‘Turning the Water Wheel Inside Out’

Verkenningen, deel 7

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Royal Netherlands Academy of Arts and Sciences
Dutch Foresight Committee on Hydrological Science

Turning the Water Wheel Inside Out

Foresight Study on Hydrological Science in The Netherlands

Amsterdam, 2005

De reeks verkenningen van de KNAW wordt in het Nederlands uitgegeven, deze verkenning is echter in het Engels opgesteld. Daarom zijn het voorwoord, de conclusies en aanbevelingen in het Nederlands vertaald en opgenomen.

The Academy's Foresight Study series is published in Dutch; this particular study, however, was written in English. A Dutch translation of the foreword and the conclusions and recommendations can be found in this publication.

On the cover: Raindrops, Quirin van Os, KNMI

Royal Netherlands Academy of Arts and Sciences
P.O. Box 19121, 1000 GC Amsterdam, The Netherlands
T + 31 20 551 07 00
F + 31 620 49 41
E knaw@bureau.knaw.nl
www.knaw.nl

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Voorwoord

Inzicht in de ontwikkeling van de wetenschapsbeoefening is een voorwaarde voor een beleid dat recht doet aan de wetenschap. Het ligt op de weg van de Koninklijke Nederlandse Akademie van Wetenschappen om dit inzicht te verschaffen. De Akademie heeft dan ook een centrale taak bij het totstandkomen van verkenningen vanuit wetenschappelijk perspectief.

Onder een wetenschapsverkenning verstaat de Akademie het verwerven van inzicht in de wetenschappelijke ontwikkelingen op langere termijn op een bepaald gebied, het in dat licht bepalen van de internationale positie van het Nederlands onderzoek en het doen van aanbevelingen voor het te voeren beleid.

Het hydrologisch onderzoek bestudeert de hydrologische cyclus, dat wil zeggen het voorkomen, de beweging en de samenstelling van water onder en op het aardoppervlak en poogt inzicht te krijgen in de interactie van die cyclus met de geosfeer, de atmosfeer en de biosfeer.

Hydrologie is bij uitstek een interdisciplinaire wetenschap. Hydrologisch onderzoek vereist vaak expertise op het gebied van andere disciplines, zoals wiskunde, vloeistofmechanica, bodemfysica, bodemmechanica, biogeologie, biogeochemie, chemie, ecologie, meteorologie, en reservoirtechniek. De interactie van hydrologie met deze disciplines – en daar komen er in de toekomst

Foreword

Any policy intended to support and promote science must be based on a thorough understanding of current and future advances in research. It is one of the tasks of the Royal Netherlands Academy of Arts and Sciences to investigate such advances and to make it possible for research foresight studies to be carried out.

The Academy believes that a research foresight study involves investigating long-term developments in a particular field, assessing the strategic position of Dutch research in that context, and making the necessary policy recommendations.

Research in the field of hydrology focuses on the hydrological cycle, in other words the occurrence, transport and composition of water below and on the earth's surface. It attempts to understand how that cycle interacts with the geosphere, the atmosphere and the biosphere.

Hydrology is an interdisciplinary science. Hydrological research often requires expertise in other disciplines, for example mathematics, fluid mechanics, soil physics, soil mechanics, biogeology, biogeochemistry, chemistry, ecology, meteorology, and reservoir engineering. The interaction between hydrology and these disciplines – and no doubt many others in the future – has led to many new and promising opportunities for interdisciplinary research.

ongetwijfeld nieuwe interacties bij – zorgt voor vele nieuwe uitdagende mogelijkheden voor interdisciplinair onderzoek.

Dit verkenningsrapport bevat aanbevelingen voor universiteiten, niet-universitaire onderzoekinstituten, financiers van wetenschappelijk onderzoek en beleidsmakers. De KNAW hoopt hiermee een bijdrage te leveren aan de verdere groei en grotere zichtbaarheid van dit internationaal georiënteerde veld.

Wegens de internationale oriëntatie van hydrologisch onderzoek wordt het rapport van de Verkennings Commissie Hydrologie in het Engels gepubliceerd, de conclusies en aanbevelingen zijn in het Nederlands opgenomen.

De Akademie hoopt en verwacht dat dit Hydrologie-verkenningsrapport en de daarin geformuleerde aanbevelingen als belangrijk richtsnoer zullen dienen bij het te voeren langetermijnbeleid voor de hydrologie.

Prof. dr. W.J.M. Levelt
President KNAW

The present foresight study makes recommendations for universities, non-university research groups, research financing bodies and policy-makers. The Academy hopes in this way to draw attention to this international field of research and to contribute to its growth.

Because hydrological research is international in nature, the report of the Foresight Committee on Hydrological Science has been published in English. A Dutch version of the conclusions and recommendations is also included.

The Academy hopes – and indeed expects – that this Foresight Study on Hydrological Science and the recommendations it puts forward will provide important guidelines for a long-term policy on hydrology.

Prof. W.J.M. Levelt,
President

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Summary

In this report, the Hydrology Foresight Committee presents her findings of the study of the current status and potentials of hydrologic research in The Netherlands, and prospects for future developments. Terms of Reference of the Committee and details of her activities are described in Chapter 1.

A detailed description of hydrological science, its strong interdisciplinary character, and its social relevance are given in Chapter 2. Various disciplines of hydrology are described in Annex D. The Committee elucidates that hydrology is a vital component of the earth system science. Hydrology concerns the occurrence, movement and composition of water below and on the earth's surface. It is an interdisciplinary science with strong links to biology, geology, oceanography, atmospheric and solid earth sciences.

The Committee explains the social relevance of hydrological research as it plays an important role in helping to solve global problems, such as water scarcity and lack of food security. Hydrology provides the knowledge that is needed to predict the occurrence of natural and human-induced hazards such as floods, droughts, and water pollution.

The Committee identifies a number of major challenges in international hydrological research, as detailed in Chapter 3. These are classified under four key

research areas and four methodological issues. The key research areas are listed as:

- Interaction between the hydrological cycle and terrestrial ecosystem.
- Human impacts on the water cycle and the geo-environment.
- Interaction between the hydrological cycle and landscape processes.
- Climate change and variability.

Progress in these research areas can be made only if we find solutions to the following methodological issues:

- Heterogeneity and scale.
- Observation and measurement techniques.
- Fundamental theories.
- Quantification of uncertainties.

The Committee recognizes that Dutch hydrologists play a prominent role at the international level, and that there are tremendous opportunities for them to become key players in a number of important breakthroughs in global hydrology. To make this possible, it is necessary to formulate a focussed research agenda and to establish an effective organizational structure for coordinating hydrological scientific research.

The Committee has identified three priority research themes that should form the basis for a focussed research agenda. These choices are made based on the prospects for keeping Dutch hydrology at the forefront internationally, stimulating intensive interdisciplinary research, and enhancing the funding potentials. The three priority themes for Dutch hydrology, explained in detail in Chapter 4, are:

1. Hydrology and climate.
2. Hydrology and geo-ecosystems.
3. Hydrology and geo-environment.

The Committee has prepared a thorough overview of hydrology education programmes in the Netherlands, as detailed in Chapter 5, where possibilities for improving these programmes are also discussed.

The Committee has performed a SWOT analysis of Dutch hydrologic research and education in Section 6.2. This SWOT analysis has aided in outlining and identifying measures that are needed to advance hydrological science in The Netherlands.

The Committee recommends establishing a virtual research centre dedicated to focussing and strengthening hydrological research in The Netherlands, based on the priority themes mentioned above, and within an interdisciplinary research framework. Details of major activities and the various phases of implementation of such a hydrology research centre are described in Section 6.3.

1. Introduction

1.1 Background

The Academy
The Royal Netherlands Academy of Arts and Sciences (KNAW) is the official advisory body to the government on scientific matters. Disciplinary councils of the Academy prepare and implement reports both on request and on their own initiative. The 'core business' of the advisory councils is to organise research foresight studies. The main purpose of these foresight studies is to give direction to scientific developments and to offer a basis for the setting and selection of priorities.

Earth and Climate Council (RAK)
The Earth and Climate Council of the Royal Netherlands Academy of Arts and Sciences was established in 2000 as one of the Academy's advisory councils. These councils consist of both Academy members and non-members, including university professors and researchers from public research institutes and private industrial companies. The Earth and Climate Council aims to develop a coherent vision of the Earth Sciences in The Netherlands. The Council gives solicited and unsolicited advice to the Academy Board and, through the Board, to the government, universities, research institutes, funding agencies and

national and international organisations. The scope of the Council includes sciences involved in describing and understanding the earth system and covers the study of physical, chemical, geological and biological processes which regulate the earth system and their interaction in the past, the present and the future. In 2001, the Council decided, after close consultation with the Dutch Hydrological Platform (see next paragraph), to seek the Academy Board's consent to conduct a preliminary foresight study to investigate the impetus and necessity for an hydrology foresight study. The RAK suggested to the Academy Board that it should install a committee consisting of hydrology professors who had recently been appointed to Dutch universities.

The Dutch Hydrology Platform

Dutch hydrologists have always had a prominent role in the international hydrological community and they have contributed significantly to hydrological science. In recent decades, the severity of many water-related global and regional problems has increased dramatically. Hydrologists worldwide have taken up a central role in searching for solutions to world water problems. In order to unify the efforts of Dutch hydrologists in meeting the challenges ahead and in order to improve the visibility of hydrology at the national level as a separate scientific discipline within the earth sciences, the 'Netherlands Hydrology Platform' (Nederlands Hydrologisch Platform, NHP) was established in 2001. The objectives of NHP are: to show the strength and possibilities of hydrology as an independent science; to survey all hydrological research activities; to improve communication between PhD students and researchers; and to create a database with information on hydrological research in The Netherlands. Members of NHP are the hydrology professors at Dutch universities and key scientists at institutes that are involved in hydrological research.

Preliminary Foresight Committee

A Preliminary Foresight Committee has carried out an extensive preliminary foresight study and produced a report entitled 'Hydrology: a Vital Component of Earth System Science' in December 2003.

The main tasks of the *preliminary* committee were:

- To draw up an overview of the field of hydrology, the place of fundamental hydrological science, the direction in which hydrological science is developing and the scientific challenges of hydrology.
- To compose a list of related disciplines (such as biology, geology, meteorology, oceanography and mathematics) that must be taken into account.

– To conduct a survey of hydrological research in The Netherlands: what type of research, who is involved, and where is it executed.
– To make recommendations for a possible in-depth foresight study and how such a foresight should be executed.

The Preliminary Foresight Committee proposed four priority themes for hydrological research in The Netherlands for the next ten years. The preliminary committee strongly recommended that an in-depth foresight study of hydrological science should be carried out, in order to address a number of important questions, which are described below. The Committee suggested enriching the current preliminary committee with three members from the related disciplines of mathematics, biology, and meteorology.

1.2 Terms of Reference Foresight Committee

Following the publication of the preliminary foresight study report, the Royal Netherlands Academy of Arts and Sciences decided to commission a Foresight Committee on Hydrological Science (*Verkennings Commissie Hydrologie*, VCH) to conduct a foresight study describing in detail the relationship between hydrology and other disciplines, for example ecology, meteorology and mathematics. The foresight study on hydrology must produce specific recommendations for government and other sponsors, universities, and research organisations.

The Royal Netherlands Academy of Arts and Sciences wishes to use the foresight study on hydrology to identify the most important advances in international research in this field and to map out a strategic position for Dutch research within that context.

The VCH should:
– confirm the priority research themes identified in the preliminary report and explore these themes, and the relationships between them, in detail;
– consider how the priority research themes can be incorporated into interdisciplinary research programmes;
– analyse the strengths and weaknesses of hydrological research in The Netherlands, as well as study how the strengths can be enhanced and the weaknesses eliminated;
– investigate structural changes that will benefit the way in which hydrological research is organised and financed;
– consider the Masters degree programmes in hydrology and related disciplines. The VCH should specifically consider how best to design programmes in hydrology and related disciplines such that they train a sufficient number of researchers in hydrology in the future.

The Committee members and their curricula vitae are included in Annex A.

1.3 Committee's activities

The Committee consisted of eight members: the five members of the Preliminary Foresight Committee plus an ecologist, a mathematician, and a meteorologist. This Committee was able to continue building on the work done by the Preliminary Foresight Committee.

Chapters 1, 2 and 3 of this report are based mainly on the preliminary foresight study report. After describing hydrological science as an earth science and the general international challenges for hydrological science, the Preliminary Foresight Committee goes on to identify five methodological issues and four thematic key research areas. The thematic key areas concern the fundamental understanding of the hydrological cycle in relation to:

- Terrestrial ecosystems.
- Human impacts.
- Landscape processes and,
- Climate change and variability.

The key research areas and five methodological issues identified in hydrology are described in Chapter 3.

Based on these key research areas, the Preliminary Foresight Committee selected four priority themes for hydrological research in The Netherlands to investigate in greater detail:

- Interaction of the hydrological cycle with the terrestrial biosphere ('ecohydrology').
- Hydrology of large river systems: human impact and climate change.
- Soil moisture dynamics at the landscape scale.
- The fate of contaminants in the subsurface.

These 'Dutch' priority themes, which were described in detail in the report of the Preliminary Foresight Committee, were discussed with a group of active researchers from hydrological and related disciplines during four Expert Meetings in March 2004 (see Annex B for the list of participants). Based on results of these expert meetings and internal discussions of the Committee, the above-mentioned priority themes were revised and reformulated into three priority themes with a strong internal coherence. The priority themes for The Netherlands are described in detail in Chapter 4.

In addition to expert meetings, input was sought from the hydrological community through visits to the coordinators of Masters Programmes in Hydrology in The Netherlands and interviews with a number of prominent scientists who were not visited during the Preliminary Study. The people visited during both the Preliminary Study and the Foresight Study are listed in Annex C.

2. Hydrology, the science

2.1 Definition

Hydrology is a scientific discipline within the earth sciences. Its main focus is the terrestrial part of the hydrological cycle (see Figure 1). Hydrology concerns the occurrence, movement and composition of water below and on the earth's surface. Hydrological science has strong links, on a wide range of spatial and temporal scales, with oceanic, atmospheric, and solid earth sciences as well as with biological sciences.

More specifically, the aims and scope of hydrology are:

- To understand the mechanisms and underlying processes of the hydrological cycle and its interactions with the lithosphere, atmosphere, and biosphere.
- To enhance our knowledge of interactions between hydrosphere and atmosphere, hydrosphere and lithosphere, and hydrosphere and biosphere, thereby increasing our understanding of the role that water plays in the Earth System.
- To quantify human impact on past, present, and future conditions of hydrological systems.
- To develop strategies for sustainable use and protection of water resources, hydrological systems, and associated environmental conditions.

Within hydrology, fundamental and applied research emphasises the development of explanatory and predictive models of water availability, flow, solute transport, and fluxes of energy, nutrients, and carbon, and their interactions. Hydrological research is based on sound physical and chemical theories and takes account of geological and biological environmental controls.

One should not confuse hydrology with 'water science'. Water science is a much broader field that deals with all aspects of water and includes disciplines such as aquatic ecology, social economy, etc. It has received considerable attention in recent years due to possible changes in water availability and quality that may occur as a result of climatic and global change. Of course, in these issues, hydrology plays a role in understanding specific changes in stocks and fluxes that may occur.

Hydrology and water management are, despite their strong traditional links, rather distinct disciplines. Water management is primarily concerned with policies and methodologies that are related to optimising water quantity and quality for agriculture, fisheries, transport over inland waters, urban settlement, industrial activities, infrastructure, and the protection of the population against floods and droughts. Hydrology is concerned with the dynamics of water in the hydrological cycle, both with regards to stocks and fluxes. As such it provides the background scientific knowledge and the predictive/descriptive models that are needed for the development of methodologies and policies of water management.

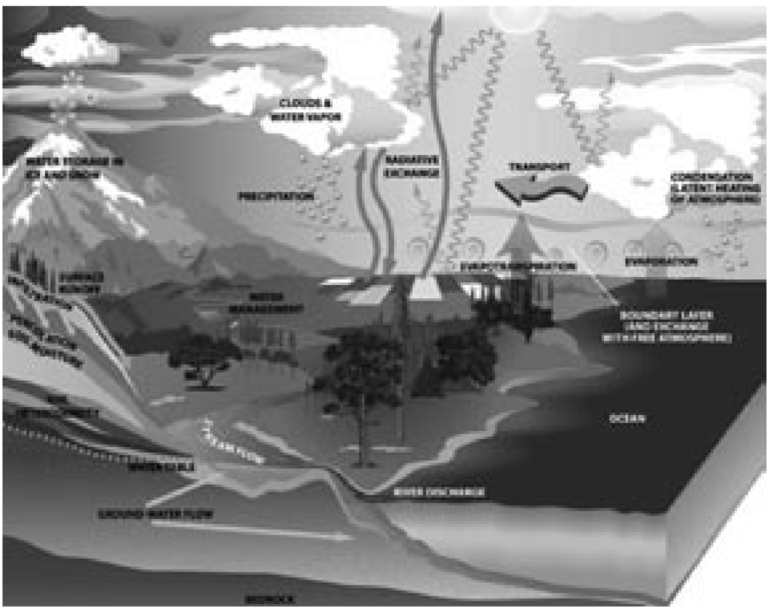

Figure 1. Elements of the Hydrological Cycle.

This foresight study deals with hydrology as a distinct discipline in earth system science and for this reason, water management issues are not explicitly addressed, except in the discussion of global change impacts on hydrological systems.

2.2 Hydrology: an interdisciplinary science

Water plays an important role in almost all human activities on the earth. As a result, hydrology has close links with many branches of science. But, the strongest links are, through the hydrological cycle, with other Earth System sciences such as atmospheric sciences, biology, geology, oceanography and solid earth sciences. A schematic presentation of the controlling role of the hydrological cycle (and thus hydrology) in other systems on the earth is given in Figure 2.

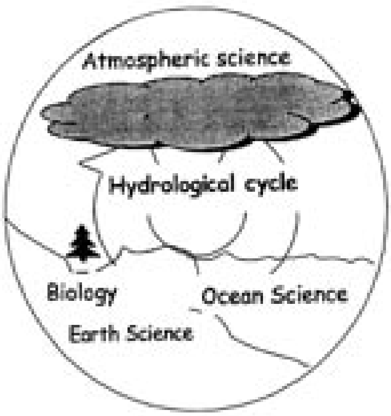

Figure 2. The central role of hydrology as an earth system science (redrawn after Eagleson et al., 1991).

Hydrology has important links to solid earth science through geomorphology, geology and geophysics. Water, its movement and its properties play a central role in shaping the surface of the land; geomorphology is the science that deals with this interaction. While shaping the land surface, water's biogeochemical properties change and nutrients and other solutes dissolve in it. The flow of small streams to rivers redistributes the dissolved elements and this has major implications for the nutrient availability in coastal areas and that, in turn, determines the growth of phytoplankton. On geological time scales, groundwater interacts with sediments during diagenesis and may enhance secondary permeability while seeping through cracks. Geophysical methods are very important in the study and characterisation of groundwater systems (both saturated and unsaturated).

Links with oceanic science exist particularly in the case of shallow coastal zones, where input into the ocean is important and interactions between the salty and fresh groundwater can occur. The input of fresh water into the oceans, particularly in the Arctic, affects the thermo-haline circulation.

The link between hydrology and biology is through vegetation at the land surface, biogeochemistry in the subsurface, and aquatic ecology. Vegetation plays a pivotal role in that, on one hand, it regulates the flow of water through evaporation, and on the other hand, it is dependent on adequate water supply. Water flow, often influenced by vegetation itself, also causes spatial redistribution of nutrients and thus influences growth conditions and through this the vegetation patterns we observe. Vegetation also plays a key role in helping to shape the land by changing infiltration characteristics through root growth, and by controlling the soil moisture supply, which in turn, affects runoff patterns and groundwater recharge.

Links with the atmospheric sciences are obvious: the study of the hydrological science requires a thorough understanding of rainfall and evaporation processes over land and ocean, while successful prediction by atmospheric circulation models requires a knowledge of surface hydrological processes.

One of the strongest and broadest cooperation links has been with mathematicians. Many mathematicians have taken a wide-ranging interest in, and have contributed significantly to, the study of equations that govern hydrological processes. The cooperation with mathematicians over the years has involved the analysis of (often leading to analytical solutions for) governing equations, numerical solution of these equations (resulting in simulation models), and development of various methods for stochastic analysis, inverse modelling, parameter estimation, and data assimilation.

In surface hydrology, there are close links to fluid mechanics, which is one of the basic scientific disciplines of hydrology, and to river hydraulics, in relation to the study of flood wave propagation, sedimentation and erosion, and river morphology.

Subsurface hydrology shares many areas of common interest with reservoir engineering, soil physics, soil mechanics, geotechnical engineering, chemical engineering, river and hydraulic engineering, and any science or industry where porous media flow and transport occurs (as in plant physiology, medical engineering, paper and textile industry, etc.). In relation to the unsaturated zone hydrology, the movement of moisture and solutes is an area of common interest to soil physicists, plant physiologists, agronomists, and hydrologists. In particular, there has been much collaboration between soil physicists and hydrologists. In this same area, researchers in soil mechanics have been working with hydrologists to study the effect of soil saturation and moisture movement on soil strength and stability. There are also links with plant physiology (uptake of moisture and solutes by plants and flow of sap through plant tissues), medical engineering (flow of fluids and gasses in human tissues or implants), and with paper and textile industry (moisture transport), and food sciences (drying processes).

A detailed description of various disciplines of hydrological science is given in Annex D, where also a comparison between hydrological science and engineering hydrology has been made.

2.3 Relevance of hydrology

There are four basic requirements to support the sustainability of a human population at any scale, be it a tribe, a village, a city, an entire nation, or a whole continent. These are: sustainable supply of fresh water, food, energy, and the availability of habitable space. Of these, loss of fresh water is the most life-threatening factor. Many civilisations (for instance the Mayas) are believed to have disappeared due to the decline or disappearance of fresh water resources.

Fresh water is perhaps the single most important resource on earth. Water on land serves as a source of drinking water and food production and is vital to almost all ecosystems. The presence of water vapour in the atmosphere causes the earth's surface temperature to be suitable for living organisms. Clearly, water makes life possible. However, lack of water (droughts) or too much water (floods) can also pose threats to mankind.

