputs for agricultural production**, in order to safeguard the environment and improve socio-economic benefits. This includes improved knowledge on biogeochemistry and the fate of nutrients, agrochemicals and other organics, improved knowledge of scaling processes, closing the mass cycles and reduction of emissions (more balanced diet for animals/fodder improvement, replacing mineral fertilisers by safe and sustainable alternatives, models for optimal use of inputs) and integral monitoring and application systems (plant level monitoring and detection systems for nutrients and agrochemicals, auto-adaptive application technologies).
- **Improve governance, institutional framework and stakeholders participation for a sustainable use of water in agriculture.** This includes developing tools for farmers to mitigate and adapt to extreme events (for example modelling scenarios and develop early warning systems for drought and floods), governance, for example tools to support co-decision rights in policy making, tools and technologies to support local to regional networks and knowledge building and transfer.

Water productivity of crops - from field to regional scale

REINDER A FEDDES, PROFESSOR, WAGENINGEN UNIVERSITY, THE NETHERLANDS

In agriculture, water use efficiency is defined by crop yield produced per amount of water used, measured in dry matter yield (kg/ha^{-1}) and transpiration (m^3/ha^{-1}) respectively. However, when discussing water efficiency of different crops one also has to consider the food value of the crop.

Different stakeholders have different interests and thus different points of measurement as concerns water efficiency (table 1). The agronomist measures the relation between yield and evapotranspiration. The farmer is interested in yield/water supply, which is the effectiveness of irrigation, and he wants to maximise his income. The irrigation engineer works above field scale, in an irrigation scheme, and wants to achieve proper water allocation. Purpose, scale and target are usually different between the operators, and therefore it can be difficult to reach agreements.

The theoretical maximum possible dry matter yield of a crop that can be obtained under the prevailing solar radiation regime is termed potential yield. This theoretical production ceiling can be computed for optimal conditions of soil moisture, nutrients, pest-, weed- and disease-control and farm management. It is a valuable way to assess the crop productivity potential of a region.

When considering plant production/water use relationships one should consider the water use by the plant only, i.e. transpiration. The reason is that photosynthesis/dry matter production and transpiration are directly related through the processes of diffusion of carbon dioxide and water vapour through the stomata of the leaves. Hence water use efficiency of crops, in practice often called “water productivity A” can then be defined as in the green box.

During the past 30 years increasing efforts have been put into the development of numerical field scale models that simulate in a dynamic way crop development and yield from inputs of

STAKEHOLDERS AND DEFINITIONS

STAKEHOLDER	DEFINITION	SCALE	TARGET
Plant physiologist	Dry matter/transpiration	Plant	Utilise light and water resources
Nutritionist	Calorie/ transpiration	Field	Healthy food
Agronomist	Yield/evapotranspiration	Field	Sufficient food
Farmer	Yield/supply	Field	Maximise income
Irrigation engineer	Yield/irrigation supply	Irrigation scheme	Proper water allocation
Groundwater policy maker	$/groundwater extraction	Aquifer	Sustainable extraction
Basin policy maker	$/evapotranspiration	River basin	Maximise profits

Table 1. Different stakeholders have different interests and thus different points of measurement as concerns water efficiency.

$$A = \frac{\textit{Crop Yield produced}}{\textit{Amount of Water used}} = \frac{\text{Dry Matter Yield}}{\text{Transpiration}} = \frac{Y}{T}\,\frac{(\text{kg ha}^{-1})}{(\text{m}^{3}\ \text{ha}^{-1})} \qquad (\text{kg m}^{-3})$$

soil and climatic data. Such a model approach was applied to derive criteria for the design of optimal drainage for growing arable crops on major soils in the Netherlands. The outcome of this study was used as a basis for a nationwide system for evaluating the effects of soils and drainage upon crop yields. The methodology of such a model approach can be applied to crops growing in other climates, soil types and under different conditions of irrigation and drainage.

Horizontal upscaling from field to regions can be performed by identifying areas that are homogenous with respect to soil and hydrological properties. Effects of spatial heterogeneity can then be analysed by running a field scale agrohydrological model for all combinations of soil-water-crop and weather combinations i.e. simulation units for the areas under investigation.

Figure 1 shows an example of a model, the SWAP-model that works well on the scale of a region with a similar soil type. Moving on to the basin scale, soil-water-flow-solute transport models linked to crop growth-yield models are used. They are well-defined at field scale level, integrate crop growth and soil-water flow-solute transport, generalise measured crop and soil data and can be calibrated and validated at field scale. The model predicts the development of the crop over time depending on what is happening in the soil. At regional scale, however, data requirements may pose a problem.

To give one example, the SWAP-model has been used to improve the drainage criteria in the Netherlands. In Holland there are high groundwater tables, so the drainage design is very important. In this case we took the SWAP-model,

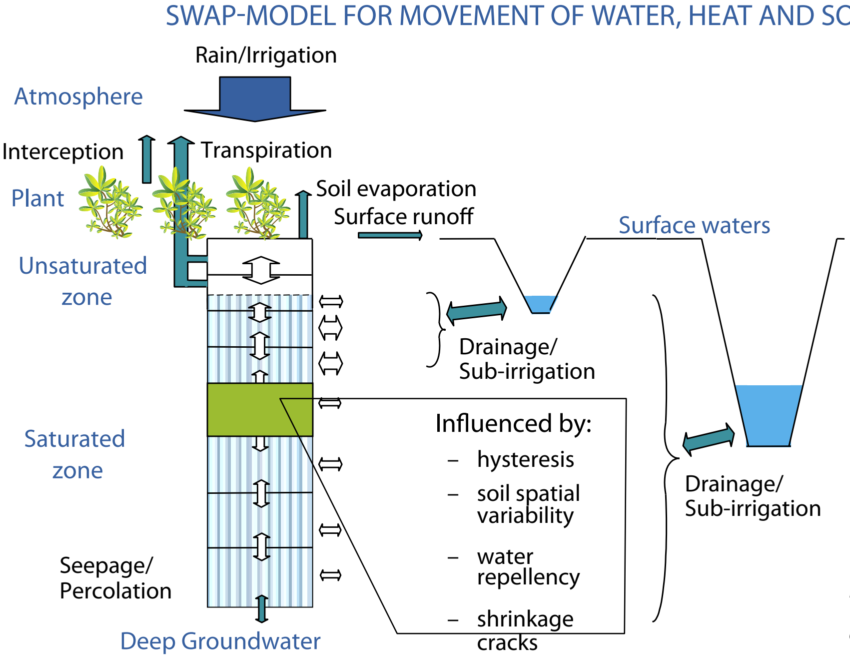


Figure 1. The SWAP-model works well on the scale of a region with a similar soil type.

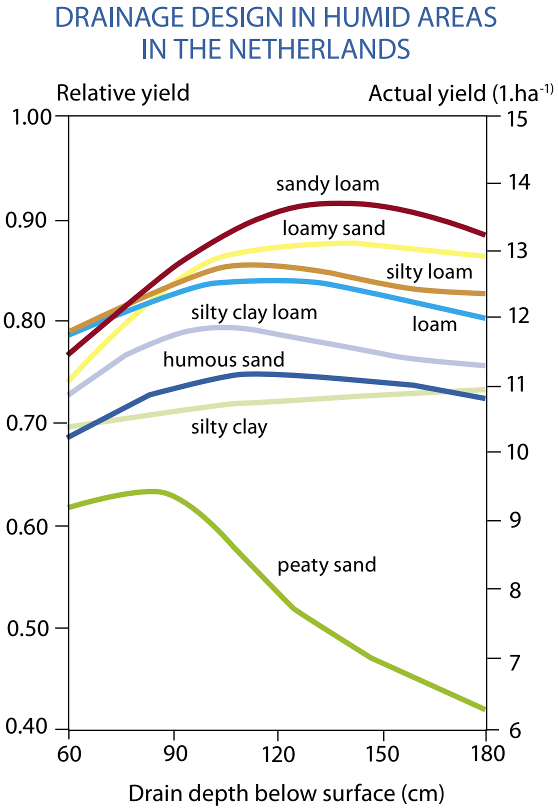


Figure 2. The starting point in the springtime depends on the drainage depth. Different soil types require very different drain depths.

analysed a hydrological period of 30 years for drain depths of 60-180 cm below soil surface and for eight different soil types. Drainage is usually considered of importance just for drying the soils only, but the study showed that for Dutch conditions it is of importance also because it allows the machinery to work on the fields earlier in the springtime allowing for earlier sowing and emergence. It was found that the starting point or day of field work in the springtime depends on the drainage depth, and that different soil types require very different drain depths (figure 2). Some soils, however, are hardly depending on drain depths. Figure 3 shows the outcome of a similar study from Pakistan, indicating that the optimum drain depth in semi-arid areas is about 2.2 meters.

To get an idea of what is happening at river basin scale, remote sensing can be used. Remote sensing measuring provides independent information on land use, evapotranspiration and crop yield. It is not easy to analyse evapotranspiration by remote sensing only, but an algorithm has been developed to calculate evapotranspiration from the energy balance, albedo, leaf area index, normalised vegetation index and the remotely sensed surface temperature.

Remote sensing has high spatial coverage. It can be used to understand past and current water resources, but not to predict the future. SWAP-models, on the other hand, have high temporal resolution (figure 4).

Combinations of modelling and remote sensing could be used to up-scale water productivity studies from fields to regions. This method has been applied in a study of water and crop management in the Sirsa District, India. Initially areas homogeneous in soil and hydrological properties were identified, compared with field

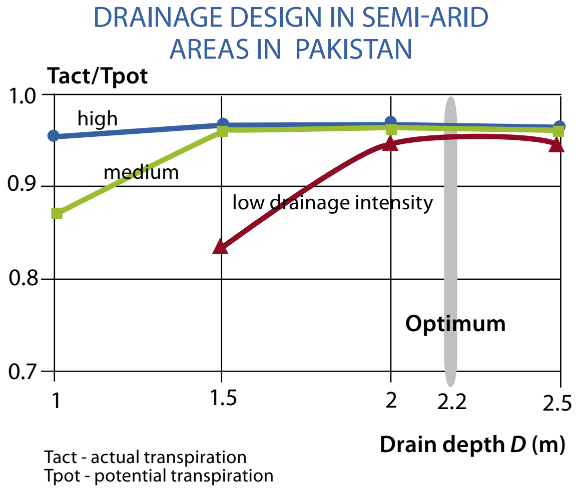


Figure 3. In Pakistan the optimum drain depth in semi-arid areas is about 2.2 meters.

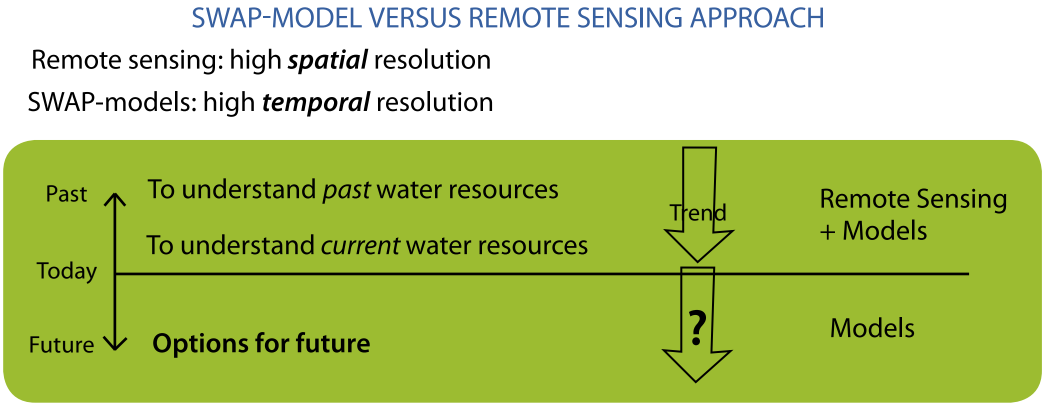


Figure 4. Remote sensing has high spatial coverage. It can be used to understand past and current water resources, but not to predict the future. SWAP-models, on the other hand, have high temporal resolution.

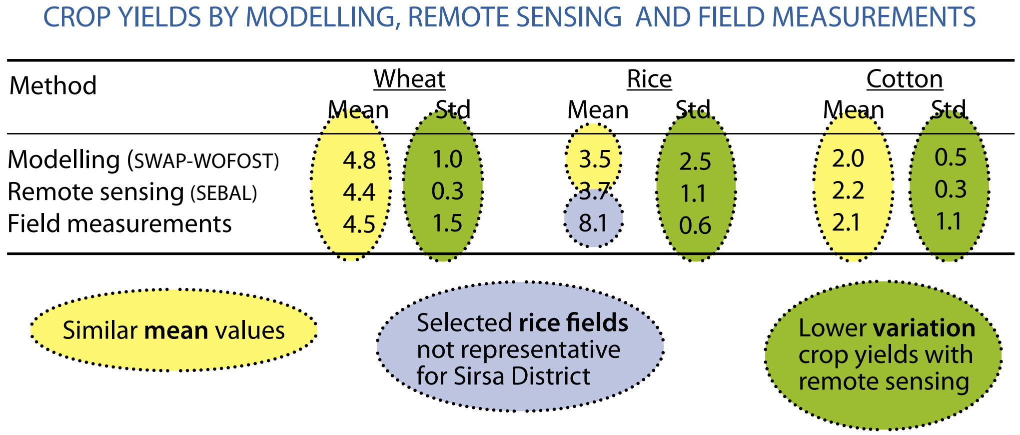
data, and run in the SWAP-model. Using irrigation maps, land use maps from remote sensing and GIS, it was possible to run the model for all soil-water-crop-weather combinations in the district, which shows that a one-dimensional vertical model could be up-scaled for large areas. In the Sirsa District there was a problem of saline groundwater inflow. The soil texture in the district varies from sand to sandy loam, with a belt of silty loam to silty clay loam along the Ghagger River. Two crops per year are grown, the main rotations being wheat-cotton and wheat-rice. Canal water is insufficient and is divided according to the amount of cultivated land. Farmers extract in addition groundwater with tube wells. Groundwater quality in the northern and southern parts is poor; groundwater levels rise in part of the region, while they decline in other parts.

The crop yield can be measured, but also simulated with the SWAP-model. Usually the simulations give a far too high result, and that is because simulations include water and salinity stress only. The model assumes also timely cultivation, optimal nutrients, optimal pesticides, weed control and so on. Furthermore, the time of sowing is of great importance for water productivity. In this case, early sowing increased water productivity by 20 %.

In the Sirsa district study, remote sensing was (independent of the SWAP-model) used to determine grain yield, evapotranspiration and, as a function of these two factors, water productivity. Figure 5 is a comparison of the outcome of modelling, remote sensing and field measurements. The mean values are similar, except for rice, because the selected rice fields were not representative for the area. The variation in crop yields tends to be lower using remote sensing, because it smoothes out the data.

As a whole, remote sensing gave a good idea of the problems. A scenario analysis was made to identify possible means of improvements, which mean higher water productivity, less salinisation and more equal distribution of groundwater recharge, since the groundwater levels were decreasing in one part of the area and increasing in another. Five scenarios were calculated:

1. The reference situation (no change),
2. Increased crop yields (15%), which would require improved crop varieties, better nutrient supply and effective pest and disease control,



CROP YIELDS BY MODELLING, REMOTE SENSING AND FIELD MEASUREMENTS

Method	Wheat		Rice		Cotton	
	Mean	Std	Mean	Std	Mean	Std
Modelling (SWAP-WOFOST)	4.8	1.0	3.5	2.5	2.0	0.5
Remote sensing (SEBAL)	4.4	0.3	3.7	1.1	2.2	0.3
Field measurements	4.5	1.5	8.1	0.6	2.1	1.1

Similar **mean** values

Selected **rice fields** not representative for Sirsa District

Lower **variation** crop yields with remote sensing

Figure 5. A comparison of the outcome of modelling, remote sensing and field measurements. The mean values are similar, except for rice, because the selected rice fields were not representative for the area. The variation in crop yields tends to be lower using remote sensing, because it smoothes out the data.

3. Reduced seepage losses (25-30%), requiring lining an improved maintenance of irrigation canals,
4. Canal water reallocation (15%), requiring diverting canal water from northern parts to central parts, and
5. A combination of the scenarios 2, 3 and 4 above.

The scenario analysis showed that improved crop husbandry, reallocation of canal water from fresh to saline groundwater areas and reduction of seepage losses in saline groundwater areas are effective measures to increase overall water productivity and to attain sustainable irrigation in the Sirsa irrigation district.

The conclusion is that by the described approach of applying soil and crop models both at field and regional scale in combination with geographical and satellite data, it is possible to analyse an entire irrigation district in detail and to give specific recommendations for improvement.

Use of lysimeter data in deriving effective soil hydraulic properties

WOLFGANG DURNER, PROFESSOR, BRAUNSCHWEIG TECHNICAL UNIVERSITY, GERMANY

The accurate characterisation of the hydraulic properties of unsaturated soils is critical in addressing many problems in hydrology, ecology, environmental sciences, soil science, agriculture and other disciplines. Knowledge of the hydraulic properties is required in nearly all basic and applied aspects of soil, water, nutrient, and salinity management research.

The classical technique is to take point measurements and to try to reconstruct the whole field from these data, or to take subsamples for isolated experiments and then extrapolate the results. This may work in some cases, but often it does not because all processes in the soil are interrelated and cannot be studied separately. Instead we have to look at the entire system. This can be done through inverse modelling.

Inverse modelling of transient flow experiments has become a widely used method to determine the hydraulic properties of soil samples in the laboratory in a fast, accurate, and efficient manner. The basic requirements on the experimental procedures and on type and quality of data that are needed to obtain accurate and reliable estimates of the hydraulic parameters are nowadays quite well known. However, the experimental scale does currently not match the scale of interest. Thus, an extension of inverse modelling procedures from the laboratory to the field scale is required. Open questions concerning this upscaling are the existence, the uniqueness, the type and the uncertainty of effective hydraulic properties of large soil bodies with internal heterogeneity. Furthermore, a variety of effects that play only a minor role at the laboratory scale, but are important in the field must be considered. Examples are temperature effects, temporal variability, water uptake by plant roots, and the change of system properties by plants.

At a mid-scale between laboratory and field, lysimeters can play a key role for developing inverse methods for larger scales.

Inverse modelling of lab systems

Inverse modelling involves

- Experiments where the system state changes, as enforced by boundary conditions (controlled or just observed).
- State observations (water contents, water potentials, concentrations, water fluxes at boundaries, mass fluxes at boundaries).
- Simulation of the experiment aiming at an optimal match between observations and simulation (involves non-linear minimisation of an error criterion).

It can be shown that inverse modelling is able to simulate the outcome of standard laboratory inflow/outflow experiments with a high degree of accuracy. However, one has to ask whether perfect laboratory measurements are of any relevance for the field. In the field you have no control of boundary conditions, a limited moisture range and unknown spatial heterogeneity.

The key hypothesis investigated here is that

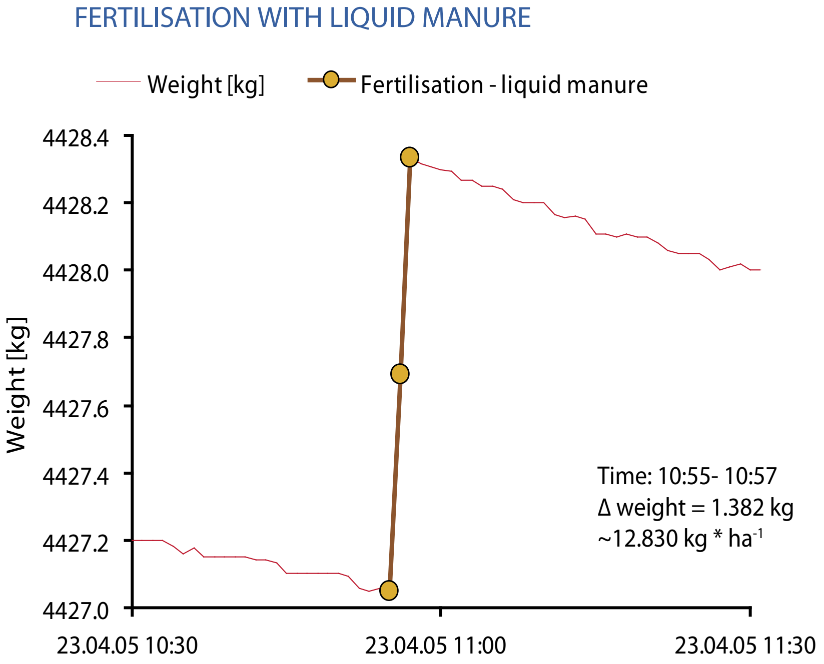


Figure 1. The data precision of modern lysimeters is exceptional. The figure shows the change in weight of the lysimeter as liquid manure is spread over the field. The slow weight loss due to evaporation is, within minutes, interrupted by a weight gain of a little more than a kilogram.

lysimeters are ideal for further development of inverse methods, helping to bridge the gap between the lab and the field scale. Lysimeters have been used for a long time, and there are a number of well-known objections against them:

- Lysimeters contain disturbed soil material.
- Lysimeters produce a permanent saturated capillary fringe at their outlet.
- Lysimeters cannot be managed in the same manner as the open agricultural field.
- Lysimeters are different from the undisturbed soil with respect to thermal, hydraulic and microbiological regime.

However, these objections are not necessarily correct. Modern lysimeters have properties different from older ones. There are methods to enclose more or less undisturbed soil material in lysimeters. Modern lysimeters have real time controlled suction at the lower boundary, which makes it possible to create the same conditions as in the field in this respect. They can be weighed with very high accuracy and high time resolution and equipped with sensors at multiple levels and finally they can be ploughed and otherwise treated in the same way as the surrounding field. These modern lysimeters are not visible in the field, and they are systems at the appropriate scale when dealing with unsaturated soil hydrology. So with respect to the scale these modern lysimeters offer field conditions, while with respect to controlled conditions they can compete with lab conditions.