Hydrology is concerned with the terrestrial part of the water cycle. This is by far the most relevant part, as it is attainable for human consumption and use, while it is also the part that is linked to natural hazards. By studying the terrestrial water cycle, hydrology thus plays an important part in helping to solve global issues such as water scarcity and lack of food security. Hydrology also provides the knowledge to predict the occurrence of natural and human-induced hazards such as floods, droughts, erosion, landslides, mud flows and water pollution. Also, measures to mitigate such hazards can only be based on sound hydrological knowledge.

The fate of many precious ecosystems on earth, such as rain forests and wetlands, depends heavily on the abundance of water and its composition. Hydrology helps us understand how water quantity and quality relate to climate change and human impact. It is also instrumental to understanding the dependence of ecosystem functioning and biodiversity on water quantity and quality.

Recent insights into the climate system show that terrestrial water provides an important control on climate variability and change, both directly, through land-atmosphere exchange of water and energy, and indirectly, through fresh water influx to the oceans. Also, global cycles of carbon and nitrate (including their occurrence as greenhouse gasses) are intimately linked to the hydrological cycle. Although crucial, this link is often not taken into account properly. Understanding the mechanisms of the water cycle thus contributes significantly to understanding global change.

Human activities have affected and continue to affect quality and quantity of surface and subsurface water resources and ecosystems. These include not only traditional domestic agricultural and industrial activities but also attempts to ensure the safe disposal of hazardous waste, CO_2 storage, energy storage, sustainable use of underground space, etc. Hydrologists have been assuming a leading role in studying the consequences of such actions for the quality of water resources and the fate of ecosystems. Apart from these globally important problems, hydrology is also pertinent to specific issues of water management in The Netherlands. Particularly relevant is the influence of climate change and rising sea levels on river floods, low river stages (important for shipping), and local water management, as well as the effect of sea level rise and subsidence on groundwater levels and salt water intrusion.

A new and significant development in hydrogeology relates to the use of the subsurface for the sustainable management of the environment. Major examples are the seasonal storage of thermal energy, safe storage of hazardous waste, and sequestration of CO_2. To ensure that in trying to solve one problem we do not create new ones, it is of vital importance to have a profound knowledge of processes that play a role in such activities and to be able to quantify the consequences of our actions. This is an area of research where subsurface hydrology and other geosciences disciplines must work together. Research and modelling are in the early stages of development. Another significant development in hydrogeology relates to the increasingly important role that the subsurface is playing in sustainable urban development. In densely populated areas and/or industrial regions, the third dimension is considered the solution to the many limitations of urban development. The use of the subsurface for various underground structures will become more and more important in the near future. In designing projects for the use of subsurface space, we must try to understand fully the consequences for the soil and groundwater ecosystem, for groundwater flow and quality, and for soil quality and strength. Research and modelling in this area have yet to begin.

This brief account of the enormous significance and the wide-ranging role of hydrological processes in all facets of life and the environment on earth testifies to the importance of hydrological research. It is time to introduce measures to ensure that hydrology, the science dealing with the most important substance on our planet, will be able to help generate the knowledge needed for the continuation of civilisation on the earth.

A detailed description of the hydrological science disciplines can be found in Annex D. For a comparison between hydrological science and engineering hydrology, see also Annex D.

Existing and emerging remote sensing techniques for hydrological applications, Peter Troch

Precipitation: Remote-sensing-based rainfall estimation techniques include ground-based radar methods, satellite-based cloud indexing methods using visible/infrared observations as well as passive microwave observations. Space-borne passive microwave data-based techniques provide a more direct measurement of rainfall characteristics than visible/infrared techniques, and are reported to be superior. Recent developments in rainfall estimation from space include the Global Precipitation Mission (gpm) initiative. Snow and ice: In many mountainous areas, snow is the main source of stream flow during spring and summer. Since snow is often located in remote and inaccessible regions where extensive field measurements are very difficult and expensive to perform, remote sensing techniques are obviously advantageous. These techniques include applications such as mapping of areal snow cover by visible and synthetic aperture radar (SAR) sensors, measuring snow accumulation, snow water equivalent and snow albedo by microwave sensors.

Evaporation: Evaporation is of great importance in water balance modelling of a river basin, but cannot be measured directly by remote sensing techniques. However, several parameters and variables needed for calculating evaporation from the land surface energy budget, such as incoming solar radiation, surface albedo, surface temperature, land cover, vegetation density and soil moisture, may be estimated using remote sensing data. Recent developments include the use of eddy correlation scintillometry to observe surface fluxes over natural landscapes.

Soil moisture: Soil moisture is a key variable in hydrological, agricultural, ecological, meteorological, and climate studies. Conventional methods for soil moisture measurements are both time-consuming and labour-intensive and are every difficult, if not impossible, to deploy over a large river basin. Remote sensing measurements of near-surface soil moisture may be based on the following methods.
(1) Measuring bare soil reflectance in the visible and near-infrared regions of the spectrum. This provides only a poor indication of soil moisture, since soil reflectance is heavily influenced by soil texture and colour.
(2) Measuring the surface temperature and/or thermal inertia in the thermal infrared region. The limitations of this type of measurement are due to effects of cloud cover, vegetation and meteorological factors.
(3) Measuring the brightness temperature in the microwave region. This passive technique utilises the distinctive difference of the dielectric constant of water and dry soil for determining soil water content in the top soil layer of about 5 cm.
(4) Measuring the backscattering coefficient with active microwave sensors. Recent developments in soil moisture observation from space include SMOS (Soil Moisture

and Ocean Salinity mission), envisat (with the Advanced sar [ASAR] instrument on board), and Differential Interferometry sar techniques (DINSAR).

Surface water and runoff: Remote sensing data can generally enhance conventional methods used in surface water inventory, including mapping changes of surface water coverage, flood plain and flood damage determination, in improving management of inland waters and wetlands, and more recently in providing information of water levels over extended areas by means of sar interferometry. Although surface runoff cannot be measured directly from remote sensing platforms, remotely sensed data can play an important role in providing input data to distributed hydrological models, in measuring state variables such as soil moisture, and in estimating model parameters, so that runoff can be simulated more accurately.

Catchment storage changes: The most innovative development at the moment is the potential of using information about the time-variable gravity field of the earth for inferring water storage changes in large river basins. Since 2002, the Gravity Recovery and Climate Experiment (GRACE) satellite system has been mapping gravity anomalies of the entire earth. The accuracy of the grace system is such that it allows the detection of water mass storage changes of less than 1 cm. This offers enormous possibilities for use in hydrological studies, as for the first time the water storage changes of river basins (usually treated as a closure term in the water balance) can be measured.

3. Challenges ahead in international hydrological research

3.1 Introduction

The central role of the hydrological cycle in shaping human activities and affecting the environment was elucidated in Chapter 2. In Chapter 2 it was explained that an adequate knowledge of the hydrological cycle and its processes is essential if we are to meet one of the most difficult and significant challenges of the 21st century: namely to ensure the availability of an adequate supply of water for the populace, agriculture, industry, and environment, and to prepare to take mitigating measures against droughts and floods. This knowledge must pertain to the actions and interactions of the hydrological cycle, human activities, ecosystem, land surface, and climate change.

Based on the foregoing considerations, extensive internal discussion, and input from various sources and activities, the Committee has identified major challenges in international hydrological research that are believed to be of great significance in hydrological science for the coming decade. The topics identified are not only internationally relevant, but also form a crucial basis for making the choices we will propose for Dutch hydrological research. Moreover, each topic has the potential for strong interdisciplinary research with one or more related disciplines.

International challenges of relevance to Dutch hydrology have been divided into two categories: four key research areas and four methological issues. The four key areas involve a fundamental understanding of the hydrological cycle in relation to: terrestrial ecosystems, human impacts, landscape processes, and climate change and variability.

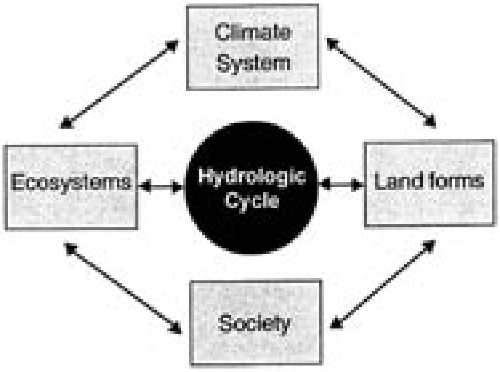

Figure. 3. Key research areas and their interactions.

These research areas are described in Sections 3.2 through 3.5 below. A schematic representation of the interactions among the systems underlying these research areas is given in Figure 3.

The set of four 'Methodological Issues' relates to the mathematical modelling of hydrological processes that are encountered in the four key research areas. These are: heterogeneity and scale, observation and measurement techniques, fundamental theories, and quantification of uncertainties. The methodological issues are described in Section 3.6.

3.2 Interaction between the hydrological cycle and terrestrial ecosystems

The study of the interaction between the hydrological cycle and terrestrial ecosystems is the focus of the emerging field of ecohydrology. This includes not only the water cycle, but also the nutrient cycle. Ecohydrology seeks to identify and understand the underlying hydrological patterns and causes that determine the enormous diversity of ecological functioning and the way these feed back into the water cycle. Ecohydrology deals with issues that range from local to regional to global scale. A crucial question at the local to regional scale is whether the observed patterns of vegetation are the results of imposed heterogeneity of climate and soil, or whether they are the outcome of self-organisation. For instance, the occurrence of patches of vegetation alternating with patches of bare or almost soil at multiple scales is a common feature in semi-arid areas. In more temperate or humid environments as well, at local to regional scale, vegetation development depends on local topography and related soil moisture availability. Our knowledge of the role of hydrology (*e.g.* surface runoff, soil water availability) in the pattern development in such systems and their self-organising properties is poor. The key questions on the global scale are as follows: How do ecosystems interact with their environment to create sustainable boundary conditions for growth? What are the generalities behind this apparent diversity in the real world? Is there functional convergence?

The interactions between water and other biogeochemical cycles take place at the level of ecosystems. Improving our understanding of the critical nodes of interaction between these cycles is probably one of the great challenges for ecohydrology in the next decade. We need to fully understand the way vegetation optimises the trade-off between carbon uptake and water loss, sediment loss, and nutrient availability. The question itself is not new, but the existence of large-scale data sets that allow testing at the ecosystem level gives a totally new impetus to it. Furthermore, it is extremely important to recognise that working with average values for water cycle components in a given region is often not acceptable when characterising nutrients cycles. In most regions of the world, it will be necessary to account for fluctuations in hydrological dynamics when linking the hydrological cycle to those of the key nutrients. So, for example, one should take into account the stochastic character of rainfall and its role in the cycles of nutrients.

Another major control in ecohydrology is soil moisture. There is an obvious link between soil moisture and the transpiration process of vegetation. But it also plays an important role in ecosystem assimilation, and also in the respiration control of Mediterranean and semi-arid ecosystems. On a global scale, crucial sensitivities have been identified between carbon sequestration and loss, climate change, and rainfall. Considerable progress has been made in the last few years in the measurement of evaporation through the use of micrometeorological techniques such as eddy correlation, which now allow comparison between vegetation under different climates and different geological environments. These developments in measurement techniques have opened up new areas in the study of inter-annual variability in evaporation and the interaction of terrestrial ecosystems with the hydrological cycle.

Ecosystems are generally exposed to gradual changes in climate, nutrient loading, habitat fragmentation or biotic exploitation. Nature is usually assumed to have a relatively smooth response to these gradual changes. Recent work on the analysis of ecosystems, however, suggests that the state of ecosystems, for instance indicated by their greenness or amount of vegetation, may suddenly shift to an opposite state (e.g. from bare soil with little vegetation to a lush green forest with a corresponding increase in precipitation). Studies of lakes, coral reefs, oceans, forests and arid lands have shown that such sudden drastic switches to a contrasting state can interrupt the usual smooth change. Although diverse events, including human behaviour, can trigger such ecosystem shifts, recent studies show that a loss of resilience usually paves the way for a switch to an alternative state. There is considerable scope to extend this theory to the interaction of ecosystems with hydrology and human impact.

Another important issue in ecohydrology is that vegetation and the underlying geology are in constant interaction. Root systems, for instance, develop and change the soil and underlying medium structures, and nutrients provide the building blocks for vegetation to develop. These interactions, wherein water plays a key role, take place at time scales from a year to several dozens of years. The resilience of this coupled vegetation-soil-hydrological system depends critically on the sensitivity of the coupled soil-vegetation system to changes in its environment, i.e., the availability of water in the root zone and sediment transport. These processes are both one- and three-dimensional in nature. Our understanding of these processes is at present poor and needs to be improved. The study of these complex interactions, where micro-behaviour results in patterns emerging at larger scales, is a new, exciting area of research in ecohydrology.

Key scientific questions in ecohydrology involve finding answers to the following key research questions:

- What are the hydrological boundary conditions that create ecosystem patterns and variability on the earth?
- What are the hydrological processes that determine the variability in ecosystem structure and function?
- How do ecosystems interact with their hydrological environment to create sustainable boundary conditions?
- How does the water cycle interact with major biogeochemical cycles in ecosystems?
- Which are the crucial processes in the soil-vegetation-atmosphere interaction that cause self-organised behaviour and critical shifts?

3.3 Human impacts on the water cycle and the geo-environment

Population growth and land use change have a major impact on both quantity and quality of surface water and groundwater resources. The increasing demands on fresh water, especially for agriculture, have produced water stress in many areas of the world and this trend is continuing. This has been aggravated by the deterioration of water resources quality as a result of agricultural, industrial, and urban activities; with serious adverse effects on human health and aquatic life. One of the major challenges in hydrology is to describe and predict the interactions among human activities, the water cycle, water resources quantity and quality, and the consequences for sustainable development. These issues are the subject areas of environmental hydrology, where both water quantity and water quality aspects are studied.

Water quantity aspects

Increasing water use for agriculture, withdrawn from groundwater bodies and large rivers, augments evaporation and transpiration and may thus have a significant influence on the water cycle. Land use change associated with population growth can also lead to changes in runoff behaviour of river systems. In developed countries, industry competes with agriculture for water resources and puts stress on domestic water supply through its polluting effects. Meeting these conflicting demands and proposing mitigating strategies require an understanding of trends in population growth and associated land use change and the way in which water demands influence the local, regional, and global water cycle.

Apart from the negative human impact on water resources, positive impacts may be achieved through sustainable water management. In the context of the expected climate change and the associated risks of floods and droughts, there is a need for water management strategies that can mitigate these effects. Climate change and demographic and socio-economic trends are extremely uncertain. Thus, one has to find robust water management strategies that will yield satisfactory living conditions for a wide range of possible scenarios. A more technical aspect of this issue is how the almost infinite number of possible scenarios can be analysed. It is extremely difficult to explore this vast 'space of uncertainty.' So, clever methods have to be designed to sample this space adequately. Possible directions are the definition of storylines from socio-economic theory, i.e. coherent combinations of world views, climate scenarios, and management styles. A prerequisite for analysing robust strategies is the development of fully coupled models of the hydrological system and the socio-economic system. Such coupled models must show full interaction. They should not only portray the impact of the socio-economic system on the water cycle, e.g. through land use and water management strategies, but also show the reaction of the socio-economic system to hydrological events, such as floods.

Water quality aspects

Water in the environment always contains many dissolved components of natural or anthropogenic origins. Some components are undesirable and harmful to the environment and/or human health, and some others are useful and needed for certain environmental processes or human activities.

The fate of dissolved components in the hydrological cycle is affected by complex and coupled interactions in the air, in rivers and lakes, on land, and in the underground. Hydrologists have always been active in the study of the transport of solutes in the environment. In doing so, they have worked closely with researchers from other disciplines. However, models of transport in the diverse systems mentioned above have been isolated from one another. There is a need to explore the common nature of processes occurring in these systems and develop a unified approach to the study of movement of solutes in the environment. This is a task for environmental hydrologists. Together with water managers, biologists and biogeologists, chemists and geochemists, they have a responsibility to find ways of granting society the benefits of using freshwater resources, while at the same time preventing the degradation of environmental quality.

Environmental hydrology should aim to develop scientifically robust methods for ecosystem risk assessment, soil and groundwater protection and remediation, and options for improved nutrient management.

In order to address these issues, one must have a thorough knowledge of the physical, geochemical, and microbiological processes that control the fate of substances in hydrological systems. Deepening our understanding of the interplay of these processes and developing robust models for explaining and predicting the quality of water must be a priority.

Although processes that occur in surface and subsurface waters are linked and have a common nature, they are considerably different in terms of temporal and spatial scales. In the study of environmental hydrology, the incompatibility of scales must be bridged. Regarding surface waters, hydrological responses to anthropogenic activities, as influenced by climate, soil properties, soil water dynamics, and landscape positioning, should be determined at a scale of observation that is germane to such activities. Understanding the within-field variability of hydrological processes at the watershed scale will be critical in developing improved strategies for sustaining industrial, urban, and agricultural activities while conserving natural resources. Emphasis should be placed on physically-based models that describe fluxes of energy, water, pesticides, and carbon at the small watershed scale so that field scale processes like volatilisation, infiltration, erosion, and preferential flow can be effectively integrated into dynamic hydrological models.

Regarding the contamination of soil and groundwater resources, despite a considerable increase in our knowledge of relevant processes, many questions have remained unanswered. We are still unable to make reasonably good predictions of the fate of pollutants and the effectiveness of remediation techniques. Even if we no longer intend remediating all polluted sites, we must be able to predict how the pollution at a given site will develop, whether natural attenuation processes will result in confining it, and how long it will take before the site can be declared fit for certain uses in the future.

Key scientific questions related to the human impact on the water cycle and the geo-environment are:

– What is the impact of increased water demand and land use change on groundwater reserves and river discharge, and what is the extent of expected water stress in the coming decades?
– To what extent do increased evaporation and transpiration resulting from increased withdrawal of groundwater and surface water lead to changes in the local and global water cycle?
– What are the impacts of population growth and land use change on the quality of groundwater reserves, soils, and rivers and what are the effects on natural ecosystems that depend on them?
– How can we successfully identify, describe, and model mechanisms by which pollutants find their ways into surface and subsurface waters?
– What is the self-cleaning capacity of aquifers and rivers for various pollutants and how should the relevant physical and biogeochemical processes be quantified?

3.4 Interaction between the hydrological cycle and landscape processes

For catchment-scale water and land management, it is essential to understand the interactions and feedbacks between hillslope forms and channel networks on one hand and the movement of water, sediments, and pollutants on the other hand. A river basin is made up of interconnected hillslopes and a channel network that drains these hillslopes. To describe flow and transport processes at the catchment scale, it is necessary to understand the characteristic response of hillslopes and the channel network within the catchment. Hydrological research during the last few decades has focused mainly on modelling the dynamic response of the channel network, usually by accounting for network geometry. The rationale behind this approach has been that both centre topology and geomorphology are essential in defining the catchment's response to a given volume of surface runoff, and, for increasing catchment size, these processes are dominant in explaining the timing and magnitude of hydrographs. Enhancing our understanding of catchment-scale flow processes, especially when viewed in the context of water quality prediction, requires extending this approach to include relevant hillslope flow processes. The geometry of the hillslope controls hydrological response to a major extent, because it defines the domain and the boundary conditions of moisture storage.

Three-dimensional landscape flow domain geometry should have a central place in the description of catchment-scale surface and subsurface flow processes, without leading to unnecessarily complicated process descriptions. Collaborative research among hydrologists, geomorphologists, geologists, and pedologists is needed to identify scaling relationships present in flow domain structures (e.g. distribution of soil depth over a range of scales, joint probability density distributions of basic hillslope forms and their interaction with network topology). These scaling relations will allow not only a better formulation of catchment-scale flow processes but, most likely, also a more simplified description as compared to purely distributed modelling exercises, especially in the context of curse of dimensionality.

In predicting the evolution of alluvial systems in the context of climate change, there are important unresolved issues to which hydrology can provide answers. The first important issue is the relationship between sediment supply and climate. Integrated modelling of upstream catchment response and geomorphological development as a function of climate variability must make it possible to predict changes in both discharge and sediment supply. Such modelling efforts also mean making allowances for vegetation changes, permafrost, and pedogenesis. Another important issue, which is not yet resolved, is the influence of discharge regime, sediment supply, slope of the valley floor, and base level movements on river plan form (i.e. meandering versus braided stream). Up to now, only empirical relations have existed, mostly derived by geomorphologists. It is a great challenge to develop a physical theory of river plan form by combining the work of geomorphologists and hydrologists based on thermodynamic principles, such as the principle of minimum entropy production.

Key scientific questions related to the interaction of the hydrological cycle and landscape processes are:

- What are the hidden unifying scaling relationships in the three-dimensional geometry of landscapes and how are they related to the hydrological/mass response of a basin?
- Can we accurately describe the relationship between discharge, sediment supply, and climate change at basin scale?

– Can we develop a physical theory of river morphology based on thermodynamic principles of irreversible dissipative systems?

3.5 Climate change and variability

According to the IPCC Third Assessment Report, precipitation over the mid and northern latitudes has increased by 5-10%. There has been an increase in heavy precipitation events and a shift in peak flow from early spring to winter in Eastern and Russian Europe, while prolonged periods of drought and flooding have also been observed as a result of enhanced El-Niño cycles. There is a need to further document, understand, and predict these changes, which appear to have led to an intensification of the hydrological cycle. Key questions concern the variability of stocks and fluxes at inter-annual to decadal time scales. This leads to questions on resource availability and flood hazards. We need to understand and explain changes that are currently observed in water availability and flooding events. We must also identify critical regions where the interplay between water availability and human demand has or will become problematic.

There is also a need to investigate past climates in order to better understand the palaeo-hydrological behaviour of the water cycle. This can be achieved by a better integration of biological and sedimentological indicators. These data should be used to check the capability of the current catchment and river models in dealing with natural and climatic variability outside the current instrument records at centennial to millennium time scales.

Recent studies show that, certainly for continental climates, soil moisture is a more important control on climate variability than sea surface temperature. Climate change and variability have a direct impact on precipitation and evaporation. Changes in precipitation and evaporation will, in turn, affect soil moisture content either directly or indirectly through changing vegetation. Soil moisture content, in its turn, may affect the climate through evaporation and precipitation. Our understanding of this feedback between the climate system and the hydrological cycle is still inadequate, so that substantial measurement and modelling efforts are required.

The role of fresh water in thermo-haline circulation is one of the critical areas of sensitivity within the coupled climate-hydrology system in the Northern hemisphere. We therefore need to identify and describe the role that continental scale hydrology, including the role of ice in river flow, can play in improving the predictive capability of a coupled ocean-climate model.