The data precision of modern lysimeters is exceptional, as illustrated by the example in figure 1. It shows the change in weight of the lysimeter as liquid manure is spread over the field. The slow weight loss due to evaporation is, within minutes, interrupted by a weight gain of a little more than a kilogram.

Challenges for the future

As said above, lysimeters are ideal for further development of inverse methods. One of the challenges here is due to the fact that we have transient boundary conditions, which automatically includes the problem of hysteresis. To my knowledge there is still no hysteresis model good enough to do the job properly in inverse modelling. Other problems that need to be addressed are:

- Internal heterogeneity
- Existence and uniqueness of effective hydraulic properties
- Roots, root growth and root water uptake
- Temperature effects
- Frost effects

The way we address these challenges is to start with systems with known properties, to show that the model can work in principle. So we start with the creation of 'virtual realities' with different degrees of complication – homogeneous, layered, stochastically heterogeneous, without roots, with roots etc. Then we use these virtual realities to obtain synthetic measurement data, which are observations of the simulations. This can be done for a number of experiments. Finally we evaluate these data by inverse simulation in order to investigate the role of type and density of data, noise, errors in measurements etc. An important issue is to investigate the effects of erroneous assumptions with respect to the shape of hydraulic functions and with respect to the physical model of water flow.

Conclusions

- Basically, it works! Investigating water transport processes in *lysimeters* by inverse modelling allows exploring effective water and solute behavior at scales relevant for practice.
- System understanding. Studies on *virtual realities* help to understand the significance and interpretability of measurements in heterogeneous systems.
- From synthetic data to reality. The *combination* of studies on virtual realities and real systems bears a great potential for progress in the future.

Big challenges for the future are:

- Improvement of sensor technology.
- Adequate treatment of hysteresis.
- Heterogeneity.
- Root water functioning.

Water in the soil-plant-atmosphere-continuum and water use in willows

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Evaporation is an important process for the greenhouse effect and also for the agricultural productivity. In vegetation there are three types of evaporation: Evaporation of intercepted precipitation, transpiration and soil evaporation. The most extensive evaporation is usually transpiration, which takes water from the root zone.

The concept for how water is transported up through the plant is called the soil-plant-atmosphere continuum (SPAC) (figure 1). The driving force of this process is the sun. The radiation from the sun is absorbed by the leaves of the plant. On a sunny day the net radiation increases during the day and so does the temperature of the leaf and the air. The vapour pressure deficit increases; the air becomes drier and the demand for water increases. As the solar radiation has opened the stomata of the leaves, the transpiration starts. Water from the leaves is emitted into the atmosphere, while the water content of the leaves drop. So does the leaf water potential and it becomes lower than the water potential in the soil, which creates a force that transports the water up to the leaves. This

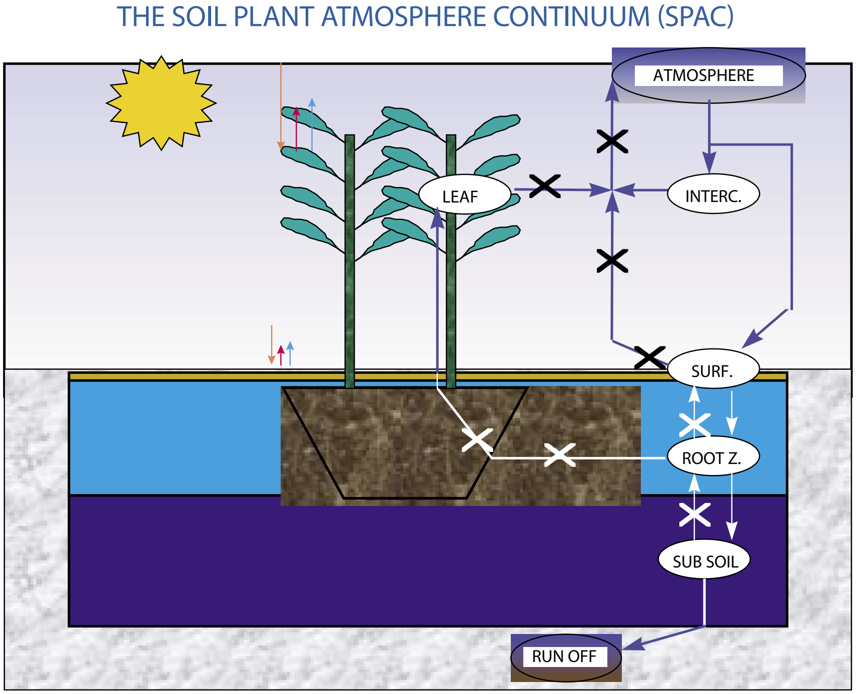


Figure 1. The concept for how water is transported up through the plant is called the soil-plant-atmosphere continuum. The driving force of this process is the sun.

uptake is delayed in comparison to the transpiration, depending on the properties of the plant and soil, and the soil water content. Later in the day transpiration decreases, but the uptake continues because the plant takes up water until its water content is recovered, which it normally is by midnight.

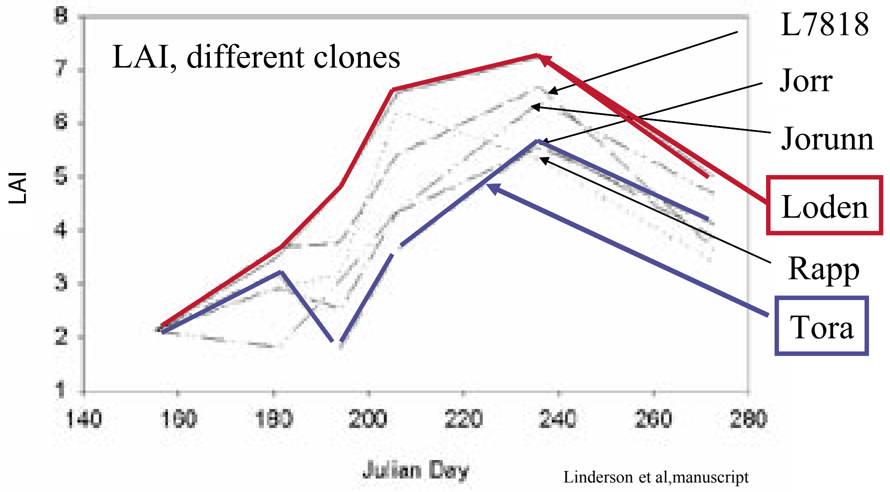
An important part of this concept is the energy balance of the canopy. Most of the solar radiation absorbed by the canopy is used for transpiration, until the stomata starts to close by midday. Then there is a surplus of energy, which causes heating of the system, meaning that the leaf gets warmer than the surrounding air. This temperature difference is an important indicator of the plant water status.

The root water uptake can be measured with sensors inserted into the stems of plants. Usually one wants to know the uptake on an area basis, which makes it necessary to make measurements on several plants. The total uptake over a full day is about similar to the daily transpiration as the plant water content in most cases is recovered every night.

Anders Lindroth and his research group at Lund University in Sweden have made these kinds of measurements for different clones of willows *(Salix)*. The interest in growing Salix on arable land has strongly increased because of increasing demand of biofuels mainly for use in power plants. There is also a potential for production of ethanol to be used as car fuel. The main reason for this is the growing awareness of climate change being a reality and that the use of fossil fuels must be reduced. Increased use of bioenergy is also in accordance with the government's objectives to develop a sustainable society.

The success of Salix as an energy crop depends very much on how much biomass that can be produced per land area unit. After a successful establishment, the production depends very much on the availability of growth required resources available at the site. Besides the climatic factors, which cannot be controlled, nutrients and water are the main resources required. As nutrients are normally added by the

LEAF AREA INDEX IN DIFFERENT SALIX CLONES



Linderson et al,manuscript

Figure 2. In the willow experiment the leaf area index was highest for the clone Loden and lowest for the clone Tora.

farmers, water can be expected to be the main limiting soil resource.

Anders Lindroth and his group found that transpiration differed considerably between Salix clones (figure 2). Transpiration is related to growth. Water is leaving through the stomata, and carbon dioxide (CO_2) is entering the leaf the same way. The uptake of carbon dioxide can be calculated from the difference between the carbon dioxide concentration in the atmosphere and in the leaf, divided by the resistance in the pathway. This resistance is to a large extent similar to that of water leaving through the stomata. When the stomata open the outward flux of water increases, but so does the flux of carbon dioxide in the opposite direction. Also the number of stomata matter, which means that the stomata resistance is related to the leaf area index (LAI).

In the willow experiment the leaf area index was highest for Loden and lowest for Tora, but the transpiration was highest for Jorr and lowest for Jorunn, so there is no simple correlation. There are probably other factors that also matter. Jorunn had the lowest production, and Tora the highest, indicating that a low transpiration was related to a low production. However, there was no such relation for high production. This is why water use efficiency varies considerably more among the clones than transpiration, and it also explains why the variation shows a pattern similar to that of production. Water use efficiency is defined as stem production divided by transpiration. Radiation use efficiency was also used to estimate the resource use. This was also strongly influenced by the production of the plant.

The results discussed above were obtained under rain fed conditions. Under drought treatment the transpiration decreased, as expected, except for one clone that increased its transpiration. The production was less affected by the drought. Generally, there was some decrease, but three clones were not affected at all as concerns growth. Only Tora decreased quite a lot. When interpreting these results one should keep in mind that only the above ground biomass was measured. We do not know if reduced growth above ground may be due to increased root growth.

Simulating growth of the willow clones as a function of solar radiation and air temperature in a radiation use model gave a fairly high degree of predictability of growth of several experimental fields in Sweden. Introducing water as a parameter in the model did not improve the predictions. This may be caused by the introduction into the model of additional uncertainties that are larger than the water effect on the harvested amount.

Conclusions

- Water use efficiency varied between clones.
- Radiation use efficiency varied more.
- Drought both reduced and increased the efficiencies. The variation between clones decreased. Radiation use was less influenced than water use by drought.
- We could not improve biomass predictions in willow plantations, by introducing a water factor.

Diffuse pollution modelling of nutrients and pesticides

MARNIK VANCLOOSTER, PROFESSOR, UNIVERSITÉ CATHOLIQUE DE LOUVAIN, BELGIUM

Diffuse pollution is pollution of groundwater bodies arising from agricultural land-use activities that are dispersed across a catchment or sub-catchment area. By this definition the pollution generated by domestic or industrial use of land is not considered. In practice, there is of course often a mix between these types of activities in an area.

Excluding water within glaciers 97 % of the fresh water is in groundwater bodies. Groundwater is a very important resource. It is essential for securing global food production. If groundwater becomes polluted it is difficult, time consuming and expensive to take measures to restore the natural state of the resource. That is why pollution should be prevented as far as possible.