Upscaling, why and what

Toon Leijnse

Transfer of information across spatial and/or temporal scales is one of the most fundamental issues in the natural sciences. Typically, in analysing the behaviour of natural systems, different scales come into play:

– the scale of measurement, or the spatial/temporal support of physical measurements;
– the scale of processes, or the spatial/temporal scale at which process definitions can be given;
– the simulation scale or the spatial/temporal scale at which our prediction tools work.

In general, these scales are different, and transfer of information from one scale to the other is required to allow us to make comparisons between measurements and model results, to define processes (and governing equations) at the scale of simulation models, to obtain effective parameters at the scale of simulation models for predictions, etc. This transfer of information is called upscaling or downscaling.

In the following, we will limit our discussion to spatial upscaling, i.e. the transfer of information from a small to a larger spatial scale. We define upscaling as the procedure by which the mathematical description of physical/chemical/biological processes at a given spatial scale is reformulated for a larger scale. There are three main reasons why upscaling is necessary:

– There is almost always insufficient data available for a full characterisation of the process at a small scale.
– Even if there were sufficient data, modelling of a system at a small scale will require prohibitive computational effort.
– Even if sufficient data and computer resources were available, often we are not interested in the detailed small-scale information.

Stated simply, we want to be able to describe the behaviour of a natural system in terms of lumped quantities such as mass fluxes, energy fluxes, etc., without having to deal with small scale information on state variables such as pressure, temperature, concentration, etc. As a consequence, we are interested in small scale values of these state variables only in so far as they determine the larger scale behaviour. That does mean that we should be able to determine or measure the large scale behaviour without having to resort to the complete small scale information. Another consequence is that the small-scale measurements (usually limited in number) cannot be reproduced by the scaled-up process descriptions.

Spatial upscaling can be carried out in a number of ways, all based on sound physical and mathematical principles. Examples of such upscaling techniques are volume averaging and homogenisation methods. Irrespective of the technique used, upscaling is only useful if it provides us with the following information:

- How do process descriptions change by transfer to a larger scale?
- How are new parameters and/or effective parameters in the upscaled process description defined?
- Which information on the underlying structure of the small-scale process must be known for the upscaling to be meaningful?

One should e.g. realise that upscaling is only useful if we do not need all the small-scale information to make the upscaling meaningful.

A typical example of upscaling is the occurrence of hydrodynamic dispersion of a substance dissolved in moving water if described in average terms on a large scale. Hydrodynamic dispersion occurring at the larger spatial scale is the result of small scale variations of the water flux and the concentration of the dissolved species. Under certain conditions, the characteristic parameter describing hydrodynamic dispersion, the dispersivity, follows from the stochastic properties of the small-scale velocity field, i.e. no information on the complete small-scale velocity field is required. Obviously, this example is one of the very few where upscaling has been successful so far.

Our ability to predict changes in stocks and fluxes of water under various scenarios of climate change is poor and ignores interaction between the water system and its natural and socio-economic environment. In particular, we need to quantify the resilience of water systems and the vulnerability to climate change more accurately. This requires us to improve our capacity to provide input (e.g. precipitation data) for hydrological models.

Key scientific questions regarding climate change and variability are:
- What is the inter-annual and decade-scale variability in stocks and fluxes of water?
- How much of this variability can be related to changes in climate and human use and abuse?
- What is the resilience of water systems to ongoing and future global change?
- What is the interaction between moisture sources and sinks on the land and in the atmosphere and how does this interaction affect and our ability to predict climate and weather?
- Can we use paleo-hydrological data to reconstruct past hydrological regimes beyond available records, and what can we learn from such reconstructions about the interaction between climate and the hydrological cycle on centennial to millennium time scales?

3.6 Methodological issues in hydrological research

Hydrological systems are extremely complex. We are dealing with coupled physical, chemical, and biological systems with highly non-linear behaviour. Characterisation and modelling of these systems are by no means straightforward. Our ability to analyse and predict the behaviour of hydrological systems is challenged by a number of persistent and unresolved issues, which are briefly described below. These issues are methodological in nature and are common to all the research areas described above. Indeed, we can only make progress in these research areas if we can find solutions to the following methodological challenges.

3.6.1 Heterogeneity and scale

Perhaps the most typical features of hydrological systems are spatial heterogeneity and temporal variability. Hydrological processes occur at a multiple of scales. The mathematical descriptions of these processes at different scales are not necessarily identical. Theories of upscaling and downscaling attempt to develop quantitative links among process descriptions at various scales. However, due to the presence of spatial heterogeneity and temporal variability and the highly non-linear nature of hydrological processes, upscaling is not an easy task. Sometimes, new governing equations have to be obtained and constitutive relations have to be identified and defined, resulting in a number of upscaled parameters that have to be measured directly or indirectly. These parameters are either new (meaning they exist at the larger scale only), or are averages of small-scale parameters (also called effective parameters). Questions that need to be answered are:

- How can parameter values measured at a small scale (e.g. laboratory experiments or plot-scale measurements) be translated to effective values at a larger scale?
- How can effective parameters of the larger scale be measured directly?
- How can small-scale heterogeneity be accounted for in large-scale descriptions of hydrological systems without being modelled explicitly?
- How can large-scale descriptions and observations of a system be downscaled to determine its behaviour at a smaller scale?

3.6.2 Observation and measurement techniques

Observation and measurement take place on a variety of scales. So are system descriptions. There is almost always a discrepancy between the measurement scale and the descriptive scale of interest. The problem is not necessarily a lack of data, but rather that the data pertain to scales much smaller or much larger than the scale of interest. Moreover, almost all measurement techniques are designed for state variables such as pressure, temperature, moisture content, concentration, humidity, etc. However, we also need to be able to measure fluxes of water, energy, and solutes in order to improve the testing of our models and enhance their predictive abilities. In almost all cases, fluxes are determined indirectly through gradients of state variables. This requires a mathematical model that itself needs to be tested and validated. In fact, the absence of reliable methods for direct measuring of fluxes has been an important obstacle to the advancement of modelling in hydrology. There is therefore a need to develop methods to measure/observe state variables and fluxes at the scale required to model a hydrological system or to transfer the available data to the scale of interest. Questions that need to be answered are:

- How can fluxes of water, heat, and solutes be measured directly?
- How can state variables and fluxes be measured at various spatial and temporal scales?
- How can measurements of state variables and fluxes at one scale be transformed to another scale?

3.6.3 Fundamental theories

Many common theories in hydrology are based on empirical observations of simple systems or of parts of the system of interest. Their validity is often extended to more complicated systems by defining empirical functional relationships. As discussed earlier, hydrological systems are quite complex. Also, as described above, equations valid at one scale are not necessarily valid at other scales. One may therefore question the applicability of theories that were originally developed for simple systems. Moreover, hydrological processes are non-linear and there is strong coupling among them. As a result, the effect of one process is influenced by the occurrence of other processes. Due to the non-linearity, a negligible effect in one process can lead to a significant impact on another process. There is a clear need to develop rigorous and physically-based theories for the description of coupled non-linear hydrological processes at various scales. Questions that need to be answered are:

– Are the governing equations that are currently being used for small-scale homogeneous systems valid for larger scale heterogeneous systems?
– Are there important effects missing in our current equations, often developed for individual and isolated processes, when used for coupled non-linear processes?
– Do the empirical functional relations often used in hydrology really have a sound physical basis?
– Does complex system theory provide an efficient new way to describe the state and response of hydrological systems to perturbations?

3.6.4 Quantification of uncertainties

Currently, we have no hope of fully characterising physical, chemical, and biological properties of hydrological systems or of providing deterministic or even stochastic predictions of their behaviour. Even when we make direct measurements of certain properties, there may be large uncertainties associated with our measurements. We must acknowledge that our knowledge of hydrological systems is limited, and instead of trying to make single-valued predictions of their behaviour, we must provide a range of possible states that the system may undergo. We therefore need to develop robust methods for quantifying the prediction uncertainty of hydrological systems behaviour due to both parameter uncertainties and possible errors in conceptual model description. Questions that need to be answered are:

– How can uncertainties owing to improper or incomplete process descriptions be quantified?
– How should uncertainties in parameter values in highly non-linear systems be efficiently translated into probability distributions of model predictions?

The contribution of Hydrology to Ecology
Jan van Groendendael

The availability of fresh water is a fundamental condition for life. It is also an universal solute and transport medium for a great many compounds derived from the earth's surface, including the nutrients that determine primary biological production. Fresh water and the minerals in it can rightfully be considered the lifeline for all ecological life support processes. Hydrology, the science that studies the processes that determine the movement of water in and on the earth's surface, is therefore of eminent importance to ecology, the science that studies the relationship between organisms and their environment.

The worldwide problems that surround the availability and quality of fresh water require an integrated approach involving the combined knowledge of hydrologists and ecologists. The forcing physical and chemical processes lay the scene for the modifying ecological processes on a variety of spatial and temporal scales, ranging from the sediment particle in the soil to complete river catchment systems and from minutes for a raindrop to centuries for groundwater flows. The interaction between the physical and chemical conditions to which hydrology makes a major contribution and ecological processes is especially prominent in two vital research areas within the field of ecology: biogeochemistry and landscape ecology.

Biogeochemical processes focus on the availability of biologically active minerals in the soil and surface waters. That availability depends on erosion and redox properties and these are most pronounced at the interface between water and air, water and soil and surface water with groundwater. Biological activity is concentrated at these interfaces, e.g. by microbial transformation and the higher organisms that in turn depend on these primary processes. Hydrology can contribute towards acquiring a better understanding of absorption and transport of water in the soil, leaching and deposition of secondary minerals.

On the landscape scale, ecologists are becoming aware that the natural unit of study in that discipline is the catchment area because of the dominant role of water flows play within the catchment when it comes to the distribution and abundance of organisms in that area. Each catchment has its particular interactions between hydrosphere, pedosphere and biosphere, but the hydrological laws of water transport are the starting point of any further understanding of the ecological relationships that govern productivity and biodiversity within a catchment. Understanding these relationships is vital to successful and cost-effective nature conservation and restoration.

Many of these phenomena in the hydrosphere and pedosphere are fractal and are repeated over a range of scales and can be expressed as power laws. They also contain strong ecological feedbacks leading to non-linearity and systems of so-called self-organising complexity. This is especially true for the vegetation cover, in which the carbon and water cycles are intimately interwoven through the process of photosynthesis, affecting the retention capacity for both carbon and water, with all its consequences for the local and ultimately the global environment.

Insight in these complex systems is therefore essential to our understanding of and our capacity to model these coupled hydro-pedo-ecosystems and requires a much closer interdisciplinary collaboration between hydrologists and ecologists to the benefit of both disciplines.

4. Priority themes for Dutch hydrological research

4.1 A Focused research agenda for Dutch hydrological science

The Dutch hydrological science community has an important role to fulfil in solving water problems in the 21^{st} century. Dutch hydrologists have proven in the past that they have the talent and the drive to initiate breakthroughs in important research areas. Almost all water problems in The Netherlands concern issues of worldwide interest. Thus, there are tremendous opportunities for Dutch hydrologists to become key players in their areas of expertise in hydrological science internationally. What is needed is a well-prepared and focused research agenda with clear priorities that help addressing both the nation's and the world's most pressing water problems.

As a first step, the Preliminary Foresight Committee identified a number of priority research themes for Dutch hydrology. In making these choices, the Committee primarily considered the potentials of keeping hydrological science in The Netherlands at the forefront by stimulating new areas where we can contribute and perhaps play a major role internationally. Secondary motivations for these choices were the possibility of enhancing the funding prospects for hydrological research, and stimulating collaboration within the Dutch hydrological science community and with related disciplines.

During the Foresight Study, the priority themes, suggested by the Preliminary Foresight Committee, were extensively discussed with the scientific community (e.g. during four Expert Meetings; see Annex B for the list of participants). These discussions led to a further consolidation and focusing of priority themes. The Foresight Committee has finally identified the following three priority themes for Dutch hydrological research:

– *Hydrology and Climate.*
– *Hydrology and Geo-ecosystems.*
– *Hydrology and Geo-environment.*

These themes will form a solid basis for hydrological research in The Netherlands for the coming ten years. They encompass major hydrological research issues that involve different systems and span a wide spectrum of spatial and temporal scales. Roughly speaking, research topics of *Hydrology and Climate* regard large scale processes, manifested at scales of river basins and (sub)continents. In this theme, hydrological cycle and the atmosphere's role therein stand central. Biological systems and human beings display an indirect role. Topics in *Hydrology and Geo-ecosystems* regard medium scale, landscape processes, typical of large hillslopes and catchments or subcatchments. In this theme, the interaction among geological/pedological, hydrological, and ecological processes plays the central role. Finally, *Hydrology and Geo-environment* deals with yet smaller scale processes, ranging from pore fraction of millimetres to core (tens of centimetres) to field scale (up to hundreds of meters). In this theme, the effect of human activities has a central role.

This huge range of scales and the variety of systems involved have made hydrology a multidisciplinary science where knowledge of water properties and behaviour must be supplemented with knowledge of biological, chemical, ecological, and atmospheric subsystems. It has also led to the highly complex nature of hydrological problems. Specific priority research topics selected here fully reflect the complexity and multi-disciplinary nature of hydrological research questions.

4.2. Hydrology and Climate

The climate system and the hydrological cycle are intimately linked. Climate change is felt most strongly through changes in stocks and fluxes of the hydrological cycle. Hydrological states (e.g. soil moisture content and groundwater levels) exert a strong control on climate variability by affecting the magnitude and variability of hydrological fluxes (e.g. fresh water inflow to the oceans, evaporation, precipitation). Thus, it is important to study them as two strongly coupled and interacting systems. As argued in Chapter 3, a fundamental insight into the workings of the hydrological cycle hinges on understanding the interaction between surface and subsurface water and the climate system. The importance of understanding this interaction is further emphasised by international initiatives such as the Global Water Systems Project (GWSP), national research programmes such as NWO-Water, BSIK Climate Changes Spatial Planning, BSIK Living with Water, and EU research programmes that include global change.

When analysing the research questions at hand and focussing on those questions that are predominantly hydrological and in line with the expertise of the Dutch hydrological community, three subthemes can be distinguished:
- Detection of changes in the hydrological cycle.
- Impacts of climate on the hydrological cycle.
- Feedback mechanisms between the hydrological and climate systems.

In the following sections, these sub-themes as well as the particular role of the Dutch hydrological community therein are described.

4.2.1 Detection

A major research question that is yet unresolved is whether the hydrological cycle is really accelerating due to greenhouse-induced climate change. This question may be studied both directly and indirectly. The most direct way is to determine whether the retention time of atmospheric water is decreasing, e.g. measuring global evaporation and precipitation by analysing historic time series around the world. Isotope analysis of atmospheric moisture and rainfall may provide further evidence. Indirect methods involve the analysis of terrestrial hydrological time series, such as runoff and groundwater levels. High-resolution dating of groundwater, using various environmental and isotopic tracers, may also be used to document changes in recharge. Even more indirect, but nevertheless extremely important for our understanding, is to use realistic models of coupled (sea or land) surface and boundary layer dynamics to study whether evaporation will increase as a result of temperature rise. Studying the latter question requires close cooperation among oceanographers, atmospheric scientists, and hydrologists. Biologists will also play a role here, as increased CO_2 levels may influence the stomatal behaviour of plants and shifts in vegetation patterns may affect regional and even global climate.

Given their expertise, Dutch hydrologists should direct their research to the following topics related to possible changes in the hydrological cycle:

The analysis of hydrological time series (of precipitation, evaporation, runoff, groundwater levels) for identifying trends and variability.
Classical methods such as intervention analysis and generalised least squares regression come to mind, but also more fashionable methods such as wavelet analysis are applicable. Typically, stochastic hydrologists, atmospheric scientists, and mathematicians can work together on this subject.

Documenting recharge response to historical changes using the groundwater archive on time scales of years to thousands of years in various settings and analysing how these changes are linked to local/regional meteorological and climatic records and the above-mentioned hydrological time series. Results should subsequently be used to constrain/calibrate predictions of coupled land surface hydrology and boundary layer dynamics models.

Coupled modelling of land surface hydrology and boundary layer dynamics to assess changes in evaporation under increased atmospheric temperatures.
The research into evaporation has been the domain of both atmospheric scientists and hydrologists, and has a strong tradition in The Netherlands. It would be possible to provide added value to existing studies by concentrating even more on temperate and sub-Arctic climates where groundwater and snowfall play an essential role, and by including the effect of vegetation adaptation (stomata, leaf area, plant type, species composition) on increased CO_2 levels and changing temperature and precipitation patterns. This topic requires close cooperation among hydrologists, atmospheric scientists, mathematicians (computational science), and plant physiologists and ecologists. This cooperation could be given form by focussing on the same experimental study areas.

4.2.2 Impacts
The impacts of climate change on the hydrological cycle have been studied worldwide since 1990. Most of the studies have concentrated on changes in runoff regime (runoff volumes, frequency and magnitude of floods). More recently, research has also included the impacts on ecology, social systems, and water management, as well as other components of the water system, such as nutrients, carbon, and sediment transport. The Dutch hydrological community has a strong research tradition in this field, particularly the groups that participate in The Netherlands Centre for River Studies NCR. The most recent developments include the coupling of river basin hydrological models with socio-economic models to study the interaction between hydrology, water management, and society under changing climates.

Given the expertise in The Netherlands, the following major research topics should be pursued:

Impacts of climate change on the hydrology of large river basins, including local and basin-wide water management.
This topic entails studying the effect of predicted climate change on stocks and fluxes of water, sediments and nutrients in river basins, studying runoff and sediment generation mechanisms and evaluating mitigating and adaptation strategies in water management. New venues of research are the inclusion of groundwater dynamics in large-scale hydrological models, the study of sub-Arctic hydrological systems (where changes are expected to be largest) and the coupled modelling of meteorological, hydrological, and socio-economic aspects. Hydrologists should work together with experts on fluid mechanics, river morphologists, ecologists, meteorologists, water managers, and social scientists.

Understanding impacts of climate variability on water and sediment stocks and fluxes on a geological time scale.
Many Paleo-environmental reconstructions are based on proxy data, sedimentary records, and qualitative geological models. The response of discharge regime, sediment yield, and groundwater regime to changes in temperature and precipitation are either assumed or based on simplistic hydrological rules of thumb. Paleohydrology could play a major role by providing realistic assessments of changes in the hydrological cycle due to changing climatic inputs. This topic requires the co-operation of hydrologists, quaternary geologists, climate researchers, geologists and biogeologists, and ecologists.

Climate change and droughts.
Hydrological impact studies of climate change have focussed mainly on floods. However, in many parts of the world, climate change is expected to increase the frequency and duration of droughts as well. In the case of water-limited systems (mostly semi-arid regions), only meteorological drought (precipitation) and agricultural drought (soil moisture) are involved. But even in temperate climates such as in The Netherlands, hydrological drought may be important too, as it results in low discharges and groundwater levels. Initial droughts may show persistence and affect seasonal climate due to a negative feedback loop of sequential reduction of soil moisture, evaporation, and precipitation. Hydrological drought has a negative influence on the availability of drinking water and irrigation water, the navigability of rivers, and the quality of wetland ecosystems. Most importantly,

hydrological drought can be very persistent, sometimes lasting several years in the case of large groundwater bodies. Understanding the nature of hydrological droughts (i.e. associated thresholds and non-linearity) is vitally important, if the effects of climate change on water availability are to be quantified. To assess the spatio-temporal persistence of drought events, and possibly the effects on water quality, the dynamics of the groundwater system should be included in the analysis.

4.2.3 Feedbacks

Feedbacks between the terrestrial part of the hydrological cycle and the atmosphere are abundant. One well-known example, which is most prominent in continental climate zones, is the positive feedback between soil moisture content on the one hand, and precipitation and temperature of the lower atmosphere on the other. Another example is increasing continental runoff in the Arctic due to climate change, which influences the occurrence of sea ice and thermohaline circulation, which in turn may impact regional climate. To fully understand these feedback mechanisms, it is important to have a realistic representation of hydrological processes in the land surface and boundary layer components of atmospheric circulation models. Research is currently being carried out on these topics. The Dutch hydrological science community, with its experience of modelling hydrological processes in a variety of climatic zones, will be able to contribute to land surface studies
Two important topics that should be studied by Dutch hydrologists are:

Complexity, heterogeneity, and feedback mechanisms.
Strong positive feedbacks between the land surface and the atmosphere were initially observed in results of atmospheric circulation models coupled with simple land surface parameterisations. However, when the land surface schemes were improved by calibration with new data sets, by adding complexity (more hydrological processes) and heterogeneity (spatial variation and subgrid variability), the strength of these positive feedbacks seemed to diminish. The same tendency has been found in spatially explicit ecological models of pattern formation. The question that arises is whether the observed positive feedbacks exist in reality or if they are an artefact of the models used. Investigating this requires performing systematic sensitivity studies using coupled land surface atmosphere-models with varying degrees of complexity and heterogeneity. Also whenever possible, long-term records of climate and land use change can be used to provide further empirical evidence. A related question is: what is the level of complexity needed

to realistically represent land-atmosphere coupling? This type of research must involve cooperation among hydrologists, ecologists, atmospheric scientists, and mathematicians. The latter can contribute with their knowledge of the analysis of coupled and non-linear dynamic systems. Ecologists can contribute their experience in dealing with positive feedbacks in ecological modelling, not least because vegetation plays an important role in soil-moisture-atmosphere coupling. This research theme has strong ties with the priority theme 'Hydrology and Geo-ecosystems', where studies on the spatial variation of soil moisture, soil temperature, vegetation pattern and structure, runoff and evaporation can serve as a source of inspiration for how to represent subgrid variability in land surface models.

Groundwater-soil moisture-atmosphere coupling.
Many atmospheric circulation models overestimate the positive feedback between soil moisture storage and the atmosphere, leading to overly dry soils and excessively high temperatures even at the start of the dry season. One possible cause of this artefact may be that no lateral redistribution of subsurface water is allowed in the land surface models. Including lateral redistribution of groundwater may keep soil moisture (through capillary rise) and atmospheric moisture (through evaporation) at higher levels during the dry season, and consequently correct for unrealistic soil moisture depletion and temperature rise. Moreover, groundwater storage represents a large water volume that may be evaporated or replenished by precipitation, with typical time scales clearly extending beyond a single season. It may therefore be important to include the groundwater reservoir in simulations of the climatologic hydrological cycle when variability at multi-year time scales is of interest. Based on these considerations, one may argue that atmospheric circulation models should be improved by including groundwater dynamics using a groundwater flow model. Virtually no research has been done on this subject, and the Dutch hydrological community, in combination with atmospheric scientists and numerical mathematicians, can definitely make significant contributions in this area.