There is already degradation of the groundwater resources, because agriculture is putting a series of pressures on the groundwater, for example by exaggerated use of fertilisers and pesticides that dissolves in the soil and pollutes the groundwater. According to a recent report from EEA (European Environment Agency) there is no significant evidence of a reversal in the negative trends in nitrate contamination of European groundwater, while residues of pesticides occur everywhere. This is not only a problem in Europe, but also in Northern Africa (Morocco), where there is intensive agriculture, sometimes

SQUASH EXPORT AND THE USE OF AGRICHEMICAL PRODUCTS IN TONGA

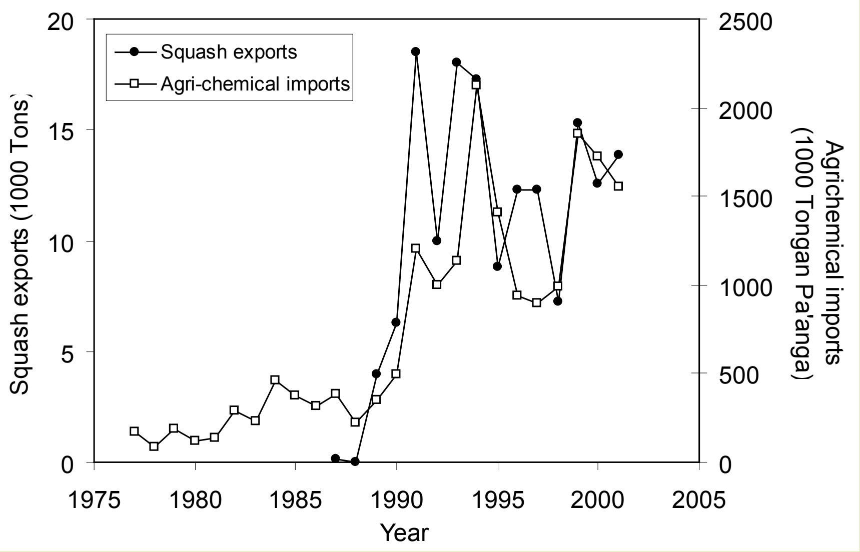


Figure 1. In the 1980s Tonga decided to develop a new niche market of agricultural products. Today 80 % of the total economy is depending on the export of squash pumpkins to Japan. A drawback of this development is a massive increase of agrichemical products.

with irrigation using groundwater resources.

Other examples are the small islands in the Pacific with extensive agricultural development. In the 1980s for instance, Tonga decided to develop a new niche market of agricultural products. Today 80 % of the total economy is depending on the export of squash pumpkins to Japan. A drawback of this development is a massive increase of agrichemical products (figure 1). The situation is very vulnerable, because the islands are isolated and it is difficult to import fresh water. When the groundwater table is lowered, severe problems will occur.

These examples stress the need for agricultural water management strategies. Agricultural activities must be developed taking the vulnerability of groundwater bodies into consideration. Mapping of vulnerability and predicting environmental concentrations in terms of space and time variable soil-climate and crop properties is needed to design and evaluate a large scale agroenvironmental policy.

Modelling diffuse groundwater pollution

Vulnerability maps are tools to evaluate and design agricultural policies at a large scale. Below is described how they can be generated and how diffuse pollution of groundwater from agricultural origin can be modelled in large scale and in an efficient way.

The starting point is to look to the terrestrial system, including of course the agricultural system and the groundwater body, considering that the system is very heterogeneous. Water is the principal vector of the system. We can decompose the heterogeneity by recognising that there are surface processes, soil and vadose zone processes and groundwater body processes. There are also crops or plants in the area. Furthermore, the processes are interacting and all processes are variable in space and

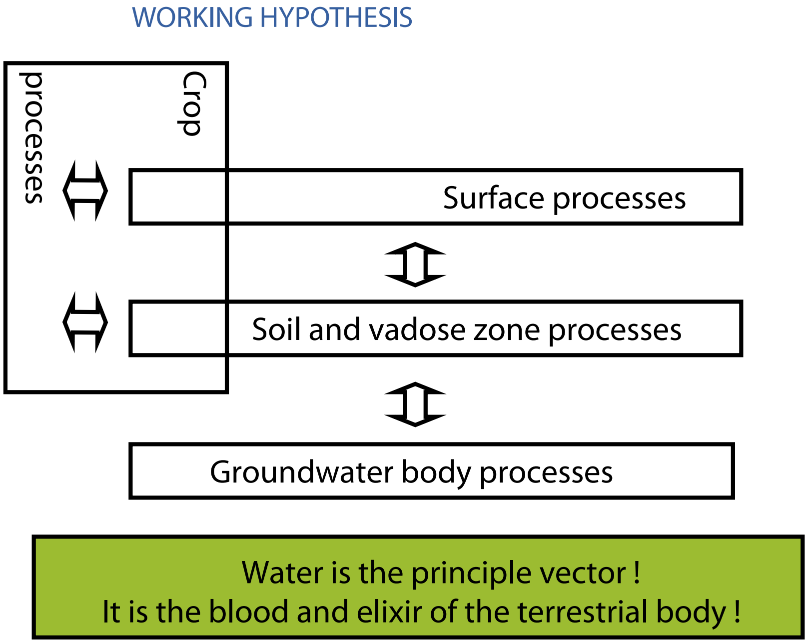


Figure 2. Water is the principal vector of the system. There are surface processes, soil and vadose zone processes and groundwater body processes. There are also crops or plants in the area. Furthermore, the processes are interacting and all processes are variable in space and time.

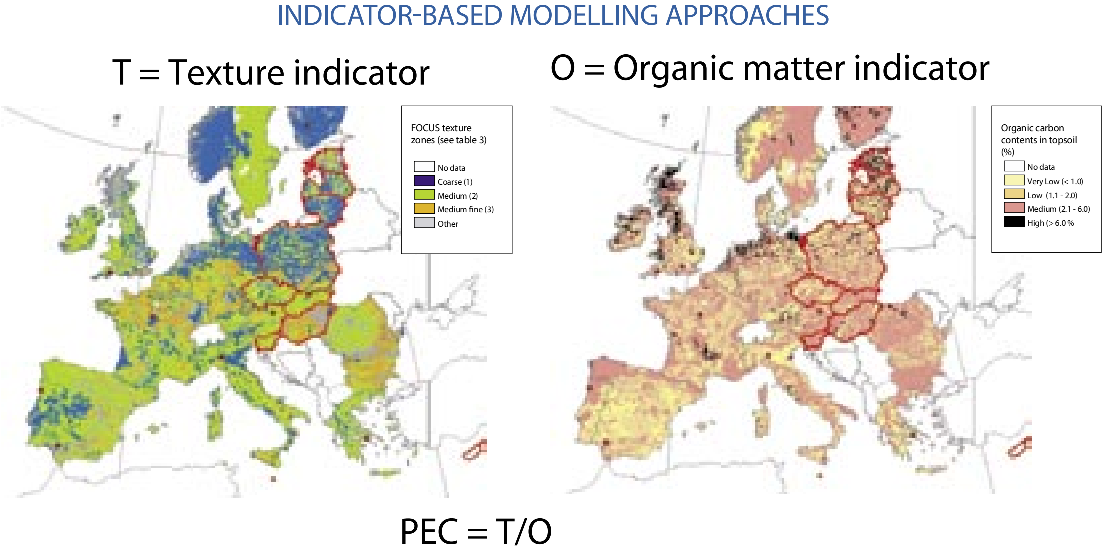


Figure 3. Indicator-based modelling approaches are much simpler. Here we look at basic parameters, such as soil texture and organic matter. Predictions of environmental concentrations are made on the basis of combining a limited number of such indicators.

time (figure 2). If this variability is considered it is possible to create a type of quasi 3D-model, where the terrestrial system is decomposed into a number of blocks. Each block can be seen as a very large lysimeter, for which it is possible to define effective properties. For each block a 1D-model can be developed and spatial integration can be used in order to create a large-scale 3D-assessment of the impact of agriculture on groundwater bodies.

Here are a few examples of implementation of this method. The first is about predicting concentrations of pesticides in the environment at a very large scale (Europe), which was made to support the implementation of the EU Pesticide Registration Directive. Approaches are developed which allows evaluation of the vulnerability of crops and soil systems before new pesticides are put on the market. In order to do this three different types of approaches can be used:

Mechanistic modelling approaches, where models of the type described above are linked to a GIS for spatial mapping. There are laws and equations allowing us to describe the chemical transport in the soil-plant system. There are also analytical and numerical solvers for appropriate boundary conditions. However, this type of approach is extremely time consuming.

Indicator-based modelling approaches are much simpler. Here we look at basic parameters, such as soil texture and organic matter. Predictions of environmental concentrations are made on the basis of combining a limited number of such indicators, as for example shown in figure 3.

Meta-modelling approaches, based on the assumption that in most models there are some significant input parameters which to a large extent determine the output. In other words this approach is based on a kind of sensitivity analysis trying to identify the most crucial parameters in order to predict large-scale pesticide environmental concentration. A result of recent calculations in which a meta-model has been used is showed in figure 4. In this case it is based on a very simple description of the leaching behaviour. The output is rather similar to

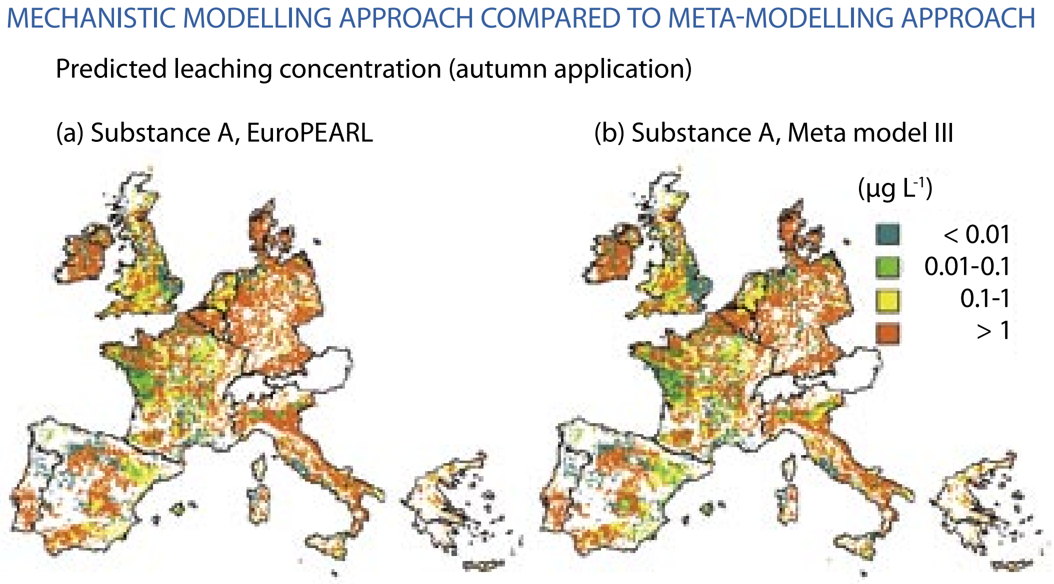


Figure 4. A result of recent calculations by using a meta-model (right). In this case it is based on a very simple description of the leaching behaviour. The output is rather similar to that from the mechanistic EuroPEARL-model (left) for the same substance, with the difference that the meta-model approach just needs three minutes of calculation time to generate the map.

that from the mechanistic EuroPEARL-model for the same substance, with the difference that the meta-model approach just needs three minutes of calculation time to generate the map.