4.3. Hydrology and Geo-ecosystems

Geo-ecosystems are coupled systems within which there is a powerful interaction between the ecosystem and pedological, geological, and hydrological processes. Geo-ecosystem science aims to understand how earth surface processes work and interact in a dynamic landscape by analysing the evolution of landscape ecosystems over various temporal and spatial scales. A major sub-discipline of geo-ecosystem science is ecohydrology. Ecohydrology seeks to describe the interaction between hydrological and ecological patterns and processes. This interaction takes place at a multitude of scales.

Critically, the resilience of geo-ecosystems depends on the existence and strength of a large number of feedback and interaction mechanisms. Small but persistent changes in the environment, e.g. water availability in the root zone, sediment transport, and nutrient availability, can have large amplified effects on the stability of geo-ecosystems. Major, sudden changes may induce scale shifts and catastrophic behaviour. At larger scales, the interaction between landscape elements and the atmosphere determines the climatic boundary conditions for ecosystem development. Deforestation and desertification studies with GCMs have provided ample evidence for the existence of such feedbacks.

Understanding the (eco)hydrological processes behind the vulnerability and resilience of coupled geo-ecosystems and hydrology is one of the key challenges for the Dutch hydrological community in the next 10 years. Developing this theme requires close collaboration between hydrologists, meteorologists, mathematicians, geomorphologists, pedologists, ecologists, geochemists and biogeochemists. This is an area in which the Dutch hydrological community has an excellent track record and can make significant contributions to the development of an emerging hydrological science.

We can identify two related subthemes:

- Patterns and complexity in landscapes.
- Interaction between land use, surface hydrology, biogeochemistry, and climate.

4.3.1 Patterns and complexity in landscapes

Vegetation and the underlying geology are in constant interaction. For instance, root systems develop and change the soil and the underlying medium structure (soil catena development), while nutrients provide the building material for vegetation to develop. This interaction has a major effect on hydrological processes taking place along hillslopes. Hillslope properties are not randomly distributed within catchments, but are the result of geomorphological, geological, pedological, and ecological processes. These interactions take place at time scales ranging from one to several thousands of years.

We can identify three related research questions:

- What are the controls on hillslope-scale redistribution of water and is there spatial organisation of these controls?
- Are the observed patterns of vegetation the result of prevailing heterogeneity of landscape, climate, and soil, or of self-organisation?
- New avenues for ecohydrological modelling in the Earth System.

Controls on hillslope-scale redistribution of water and responses of ecosystems to such flow processes.
Ecosystems have a major controlling effect on the fluxes of evaporation from catchments. In turn, these fluxes determine the magnitude and variability of soil moisture, and thus to a large extent influence the generation of runoff. Vegetation influences soil hydraulic properties, which in turn influence water transport and erosion-sedimentation patterns. These processes not only determine the *co-evolution* of landscape and ecosystem, but also the overall hydrological behaviour of catchments. The development of landscape-scale flow equations that take into account the spatial structure of first-order controls of water mobility should provide new insights into travel time distribution within catchments. The resulting moisture patterns at landscape scale determine ecosystem growth and resilience. Results from these research efforts can also be used as input for a more global assessment of climate change on water and sediment stocks and fluxes (see Section *4.2.2*).

Observed patterns of vegetation: the result of imposed heterogeneity of landscape, climate, and soil, or of self organisation?
The occurrence of patches of vegetation alternating with patches of bare or almost bare soil on multiple scales is a common feature in semi-arid areas. Many arid and semi-arid ecosystems are resilient to periods of drought. The vegetation cover appears to be more sensitive to temporary climate change than vegetation in other climate zones. The redistribution of surface water is regarded as an important factor in determining spatial plant distribution. Rain falling on bare patches of soil will fail to infiltrate and will run off. This runoff water subsequently accumulates in the vegetated patches, where it can infiltrate more easily with the spatial distribution of soil particles, organic matter and nutrients. Recent analytical work, based on self-organisation principles, shows considerable promise for developing a more general theory of stability that can identify possibilities for scale shift and scale slides as well as catastrophic switches to new stable states. Collaboration with ecologists and mathematicians is a prime requirement. Again,

the question is whether omitting complexity and spatial heterogeneity will lead to an overestimation of self-organisation. Insights into this matter should be shared with similar research efforts conducted in the Feedbacks part of Hydrology and Climate (Section 4.2.3).

New avenues for ecohydrological modelling in the Earth System.
The current generation of global land surface or vegetation models is largely based on local process descriptions. This has led to models that are inherently complex, and often difficult to parameterise. The question arises as to what level these local processes need to be taken into account to study vegetation-climate interaction. There appear to be strong within-plant trade-offs (e.g. leaf longevity, leaf size etc.) that constrain the range of successful combinations of physiological properties. It also appears that key chemical, physiological and structural leaf properties exist in a continuum that operates largely independent of growth form, climate and plant functional type. This suggests that common fundamental 'building blocks' underlie the large variation in biomes around the world. This knowledge can be used to build a new generation of land surface models. These models would consider the world's ecosystems as local or regional optimal configurations of these physiological building blocks (ecological and hydrological optimality theory would be starting point for analysis). The limited range of combinations of plant functional properties observed in the real world strongly suggests that self-organisation may be a key factor in shaping these configurations. It is important to gain a better understanding of the constraints and interactions that operate in geo-ecosystems so as to be able to predict sensitivity to future environmental change.

4.3.2 Interaction between land use, surface hydrology, biogeochemistry, and climate
Modelling studies have highlighted the impact that ecosystems can have on weather and climate patterns. Regional scale studies have provided insights into the interaction of ecosystems with climate at the scale where land surface changes (and ecosystem disturbances) occur. Unlike global studies that often model rather idealised and extreme conditions, regional studies can be used to simulate real changes that occur in man-made landscapes. Additionally, at the local, site scale, there is extensive empirical evidence of how ecosystems modify their hydrological environment and climate.
We can identify the following three research questions:
- How does the interaction between land use (or land-use change) and hydrology affect the vulnerability and stability of geo-ecosystems?

– What are the interactions between the hydrological cycle in ecosystems and main biogeochemical cycles of the earth?
– How do interactions among landscape, hydrology, and the underlying geomorphology produce resilience in coupled geo-ecosystems and influence biodiversity?

The interaction between land use (or land-use change) and hydrology, and its effect on the vulnerability and stability of geo-ecosystems.
Climate variations cause changes in vegetation cover, which in turn change the hydrological cycle and thereby the climate itself. Long-term modelling studies show that multiple equilibria for vegetation may exist and that sudden chaotic switches may occur. The existence of these multiple equilibria is something of a new finding, and there is still little to support empirical evidence. New paleo-climate studies in combination with paleo-ecological and paleo-hydrological studies are urgently needed to provide further empirical evidence. Together with mesoscale modelling studies, new insights can be gained into the effects of regional scale land surface changes on the atmosphere.

Interactions between ecosystems, the hydrological cycle, and the main biogeochemical cycles of the earth.
Understanding and modelling the relationship between water and other biogeochemical cycles is arguably one of the great challenges hydrology will face in the next decade. How does vegetation optimise the trade-off between carbon uptake and water loss? What is the interaction between water availability, soil moisture, and key geochemical processes in producing nutrients for growth? These questions themselves are not new, but the existence of new data sets that allow testing at ecosystem level gives a totally new impetus to this question. Soil moisture also plays an important role not only in ecosystem assimilation, but also in respiration control of Mediterranean and semi-arid ecosystems. At the global scale, mutual sensitivities have been identified between carbon sequestration and loss, climate change, and rainfall. These sensitivities are poorly understood, while understanding them is required for management purposes and global change studies. While there may be great potential for reducing CO_2 emissions in, for instance, exploited fen meadow ecosystems, in wet mires and fens, increased emissions of CH_4 could partially undo the mitigating effect of CO_2 fixation. Similarly, the magnitude and timing of nitrous-oxide emissions are poorly understood and appear to depend on soil moisture levels. These interactions are poorly understood and need to be investigated in greater depth.

Resilience and biodiversity of ecosystems; interactions between hydrology, geomorphology and climate.
Several studies have suggested the vulnerability of ecosystems to climate change. Such predictions are controversial because they ignore several feedbacks that could result in considerable resilience of the ecosystems. These feedbacks are poorly understood. Many of the current disturbance studies for tropical rainforests are still inconclusive, as they focus on single processes and ignore the multiplicity of interactions between hydrology, geology, ecosystems, and climate. A more integrative analysis is required that accounts for the way in which hydrological systems amplify or attenuate the impacts of environmental change. Such an analysis should also account for differences between geographical areas in terms of geomorphology, climate, and ecosystem response. Key issues to be addressed are the identification of the interaction mechanisms in the evolution of landscape and ecosystems, the relevant scale at which they start to operate, and the effect of these on ecosystem sensitivity to environmental change.

Worldwide, the number of species is declining dramatically. Natural regulation of hydrological flows, storage and retention of water, retention of soil within a river catchment, and soil formation are depend to a great extent on fully functional ecosystems, which in turn depend on appropriate levels of species and genetic diversity. It is important to appreciate that ecosystems provide human beings with essential services, such as the provision of fuel wood and clean drinking water. The sustainability of water resources also requires management practices that safeguard the biodiversity of catchments. However, key links between functional biodiversity and hydrological functioning are not well understood. A key question is what level of biodiversity is required for proper (i.e. including the sustainable provision of essential services) hydrological functioning of a catchment? How does hydrological behaviour change with changing land use or other human impacts? Can we restore the biodiversity of over-exploited catchments, and do we understand the relevant time scales of change and stability and the interaction of hydrology with ecosystems sufficiently well?

4.4 Hydrology and Geo-environment

A large portion of the world population lives in deltaic regions, which are almost always flat and low lying, and where there are strong interactions among surface water, groundwater, and the sea.Intensive human activities (urban, agricultural, and industrial) result in a heavy demand for fresh water resources and put major stresses on water quality. Despite stricter environmental regulations for both industry and agriculture, in the past century intentional and accidental industrial spills and extensive use of pesticides and manure have led to large-scale pollution of the subsoil, the groundwater, and the surface water. Moreover, enormous changes in groundwater flow patterns, brought about by human activities, have also greatly disturbed pre-existing hydrogeochemical conditions, often leading to deteriorating water quality. A typical example is the mobilisation of arsenic in Bangladesh groundwaters.

A recent survey has shown that there are some 600,000 sites in The Netherlands which are possibly polluted. Of these, about 10% (that is, on average, about two sites per km^2) need to be cleaned up. Many of the polluted sites have been caused by accidental spills of organic liquids. The country's flatness means that polluted groundwater can contaminate surface water and vice versa. Other threats to the geo-environment in densely populated countries come from plans for subsurface construction activities as well as storage of energy, radioactive waste, chemical waste, and carbon dioxide in deep geological formations. Examples of underground constructions in The Netherlands are two major railway lines and networks of pipelines for the transport of gas and other substances. Risk assessment of such storage facilities should obviously take into account the possibility that hazardous wastes may be released into the environment.

Another issue of major concern in deltaic areas is salt water intrusion, which can cause deterioration of the quality of both surface and groundwater. The possible rise of the sea level due to climate change will obviously aggravate this situation.

In order to make progress on solving the various problems described above, we must perform research in various areas of geo-environmental hydrology. Obviously, a host of research questions need to be studied. To achieve a focussed programme, a selection of most relevant research questions have been grouped into the following four fields of interest:

- Interaction of surface water and groundwater. This plays a major role in all cases dealing with the availability and contamination of fresh water resources.
- Improved theories for multiphase flow. The knowledge of multiphase flow processes is essential for the analysis of pollution caused by spills of organic liquids, in studies of the sequestration of CO_2, and in the assessment of the role of natural gas transport, such as radon, methane, and nitrogen oxide, in groundwater systems.
- Density-dependent flow and transport. This plays a central role in saltwater intrusion problems, infiltration of leachates from landfills into the subsurface, and energy storage.

– Multiscale reactive transport. This is an area of research where small-scale instabilities in reactive processes have to be studied at a variety of scales.

Some aspects of these research areas have received considerable attention in the past few decades, and Dutch hydrologists have made substantial contributions to research. However, many important and fundamental questions still need to be answered to provide a scientific basis for environmental policies, the sustainable development of soil and water resources, and the evaluation of events such as rising sea levels in deltaic areas.

Research on the topics identified above must be carried out using diagnostic and prognostic models with a sound scientific basis. These models should enable us to understand and predict the fate of natural and anthropogenic substances in surface and subsurface water. However, our ability to model transport processes in the geo-environment has been hampered by three main characteristics of these systems: nonlinearity, coupling, and heterogeneity.

Therefore, the major challenge when studying the four research topics identified here is to develop rigorous and physically-based theories for describing coupled non-linear hydrological processes at various scales and to improve field characterisation of hydrological systems. Research on these topics requires the close collaboration of hydrologists with chemists and geochemists, geologists and biogeologists, and mathematicians. The contribution of chemists and geochemists will be in the description of reactive processes such as those occurring within bottom sediments of surface waters and under landfills. Input from microbiologists is needed in the research on biodegradation and natural attenuation. The role of geologists and geophysicists will be in the characterisation of heterogeneity. Mathematicians will contribute to the analysis of non-linear partial differential equations, numerical methods and upscaling theories such as homogenisation.

4.4.1 Interaction of surface water and groundwater

In deltaic regions, there is a strong interaction between surface water and groundwater due to the high density of surface water elements (brooks, ditches, streams, canals) and the shallowness of groundwater table. Groundwater hydrologists usually treat the surface water system as a boundary condition, while surface water hydrologists use the groundwater interaction as a source/sink term in the water balance. Obviously, this approach is too simplified. Surface and groundwater systems cannot be separated, as there is a two-way coupling, particularly regarding solute transport.

Consider a typical situation in The Netherlands. Plots of agricultural land and/or pasture are criss-crossed by ditches, streams, and canals, which are in contact with the shallow groundwater. Precipitation causes overland flow and transport of fertilisers, pesticides, manure, etc. to the surface water system, where a partial mixing of solutes occur. The pollutants are then transferred to the groundwater through permeable sediments at the bottom of streams. These bottom sediments have dimensions of only a few centimetres. Nevertheless, they have a great influence on the transfer of reactive solutes to the groundwater and, as a result, on their spread through the subsurface. There are large gradients in concentrations (of oxygen and solutes) across them, and they are the site of much biological activity. The boundary layer is therefore the site of processes of biodegradation under highly variable conditions, chemical reactions, and transport by advection and diffusion/dispersion, mostly enhanced by bioturbation. These processes are strongly coupled and highly non-linear.

In practice, we do not need details of the concentration distribution overland, in individual surface water elements, or across the bottom sediments. Rather, we need to know average concentrations and fluxes of solutes in surface water and groundwater. Therefore, appropriate theories are needed for modelling these coupled systems at the scale of plots, taking into account the controlling role of the processes that occur within bottom sediments.

Another major problem in modelling these systems is the discrepancy between scale and measurement. Monitoring the distribution of different species (including bacteria) across the bottom sediment layer requires the use of very small probes. However, it is virtually impossible to model the bottom sediment in detail at the scale of a lake or a river reach. Modelling of the groundwater-surface water interaction therefore requires rigorous upscaling of the coupled non-linear processes in these sediment layers, taking into account the spatial and temporal physical, chemical and biological heterogeneity of the layer.

Major research questions include:

- How should small-scale physical and biogeochemical processes within the sediment layers at the bottom of surface water systems be modelled, taking into account very large temporal and spatial variations in fluxes and concentrations?
- How should these small-scale processes and conditions be characterised or measured in the field?

– How should the small-scale information be transferred to the large-scale groundwater-surface water models?

4.4.2 Improved theories for multiphase flow

Multiphase flow in porous media (including vadoze zone) constitutes a complex system involving the flow of two or more immiscible fluid phases, as well as the spread and exchange of many constituents in these phase. The constituents undergo processes such as dissolution, adsorption, volatilisation, and biodegradation. The performance of current models of two-phase flow has been typically unsatisfactory in geo-environmental applications. This is to a large extent due to the lack of rigorous theories that are applicable at different scales. In particular, research is needed to develop a scale-dependent capillarity theory, including hysteretic effects. In addition, fingering due to instabilities and the occurrence of preferential flow paths need to be investigated and quantified. In projects relating to the storage of CO_2 in deep formations, coupling of multiphase flow with geochemical and deformation processes must be considered. This is a growing area of research that deserves special attention.

One of the main questions in the study of polluted sites and the design of remediation projects involves establishing the presence, location, and amount of organic liquids in the subsurface. So far, this question has remained unanswered due to the lack of experimental methods and reliable theories.

Major research questions include:

– How should capillary pressure and relative permeability curves measured in small-scale laboratory experiments be adapted for use in large-scale models?
– How should basic theories of two-phase flow be modified in order to take into account small-scale heterogeneity?
– How do biogeochemicial processes affect the fate of organic liquids in soil and groundwater?
– How should processes such as fingering and preferential flow be modelled?
– What is the role of natural gas transport in soil and groundwater systems and how should health threats be quantified?

4.4.3 Density-dependent flow and transport

In most environmental systems, the flow of water is not affected by the transport of dissolved solutes. But in a number of situations, there is a coupling between the flow and transport, mainly through variations in fluid density due to gravitational effects.

A well-known example is salt water intrusion in coastal areas, which is of great significance in deltaic regions. In the case of salt water intrusion, and in general when water density variations are large, the classical dispersion theory needs to be revisited. The coupling between small-scale heterogeneity and gravitational forces is known to result in a non-linear dispersion behaviour. As yet, an adequate upscaled theory of dispersion for high concentration situations is lacking, however.

A more complicated situation arises in relation to the possible transgression of coastline due to climate change. In such an event, heavy salt water can override fresh water and create a hydrodynamically unstable situation. It is difficult to model such systems because, on the one hand, the dynamics of the growth of instabilities at the local scale are not well understood and appropriate theories have yet to be developed, and, on the other, there is no larger-scale description of the unstable mixing zone.

Another important situation arises in aquifers where reactive transport processes result in variations in water density. This can occur, for example, under landfills and harbour sludge depositories. This is obviously a highly complex system; reaction processes can cause a change in water density, resulting in the change of flow patterns, which in turn affects the distribution of reactive solutes.

Major research questions include:

- What is an appropriate non-linear dispersion theory that accounts for the coupling between small-scale heterogeneity and gravity effects at high concentrations?
- What is the dynamics of gravity-induced fingers in unstable situations?
- How should small-scale reaction instabilities be upscaled?
- How is hydrogeochemical transport affected by variable-density flow in coastal aquifers?

Dutch hydrologists have traditionally played a prominent role in research in this area, in particular in the study of seawater intrusion problems. A number of well-sited experimental and theoretical studies have also been carried out on basic theories of large concentration transport. Closer collaborations among hydrogeologists, geochemists, and mathematicians will result in significant contributions in this area.

4.4.4 Multi-scale reactive transport

Groundwater commonly contains many dissolved substances of natural or anthropogenic origin. The majority of these substances are reactive and interact with each other as well as with soil grains. The spread of these components through the environment is governed by a large number of physical/chemical/biological processes and the strong heterogeneity of the subsurface on multiple scales. Almost all reactive processes occur at the scale of pores and grain surfaces. However, their effect needs to be determined and quantified at a much larger scale. Currently, in models of reactive transport, mass or heat exchange processes are predominantly assumed to be in equilibrium at all scales. But there is ample theoretical and experimental evidence that larger scale equilibrium does not exist. This is particularly true in adsorption/desorption, heat transport, dissolution, and redox processes. The question then is whether processes that are in equilibrium at the micro scale can be modelled as such at a larger scale.

Another major question which has yet to be answered relates to the class of reactive processes that can occur only if a threshold value is surpassed. Examples are precipitation of dissolved inorganics and some bacteriological processes. While the threshold value is a microscale property, the modelling is based on average values defined at larger scales. Thus, it could happen that according to average values the process will not occur, whereas locally the threshold value could have been surpassed at various places, and the process will occur.

Major research questions include:

- How should local (equilibrium) processes be modelled at larger scale?
- How should lab measurements of (equilibrium) coefficients be adapted to be used at a larger scale?
- How should large-scale models take into account local threshold values?
- What is the correlation between chemical and physical heterogeneity?
- How should the effect of chemical/bacterial processes on physical properties (as they occur, e.g., in clogging, dissolution, CO_2 sequestration) be taken into account?

A number of research groups within Dutch universities and research institutes have been successful in this area. Collaboration among these groups, which are active in hydrogeology, aquatic chemistry, geochemistry, microbiology and mathematics, must be strengthened in order to force new breakthroughs.

Interactions of the Atmospheric Boundary Layer with the Land Surface
Bert Holtslag

The characteristics of the Earth's surface strongly influence the motions and processes in the lower part of the atmosphere, known as the Atmospheric Boundary Layer (ABL). Wind friction usually causes turbulence in the ABL, and this increases with the roughness of the surface. Over relatively warm surfaces, the ABL is heated from below and convection may greatly amplify the environmental turbulence. On the other hand, over relatively cold surfaces the presence of turbulence may vanish completely due to the cooling of the ABL. Thus the climate in the atmospheric boundary layer depends largely on the presence of turbulence in response to the surface characteristics and the atmospheric flow above the ABL.

Turbulence has a direct impact on the transfer between the surface and the atmosphere of momentum, sensible heat, water vapour, ozone, and methane, among many other quantities. Turbulence also defines the mixing of properties inside the atmospheric boundary layer, the transfer of quantities between the boundary layer and the clear or cloudy atmosphere above, and the mixing inside clouds. The surface temperature over sea is rather constant on the time scale of a day, while over land the surface temperature may vary considerably due to solar downward radiation and long wave cooling of the surface. This has important implications for the turbulence and the processes in the ABL.

Figure 4 (after Ek and Holtslag, 2004) gives a schematic illustration of the relevant processes and interactions in an ABL over land during daytime conditions. In such conditions, the sensible heat arising from the surface supports a growing boundary layer with a rising temperature. This may be amplified by the mixing of warmer air from above the boundary layer, known as 'entrainment'. Given a certain value of specific humidity in the ABL, a rising temperature in the ABL means a lower value for the relative humidity (RH). This normally implies greater evaporation or transpiration (latent heat flux) from the surface given that sufficient soil moisture is available. However, the energy for sensible and latent heat at the surface is limited by the available net radiation and soil heat flux. These variables depend in turn on the characteristics of the surface and the temperature and moisture conditions in the soil.