Can the modelling approaches be validated?

It is important to look critically at this information. It is not difficult to link a model with a GIS and generate maps that have a lot of colours. The question is whether these maps can be used and are valid. Validation is definitely needed, particularly when the results are going to be used for decision support. But it is also difficult, because these concepts are hardly measurable. Vulnerability cannot be measured.

The kind of approache that can be used for validation is inter-model comparison, where the spatial convergence is evaluated. Another validation method is proxy-data convergence, in which model-based approaches are compared with monitoring data.

Conclusions

- Diffuse pollution of groundwater resources with pollutants of agricultural origin remain a key issue in Europe and abroad.
- Modelling approaches with different modelling complexity exist, yet little attention has been given to diffuse pollution modelling validation.
- Adopting a ‘proxy data’ validation approach, good convergence between modelled data and monitoring data can be obtained, but the power of the validation test is low, given the low resolution of the monitoring data.
- Adopting a ‘model comparison’ validation approach, significant differences between diffuse modelling approaches can be obtained.

Water quality and constructed wetlands

PETER RANDERSON, DR, CARDIFF UNIVERSITY, WALES

Clean water is a vital and increasingly limited resource. This is why water treatment is important. Effective treatment will enable us to re-use water so that it becomes not a burden on the environment, but an asset, and can be used in agriculture.

Constructed wetlands are man-made vegetation filter systems which simulate the ability of natural wetlands to remove pollutants from water. Constructed wetlands are of course complex systems, consisting of many components and flooded with water at least for part of the time. They are relatively inexpensive, low-tech, low maintenance systems and they create new wildlife habitats.

One kind of constructed wetland is a buffer strip of trees, planted to intercept water draining from agricultural land. Levels of nitrogen and phosphorus nutrients are reduced by passing through the vegetation filter compared to the water that drains directly into surface water bodies.

A constructed wetland is a complex of interacting components (figure 1). There are plants, microbes and soil matrix. The particle size and porosity of the soil is also important, as well as the diversity of different components of the microbe community, and the species of plants

INTERACTIONS IN THE CONSTRUCTED WETLAND

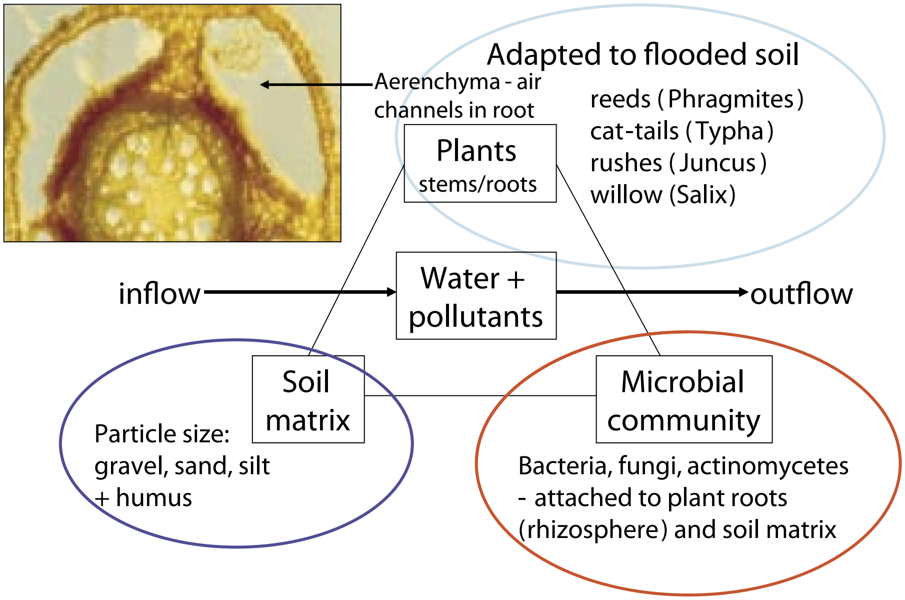


Figure 1. A constructed wetland is a complex of interacting components. There are plants, microbes and soil matrix.

which are involved in the constructed wetlands. These plants have to be adapted to flooded soil conditions, and typically they are adapted to survive in this condition by having air channels in their roots.

In constructed wetlands, pollutants are removed firstly by a series of aerobic microbial processes. Organic matter is degraded, ammonia is released, carbon dioxide is produced, and if there is enough oxygen available nitrification can take place to produce nitrate. Under anaerobic microbial processes organic matter is also degraded, but more slowly, and methane is typically produced. If there is nitrate available, it can be removed from the system as nitrogen gas. Further, absorption in the bed can remove phosphate and metals, and plant uptake can remove nitrogen, phosphorus and metals.

Plants play an active role in wetlands and in constructed wetland beds in many ways:

- Root system provides a large surface area for microbial attachment.
- Exudates of organic compounds from roots provide substrate for carbon-limited microbes (denitrifiers).
- Oxygen transfer to the roots may provide an aerobic zone to aid nitrification.
- Nitrogen removal by plant uptake – important in nutrient-demanding fast-growing trees.
- Removal of metals from effluent (e.g. Manganese (Mn), Zinc (Zn), Copper (Cu), Cadmium (Cd)) – some willow varieties are especially tolerant.
- Evapo-transpiration reduces volume.

The best known application for constructed wetlands is sewage waste water treatment in reed beds, of which there are two types: horizontal flow system and vertical flow system. In the horizontal flow system the oxygenation of the bed is limited to surface diffusion, whereas in the vertical, air is drawn in more effectively. There are a lot of other situations where constructed wetlands can be used, such as in connection with landfills, industries and mines to avoid surface water pollution. Another type of vegetation filter is an irrigation system, where

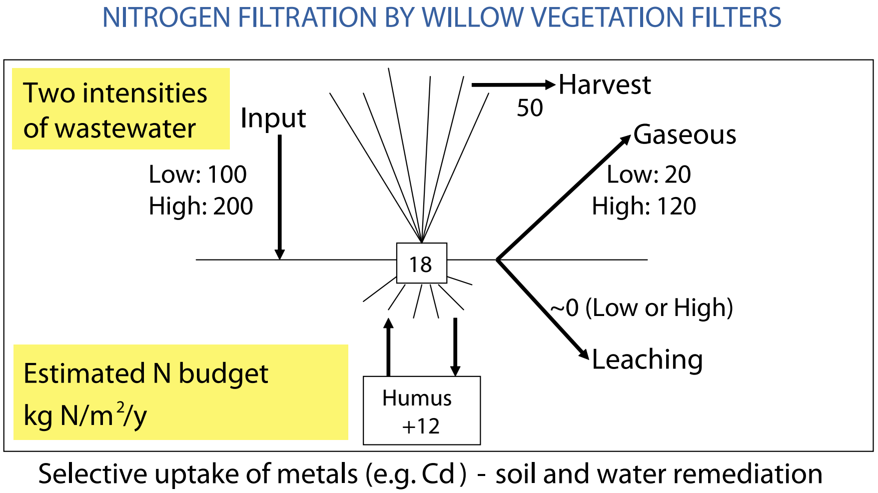


Figure 2. Fast growing willow coppice has a high capacity for nitrogen removal by root uptake, soil binding and denitrification in the root zone.

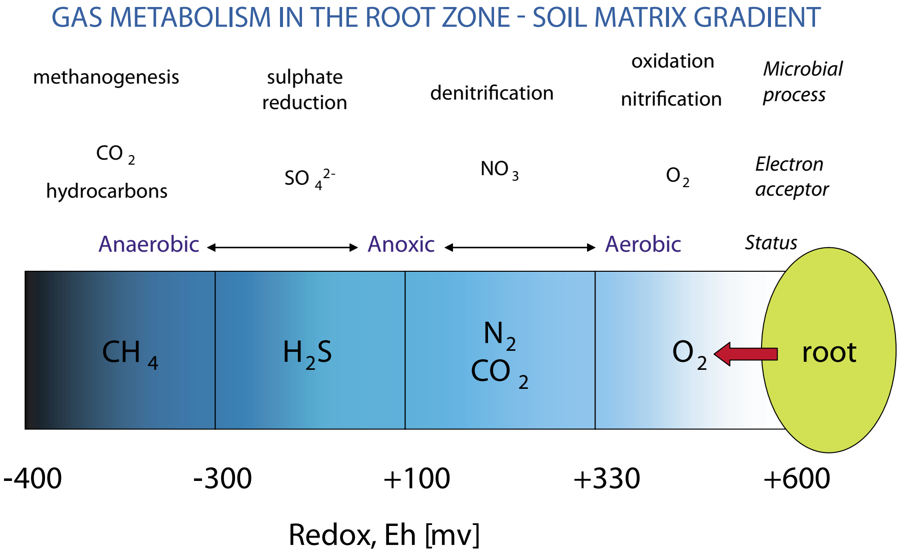


Figure 3. Along the redox gradient microbial processes are taking place at different points, and these processes are using different terminal electron acceptors for their metabolism.

trees are flooded intermittently with flood channels coming out of a feeder.

In Sweden there has been a lot of work with these vegetation filter systems based on willow trees (figure 2). Fast growing willow coppice has a high capacity for nitrogen removal by root uptake, soil binding and denitrification in the root zone. Re-use of waste water provides a cost-effective fertiliser for biomass crops.

Willow vegetation filter systems can also be used in landfill leachate, using a tidal flow system of filling and emptying the container where the willows are planted. It can be combined with reed beds to process the landfill leachate. The result is that ammonia is oxidised very effectively, since the reed beds transform ammonia into nitrate, which then is removed by the willows, by uptake and denitrification. Surprisingly, willows operating without the reed bed are just as effective at removing both forms of nitrogen. This is because there are both aerobic and anaerobic conditions within the willow bed.

The sub-surface environment of constructed wetlands is non-uniform in both space and time, and there are micro-zones and micro-gradients which relate to the position of plant roots. Since this is the case particular microbial transformations take place in restricted locations, and aerobic processes can only occur where there is a continual source of oxygen. Obviously, this will affect the pollutant removal efficiency in the bed.

Along the redox gradient shown in figure 3 microbial processes are taking place at different points, and these processes are using different terminal electron acceptors for their metabolism.