The above illustrates that the coupling of the ABL to the land surface is rather complex and depends on many variables. In general, the correct modelling of the different processes and feedbacks is not at all easy, certainly not for the complex situations which may occur in reality. In any case, to understand and to correctly model boundary-layer climates as well as the feedbacks in the coupled land-atmospheric system, a realistic model of both the atmospheric boundary layer (ABL) and the land-surface (LS) is needed. Based on a realistic and coupled land surface – atmospheric boundary layer model of this kind, we can, for example, explore the interaction of the land-surface with the ABL and the effect on boundary-layer cloud development. As such, we can focus on the role of soil moisture and consequently can make a series of model runs where we change the soil moisture from dry to wet conditions under a variety of environmental conditions.

By doing so, it can be shown that the effect of soil moisture is typically to increase the tendency of relative humidity (RH) at ABL top and thus the potential for ABL cloud formation (confirming intuition), but this occurs only if the stability of the air above the ABL is not too weak (and given sufficient initial RH in the ABL and air above the ABL that is not too dry). Alternately, for weak stability above the ABL, drier soils yield a greater tendency for RH at ABL top, and thus the potential for ABL cloud formation (somewhat counter-intuitive). In this case, soil moisture acts to limit the increase of relative humidity at ABL top. It is then the largest values of ABL top RH tendency that are predicted over dry soils. This can be illustrated with analytic studies confirmed by many runs with a full model (Ek and Holtslag, 2004[1]).

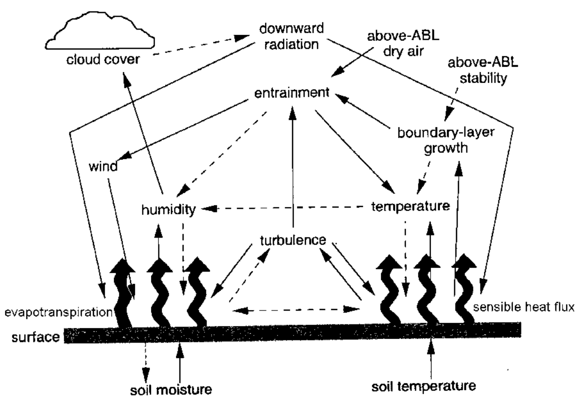

Figure 4. Diagram showing important interactions between the land-surface and atmospheric boundary layer for conditions of daytime surface heating (Ek and Holtslag, 2004). Unbroken lines indicate the direction of feedbacks, which are normally positive (leading to an increase in the recipient variable), while dashes indicate negative feedbacks. Two consecutive negative feedbacks make a positive one. Note the many positive and negative feedback loops, which may lead to increased or decreased humidity and cloud cover.

[1] Ek, M. B., and A. A. M. Holtslag, 2004: 'Influence of soil moisture on boundary layer cloud development'. *Journal Hydrometeorology,* 5, 86-99.

5. Education Programmes in Hydrology

5.1. Introduction

Since the introduction of the Bachelor-Master (BaMa) system in The Netherlands in 2002, a number of MSc programmes in Hydrology have been launched. Although the development of these programmes seems to be well under way, it is too early for an evaluation and comparison of their content.

Two-year MSC programmes (120 ECTS) in Hydrology are offered at four universities: Vrije Universiteit Amsterdam (VU Amsterdam), Delft University of Technology (TUDelft), Utrecht University (UU), and Wageningen University (Wageningen UR). The UNESCO-IHE Institute for Water Education in Delft offers an 18-month (106 ECTS) MSC programme in Hydrology.[2] At the Universiteit van Amsterdam (UVA) and University of Twente (UT), hydrological components are part of other MSc programmes. See Annex G for details.

MSc students are graduates of the new Bachelor programmes (mainly from the same university) or come from foreign BSC and MSC programmes or higher professional education programmes in The Netherlands (Dutch *HBO*). Currently, the four hydrology programmes each attract 15-20 students per year, of which

[2] Students at UNESCO-IHE originate from developing countries and countries in transition, and are required to possess a university BSc plus at least three years of relevant practical experience. The hydrology progamme attracts 20-25 students per year, of which approximately 20% is female.

around 40% are foreign students, mainly men. About 40% of the student population is female. All four universities expect a growing number of hydrology MSc students, up to 30 per year at each university, and a larger number of women and foreign students.

The main admission requirement is a BSc or '*HBO*' degree in a relevant discipline, such as civil, agricultural or environmental engineering, and geosciences. Sometimes (especially with foreign students), the educational background may not correspond. In such cases, the students need to follow extra convergence courses. However, an even bigger problem for excellent foreign students who wish to study hydrology in The Netherlands is the lack of grants or scholarships available to them. If a grant system is developed to overcome this problem, the intake of excellent foreign hydrology students may rise considerably.

Within The Netherlands, graduate studies leading to PhD degrees in hydrology are being pursued in the framework of four different research schools: Centre for Technical Geosciences (CTG), Centre for Geo-ecological Research (ICG), Netherlands Research School of Sedimentary Geology (NSG) and the Netherlands Research School for Socio-Economic and Natural Sciences of the Environment (SENSE). Detailed descriptions of the focus areas of these Research Schools can be found on their webpages (see also www.KNAW.nl/cfdata/ecos/technisch.cfm, www.KNAW.nl/cfdata/ecos/ aardwetenschap.cfm). An important aspect here is the collaboration with other earth sciences. There is also close cooperation with foreign researchers. Unfortunately hydrological research is not adequately embedded in the research programmes of these schools.

5.2 Specialisations

The main components of the five MSc programmes in hydrology are common: course work, field work, traineeship, and thesis. There are, however, major differences in compulsory and optional courses and their subjects. The differences reflect the specialisations of the corresponding hydrology groups. An overview of compulsory BSc and MSc courses at various universities is given in Annex G.
A short description of specialisations offered in the four MSc programmes in hydrology is given here:
Delft University of Technology's specialisations:
- Hydrology: problem solving (engineering) character. Delta's, rivers, high waters.
- Land and Water Management: this track will be omitted from this list.

Utrecht University's specialisations:
- Earth Surface Hydrology: processes at the earth's surface; watershed hydrology; stochastic hydrology.

– Environmental Hydrogeology: environmentally-related processes in the subsurface, groundwater flow; transport of dissolved matter and energy; multiphase flow.

Vrije Universiteit's specialisations:
– Ecohydrology: e.g. carbon cycle, climate change.
– Hydrogeology: integrated hydrogeological systems analysis; field methods and characterisation; flow and transport processes; isotope and tracer hydrology; geological, climatic and human influences; paleohydrology.

Wageningen University's specialisations:
– Soil Physics, Ecohydrology and Groundwater Management: soils; unsaturated zone hydrology; agricultural and ecohydrological components; relationship with vegetation.
– Hydrology and Quantitative Water Management: catchments; hillslopes; soil moisture; hydraulics; hydrogeology; hydrometeorology.

Universiteit van Amsterdam has a BSc programme in hydrology but has no separate MSc programme. The MSc programme 'Computational Bio- and Physical Geography' contains hydrological components. This MSc is focussed on modelling and the study of semi-arid regions, desertification and erosion.

University of Twente: The MSc programme 'Civil Engineering and Management' contains hydrological components. The specialisation 'Water Engineering and Management' within this MSc programme focuses on physical processes in river, coastal and marine systems and quantitative and qualitative tools for management.

UNESCO-Institute for Water Education's specialisations:
– Surface water hydrology: catchment hydrology, hydrological processes, monitoring.
– Groundwater hydrology: water resources assessments, exploration and monitoring, pollution and transport.

UNESCO-International Institute for Geo-Information Science and Earth Observation's specialisations:
– Water resources: Water resources analysis and management, satellite hydrology, groundwater management, environmental hydrology, geo-information for coastal zone management and information systems for integrated water management.

5.3. Collaboration

The four MSc programmes at the Dutch universities briefly described above (and in Annex F) are complementary, as they cover different areas of hydrology. Currently, each programme attracts enough students. The university programmes each have the potential to be an international centre of higher education, while the focus of UNESCO-IHE is exclusively international. It is therefore not desirable for these programmes to be merged. It goes without saying, however, that collaboration among the four MSc programmes would be beneficial to hydrological education in The Netherlands. Because of the varied expertise of the hydrology groups, such collaboration will enrich all MSc programmes. An integration of the course programmes, however, is currently almost impossible because of the incompatibility of the scheduling systems. Still, it would be possible to collaborate on setting up joint field work, traineeship activities, and MSc thesis supervision. Joint summer courses could also be organised and indeed, plans for such courses have been already implemented.

5.4 Career prospects

There does not seem to be significant differences among Dutch Hydrology MSc students as far as their first job is concerned. Dutch hydrology students can be found in the following lines of work (percentages are estimates based on information from corresponding MSc coordinators):

– scientific research at universities and research institutes in The Netherlands (25-30%)
– management and policy work at Dutch local councils, provinces, water authorities ('polder boards') and ministries (40-60%)
– consultants, engineering firms, other industries (25%)
– secondary education, communication or informatics (< 3%)
– foreign institutions (5%)

Upon returning to their home country, UNESCO-IHE alumni usually continue in their positions in government organisations, universities, the private sector, etc. In general, within 5 to 10 years of their return, the majority of the alumni hold senior positions.

A growing number of students from foreign (European, African and Asian) countries are expected to come to The Netherlands in the coming years to study hydrology and then return to their own countries. Many of these regions suffer from widespread water problems. Dutch hydrology Master programmes have the potential to play a constructive role in training these students to solve these problems. Here, a grant system as mentioned earlier could play a stimulating role in attracting good students. Ideally, such a grant system should be supported and funded – at least in part – by research institutes and large consultancies. This will be beneficial to both sides. On one hand, the universities will be able to recruit high-quality students and thus increase the level of their educational programmes. At the same time, the students will work on the research institutes' projects as part of their MSc research, providing an inexpensive source of labour. The research institutes will then have the chance to offer jobs to the best of these students. Also, as students go back to their own countries, the institutes will establish a strong link which may lead to new international projects.

Gravitational instability: a mathematical approach
Hans van Duijn

When the presence of solutes affects the density of a fluid, gravity will induce a flow which may have a dramatic effect on the solute distribution. Roughly, we can distinguish two cases: (i) the density increases with respect to the direction of gravity, resulting in a stabilising flow; (ii) the density decreases with respect to the direction of gravity, inducing a destabilising flow. The second case often gives rise to unexpected solute patterns.

To be more specific, we are considering evaporation at the horizontal surface of a porous medium. This is relevant when describing the groundwater dynamics below salt lakes, where evaporation induces an upward movement of groundwater containing high concentrations of minerals. These minerals are deposited at the outflow surface, where they result in the formation of a salt lake. Directly below the lake, the flow pattern of the groundwater can be extremely complex. A diffusion/dispersion controlled boundary layer will be formed near the outflow surface which is of higher density then the fluid below. This raises the question of gravitational stability. If stable, this boundary layer grows to a finite thickness at equilibrium. However, numerical and Hele-Shaw experiments show that the boundary layer may become unstable due to perturbations and will break up into convection cells for the flow and fingers for the solutes. Critically, this depends on the values of the system parameters, combined into the Rayleigh number R.

In mathematical terms, the Rayleigh number R acts as a bifurcation parameter. For R to be sufficiently small (i.e. large enough evaporation), the boundary layer below the surface must be stable and the flow uniform in an upwards direction. Above a critical value of R, the system bifurcates to a convective regime. The shape and number of cells/fingers depends on the initial configuration and, of course, on the value of R. Figure 5 shows the L2 -norm of perturbations as a function of time.

Understanding the dynamics requires using a lower-order model approach. This involves reducing the original system of non-linear partial differential equations to a finite dimensional system of non-linear ordinary differential equations, leading to a significant reduction of the costs of the numerical bifurcation analysis. Some results are shown in Figure 6 for two characteristic patterns: rolls and hexagons. The hexagonal patterns corresponding to the upper stable branch in Figure 2 (right) are shown in Figure 7.

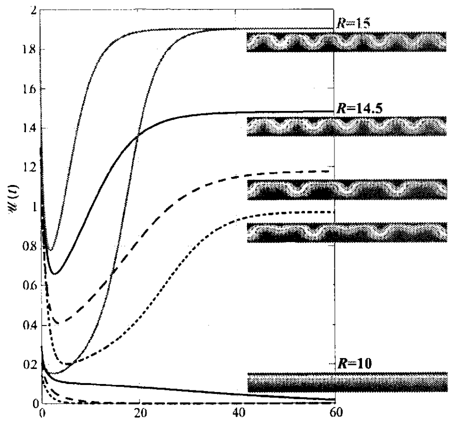

Figure 5. Behaviour of perturbations

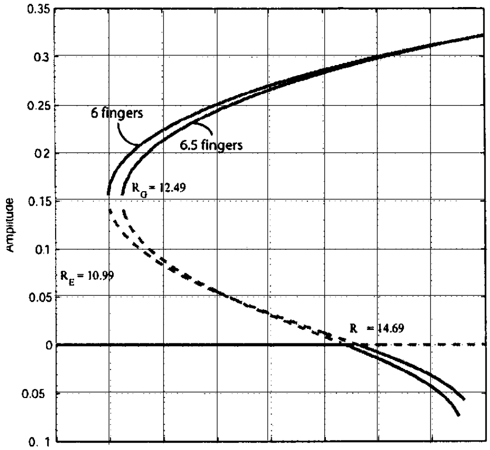

Figure 6. Bifurcations of rolls (left) and hexagons (right).

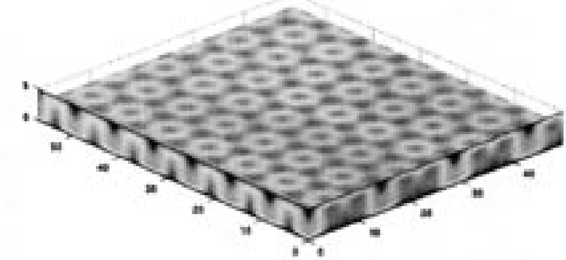

Figure 7. Hexagonal patterns

6. Research Infrastructure

6.1 Introduction

Sustainable solutions to various environmental problems must be based on sound knowledge. However, without a proper infrastructure, efforts to create and utilise knowledge would be very ineffective, if not impossible. Similarly, in hydrology, identifying most important research challenges and formulating a research strategy are necessary but not sufficient. We must develop the appropriate infrastructure which promotes and facilitates the advancement of hydrological research in The Netherlands. The pillars of such an infrastructure are formed by university groups and research institutes that are active in hydrology. However, there is more needed to create a strong framework within which the potentials of these research groups can be fully developed and exploited.

In order to provide a picture of the current situation, we have performed an analysis of strengths, weaknesses, opportunities, and threats (SWOT) for Dutch hydrological research and education. This analysis helps us to identify most critical shortcomings and most promising improvements in the existing situation. Thereafter, we suggest concrete solutions discuss them in detail.

6.2 SWOT analysis of Dutch hydrological research and education

Hydrological scientific research in The Netherlands is currently carried out at universities and seven research institutes. The main focus of the universities is on fundamental science and education, whereas the research institutes carry out strategic and/or applied research. Overviews of the hydrology groups at Dutch universities and the relevant research institutes and their areas of expertise can be found in Annex E. A SWOT analysis of Dutch hydrological research and education is given below. This analysis is based on the results of discussions at Expert Meetings and during interviews with scientists (both hydrologists and scientists from related disciplines).

Strengths

- Dutch hydrology has an excellent international reputation. A relatively large number of hydrologists who have graduated from Dutch universities are working at leading universities and research institutes in Europe, North America, Australia, and other parts of the world. It is said that 'hydrologists' are among The Netherlands' export products! In addition, many international meetings and conferences are regularly held in The Netherlands and Dutch hydrologists are frequently invited as keynote speakers at international meetings.
- Dutch hydrology education programmes have delivered both fundamentally-oriented scientists and practically-oriented hydrologists. These hydrology graduates are successfully employed by water companies, Dutch universities, research institutes, consultancies and government bodies dealing with water management.
- Each of the four university hydrology groups has established its own research 'niche'. Their areas of expertise are complementary and yet show sufficient overlap.
- There is a close link between MSc/PhD education and the research areas of the various hydrology groups. This has led to strong PhD and MSc programmes.
- Dutch hydrology university groups also have close relationships and/or collaborate closely with international researchers in hydrology. In particular, Dutch hydrologists have been very active as partners in EU projects and global change programmes.
- Many hydrology groups in The Netherlands have developed an active field research programme, in field sites inside and outside The Netherlands, including investigations of hydrological processes in humid temperate, semi-arid, and humid tropical catchments. Some of these field sites have been studied for many years and have produced important time series for theory development and model evaluation.

– There is fresh impetus to carry out innovative research and take the lead in the formulation of new hydrological theories and measurement techniques. This has resulted in an increase in the number of publications in refereed journals by Dutch hydrologists.

Weaknesses

– In spite of initiatives such as The Netherlands Hydrology Platform and the NCR, there is not enough structural collaboration among the fundamentally-oriented hydrological research groups. This is to a large extent due to the absence of an organisational structure (such as a research school) in hydrology.
– Compared to its prominent role in the international hydrological community, the visibility of Dutch hydrology within the Dutch scientific community is low. Indeed, given the geographic proximity in The Netherlands, the potential for scientific collaboration with scientists from related disciplines (meteorology, ecology, mathematics, soil sciences, geomorphology and geology) is under-exploited. This is also partly due to the absence of an organisation such as a research school.
– Dutch hydrological research is scattered over, and partially included in, four different research schools in earth sciences. Although this increases the potential for cross-disciplinary collaborations, it has resulted in the fragmentation of the research. Indeed, Dutch hydrological research at times seems to lack focus.
– Although there are a number of field sites for some areas of hydrological research in The Netherlands, there is no concerted measurement programme in a single field site. Bringing all field activities together in one field site would, in principle, increase efficiency and stimulate collaboration. This may not, however, be feasible. Instead, a mechanism for collaboration and data exchange should be created.

Opportunities

– Hydrology is interdisciplinary in character. It is in the nature of hydrological research to cooperate closely with disciplines such as ecology, geomorphology, mathematics, meteorology and soil physics.
– Within Dutch universities, the relevant related disciplines – and thus potential and qualified partners – are always in the vicinity.
– Increasing international (and national) water and climate 'problems' of a complex nature have highlighted the need for well-educated and experienced hydrologists as well as sound hydrological research. Here again, collaboration with other disciplines is vital.

– Dutch hydrological science is well known in the world and has an excellent reputation. Thus, there is a clear interest from colleagues in Europe and America, as well as developing countries, in collaborating with Dutch hydrologists on formal and informal research projects and educational programmes.
– Recent efforts to create strategic links between research institutes and universities (examples are: TNO-NITG with Utrecht University; Alterra with Wageningen University, KIWA-VU, UNESO-IHE-VU, UT-ITC, WL with TUD) have produced new opportunities for research and education in hydrology.[3]

Threats
– Funding for fundamental hydrological research is not compatible with the tasks and challenges ahead. Research funding comes from different sources and is not adequately coordinated. The available funding therefore tends to result in fragmentation of research and does not promote continuity of research in specific areas.
– Continuous budget cuts for universities and research will lead to the deterioration of laboratory facilities and will make it difficult to build new infrastructure.
– Dutch university boards – in their attempts to define a robust profile – stimulate national inter-university competition more than collaboration between groups from different universities.

Based on this analysis, we can identify two critical issues that must be addressed with a view to setting up a strong and robust infrastructure for hydrology research in The Netherlands. These issues are discussed in detail below.

1. Creating an effective structure for directing and prioritising hydrological research.
2. Developing the existing potential in MSc and PhD education.

6.3. Towards an infrastructure for directing and prioritising hydrological research and education

6.3.1 Introduction
The SWOT analysis above suggests that the ongoing hydrological research efforts in The Netherlands are not sufficiently focussed. This is partly because hydrological research groups belong to four different Research Schools and partly because much of the national funding for fundamental research is scattered over a number

[3] It must be cautioned, however, that bureaucratic unification may severely reduce the effectiveness, agility, and independence of university operations.

of different programmes. To strengthen hydrological research in The Netherlands and direct it to the priority themes identified in Chapter 4, a new kind of organisation is needed. In this section, we propose an organisational framework through an improved research infrastructure.

The first possibility that comes to mind regarding an infrastructure for hydrological research is the establishment of a research school in hydrology. The Foresight Committee, however, would argue against this option for a number of reasons. First, establishing a research school in hydrology would rupture the interdisciplinary research links already established between hydrologists and other geoscientists. Moreover, it will have a strongly negative effect on the PhD education programmes that have been established with great effort within the existing research schools.

Another idea is to try to establish programmes within the current research schools, focusing on the priority themes of Chapter 4. However, the research lines of the research schools are much broader than hydrology and as a result hydrology can be included only as a subsidiary discipline. What is therefore needed is a research infrastructure dedicated to the priority themes of Chapter 4 while advocating an interdisciplinary research approach to these themes. This could be best achieved within the framework of a scientific hydrology Centre as described below.

6.3.2 Boussinesq Centre for Hydrology

We propose to establish a national scientific hydrology centre called the *Boussinesq Centre for Hydrology.*[4] The *Boussinesq Centre* will be dedicated to focussing and strengthening hydrological research in The Netherlands, based on the priority themes identified in this report. It will also strive to create favourable conditions for an efficient multi-disciplinary research environment. It will be an umbrella organisation of the four university hydrology groups, at Delft University of Technology, Vrije Universiteit Amsterdam, Utrecht University, and Wageningen University, together with a number of groups from related disciplines that actively co-operate with hydrologists or are tackling hydrological-type problems. A complete list of these groups is given in Appendix F. The *Boussinesq Centre*

[4] Valentin Joseph Boussinesq (1842-1929) is an excellent example of an interdisciplinary scientist with groundbreaking contributions to hydrological sciences. He was a French physicist and mathematician and became a member of Académie des Sciences in 1886. Boussinesq has made important contributions to many branches of mathematical physics in general, and to hydrodynamics, in particular. His areas of research were hydrology, hydraulics, meteorology, oceanography, and mathematics. He studied groundwater flow, hill slope hydrology, the problem of liquid waves, the flow of fluids, the mechanics of pulverulent masses, the resistance of a fluid against a solid body, and the cooling effect of a liquid flow.

would thus employ at least 30 FTEs of scientific staff and approximately 45 PhD students. Technological research institutes (TNO-NITG, Alterra, WL-Delft Hydraulics, Geodelft, RIVM, etc.) may be included as associate members. The Centre will not be a hollow and bureaucratic organisation. Paperwork will be kept to a minimum, existing structures will be used as much as possible and efficiency will be maximised.