Oxygen comes out of plant roots, and this has been shown by planting roots in gel tanks. Initially there is no oxygen in the gel, but after two hours, oxygen starts to emerge from the roots (figure 4). Microbial processes in the soil use this oxygen. It has also been shown that oxygen accumulates quite rapidly in the light, but that process stops when it gets dark. Clearly this process is related to photosynthesis by the plants. The amount of oxygen in the container

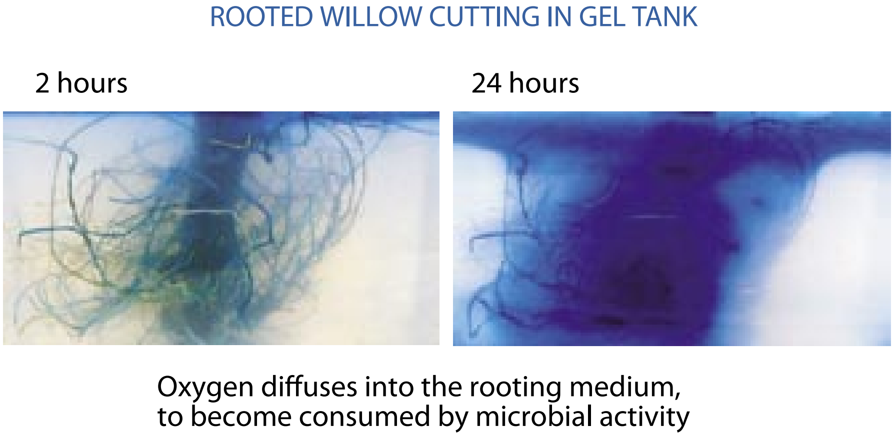


Figure 4. Oxygen comes out of plant roots, and this can be shown by planting roots in gel tanks. Initially there is no oxygen in the gel, but after two hours, oxygen starts to emerge from the roots. Microbial processes in the soil use this oxygen. Release of oxygen from roots is demonstrated by oxidation of methylene blue dye.

peaks in the day, and diminishes during the night, when it is consumed. The opposite pattern was shown for carbon dioxide (CO_2). If artificial waste water is added to the container the biological oxygen demand (BOD) draws down oxygen and this stays at a very low level for 2-3 days, during which the biological oxygen demand load is metabolised by the bacteria in the system. When the biological oxygen demand has been removed, then the oxygen released from the roots starts to come up again.

We have attempted to monitor these processes using a mass spectrometer with membrane inlet probes. Four probes were used to detect whether there is spatial heterogeneity of gases in the root zone of a constructed wetland. The general trend is the same, but there are local spatial differences in the depth profiles. An unexpected result is that there are oxygen peaks occurring at 60 cm depth. We then looked at a similar depth profile but on a finer scale, putting the probe down every 2.5 cm, and got evidence showing both aerobic and anaerobic pockets of activity, as indicated by the fact that here is a relatively deoxygenated zone with a blip of carbon dioxide.

A camera system was developed which enables us to see what was going on in the soil. Images of this sort were necessary to know where the probe was in relation to the heterogeneity of the soil. We found that the oxygen trace has peaks that correlate nicely with the position of lateral roots, indicating what could be good evidence that there is oxygen leaking out from the roots, and locally oxygenating the environment.

At a bigger scale the level of oxygen in the bed swings between high and low in 24 hour cycles. The biggest swings, from fully saturated to anaerobic occur in bright sunny days, when photosynthesis is driving the willows at a maximum rate. Methane is kept back under these sunny conditions, but when there is not enough oxygen coming out of the roots it starts to accumulate slowly in the bed.

Conclusions

Constructed wetlands are effective in treating polluted waters from a wide range of domestic, industrial and agricultural operations.

Constructed wetland technology enables us to re-use waste water in a cost-effective way and protect agricultural water from contamination while it at the same time creates small areas of wetland wildlife habitat.

Simulation of large scale infiltration experiments

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To what extent do techniques, methods and ideas from soil physics, originally applied to shallow water tables, apply where the water tables are deeper, as in arid regions? Analyses of water flow and solute transport in the deep vadose zone are often hampered by lack of adequate site data. Without such data it would be difficult to develop detailed predictive models of unsaturated flow and transport in deep heterogeneous unsaturated soils.

The question to be addressed here is under what circumstances can relatively simple models, based on data that is relatively easy to obtain, provide reliable predictions of flow and transport in the vadose zone? The presentation is largely based on a study focused on a somewhat narrower question: What is the ability of simple models and readily available data to reproduce/predict reliable space-time water content profiles in nine 14-meter deep neutron holes during large-scale infiltration experiments? The experiments were carried out at the Maricopa Agricultural Center (MAC) near Phoenix, Arizona. The approach was to conduct comparative simulations of the experiments using models of increasing complexity and a hierarchy of supporting data, starting from readily available public data and ending in site-specific measurements.

We focus on an experiment in which uniform drip irrigation was applied for a few weeks over a 50 x 50 m area. The area was protected from contact with the atmosphere by means of a plastic cover. Available public data suggested that the soil consists of sandy loam down to a depth of about 16 m, with a water table at a dept of about 20 m. This in turn would suggest that water infiltrates and is subsequently redistributed through the uniform soil profile vertically. In the absence of public information about soil hydraulic properties at the site, we decided to rely on generic data bases.

Our initial modelling assumptions were:

- Uniform sandy loam
- Mean hydraulic properties of corresponding generic data bases
- Water table at a depth of 22 m
- Vertical downward flow
- The initial water content is that measured in borehole 422 (such information is of course not available from public data).

Flow was simulated using the finite volume computer code TOUGH2 in the vertical plane, widely used in the United States.

We compared computed and measured (using a neutron probe) water contents as functions of depth and time using mean hydraulic properties of sandy loam according to the Rosetta and Carsel databases, respectively. The agreement was poor, implying that relying primarily on public data is insufficient to obtain reliable predictions of flow at the MAC site.

The next step was to use available pedologic site data consisting of soil composition data (percent sand, silt, clay and gravel) to the depth of 15 m and soil bulk density data to a depth of 5 m. Though the data appear to vary randomly across the site they are spatially correlated, with a horizontal correlation scale of 20-22 m and a vertical scale of about 2 m. This implies that the system consists of layers having an average thickness of about 2 m that are continuous over lateral distances on the order of 20 – 22 m. This in turn suggests that one consider the following hierarchy of models (from simplest to most complex):

- Uniform layers having thickness on the order of 2 m.
- Similar layers divided laterally into uniform segments of size 20–25 m.
- Nonuniform layers having thickness on the order of 2 m within which soil composition varies as a correlated, statistically anisotropic random field.

Since there were very few reliable measurements of hydraulic properties at the MAC, we estimated them on the basis of soil texture and bulk density using pedotransfer functions. In particular, we considered the probability distributions of hydraulic parameters corresponding to each of four soil categories which make up the soil layers, according to the Carsel database, as prior distributions. We then used a Bayesian approach to update these distributions in a way that honours specific site data.

Our modelling assumptions were:

- No-flow at bottom of 110 x 20 m^2 vertical flow domain.
- Constant head at lateral boundaries.
- Slightly inclined perched water table initially at 13 m (not mentioned in any of the public data sources).
- TOUGH2 grid with 200 x 10 cm^2 cells.

We started with the following hierarchy of models:

- One dimensional (1D) flow across uniform layers.
- Two dimensional (2D) flow across uniform layers.

A 1D-model yielded poor results without Bayesian updating; with such updating the results improved only slightly. Though two-dimensional results were better, they were still not satisfactory. We concluded that forward modelling on the basis of pedotransfer functions representing generic data bases is generally not sufficient to reproduce observed water contents at the site. There is a need for more complexity and inverse modelling to improve our modelling capability.

The next level of complexity was to divide the layers into 25 m long horizontal segments, assigning uniform hydraulic properties to each segment. The total number of parameters has thus increased. We used the iTOUGH2 inverse code to calibrate each model in the following hierarchy:

- 1D flow through uniform material (poor, not shown).
- 1D flow across uniform layers.
- 2D flow across uniform layers.
- 2D flow across nonuniform layers.

Calibration improved the results significantly in all cases.

If one was to select a model on the basis of best fit, one would choose a 1D model of segmented layers calibrated individually to water content data from one borehole at a time. We however propose that selection between models of different complexity must not rely solely on the quality of the fit but also on the degree of complexity: among models that fit the data more-or-less equally well, one should prefer the one which is least complex (has the fewest number of parameters). Several model discrimination or information criteria, which support this principle of parsimony by rewarding models that exhibit a relatively god fit while penalising models that are relatively complex, have been proposed in the literature. We employed two such criteria, both of which suggest that the 2D nonuniform (segmented) layered model is to be preferred, even though it does not yield the best fit and entails a larger number of parameters than do all other models.

Conclusions

- Public and generic data are too crude for detailed site modelling (not surprising)
- CARSEL generic data allowed better forward reproduction of water contents than RAWLS and ROSETTA data.
- Bayesian updating did not help much.
- Acceptable/best results were obtained using inverse 2D nonuniform layered model.
- Open question: Would more complex (random fields, stochastic flow/transport) models be needed to reproduce tracer data? We think so but are not yet sure.

Computers in evaluation of drainage and irrigation needs

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Half of the world food production originates from irrigated and drained soils: 40 % is drained and irrigated, another 10 % is drained. Agriculture uses 65-75 % of the diverted renewable water resources. Because of the growing world population the irrigated area will probably increase by 15-25 % within the next 20 years. At present 7 % of the world population live in areas where water is scarce. This is predicted to rise to a staggering 67 % by 2050.

The key to handle this problem concerning water use will be optimised crop production, sustainable groundwater exploitation and deficit irrigation. Computers potentially have a big role in supporting water allocation decisions, but this has not been materialised so far, even though mathematical models and expert systems have been developed and used by scientists for at least three decades.

One important reason to develop simulation models is that they can be used to aid decision-making. The aim of this presentation is to discuss the possibilities to use so-called management models in evaluation of drainage and irrigation needs. Management modelling is a methodology that links meteorological data, soil water model, soil nitrogen and phosphorus models, crop growth model, crop drainage requirements and drainage theory into a design method. The outputs of the model include influence of various management options on crop yield, soil water and nutrient status and leaching of nitrogen and phosphorus. To be more useful in decision-making, simulation models should evaluate uncertainties and risks.

In modelling we differentiate between strategic, i. e. long-term, and tactical decision-making. Strategic decisions with respect to agro-ecosystems are made on the basis of the expected long-term performance of these systems during the whole period for which the investment is made. Tactical decision-making refers to decisions taken in response to the actual state of the system and its environment at the decision moment. The time horizon of the tactical decision-making process is therefore within-season. Models can be utilised in both options.

An example of a strategic decision is optimising drain spacing and drain depth to maximise the average profit over a long period of time. Increasing drain saving reduces cost but can also decrease average yields. The time horizon for this kind of decision is 20–50 years. When it comes to irrigation examples of long-term decisions are:

- What type of irrigation method?
- Surface or subsurface?
- Sprinkler or drip?
- Gravity or pump?

The time horizon in this case is at least 5, and preferably 15 or 20 years.

Tactical decisions are made to reduce the yearly variation of crop yield due to too dry or too wet conditions, which means trying to increase yield during dry years, and reducing nutrient leaching during wet years.