Steering research requires financial means, which entails that establishing a research funding programme is a necessary condition. We foresee starting with 20 new PhD research projects over a period of five years, jointly financed by the participating universities and by NWO-ALW. Research proposals should not only fit the priority themes, but should also be interdisciplinary in nature and combine hydrology with mathematics, ecology, meteorology, geomorphology, and/or soil science. Whenever possible, PhD students should have two supervisors, one from hydrology and the other from one of the related disciplines involved.

6.3.3 Major activities

Major activities of the *Boussinesq Centre* will be:

– Setting-up a River Basin Data and Modelling Centre (RBDMC) for strategically selected large river basins, with an emphasis on the Eurasian continent. Most, if not all, research questions formulated under *Theme 1: Hydrology and Climate* can be efficiently tackled only if the Dutch hydrological research community has easy access to databases of atmospheric forcing (past, present and future), land surface and subsurface characteristics (topography, soils, geology, land use) and hydrometeorological time series (precipitation, streamflow, groundwater levels, soil moisture, evaporation) for large river basins in different climatic settings. These databases make it possible to develop coupled hydrological-atmospheric models, which provide the appropriate tools for hypothesis testing and innovative research. Setting up such databases and basin-scale hydrological-atmospheric models is extremely time-consuming and would be at the expense of valuable research time of our PhD students. The development of such a large river basin data and modelling centre can best be organised in three steps:
  Step 1: A feasibility study to identify the needs, costs, and benefits of the RBDMC and to prioritise and select the river basins of interest.
  Step 2: Implementation of the RBDMC if proven feasible and profitable under Step 1.
  Step 3: Maintaining and updating the RBDMC.

– Identifying and cataloguing field sites inside and outside The Netherlands in which Dutch hydrological research groups are active. The Centre will mediate and promote the joint use of these facilities. It is not possible to choose a single field site where all research questions formulated in Section 4 can be studied. However, the field sites currently used and maintained by the Dutch hydrology groups together cover most of the priority themes identified in this report. Examples of such sites are Hupsele Beek (WUR), De Noor (WUR), Langbroekerwetering (UU), Cabauw (WUR, UU), which are all in The Netherlands, as well as Huelerbach in Luxembourg (TUD, UU, WUR), Moxa Geodynamics Observatory in the Silberleite Catchment in Germany, (WUR), Bueche in France (UU), and the Ob catchment near Tomsk in Russia (UU). It would be desirable to plan new research initiatives that require fieldwork to be carried out at existing field sites. The group initialising the field work will benefit from the existing infrastructure, available data, and specific knowledge of the site. The group running the field site will gain additional data as collected by the guests and possibly be listed as co-authors in future publications. If multiple groups decide to work at one site, the funding can be combined to acquire equipment that requires a major investment.

– Identifying and cataloguing hydrological research laboratory facilities in The Netherlands and mediating the joint use of these facilities for supporting hydrological research programmes. Examples of such laboratory facilities are the advanced soil physics labs at WUR/Alterra, the surface and subsurface flow labs at TUD, UU and WUR, and the chemistry labs at UU, VU, and RUG. Various research topics described under the *Theme 3: Hydrology and Geo-environment* require robust and extensive laboratory experiments whereby processes governing the transport of matter and energy in surface and subsurface water can be studied. In particular, research on various upscaling methods and processes must be complemented by laboratory studies. Existing experimental facilities must therefore be optimally used and, whenever possible, expanded.

– Developing a Virtual Hydrological Laboratory (VHL) based on existing field sites. A VHL is a numerical simulator based on state-of-the-art understanding of flow and transport processes and fully coupled with ecological and atmospheric states and fluxes. We follow Wood et al. (2004) in asserting the need for such a virtual lab in order to advance our knowledge and understanding of catchment-scale hydrological processes. Such a VHL should typically be able to study flow and transport processes at catchment scales ranging form 1 to

100 km². It should allow easy parameterisation of subsurface heterogeneity and vegetation effects on surface and subsurface fluxes. The coupling with the atmosphere could be either through stochastic weather generators applicable to different climates or fully integrated with fine scale models. The design of this VHL requires close collaboration with mathematicians (numerical aspects, parallel computing), boundary layer meteorologists (fine scale models), biologists and ecologists (root water uptake, transpiration, interception), and soil scientists. The connection to existing field sites is provided through the model set-up and calibration activities using high-quality data sets from carefully selected experimental sites. The VHL would typically be used to answer research questions and test model concepts described under *Theme 2: Hydrology and geo-ecosystems.*

- Organising advanced courses on topics related to the research priorities identified in this report. Perhaps the easiest way to integrate such advanced courses with existing academic activities is through summer schools. In 2005, the UU, VU and WU hydrology groups will organise the first summer school of this type on Climate and the hydrological cycle. Summer schools should stimulate participation from international students.

- Organising an international prestigious lecture serie*s*. In order to critically evaluate international links of elements of the adopted research programme and to increase international visibility, a lecture series will be organised. Leading hydrological scientists will be invited to deliver the yearly Kraijenhoff van de Leur Lecture, addressing important hydrological themes of relevance to the Centre's research programme.

- Facilitating easy access to expertise from related disciplines. In fact, the success of the *Boussinesq Centre* will depend on there being a strong interaction with the disciplines relevant to hydrology. For this purpose, we foresee the formation of Liaison Offices (contact points) in mathematics, meteorology, ecology, and biology. These Liaison Offices will be situated at the most appropriate institutions in The Netherlands and will facilitate and coordinate direct links between the Centre and these disciplines. A Liaison Office should assign one or two persons as contacts it should have a sufficiently critical mass by itself, and it should have an active Centre within The Netherlands. In this way, a Liaison Office can act as an efficient mediator. For example, the Mathematics Liaison Office can be established at The Centre for Analysis Scientific Computing and Applications (CASA) at Eindhoven University of Technology. CASA is active in the areas of scientific computing, differential equations, and mathematical modelling. It has an established track record in applied mathematics, in particular in subsurface hydrology.

6.3.4 Relation to existing organisations and programmes
The *Boussinesq Centre* will carve out a clear niche in the landscape of Dutch organisations and research programmes related to hydrology. The mission of the *Boussinesq Centre* will be to prioritise, direct, and promote interdisciplinary hydrological research involving hydrology and related disciplines at universities. This is different from the role of other organisations, as explained below.

- The Netherlands Hydrological Society (NHV) is a professional society that facilitates information exchange among all professional hydrologists in The Netherlands. Besides hydrologists at universities, its members include hydrologists at local, provincial and national government organisations, water boards and technological research institutes as well as those working in consultancy. The NHV thus serves a much broader hydrological community, does not involve itself in the related disciplines, and its focus is on information exchange.
- The Netherlands Hydrological Platform (NHP) serves as a liaison between the hydrologists at the universities and those at the technological research institutes. Its main goal is information exchange and promoting hydrological sciences within The Netherlands.
- The hydrological triangle of The Netherlands Centre of River Studies (NCR) has similar goals as the NHP, but these are focused on flood forecasting and flood genesis. NCR application-driven research themes are common to universities and research institutes. NCR tries to formulate a common research agenda for its members.

Similarly to the *Boussinesq Centre* itself, its research programme shall serve a unique purpose when compared to existing funding programmes. The BSIK programme 'Living with Water' focuses entirely on mitigating climate change in water management and will be funding projects that combine applied hydrological research with social science and policy-making (beta-gamma interaction). The 'NWO Water Programme' does share some common ground with the priority themes identified in Chapter 4. However, it is completely focussed on global change issues and has a much wider scope, encompassing water in the broadest sense, including hydrology, atmospheric science (cloud formation), economics and social science issues (e.g. water scarcity and governance), aquatic chemistry and aquatic ecology. The research programme proposed here focuses on hydrological issues, while advocating an interdisciplinary approach to tackling these issues.

6.3.5 Implementation

We envisage three phases in the implementation of the *Boussinesq Centre.* In the *first phase,* preparations will be made for setting up the Centre. A steering committee aided by a provisional secretariat will be formed to coordinate the necessary actions. The steering committee will prepare a tentative research programme, draft the contours of the Centre, including a management structure, and estimate the costs of the activities and operations. The prospective participating groups will try to obtain commitment from their corresponding departments, faculties, and university boards. This phase will culminate in a proposal for the Centre to be submitted for funding to the participating universities, to NWO and to the 'Call for Dreams' initiative under the auspices of the Dutch Innovation Platform. The first phase is expected to take approximately one year.

The *second phase* will commence once financial coverage has been secured. A programming committee will be installed which will draft the research programme and call for proposals. PhD-candidates are expected to start within the first year. Work will start on the setting up of the RBDMC, the development of the VHL and the organisation of summer schools and the Kraijenhoff van de Leur Lectures. The second phase is expected to last five years (the duration of the first research programme). At the end of this phase, the RBMC should be operational and work on the VHL should be finished. Also, the majority of the PhDs, who will be starting right after the first programme call, will be finalising their theses. This phase will end with an evaluation of the Centre as a whole. Of particular importance will be whether new PhD projects that are not funded by the initial programme call have commenced during the second phase.

The *third phase* will be focussed on the consolidation and redefinition of the Centre. Based on the evaluation of the Centre at the end of Phase 2 and a new look at global issues and opportunities for hydrological research, a revised research programme will be defined, which may partly build upon previous priority themes (consolidation), and partly consist of new issues (redefinition). Additional sources of funding will be sought to continue the Centre and its associated research programme (consolidation). At this stage, the *Boussinesq Cen***tre** should be functioning on its own, be embedded in university hydrological research, and be well known internationally.

Conclusies en aanbevelingen

Conclusies

Algemeen

Hydrologie is een belangrijke tak van de aardwetenschappen. Zij heeft op zeer veel verschillende ruimtelijke en temporele schalen – ook banden met oceanische, atmosferische, biologische en geologische wetenschappen.

De hydrologische wetenschap is erop gericht inzicht te verkrijgen in de mechanismen van de hydrologische cyclus en de interactie van die cyclus met de geosfeer, de atmosfeer en de biosfeer.

Door bestudering van de terrestrische watercyclus kan de hydrologie een belangrijke bijdrage leveren aan het oplossen van mondiale problemen, zoals waterschaarste, gebrekkige voedselveiligheid, vermindering van waterkwaliteit,verdwijnen van ecosystemen, bestrijding van ziektes en wereldwijd optredende veranderingen.

Hydrologie is bij uitstek een interdisciplinaire wetenschap. Hydrologisch onderzoek vereist vaak expertise op het gebied van andere disciplines, zoals wiskunde, vloeistofmechanica, bodemfysica, bodemmechanica, biogeologie, biogeochemie, chemie, ecologie, meteorologie, en reservoirtechniek. De interactie van hydrologie met deze disciplines (en daar komen er in de toekomst ongetwijfeld nieuwe interacties bij) zorgt voor vele nieuwe uitdagende mogelijkheden voor interdisciplinair onderzoek.

Conclusions and recommendations

Conclusions

General

Hydrology is a vital branch of the earth sciences with strong links – on a wide range of spatial and temporal scales – with oceanic, atmospheric, biological, and solid earth sciences.

Hydrological science aims to understand the mechanisms of the hydrological cycle and its interaction with the lithosphere, atmosphere and biosphere.

By studying the terrestrial water cycle, hydrology thus plays an important part in helping to solve global issues such as water scarcity, lack of food security, water quality deterioration, ecosystem decline, disease control, and global change.

Hydrology is a highly interdisciplinary science. Hydrological research topics often involve and require expertise form other disciplines such as mathematics, fluid mechanics, soil physics, soil mechanics, biogeology, biogeochemistry, chemistry, ecology, meteorology, and reservoir engineering. These as well as new and emerging interactions with other disciplines offer many challenging opportunities for collaborative research.

Om te zorgen dat fundamenteel en toegepast hydrologisch onderzoek in Nederland succesvol blijft, dient de aandacht te worden toegespitst op een beperkt aantal gebieden, , en de infrastructuur te worden verbeterd, waarbij numerieke en experimentele faciliteiten gezamenlijk gebruikt kunnen worden. Ook dient de samenwerking tussen hydrologen en wetenschappers van andere disciplines te verbeteren.

Internationale hydrologische onderzoeksthema's
De internationale uitdagingen die relevantie hebben voor de hydrologie in Nederland, kunnen worden onderverdeeld in twee categorieën: vier belangrijke onderzoeksterreinen en vier methodologische kwesties.

Onderzoeksterreinen van internationaal belang

1. Interactie tussen de hydrologische cyclus en terrestrische ecosystemen.
   Het onderzoek naar de wisselwerking tussen de hydrologische cyclus en de ecosystemen op aarde is het onderzoeksterrein van de steeds belangrijker wordende wetenschap ecohydrologie. Deze wetenschap omvat ook de interactie met de nutriëntencycli. Een belangrijke uitdaging voor de ecohydrologie is de onderliggende hydrologische patronen en de oorzaken van de enorme diversiteit aan ecologische functies en de manier waarop deze van hun beurt weer van invloed zijn op de watercyclus, te ontdekken en te begrijpen.
2. Invloed van de mens op de watercyclus en het hydromilieu.
   Een van de belangrijkste uitdagingen waarmee de hydrologie wordt geconfronteerd, is het beschrijven en voorspellen van de interactie tussen menselijke activiteiten, de watercyclus, de kwaliteit -en hoeveelheid van- watervoorraden, en de gevolgen voor duurzame ontwikkeling.
3 Interactie tussen klimaatverandering en de hydrologische cyclus.
   Het is noodzakelijk de klimaatveranderingen die kennelijk geleid hebben tot een intensivering van de hydrologische cyclus nog beter in kaart te brengen, te begrijpen en te kunnen voorspellen. Het is belangrijk dat we inzicht krijgen in de waargenomen veranderingen in de hoogwaterstanden, afvoeren, neerslag, verdamping en de beschikbare watervoorraden, en deze veranderingen kunnen verklaren en verder voorspellen.
4 Interactie tussen de hydrologische cyclus en landschapsprocessen.
   Een stroomgebied van een rivier bestaat uit hellingen die met elkaar in verbinding staan, en een netwerk van geulen dat zorgt voor afwatering van deze hellingen. Om de stroming en transportprocessen op het niveau van het stroomgebied te kunnen onderzoeken, dient er inzicht te bestaan in de kenmerkende reactie van de hellingen en het afwateringsnetwerk binnen dat stroomgebied. Dit vergt innovatief onderzoek dat theoretische voortgang kan koppelen met nieuwe meettechnieken.

If fundamental and applied research in hydrology are to remain successful in The Netherlands, what is required is a strong focus on a number of selected areas, a better infrastructure with shared numerical and experimental facilities, and closer cooperation between hydrologists and other disciplines.

International hydrological research topics

International challenges of relevance to Dutch hydrology are divided into two categories: four key research areas and four methodological issues.

International key research areas

1. Interaction between the hydrological cycle and terrestrial ecosystems.
   The study of the interaction between the hydrological cycle and terrestrial ecosystems is the focus of the emerging field of ecohydrology. This also includes the interaction with nutrient cycles. A major challenge for ecohydrology is to identify and understand the underlying hydrological patterns and causes that determine the enormous diversity of ecological functioning and the way these feed back into the water cycle.
2. Human impact on the water cycle and hydro-environment.
   One of the major challenges that hydrology faces is to describe and predict the interactions among human activities, the water cycle, water resources quantity and quality, and the consequences for sustainable development.
3 Interaction between climate change and the hydrological cycle.
   There is a need to further document, understand, and predict climatic changes that appear to have led to an intensification of the hydrological cycle. We need to understand and explain changes that are currently observed in water availability and flood events.
4. Interaction between the hydrological cycle and landscape processes.
   A river basin is made up of interconnected hillslopes and a channel network that drains these hillslopes. To describe flow and transport processes at the catchment scale, it is necessary to understand the characteristic response of hillslopes and the channel network within the catchment.

Methodologische thema's

Er kan alleen vooruitgang worden geboekt op de hierboven beschreven onderzoeksgebieden als hydrologen een oplossing vinden voor de onderstaande uitdagingen, waarmee de hydrologie al heel lang geconfronteerd wordt:

1. Heterogeniteit en schaal.
   Er moeten betere theorieën voor opschaling en neerschaling worden ontwikkeld om op verschillende schalen kwantitatieve verbanden tussen processen vast te kunnen stellen.
2. Waarnemings- en meettechnieken.
   Er moeten methoden worden ontwikkeld voor de meting/waarneming van toestandsvariabelen en fluxen op verschillende schalen, zodat hydrologische modellen verder ontwikkelt kunnen worden en nieuw begrip wordt gegenereerd. .
3. Fundamentele theorieën.
   Er is behoefte aan de ontwikkeling van geldige fysische theorieën voor de beschrijving van gekoppelde, niet-lineaire hydrologische processen op verschillende schalen.
4. Kwantificering van onzekerheden.
   Er moeten goede methoden worden ontwikkeld voor de kwantificering van de onzekerheid bij het voorspellen van het gedrag van hydrologische systemen als gevolg van de onzekerheden in de parameterisatie en eventuele fouten in conceptuele modelbeschrijving en metingen.

Onderwijsprogramma's op het gebied van hydrologie

Op de volgende vier universiteiten worden masters-opleidingen op het gebied van hydrologie aangeboden: de Vrije Universiteit Amsterdam (VU Amsterdam), de Technische Universiteit Delft (TU Delft), de Universiteit Utrecht (UU) en Wageningen Universiteit (Wageningen UR).

Vier verschillende onderzoekscholen bieden een onderwijsprogramma aan voor promovendi en postdoc-onderzoekers. Dit zijn het Centrum voor Technische Geowetenschappen (CTG), het Interuniversitair Centrum voor Geo-ecologisch Onderzoek (ICG), de Nederlandse Onderzoekschool voor Sedimentaire Geologie (NSG) en de Onderzoekschool Milieuwetenschappen (SENSE).

UNESCO-IHE in Delft biedt naast een masteropleiding ook een a post-masters-programma in hydrologie aan voor buitenlandse studenten. Het promotieonderzoek wordt in samenwerking met de Nederlandse universiteiten uitgevoerd.

De belangrijkste onderdelen van de masters-opleidingen zijn: onderwijs, veldwerk, stage en scriptie. Er bestaan echter belangrijke verschillen ten aanzien van de verplichte en keuzevakken en de onderwerpen die worden aangeboden. Deze verschillen komen voort uit de diverse specialisaties van de betreffende hydrologiegroep. De samenwerking tussen de verschillende masters-opleidingen is beperkt.

Methodological issues

Progress in the four key research areas described above can only be made if hydrologists can find solutions to the following challenging methodological issues that have persisted in hydrological research:

1. Heterogeneity and scale.
   Theories of upscaling and downscaling have to be developed in order to establish quantitative relationships among process descriptions at various scales.
2. Observation and measurement techniques.
   There is a need to develop methods for measurement/observation of state variables and fluxes on the scale required for the modelling of a hydrological system or to transfer the available data to the scale of interest.
3. Fundamental theories.
   There is a clear need to develop rigorous and physically-based theories for the description of coupled non-linear hydrological processes at various scales.
4. Quantification of uncertainties.
   There is a need to develop robust methods for quantifying the prediction uncertainty of hydrological systems behaviour due to both parameter uncertainties and possible errors in conceptual model description.

Education Programmes in Hydrology
MSc programmes in Hydrology are offered at four universities: Vrije Universiteit Amsterdam (VUA), Delft University of Technology (TUD), Utrecht University (UU), and Wageningen University (WU). Graduate studies leading to PhD degrees in hydrology are being pursued in the framework of four different research schools: Centre for Technical Geosciences (CTG), Centre for Geo-ecological Research (ICG), Netherlands Research School of Sedimentary Geology (NSG) and Netherlands Research School for Socio-Economic and Natural Sciences of the Environment (SENSE).

UNESCO-IHE in Delft offers a post-initial MSc programme in hydrology for foreign students. PhD promotions are carried out jointly with the Dutch universities.

The main components of the five MSc programmes in hydrology are common to all: course work, field work, traineeship, and thesis. There are, however, major differences in compulsory and optional courses and their subjects. The differences reflect the specialisations of the corresponding hydrology groups. Collaboration among the MSc programmes is very limited mainly because of the incompatibility of their scheduling systems.

Aanbevelingen

Prioritaire onderzoeksthema's voor Nederland
Nederlandse hydrologen zouden zich in het brede hydrologische onderzoeksspectrum vooral moeten richten op enerzijds die gebieden waarop zij toonaangevende internationale expertise hebben, en anderzijds op thema's met maatschappelijke relevantie die interdisciplinair onderzoek stimuleren. Vanuit dit oogpunt zijn de onderstaande thema's volgens de Commissie van groot strategisch belang.

– Hydrologie en klimaat.
– Hydrologie en geo-ecosystemen.
– Hydrologie en geo-milieu.

Hydrologie en klimaat.
Er kunnen drie belangrijke subthema's worden onderscheiden:
– Ontdekken van veranderingen in de hydrologische cyclus. Een belangrijke onderzoeksvraag die nog steeds onopgelost is, is of de hydrologische cyclus daadwerkelijk versnelt als gevolg van de door het broeikaseffect veroorzaakte klimaatverandering.
– Invloeden van het klimaat op de hydrologische cyclus. De belangrijkste onderzoeksthema's zijn: invloed van het klimaat (o.a droogte) op de hydrologie van grote rivieren (met inbegrip van watermanagement), op watervoorraden en sedimentaire afzettingen, ook op een geologische tijdschaal,.
– Terugkoppelingsmechanismen tussen de hydrologische cyclus en het klimaatsysteem. Hierbij gaat het om het onderzoek naar complexiteit, heterogeniteit en terugkoppelingsmechanismen, alsmede om het verband tussen grondwater-bodemvocht-atmosfeer.