A case study of long-term decision-making concerning drainage was made in order to find out what is the best drain spacing and drain depth combination when crop yield is optimised, and we want to achieve average

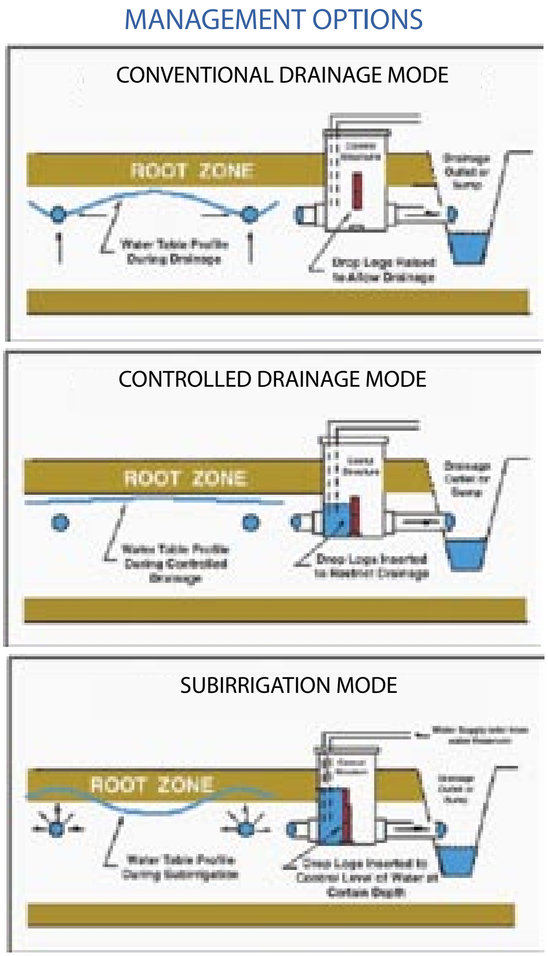

Figure 1. Three management options: conventional drainage, controlled drainage and sub-surface irrigation.

performance over a long time. In this case the model works with three management options: conventional drainage, controlled drainage and sub-surface irrigation (figure 1). The model calculates the outcome of 36 combinations of drain spacing and depths for three soil types (fine sand, silt loam and clay) and for three different crops (potato, spring wheat and barley). Meteorological data from 15 years and for three parts of Finland (south, central and north) were used.

The outcomes of the modelling are so-called nomograms where yield is related to drain spacing and drain depth for different crops, soil types and parts of the country. However, the farmer is primarily interested in the profit, which means that the model must not only calculate the yield, but also the cost for water management and the income. Calculating the cost is easy, while the yearly income is difficult to predict. The profit also depends on the return period, interest rate and so on. An attempt to calculate optimum drain spacing from a profit point of view is illustrated in figure 2. In this case, the optimum turns out to be between 12 and 25 meters.

The same model can be used to calculate the influence of drain spacing, drain depth and different management options on phosphorus and nitrogen leaching. To do this, a soil nitrogen model was added to the water management model. Phosphorus leaching was estimated based on calculated surface runoff. In general, the results show that the smaller drain spacing the larger nitrogen leaching, while it is the other way around for phosphorus. This is because too wide drain spacing will cause surface runoff. Thus, the overall conclusion is that drain spacing must be based on yield optimisation, while the question on how to consider the environmental factor of nutrient leaching remains to be answered.

The kind of calculations briefly presented here can also be made for irrigation systems.

Future challenges

There is a need for further model development. We should try to find ways to use several mo-

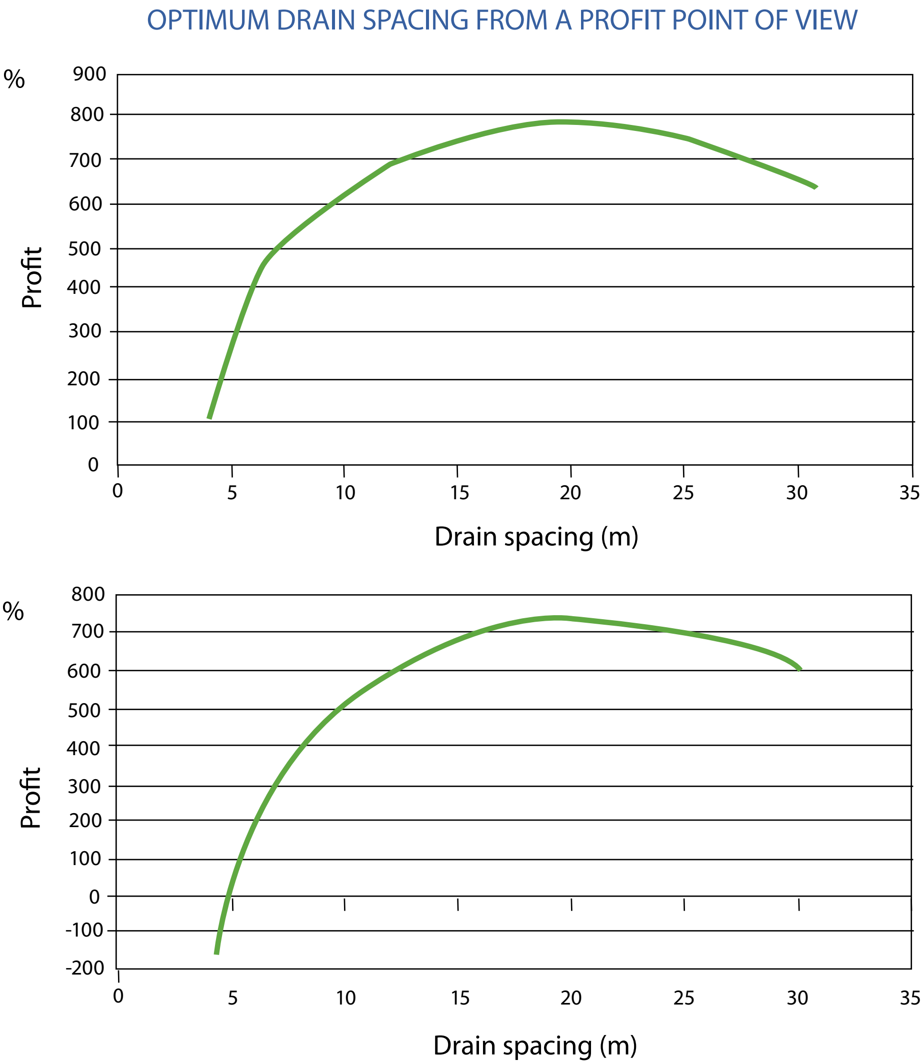

Figure 2. An attempt to calculate optimum drain spacing from a profit point of view. The profit (= yearly income - amortised costs) depends on the return period, interest rate and so on. In this case, the optimum drain spacing turns out to be between 12 and 25 meters.

dels in specific projects, from simple models to more complex, also including evaluation of uncertainty and risk. The environmental impacts should also be included in the considerations.

There are a large number of models that can be used for draining, irrigation and pesticide calculations. One problem with soil water models is that single porosity models cannot handle worm holes and other preferential flow paths well enough, even though these can be important under dry conditions and are potentially fast routes for nutrients to surface waters. Field experiments in clay soil in southern Finland has showed that around 97 % of the water was infiltrated into the soil matrix, but around 90 % of the drainage flow came via macropores. The response from rainfall to drainage was very fast, and this cannot be modelled using Richards equations, so it has to do with macropores.

Looking at crop growth modelling, a number of challenges can be identified:

- There must be a feedback from too dry or too wet conditions on crop growth (on LAI).
- Many models neglect wet part or are very sensitive to parameterisation of the sink-term close to saturation.
- Biomass partitioning: in dry conditions the relative proportion allocated to roots will probably increase: very challenging to the model.
- Simpler routines – fewer parameters - for allocation problem should also be developed.

Concerning partitioning, most crop growth models handle this parameter by deciding how much of daily growth should be allocated to each organ. This is something that is quite difficult to measure. We suggest a simpler approach using measurements on how much of the total biomass there is in each organ at different times of the growing season. This is much easier to measure, and it seems to be a relatively stable function if we normalise the growing season. In the model, partitioning comes automatically when daily biomass is added to the total and the amount in each organ is calculated from measured relationships. We have tested this method by comparing modelling results with field data and found that it seems to be valid in different parts of Europe, also under dry conditions.

Another challenge concerns the handling of uncertainties and risks.

A large number of case studies have shown that there is no unique parameter combination for any complex model, and that there are many possible parameter combinations and/or models that produce acceptable behaviour of the system. Thus, we have to give up the idea that there is a single true description of governing processes, especially for predicting impacts of change. This actually changes the philosophy of modelling. Normally we aim at one model and a single "optimal" parameter combination. In practice, this is impossible to reach due to:

- Model structural errors
- Measurement errors
- Highly non-linear phenomena
- Different processes act at various times of the season (e.g. macropores)

A method to handle this is the Generalised Likelihood Uncertainty Estimation (GLUE) suggested by Beven in the 1990's. Its starting point is that there is no optimum model. What can be done is to assess the likelihood of a model being acceptable. Different acceptable models produce different predictions. Models should be rejected if they are shown to be non-behavioural, but all acceptable parameter combinations and models can be used in estimating the uncertainty in predictions and calculating the average as well.

The idea in GLUE is to:

- Select several models to be used in uncertainty analysis.
- Generate parameter sets for the model from a given distribution.
- Calculate the model and evaluate if the combination is acceptable.
- Many parameters (thousands) should be calculated.
- Calculate confidence limits based on all acceptable simulations.
- Assess the risk that a suggested action will produce unwanted results (can be obtained from the confidence limits).

The GLUE concept can also be used in tactical management (predictions can be updated when new measured information is available). It is very simple to apply but requires a lot of computer resources, which has this far been the limitation.

Conclusions

- Computer models can be used in long-term decision-making: select drain spacing and drain depth for particular climate conditions and soil type.
- Computer models can be useful in tactical – within-season – water management
  - irrigation to increase yield during dry years.
  - controlled drainage to reduce nitrogen leaching during wet years.
- Simulation models should include a procedure for estimating uncertainty of the simulation and risk included in the suggested action - GLUE is one possible way to do this.
- Tremendous effort must be invested to close the huge gap between complex expert systems in place in Western universities and research organisations and the application of these tools to irrigation and drainage systems in poor and water-short countries.
- The challenge nowadays is to make soil water flow models more versatile for different social economic-physical conditions and for environments having poor or limited data availability.

Water and agriculture - thematic working groups

The aim of the thematic working groups was to identify areas for future research and policy recommendations that can be developed based on present knowledge. Three groups were formed, discussing water productivity, water quality and decision support systems (DSS) respectively.

Group 1 Water productivity

No more than 2.6 % of the global water resources are fresh water. Of the fresh water most is stored in ice caps and glaciers, and another substantial part is groundwater, some of which is not available for human use. Only 0.14 % is surface water in lakes and rivers, and soil moisture and water in the atmosphere (figure 1).