Hydrologie en geo-ecosystemen.
Dit onderwerp bestaat uit twee subthema's:
– Patronen en complexiteit bij ecohydrologische landschappen. Ecohydrologie heeft ten doel de interactie te kennen tussen hydrologische en ecologische patronen en processen. Deze interactie vindt op diverse schalen plaats en bepaalt uiteindelijk de ontwikkeling en de ruimtelijke verdeling van de vegetatie in landschapselementen
– Interactie tussen bodemgebruik, oppervlaktehydrologie, biogeochemie en klimaat. Er bestaan sterke interacties tussen het ecosysteem en bodemkundige, geologische, atmosferische en hydrologische processen. Een van de

Recommendations

Priority research themes for The Netherlands

From the broad spectrum of research, Dutch hydrologists should focus on those areas where they have leading international expertise, as well as on themes which are of social relevance and foster interdisciplinary research. The Committee considers the following themes to be of great and strategic importance in this respect:

- Hydrology and Climate
- Hydrology and Geo-ecosystems
- Hydrology and Geo-environment

Hydrology and Climate.
Three important subthemes have been identified:
- Detection of changes in the hydrological cycle. A major research question that is yet unresolved is whether the hydrological cycle is really accelerating due to greenhouse-induced climate change.
- Impacts of climate on the hydrological cycle. Major research topics are: impacts on the hydrology of large rivers (including water management), on water and sediment stocks on a geological time scale, and droughts.
- Feedback mechanisms between the hydrological cycle and climate system. This involves the study of complexity, heterogeneity and feedback mechanisms as well as groundwater-soil moisture-atmosphere coupling.

Hydrology and Geo-ecosystems.
Two major subthemes have been defined:
- Patterns and complexity in ecohydrological landscapes: Ecohydrology seeks to describe the interaction between hydrological and ecological patterns and processes. This interaction takes place at a multitude of scales and ultimately determines the evolution and spatial arrangement of vegetation in landscape elements.
- Interactions among land use, surface hydrology, biogeochemistry, and climate: There are strong interactions between the ecosystem and pedological, geological, atmospheric and hydrological processes. One of the key challenges is to understand the hydrological and ecohydrological processes behind the vulnerability and resilience of coupled geo-ecosystems and hydrology.

belangrijkste uitdagingen is om inzicht te krijgen in de hydrologische en ecohydrologische processen die ten grondslag liggen aan de kwetsbaarheid en het herstelvermogen van gekoppelde ecosystemen en hydrologie.

Hydrologie en geo-milieu.
Dit onderwerp bestaat uit vier subthema's:
- Interactie tussen oppervlaktewater en grondwater. Hierbij gaat het om zowel de kwalitatieve als de kwantitatieve interactie. Deze interactie speelt een belangrijke rol bij de beschikbaarheid en vervuiling van zoetwatervoorraden.
- Verbeterde theorieën voor meerfasestroming. Kennis van meerfasestromingsprocessen is van essentieel belang bij het onderzoek naar vochttransort in de bodem, naar bodem- en grondwatervervuiling als gevolg van organische-vloeistofvervuiling, naar ondergrondse opslag van CO_2, en naar de rol van het transport van in de natuur voorkomende gassen, zoals radon, methaan en stikstofoxide bij grondwatersystemen.
- Dichtheidsafhankelijke stroming en transport. Dit onderwerp speelt een centrale rol bij het onderzoek naar de infiltratie in de bodem van het percolaat van stortplaatsen, en naar energieopslag en naar zoutwaterintrusieproblematiek, met inbegrip van de problemen die worden veroorzaakt door de stijging van het zeewaterpeil.
- Meerschalig reactief transport. Dit is een onderzoeksterrein waarop onderzoek wordt verricht naar de opschaling van (kleinschalige) instabiliteit bij transport van reactieve stoffen in de ondergrond.

Onderwijs
De samenwerking tussen de vier masters-opleidingen op het gebied van hydrologie moet worden gestimuleerd door het opzetten van gezamenlijk veldwerk, uitwisseling van stagiaires, gezamenlijke begeleiding van scripties en gezamenlijke zomercursussen en betere onderlinge uitwisseling van onderwijsmodules.
Er dient een beurzensysteem te worden ontwikkeld om goede buitenlandse studenten aan te trekken. Een van de mogelijkheden is om een klein gedeelte van het huidige fonds voor promotieonderzoek te bestemmen voor dergelijke beurzen.

Infrastructuur
Een essentiële voorwaarde om te zorgen dat het Nederlandse hydrologische onderzoek zich richt op onderwerpen die prioriteit hebben (waardoor Nederland in staat wordt gesteld om een toonaangevende rol in de hydrologie te spelen) is een coherent stimuleringsbeleid door de overheid, de NWO en de raden van bestuur van de universiteiten. Dit moet gebeuren binnen een afgebakend onderzoeks-

Hydrology and Geo-environment.
Four major subthemes have been distinguished:
– Interaction of surface water and groundwater. This interaction concerns both quality and quantity and plays a major role in all cases dealing with the availability and contamination of fresh water resources.
– Improved theories for multiphase flow. Knowledge of multiphase flow processes is essential in the study of soil and groundwater pollution caused by spills of organic liquids, in the studies of the subsurface sequestration of CO_2, and in assessment of the role of natural gas transport, such as radon, methane, and nitrogen oxide, in groundwater systems.
– Density-dependent flow and transport. This plays a central role in the study of infiltration of leachates from landfills into the subsurface, energy storage, and saltwater intrusion problems, including ones caused by sea level rise.
– Multiscale reactive transpor*t.* This is an area of research where small-scale instabilities in reactive processes are studied at a variety of scales.

Education
Collaboration among the four hydrology MSc programmes should be encouraged by setting up joint field work, trainee exchanges, joint MSc thesis supervision, and joint summer courses.

A grant system must be developed in order to increase the intake of excellent hydrology students from abroad. One possible solution is to allocate a small portion of the current funding for PhD research for such scholarships.

Infrastructure
An essential condition for focussing Dutch hydrological research on priority themes and thereby enabling The Netherlands to play a leading international role in hydrology is to have a coherent policy of encouragement from the government, NWO and university boards within a limited range of the research spectrum, as well as closer cooperation between scientists in the field. The proposal is therefore to establish a national scientific hydrology centre called the *Boussinesq Centre for Hydrology.*[5] The *Boussinesq Centre* will be dedicated to focussing and strength-

[5] Valentin Joseph Boussinesq (1842-1929) was a French physicist and mathematician and became a member of Académie des Sciences in 1886. Boussinesq has made important contributions to many branches of mathematical physics in general, and to hydrodynamics, in particular. His areas of research were hydrology, hydraulics, meteorology, oceanography, and mathematics. He studied groundwater flow, hill slope hydrology, the problem of liquid waves, the flow of fluids, the mechanics of pulverulent masses, the resistance of a fluid against a solid body, and the cooling effect of a liquid flow.

terrein met een nauwere samenwerking tussen de wetenschappers in het veld. Het voorstel is hiertoe een nationaal wetenschappelijk hydrologisch centrum op te richten onder de naam *Boussinesq Centrum voor Hydrologie.*[6] Het *Boussinesq Centrum* zal zich richten op de concentratie en versterking van het hydrologische onderzoek in Nederland, waarbij het zich zal baseren op de prioriteiten zoals die in dit rapport zijn vastgesteld. Voorts is het streven van het centrum om gunstige voorwaarden te creëren voor een efficiënte multidisciplinaire onderzoeksomgeving.

Naast het vaststellen van een onderzoeksprogramma op basis van de vastgestelde prioriteiten, zullen de belangrijkste taken van het *Boussinesq Centrum* bestaan uit:

– Het stimuleren van fundamenteel onderzoek op de drie prioritaire thema's.
– Het oprichten van een RBDMC (River Basin Data and Modelling Centre) voor strategisch geselecteerde grote stroomgebieden, met een nadruk op Eurazië.
– Het inventariseren en in kaart brengen van de hydrologische onderzoekslaboratoriumfaciliteiten in Nederland en een bemiddelende rol spelen bij het gezamenlijke gebruik van deze faciliteiten ten behoeve van hydrologische onderzoeksprogramma's.
– Het inventariseren en in kaart brengen van de hydrologische veldlocaties waar Nederlandse onderzoeksgroepen actief zijn, en een bemiddelende rol spelen bij en het stimuleren van het gezamenlijke gebruik van deze faciliteiten.
– Het ontwikkelen van een Virtueel Hydrologisch Laboratorium (VHL), dit is een numerieke simulator van stroming en transport gebaseerd op reële situaties in bestaande veldlocaties.
– Het organiseren van advanced cursussen over onderwerpen die verband houden met de in dit rapport vastgelegde onderzoeksprioriteiten.
– Het organiseren van een internationaal prestigieuze lezingencyclus.
– Ervoor zorgen dat expertise uit gerelateerde disciplines beschikbaar is door de oprichting van liaison'loketten' voor wiskunde, meteorologie, ecologie en biologie.

[6] Valentin Joseph Boussinesq (1842-1929) was een Frans natuur- en wiskundige, die in 1886 lid werd van de Franse Académie des Sciences. Boussinesq heeft belangrijke bijdragen geleverd aan verschillende aspecten van de mathematische fysica in het algemeen en aan de hydrodynamica in het bijzonder. Zijn onderzoeksterreinen waren hydrologie, hydraulica, meteorologie, oceanografie en wiskunde. Hij bestudeerde grondwaterstroming, hellinghydrologie, het probleem van vloeistofgolven, het stromingsgedrag van vloeistoffen, poedermechanica, de weerstand van een vloeistof tegen een vast lichaam, en de koelende werking van vloeistofstromen.

ening hydrological research in The Netherlands, based on the priority themes identified in this report. It will also strive to create favourable conditions for an efficient multi-disciplinary research environment.
Besides establishing a research programme based on the priority themes, major activities of the *Boussinesq Centre* will include:

- Stimulating fundamental research on the basis of the three priority themes.
- Setting up a River Basin Data and Modelling Centre (RBDMC) for strategically selected large river basins, with an emphasis on the Eurasian continent.
- Identifying and cataloguing hydrological research laboratory facilities in The Netherlands and mediating the joint use of these facilities for supporting hydrological research programmes.
- Identifying and cataloguing hydrological field sites in which Dutch hydrological research groups are active, and mediating and promoting the joint use of these facilities.
- Developing a Virtual Hydrological Laboratory (VHL) based on existing field sites.
- Organising advanced courses on topics related to the research priorities identified in this report.
- Organising an internationally prestigious lecture series, to be called Kraijenhoff van de Leur Lectures.
- Providing easy access to expertise from related disciplines through the formation of Liaison Offices (contact points) in mathematics, meteorology, ecology, and biology.

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Annexes

ANNEX A. Members of the Dutch Foresight Committee on Hydrological Science

Committee members

- Prof. dr. ir. M.F.P. (Marc) Bierkens, Utrecht University, Faculty of Geosciences
- Prof. dr. A.J. (Han) Dolman, Vrije Universiteit Amsterdam, Faculty of Earth and Life Sciences
- Prof. dr. ir. C.J. (Hans) van Duijn, Eindhoven University of Technology, Department of Mathematics and Computer Science, Centre for Analysis, Scientific Computing and Applications
- Prof. dr. J.M. (Jan) van Groenendael, Radboud University Nijmegen, Faculty of Science Mathematics, and Computing Science
- Prof. dr. S.M. (Majid) Hassanizadeh, Utrecht University, Faculty of Geosciences, Chairman
- Prof. dr. A.A.M. (Bert) Holtslag, Wageningen University and Research Centre, Meteorology and Air Quality
- Prof. dr. ir. A. (Toon) Leijnse, Wageningen University and Research Centre, TNO-NITG
- Prof. dr. P.A. (Peter) Troch, Wageningen University and Research Centre, Environmental Sciences
- Ms. ir. A.M. (Alice) de Gier, KNAW, Executive Secretary

Prof. dr. ir. S. Majid Hassanizadeh is Professor of Hydrogeology at the Faculty of Geosciences of Utrecht University. He graduated with honours from the Department of Civil Engineering of Pahlavi University in Shiraz, Iran in 1975. He earned M.E. in 1976 and Ph.D. in 1979 at the Department of Civil Engineering of Princeton University. Since then he has worked as Assistant Professor with the Abadan Institute of Technology (Iran, 1979-1982), as Project Manager with the Yekom Consulting Engineers (Iran, 1982-1984), as Assistant Professor with the Technical and Engineering University of Tehran (Iran, 1982-1984, part-time), as senior researcher with the National Institute of Public Health and Environment, RIVM (The Netherlands, 1984-1995), as guest Assistant Professor with the Department of Geology of Utrecht University (The Netherlands, 1990-1994), as Associate Professor (1996-2001) and as Professor of Geohydrology (2001-2003) with Delft University of Technology. Major area of interest is modelling of multiphase flow and transport in porous media, with specific interest in developing conceptual models for non-linear and coupled processes at various scales. He has around 130 publications in journals, books, conference proceedings, and as technical reports. He has been editor of Advances in Water Resources from 1991 till 2001 and is now on the editorial board of Transport in Porous Media, Vadoze Zone Journal, and Advances in Water Resources. He was elected Fellow of American Geophysical Union in 2002. He has organised more than 10 international workshops and conferences in recent years and has been invited speaker at a large number of international meetings (see http://www.geo.uu.nl/hydrogeology/majid.html for more details).

Prof. dr. Marc F.P. Bierkens holds the chair in Geographical Hydrology at the Department of Physical Geography at Utrecht University. Marc Bierkens (1965) holds an MSc in Hydrology from Wageningen University (1990), a PhD in Physical Geography at Utrecht University (1994) and became professor of Hydrology at Utrecht University in 2002. He is also partly employed by TNO Institute of Applied Geosciences. In between 1994 and 2002 he worked as a senior scientist and team leader at Alterra Research institute in Wageningen. Marc Bierkens's fields of expertise are groundwater hydrology, stochastic hydrology, hydrological regionalisation, up scaling theory and geostatistics. Recently initiated work comprises integrated modelling of soil-water-vegetation dynamics, data-assimilation methods for operational water management and combined physical and chemical heterogeneity in groundwater flow. Marc Bierkens is a member of the European Geosciences Union, the American Geophysical Union and the International Association of Hydrological Sciences where he is vice-president of the Commission on Groundwater. He will co-organise the Model Care conference in 2005 in The Netherlands. Marc Bierkens (co-) authored 85 publications: PhD thesis, the book Up scaling and Downscaling Methods for Environmental Research which he published in 2000 with P.A. Finke and P. de Willigen (Kluwer Academic Publishers, Dordrecht), 23 peer reviewed papers, 14 papers in conference proceedings, 12 in Dutch journals and 34 reports.

Prof. dr. A.J.H. (Han) Dolman is professor of Ecohydrology and head of the department of Hydrology and Geo-environmental Sciences of the Faculty of Earth and Life Sciences, Vrije Universiteit Amsterdam. His research interests are the interaction of the terrestrial biosphere with the hydrological cycle and atmosphere and the physics of the transfer of water, energy and nutrients from soil to biosphere and atmosphere. His skill include numerical modelling of Soil Vegetation Atmosphere Transfer (SVAT) models and meso-scale atmospheric models; forest hydrology. He has published widely in peer reviewed journals and books on these issues. He has experience in The Netherlands, Europe, semiarid regions (Niger), boreal forests (East Siberia) and humid tropical regions (rainforest, Cameroon, Brazil). He is member of the executive board of Carboeurope, and active in the Global Energy and Water Experiment (GEWEX) of the World Climate Research Programme, and Secretary Climate and Hydrology of the European Geosciences Union (EGU) He is also member of the AGU and fellow of the Royal Meteorological Society.

Prof. dr. ir. C.J. (Hans) van Duijn is professor of Mathematics (Applied Analysis) at the Department of Mathematics and Computer Science of Eindhoven University of Technology. He graduated with honours from the Department of Applied Physics of Eindhoven University of Technology in 1979, and he received his PhD-degree from Leiden University, Mathematical Institute, in 1979. The PhD-research was carried out under supervision of Prof.dr.ir. L.A. Peletier. He did post-doctoral research (NWO-grant) with the School of Mathematics of the University of Minnesota (Minneapolis, USA) during the year 1979-1980. Since then he has worked as researcher with Delft Soil Mechanics Laboratory (1980-1983), as assistant (later associate) professor with the Department of Mathematics of Delft University of Technology (1983-1996), as honorary professor with the Mathematical Institute of Leiden University (1990-1997), as head of the Department 'Modelling, Analysis and Simulation' (MAS) of the Centre for Mathematics and Computer Science (1996-2000) and as part time professor with the Department of Mathematics of Delft University of Technology (1997-2000). Areas of interest are: (i)analysis of partial differential equations, in particular free boundary problems and conservation laws, (ii)homogenisation and multi-scale problems and (iii)flow and transport in porous media. He has about 100 papers in refereed international journals. He is on the editorial board of Transport in Porous Media and he was editor-in-chief of Computational Geosciences (1995-2003). He co-organised several international workshops and conferences (three in Oberwolfach) and he was invited speaker at a large number of international meetings. In 1998 he received the Max Planck Research Award for International Cooperation. Since September 2004 he is dean of the Department of Mathematics and Computer Science of Eindhoven University of Technology.

Prof. dr. Jan M. van Groenendael is Head of department of Aquatic Ecology and Environmental Biology, Radboud University Nijmegen.

MSc degree: Biology with geology (B1g). Topics: Vegetation Science, Animal Ecology and Soil Science, Radboud University of Nijmegen, 'Cum Laude', 1978.

MSc degree: Ecology with Plant Population Biology and mathematical ecology, University College of North Wales, 1979. PhD degree: Thesis: 'Selection for different life histories in Plantago lanceolata', Radboud University of Nijmegen, 1985

His main focus in research are the ecological and evolutionary implications of the population dynamics of plants, with special attention for plants with clonal growth and reproduction strategies. The study of population dynamics has four ramifications:

– The development of mathematical tools in the form of matrix projection models, and the sensitivity and elasticity measures that belong to it, to calculate long term population growth rates which is used as a measure of fitness in an evolutionary context.
– The understanding of the determining demographic processes such as longevity and dispersal, that have become crucial for the survival of species in fragmenting landscapes (metapopulation dynamics) and thereby determining for conservation and restoration of biodiversity.
– The development of molecular tools to quantify dispersal and genetic variation in populations that have become small and isolated in fragmented landscapes and that run the risk of genetic erosion and enhanced extinction.
– The understanding of the biogeochemical processes that determine the ecological quality of wet and mesotrophic habitats, habitats that have become most fragmented and threatened by dessication and eutrophication in our landscapes.

He is (co)author of over 80 papers in refereed journals, editor of two books, (co)promotor of 5 PhD theses, current number of PhD students 8, current number of Post Docs 4.

Professor dr. A.A.M. (Bert) Holtslag is professor of Meteorology and Air Quality and head of the Meteorology and Air Quality Section at Wageningen University and Research Centre (since may 1999). He holds a PhD (1987) of Wageningen University. Until 1999 he was affiliated to the Royal Netherlands Meteorological Institute (KNMI), and to Utrecht University as (part time) Professor in Meteorology (period 1993-1999). Visiting Scientist positions include those at Risoe National Laboratory (Roskilde, Denmark) in 1985, Oregon State University, Corvallis (OR, USA) in 1989, and to the National Centre for Atmospheric Research (NCAR) in Boulder (CA, USA) in 1989-1990. In addition, he has been appointed Affiliate Scientist to NCAR on 'Boundary Layers and Climate' for the period 1991-1997. Bert Holtslag is actively involved in many research projects on surface fluxes, boundary layer processes and mesoscale meteorology. This includes modelling and parameterisation studies and conceptual analysis of observations. Scientific activities include: Host and Organiser of the 15th Symposium on Boundary Layers and Turbulence of the American meteorological Society in Wageningen (2002), Organiser of an Academy Colloquium at The Netherlands Academy of Sciences (KNAW) in 1998 on 'Clear and Cloudy Boundary Layers'. Currently, member of several national and international committees, including the Dutch IGBP/WCRP committee, the GEWEX Modelling and prediction panel, and chair of the GEWEX Atmospheric Boundary Layer Study (GABLS). Chairperson of the governing board of the Dutch Buys Ballot Research School on fundamental processes in the climate system. Writer and contributor of more than 100 scientific publications, including more than 50 publications in the international peer reviewed journals. Advisor and co-advisor of many MSc and PhD students at Wageningen and Utrecht Universities (see http://www.met.wau.nl/ for details).

Prof. dr. ir. A. (Toon) Leijnse holds the part-time chair Groundwater Quality in the group Soil Physics, Agrohydrology and Groundwater Management in the sub-department Water Resources of Wageningen University since 1994. He graduated from Delft University of Technology, Faculty of Physical Engineering in 1970, and received a PhD from the University of Notre Dame (USA), Department of Civil Engineering and Geological Sciences in 1992. He worked as a reservoir engineer with Shell Exploration and Production Laboratory (1970-1976), as head of the modelling group at the Dutch National Institute for water Supply (1976-1985), as head of the department Mathematical Physics and Numerical Analysis at the Dutch National Institute for Public Health and the Environment (1985-1992), as a senior research scientist at the same institute and is since 2000 associated as a senior research scientist with The Netherlands Institute of Applied Geoscience TNO. Major areas of research are groundwater flow and reactive transport, density-dependent flow and transport in porous media and parameter estimation and uncertainty analysis. He is a member of the American Geophysical Union, the International Association of Hydrological Sciences and the International Association of Hydraulic Research, where he is a member of the International Groundwater Committee. He (co-)authored some 100 publications among which a book on 'Mathematical Tools for Changing Scales in Physical Systems'.

Prof. dr. ir. (Peter) A. Troch is since August 1999 head of the group Hydrology and Quantitative Water Management and currently chair of the sub-department

Water Resources of Wageningen University. From 1996 to 1999 he was associate-professor at the Laboratory of Hydrology and Water Management (LHWM) of the University of Gent. He obtained the diploma of Landbouwkundig Ingenieur (1985) and the diploma of Ingenieur in de Automatiseringstechniek (1989) at the University of Ghent. He obtained a PhD degree in Hydrology in 1993 at the same university. From January until August 1992 he was scientific researcher at the Water Resources Programme of Princeton University. He was involved in several international airborne remote sensing experiments in hydrology. He was principal investigator during EMAC '94 (ESA) and co-investigator of SIR-C/X-SAR, ERS-1, ERS-2, ERS-1/2 and RADARSAT projects. Peter Troch now leads research projects involving MSG, ENVISAT, and GRACE. He was scientific coordinator of a 5th FP RTD project on data assimilation within a unifying modelling framework for improved river basin water resources management (DAUFIN) and organised an international workshop on catchment scale hydrological modelling and data assimilation (CAHMDA) in September 2001. He is member of the editorial board of Advances in Water Resources, editor of the special issue on 'Catchment scale hydrological modelling and data assimilation' of Advances in Water Resources, 26(2), and associate editor of Water Resources Research. He is working member of the Large Scale Field Experimentation committee and Surface water committee of the American Geophysical Union. He has published over 50 papers in refereed international journals dealing with flood forecasting, hydrological modelling, soil moisture mapping, remote sensing applications in hydrology and data assimilation.