A balance calculated from the flows in the global water cycle (figure 2) shows that the amount of water that is newly available each year is 40 000 km^3. However, technically only a quarter of this – 10 000 km^3 – can be utilised. Today we are using half of this amount. Worldwide there is enough water available, but regionally there are large differences.

Of the global water use is

- 10 % for domestic use
- 70 % for irrigation in agriculture (of which half is lost)
- 20 % for industry use

This overall picture of present water use and potential of course gives some indications of what needs to be done concerning water productivity. An important thing is to increase yield per unit of water used. Yield in this context

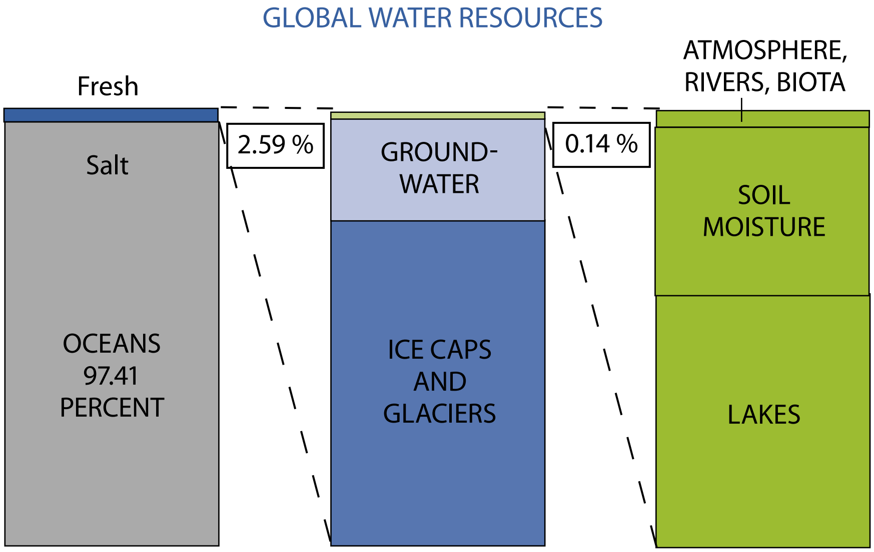

Figure 1. No more than 2.6 % of the global water resources are fresh water. Of the fresh water most is stored in ice caps and glaciers, and another substantial part is groundwater. Only 0.14 % is surface water in lakes and rivers, and soil moisture and water in the atmosphere.

THE GLOBAL WATER FLOWS

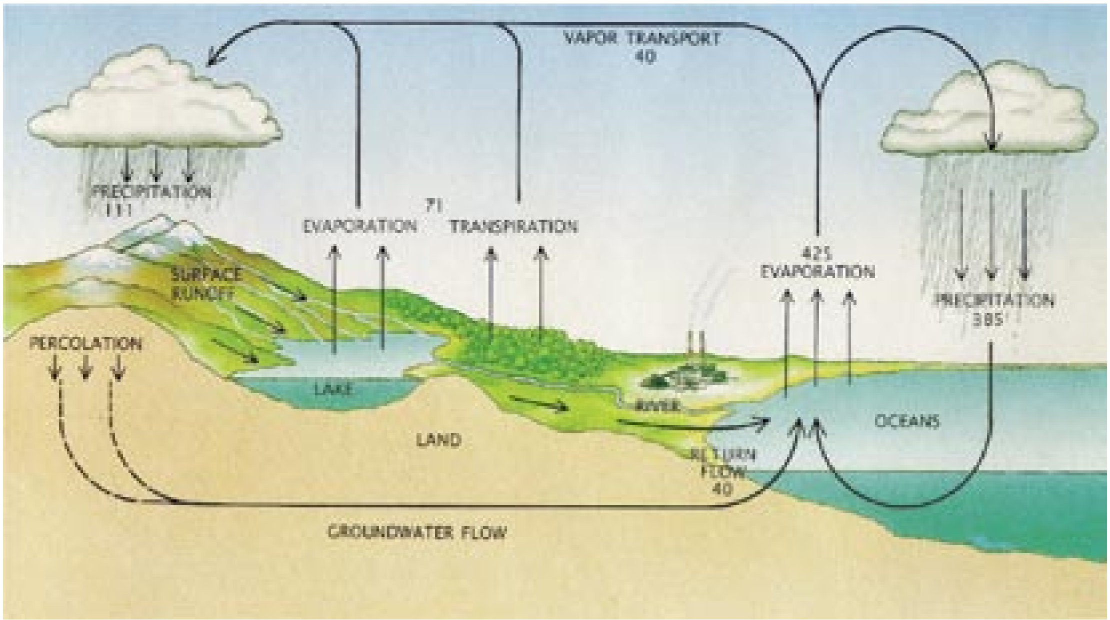

Figure 2. The flows in the global water cycle.

should be understood basically as food energy content. The group identified research needs in four fields:

Crop productivity - crop types Examples:

- Production shift from rice to sorghum.
- Development of less-water-using plant varieties (by biotechnology and genetical engineering?).
- Shift from meat consumption to vegetarian consumption.

Scientific disciplines involved: biotechnology, plant engineering and genetical engineering (?).

Water use efficiency - scientific and technical aspects of efficient water use. Examples:

- Improving irrigation technology: drip irrigation instead of flooded irrigation.
- Reduction of seepage evaporative losses by pipe and canal design and appropriate cover of soil areas between crops.
- Regional water transfer (example India).

Scientific disciplines involved: soil physics, irrigation engineering and vadose zone hydrology.

Water and soil quality - sustainable exploitation of water resources; keeping biodiversity and ecology. Examples:

- Consequences of altered irrigation schemes for surface soil, soil moisture, groundwater.
- Surface soil salinisation.
- Groundwater salinisation.
- Groundwater overexploitation.
- Ecology of wetlands.

Scientific disciplines involved: vadose one hydrology, ecohydrology, ecology, biology.

Enhancement of water availability - water harvesting. Examples:

- Increased water harvesting, for example

at small-scale in the African savannah regions.
- Transfer of virtual water, for example from water-rich regions to demanding regions.

Scientific disciplines involved: soil physics, engineering.

Group 2 Water quality

There are different kinds of waste water and water pollution by source and by type, but also in relation to the different scales in which pollution occurs:

Grey water – not heavily contaminated. For example waste water from greenhouses (fertilisers, pesticide residues).

More heavily contaminated water, for example waste water from intensive pig breeding. (nutrients, heavy metals, antibiotics).

Drainage water, runoff from farmyards. (nutrients, agrochemicals).

Diffuse pollution This category is different from the other three in the sense that it has no defined point source and thus often is difficult or impossible to take care of before it is already dispersed into the environment.

The group discussed technical solutions in relation to the different types of water pollution listed above and how possible strategies that prevent the pollution to occur should be applied. Technical solutions suggested and discussed include:

- Small-scale constructed wetlands.
- Re-use of water, including re-use of nutrients in waste water. Creating storage facilities.
- Reprocessing systems (for more concentrated pollution, i e animal manure), for reuse elsewhere reducing water content.
- Bio beds, microbial fermentation.
- Catch crops.

For all of these there is a need for improved application strategies.

Concerning research needs there is a lot to learn in all the technical solutions mentioned above. We need research into low-cost, low-tech treatment technologies, such as bio beds. There is also a need for better definitions of levels of acceptability for waters of different uses (definitions of standards). Other areas of research identified include:

- Better understanding of how constructed wetlands work.
- Collection and containment systems.
- Economic research to support improved application strategies.
- Research on emergent pollutants.
- Research on the pathways of chemicals in the agricultural system.

Finally, the group looked briefly into policy instruments, discussing what needs to be done to promote implementation of new and improved strategies. The group agreed that there are needs for new government agencies to promote re-use opportunities for water. Furthermore, economic models of different management strategies should be developed. The idea of a water quality credit exchange (similar to the trade with carbon credits) was discussed.

Group 3 Decision support systems

The group recognised some fundamental problems with the use of models in science and in applications, as well. Some of these problems are:

- Incompatibility of scales between various data.
- Resolution and scale of models.
- Spatial variability.
- Difficulties to define boundaries of systems.

However, from the standpoint that there are models that have proven themselves useful, the group focused on more practical issues. How do we make them more useful?

Decision Support Systems (DSS) are essentially computer-based systems, designed to help users make rational and timely decisions that are scientifically supported. In order to design useful systems one must have a very clear idea of who the users are, keeping in mind that there are different kinds of users, such as:

- Government regulatory agencies, using DSS to support policy decisions.
- Bodies involved in advising and supporting farmers in management decisions.
- Single farms and farmers. There are examples of farmers and farms using automated model-based systems for water management.

One problem identified was lack of communication between modellers and users. The scientists developing the models are not always aware of or considering the needs of the users. Better communication is a key issue to resolve this.

Transparent, user-friendly interfaces are of great importance. Models used as DSS should also as far as possible be bug-free. Furthermore, they should be flexible in the sense that they should provide options and give some room for expert judgement by the users.

Education and training of model-users is another key issue. Users must not understand in detail how the models work, but there must be a level of technical skills to use the models properly.

Often there is a need to include an economic dimension (cost estimation etc.) in the DSS-models.

There is a need to develop methods to handle and present uncertainties in modelling output. Presenting different scenarios can be a method to do this.

The group discussed the use of meta-models – abstractions or simplifications of more scientifically-based models. A main problem with scientific models, when applied over large areas or long periods of time, is that they require a lot of data and a lot of computer time. One of the advantages of meta-models is that they reduce the need of input data and the computer-time needed, making the use of the models manageable. A negative point is of course that over-simplified models can generate flawed results.

The problem of scale must be considered. There is an obvious need for a consistent scaling theory. When it comes to actual environmental systems, there is a huge discrepancy between data that are collected on various scales, models that typically are based on small-scale science and applications on scales of kilometres or tens of kilometres. How do we validate the results of such modelling? We simply do not have the science to find out whether such applications of models are justified or not.

Trying to simulate large systems from models constructed by adding up small-scale building blocks misses the fact that most large systems are not just the sum of their parts – they acquire a life of their own. Large systems cannot be properly understood unless they are observed directly.

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Nr 1 Water and Agriculture

Water means life and life means water. Nothing can live without water - plant, animal or human. Fresh water resources are diminishing and in many areas there is competition for water by sectors including industry, agriculture, cities and nature. Water productivity studies indicate that to obtain 1 tonne of biomass it is necessary to use at least 1 000 tonnes of water. One consequence of this is that in Southern Europe more than 70 % of all water resources are dedicated to agriculture.

One of the most important issues is water quality but salinity and water re-use are also pressing questions. Both conservation of water resources and desalinisation and wastewater treatment should be given priority in many urban and rural regions.

The main focus of this report from the Bertebos conference 2006, is on the problem of water use by agriculture - including agricultural productivity, the environment, how computer models can support decision-making, the main priorities during the process of handling the water and how to implement and evaluate the Scandinavian and Baltic dimension of the European Water Framework Directive.

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