ANNEX B. List of participants at four Expert Meetings and their disciplines, March 2004

Expert Meeting 18 March 2004 Morning Session: Large rivers and climate impact

Name	Institution	Discipline
Aerts, dr. Jeroen	Vrije Universiteit, Instituut voor Milieuvraagstukken	water management, hydrology
Beersma, dr. Jules J.	Koninklijk Nederlands Meteorologisch Instituut	climatology
Bierkens, prof. dr. ir. Mark F.P.	Universiteit Utrecht, Ruimtelijke Wetenschappen	hydrology (VCH)
Bogaart, dr. Patrick W.	Wageningen Universiteit, Sectie Waterhuishouding	hydrology, geomorphology
Booij, dr. ir. Martijn J.	Universiteit Twente, Waterbeheer	hydrology, water management
Buiteveld, ir. Hendrik	Rijksinstituut voor Integraal Zoetwaterbeheer en Afvalwaterbehandeling	(fresh) water management
Deursen, drs. Willem P.A. van	Carthago Consultancy	hydrology
Hassanizadeh, prof. dr. S. Majid	Universiteit Utrecht Faculteit Aardwetenschappen	geohydrology (VCH)
Holtslag, prof. dr. A.A.M. Bert	Wageningen Universiteit Meteorologie en Luchtkwaliteit	boundery layer meteorology (VCH)
Hurk, dr. Bart van den	Koninklijk Nederlands Meteorologisch Instituut	climatology
Leuven, dr. Rob S.E.W.	Katholieke Universiteit Nijmegen, Environmental Studies	hydrology, environmental sciences
Reggiani, dr. Paolo	Delft Hydraulics	geohydrology
Rientjes, dr. ing. Tom H.M.	Technische Universiteit Delft	geohydrology
Roelofs, prof. dr. Jan G.M.	Katholieke Universiteit Nijmegen, Section Environmental Biology	ecology
Troch, prof. dr. ir. Peter A.	Wageningen Universiteit, Sectie Waterhuishouding	hydrology (VCH)
Uijlenhoet, dr. ir. Remko	Wageningen Universiteit, Sectie Waterhuishouding	hydrology
Valkering, drs. Pieter	Universiteit Maastricht, ICIS	integrated assessment
Vandenberghe, prof. dr. Jeff	Vrije Universiteit, Faculteit Aard- en Levenswetenschappen	geology, geomorphology

Expert Meeting 18 March 2004 Afternoon Session: Soil moisture dynamics at the landscape scale

Name	Institutions	Discipline
Bierkens, prof. dr. ir. Mark F.P.	Universiteit Utrecht, Ruimtelijke Wetenschappen	hydrology (VCH)
Bogaart, dr. Patrick W.	Wageningen Universiteit, Sectie Waterhuishouding	hydrology, geomorphology
Bouten, prof. dr. ir. Willem	Universiteit van Amsterdam, IBED	hydrology
Groenendael, prof. dr. Jan M. van	Katholieke Universiteit Nijmegen, Afdeling Oecologie	wetland ecology (VCH)
Hassanizadeh, prof. dr. S. Majid	Universiteit Utrecht, Faculteit Aardwetenschappen	geohydrology (VCH)
Hurk, dr. Bart van den	Koninklijk Nederlands Meteorologisch Instituut	climatology
Moors, dr. Eddy J.	WUR Alterra	hydrology
Pop, dr. I. Sarin	Technische Universiteit Eindhoven, Applied Analysis Group	mathematics
Raats, dr. Peter A.C.	Wiskundige en statistische methoden	soil physics
Rooij, dr. ir. Ger H. de	Wageningen Universiteit, Sectie Waterhuishouding	soil,physics
Su, dr. Bob	Wageningen Universiteit, Alterra	hydrology aride areas
Troch, prof. dr. ir. Peter A.	Wageningen Universiteit, Sectie Waterhuishouding	hydrology (VCH)
Uijlenhoet, dr. Remko	Wageningen Universiteit, Sectie Waterhuishouding	hydrology
Vandenberghe, prof. dr. Jeff	Vrije Universiteit, Faculteit Aard- en Levenswetenschappen	geology, geomorphology

Expert Meeting 25 March 2004 Morning Session: Contaminants in the subsurface

Name	**Institution**	**Discipline**
Breukelen, dr. Boris M. van	Vrije Universiteit Faculteit Aard- en Levenswetenschappen	biogeochemistry
Bruining, dr. J. Hans	Technische Universiteit Delft Faculty of Civil Engineering and Geosciences	geo-environmental sciences
Duijn, prof. dr. ir. C.J. Hans	Technische Universiteit Eindhoven Capaciteitsgroep Wiskunde	mathematics (VCH)
Grasman, prof. dr. ir. Johan	Wageningen Universiteit Biometris	biometrics
Griffioen, dr. Jasper	Nederlands Instituut voor Toegepaste Geowetenschappen TNO	hydrogeochemistry
Hassanizadeh, prof. dr. S. Majid	Universiteit Utrecht Faculteit Aardwetenschappen	geohydrology (VCH)
Heinen, dr. ir. Marius	Wageningen Alterra	nutrient transport
Hofstee, dr. Cor	Nederlands Instituut voor Toegepaste Geowetenschappen TNO	soil sanitation
Kooi, dr. Henk	Vrije Universiteit Faculteit Aard- en Levenswetenschappen	hydrogeology
Leijnse, prof. dr. ir. A. Toon	Wageningen Universiteit Sectie Waterhuishouding	geohydrology (VCH)
Meent, prof. dr. ir. Dik van de	Katholieke Universiteit Nijmegen Department of Environmental Sciences	environmental chemistry
Rooij, dr. Ger H. de	Wageningen Universiteit Sectie Waterhuishouding	soil physics
Schotting, dr. Ruud	Universiteit Utrecht Faculteit Ruimtelijke wetenschappen	hydrogeology
Zijl, dr. Wouter	Nederlands Instituut voor Toegepaste Geowetenschappen TNO	mathematical physics

Expert Meeting 25 March 2004 Afternoon Session: Ecohydrology

Name	**Institution**	**Discipline**
Bosveld,dr. Fred C.	Koninklijk Nederlands Meteorologisch Instituut	meteorology
Bruijnzeel, dr. L.A. Sampurno	Vrije Universiteit, Faculteit Aard- en Levenswetenschappen	geo environmental sciences
Bruin, dr. Henk A.R. de	Wageningen Universiteit, Meteorologie en Luchtkwaliteit	meteorology
Bruin, dr.ir. Sytze de	Wageningen Universiteit, Centrum voor Geo-informatie	meteorology
Dolman, prof.dr. A.J. Han	Vrije Universiteit Faculteit, Aard- en Levenswetenschappen	ecohydrology (VCH)
Groenendael, prof.dr. Jan M. van	Katholieke Universiteit Nijmegen Aquatische ecologie	ecology (VCH)
Hassanizadeh, prof.dr. S. Majid	Universiteit Utrecht, Faculteit Aardwetenschappen	geohydrology (VCH)
Holtslag, prof.dr. A.A.M. Bert	Wageningen Universiteit, Meteorologie en Luchtkwaliteit	meteorology (VCH)
Kruijt, prof. dr. Bart	Wageningen Universiteit, Alterra	land – atmosphere interactions
Lamers, dr. Leon P.M.	Katholieke Universiteit Nijmegen	ecology
Leijnse, prof.dr. ir. A. Toon	Wageningen Universiteit, Sectie Waterhuishouding	geohydrology (VCH)
Rietkerk, dr. Max	Universiteit Utrecht, Ruimtelijke Wetenschappen	system ecology
Su, dr. Z. Bob	Wageningen Universiteit, Alterra	hydrology, Remote Sensing
Witte, dr.ir. J.P.M. Flip	Wageningen Universiteit, Sectie Waterhuishouding + KIWA	ecohydrology

ANNEX C. List of other experts consulted during the Preliminary Foresight and the Foresight Study

Invited experts

Prof. dr. Dennis P. Lettenmaier, Water Resource Engineering & Hydrology, University of Washington, Seattle (USA)
Prof. dr. Marc B. Parlange, Geography and Environmental Engineering, John Hopkins University, Baltimore (USA)
Prof. dr. Ignacio Rodriguez-Iturbe, Environmental Studies and Civil & Environmental Engineering, Princeton University, Princeton (USA)

MSc coordinators

Prof. dr. Willem Bouten, *Science Faculty*, Universiteit van Amsterdam
Dr. Martin Hendriks, MSc programme director Hydrology, Utrecht University
Dr ir. Henny van Lanen, Hydrology and Quantitative Water Management, Wageningen University
Dr. Maarten Waterloo, Faculty of Earth and Life Sciences, Vrije Universiteit
Prof. dr. ir. Huub Savenije, Hydrology and Water resources management, Delft University

List of participants in Nice discussion forum, April 7th 2003

John D. Albertson, Duke University, USA
Randel Haverkamp, Institut National Polytechnique de Grenoble, France
Jan W. Hopmans, University of Davis, USA
Gaby Katul, Duke University, USA
Marco Mancini, Politecnico di Milano, Italy
Murugesu Sivapalan, Centre for Water Research, University of Western Australia, Australia
Georg Teutsch, University of Tubingen, Germany
Stefan Uhlenbrook, University of Freiburg, Germany
Charles J. Vorosmarty, University of New Hampshire, USA
Eric Wood, Princeton University, USA

Interviewees from 'related disciplines'

Prof. dr. P. Van Cappellen, geochemistry, Utrecht University
Prof. dr. ir. H.A. Dijkstra, oceanography, Utrecht University
Prof. dr. ir. C.J. van Duijn, mathematics, Technical University of Eindhoven
Dr. B. van den Hurk, meteorology, Royal Netherlands Meteorological Institute

Prof. dr. C.P.J.W. van Kruijsdijk, petroleum geology, Delft University of Technology
Prof. dr. ir. W.H. Rulkens, environment technology, Wageningen University
Prof. dr. M. Scheffer, aquatic ecology and water quality management, Wageningen University
Prof. dr. ir. M.J.F. Stive, coastal morphodynamics, Delft University of Technology
Prof. dr. ir. A. Veldkamp, soil science and geology, Wageningen University
Prof. dr. ir. S.E.A.T.M. van der Zee, soil hygiene and soil pollution, Wageningen University

ANNEX D. Hydrological science disciplines

As in other sciences, hydrological science has developed into a number of disciplines. These are depicted in Figure 8. Obviously, these disciplines are not isolated, but exhibit a great deal of overlap. However, they have more or less their own scientific communities complete with specialised journals and conferences. A short description of these disciplines will be given here, which will also provide an overview of hydrological science. Obviously, as already mentioned in the definition, hydrology draws upon the more general disciplines such as mathematics, physics (mainly Newtonian mechanics) and chemistry. These are not depicted in Figure 8.

A traditional distinction is made between subsurface hydrology and surface hydrology. In subsurface hydrology, one is mainly concerned with the stocks and flow of water and other fluids and the transport of solutes and energy through porous media. In surface hydrology, interest is focused on the stocks, flow of water, sediments, and solutes over the land surface and in rivers as well as on the exchange of water, nutrients and energy between land surface and atmosphere. However, there is a great deal of overlap and coupling between surface and subsurface hydrology. In particular, surface water – groundwater interactions in the context of watershed modelling, and regional hydrology, ecohydrology, landscape processes, etc., are very important.

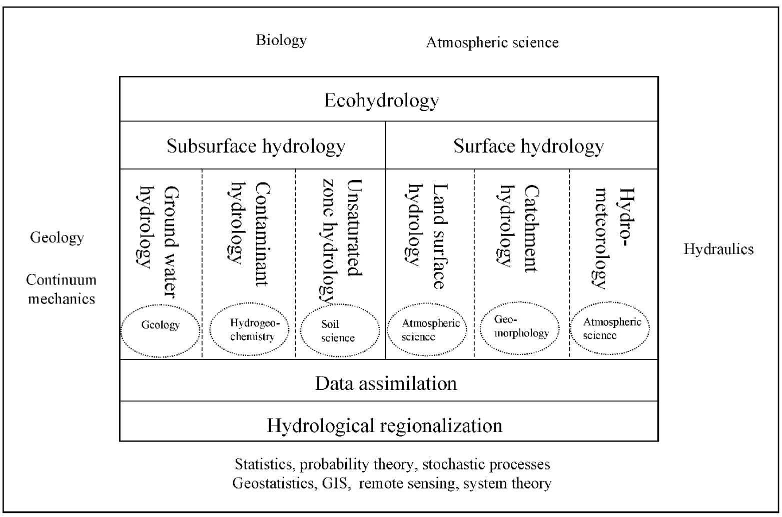

Figure 8. Overview of scientific disciplines of hydrology and their relation to other disciplines.

Subsurface hydrology

In the subsurface, three distinct phases are commonly present: liquids (predominantly water and sometimes other liquids), gasses (predominantly air and sometimes other gasses), and solid (soil and rock matrix). Subsurface processes include the movement of fluids in soils and rocks, movement of substances dissolved in these fluids, rock-fluid interactions, and biogeochemical interactions.

Until a few decades ago, the major issue of interest in subsurface hydrology was groundwater exploration and supply. The subject matter was subdivided into geohydrology and hydrogeology. Geohydrology, as the name suggests, used to deal with subterranean water hydrology. It related to the hydraulics of groundwater flow and solute transport. Hydrogeology, as the name suggests, used to deal with the geologic aspects of water (even including surface water). It regarded the 'study of groundwater with particular emphasis given to its chemistry, mode of migration, and relation to the geologic environment.' (quoted from Hydrogeology, by S.N. Davis and R.J.M. De Wiest, 1966). In the course of the second half of the last century, hydrogeologists and geohydrologists have broadened their scope of interest and the distinction between the two fields has almost disappeared. In particular, their focus has shifted from water quantity to water quality (both chemical and biological aspects). Fifty years ago, salt-water intrusion was perhaps the only important environmental research issue in subsurface hydrology. Until a couple of decades ago, groundwater curricula at universities emphasised topics relevant to water supply, well hydraulics and pumping tests, and the major issue of importance in soil quality research regarded soil salinity in the framework of agricultural practices. New developments, however, have greatly broadened the scope of problems of interest in subsurface hydrology. There are three main areas in subsurface hydrology as described below.

Groundwater hydrology

This is a traditional area that deals with the movement of groundwater in upper layers of the earth surface. Groundwater is studied both as part of a natural flow system, in the context of groundwater flow systems analysis, and in a forced flow system, mainly in the context of exploration and production for domestic, industrial, or agricultural uses. In the latter case, we are mainly interested in quantitative processes in the saturated zone. There are only marginal research areas in relation to groundwater production problems. There are robust groundwater models that are widely used.

Natural groundwater flow occurs in hierarchically structured, gravity-induced flow systems, from high-lying infiltration or recharge areas towards low-lying exfiltration or discharge areas. Groundwater flow systems analysis is the integrated and regional approach to the study of movement of groundwater, its mechanical, chemical, and thermal interactions with the subsurface, and the transport of energy and (bio)chemical components by groundwater flow. It concerns an integrated study of correlation between the cause (groundwater flow) and effects, such as pressure, water chemistry, temperature, surface moisture, vegetation type, and slope stability. The groundwater flow systems analysis, as developed in the Netherlands over the last 20 years, involves the management, analysis and interpretation of these effects using an extensive regional geohydrological information system, in combination with groundwater flow simulation. Such a systems approach is a prerequisite for a reliable evaluation of the effects of natural changes that influence groundwater flow, and of human intervention in the groundwater flow system. It is applied successfully on different spatial scales for quantitative and qualitative water management purposes in the Netherlands and abroad. Active research to improve the quantitative understanding of flow in groundwater flow systems concerns both transient aspects of flow in relation to geological processes and the hydraulic characterisation of the heterogeneous subsurface, especially of fault and fracture zones and low-permeability layers.

Unsaturated zone hydrology

Unsaturated zone hydrology studies the flow of water, solutes, and energy in the zone between the groundwater table and the land surface where both air and water are present. Although flow in the unsaturated zone is basically a two-phase flow problem, it has traditionally been described by a single-phase approach where the air-water content is described by a soil-moisture retention curve. Much research effort has been spent on the determination and parameterisation of the soil moisture retention curve and the unsaturated conductivity function. Traditionally, there have been strong links with agrohydrology (related to agricultural production), soil physics, plant physiology, and micrometeorology. In recent years, research interest has been shifting towards local and regional pollution problems. Unsaturated zone hydrology has a strong experimental tradition, where field sampling and field experiments are combined with laboratory experiments to study flow phenomena. It is now recognised that soil moisture content is the most important state variable in the continental hydrological cycle. It determines the partitioning of water and energy at the land surface and thus controls groundwater recharge, surface runoff and evaporation. These processes, in turn, determine erosion rates, vegetation development, and the way nutrients and pollutants pass through the landscape. Also, soil moisture is probably the most important control on climate variability in continental climates. Important links exist between the existence of soil moisture reservoirs and the state and development of vegetation. The new science of ecohydrology deals with soil moisture availability and vegetation development, species distribution and, ultimately, biodiversity. Therefore, unsaturated zone hydrology, the sub-discipline that deals with soil moisture, has a pivotal position within hydrological science.

Contaminant hydrogeology

Contaminant hydrogeology, or contaminant geohydrology, is the study of movement and fate of pollutants in the subsurface and the methodologies for soil and groundwater remediation and containment of pollutants. This is an extremely important field because of social concerns about our soil and groundwater resources that are constantly threatened by human activities (urban, industrial, agricultural, development of infrastructure). There is a clear need for cleaning and/or protecting these resources. In fact, due to the steady rise in population, there is an increasing demand for clean groundwater supplies. During the second half of the last century, billions of euros have been spent on the study of soil and groundwater contamination and the remediation of severe cases. Although it seems that the time for large-scale remediation projects has passed (not so in some EU countries and former Eastern Europe and Soviet Union), there is still a long way to go before all major soil and groundwater pollution problems are solved. In any case, monitoring and containment of contaminated sites shall remain important activities for many decades to come. Moreover, there are activities related to the use of the subsurface for the sustainable management of the environment and sustainable urban development. These include (seasonal) storage of thermal energy, safe storage of hazardous waste, sequestration of CO_2, and the use of the subsurface for various underground structures. In order to ensure that in trying to solve one problem, we do not create new problems, it is of vital importance to have (very) good knowledge of processes that play a role in such activities and to be able to quantify consequences of our actions.

Processes of interest in contaminant geohydrology are diverse and coupled. One must study flow of fluids (water, air, organic liquids) and their components, interactions among themselves, and their interactions with the soil and the subsurface ecosystem. Thus, often models of contaminant hydrogeology have to include a mix of processes such as advection, dispersion, adsorption, dissolution, volatilisation and biodegradation in highly complex porous media (with heterogeneity, fracture systems, or micro layers). As a result, contaminant hydrogeology has become a highly multi-disciplinary research area where exchange of expertise with geochemists, soil biologists, soil physicists, microbiologists, petroleum engineers, mathematicians, and geophysicists is needed.

Surface hydrology

Surface hydrology can be divided into three sub-disciplines: land surface hydrology, catchment hydrology and hydrometeorology.

Land surface hydrology is concerned with the exchange of water and energy between the land surface and the atmosphere, as well as with the partitioning of water at the land surface. It studies: i) the relationship between soil controlling moisture content, temperature, evaporation and transpiration and ii) the relationship between soil moisture content and the way precipitation is partitioned between canopy interception, surface runoff, soil moisture storage and groundwater recharge. Major research lines within land surface hydrology are:

- Development of the so-called soil-vegetation-atmosphere transfer schemes (SVATs) that are used in atmospheric general circulation models (AGCMs). Extension of such schemes with full-fledged land surface models is a recent development, such that land-sea freshwater runoff can also be included in AGCMs. Also, land surface models are combined with remote sensing data using data assimilation techniques to provide large-scale estimates of soil moisture content that can then be used to constrain AGCMs and improve weather prediction.
- Development of global hydrological models, which can be used to assess the impact of climate change and population growth on global water stress.
- Land use hydrology, where the distribution and exchange of water, nutrient and energy fluxes in canopies is studied, particularly in cases where land use change such as deforestation or desertification is a major issue.
- Snow hydrology, a topic of increasing importance, in particular because climate change is expected to have the largest impact in mountainous and arctic regions.
- Scaling or aggregation of land surface parameters from small to large scale. Due to the highly non-linear relations between parameters and fluxes, in general no simple aggregation rules exist.

Catchment hydrology is very much related to land surface hydrology. One difference is that in catchment hydrology the redistribution of water fluxes and the subsequent transport of substances (pollutants, sediments, etc.) is described on the scale of a catchment as a functional unit. A second difference is that in catchment hydrology interest is mainly focussed on runoff and substances transported within. Runoff is studied in three ways. The first is the study of mechanisms of runoff generation: where and by which mechanisms does runoff originate? Most of the peak runoff events are generated in upstream areas. The study of runoff generating mechanisms has culminated in a separate sub-discipline called 'hillslope hydrology'. Here, the paths by which the rain that falls on a hillslope travels to open water (streams) is studied. A correct description of the different paths water takes within the landscape is crucial to understand how pollutants and sediments are transported to the outlet of the catchment. Obviously, many principles from land surface hydrology are used here, so that the distinction between land surface hydrology and catchment hydrology at this point is rather vague. Another way by which runoff is studied is river routing; the water path trough the catchment, i.e. how does water travel through the drainage network. Routing water through stream networks has a strong relation with hydraulics. Finally, a large part of catchment hydrology has been concerned with explaining and predicting observed hydrographs at the catchment's outlet. Catchment hydrology has strong ties with geomorphology for several reasons. First, geomorphology has a major influence on the shape of the hydrograph, i.e. through hillslope form in small catchments and through river network morphology in large catchments. Also, landscape shaping processes such as erosion and mass movements are controlled by surface runoff and hillslope groundwater storage, respectively. So, predicting land degradation is usually proceeded by catchment-scale hydrological modelling. Finally, recent developments in geomorphology seek to explain the formation and form of erosive river networks from hydrological principles. An important tool in catchment hydrology is the use of isotope tracers. Of all the methods used to study hydrological processes in (small) catchments over the past 20 years, isotope tracers have provided the best new insights into the age, origin, and pathway of water movement. Isotope hydrograph separations determined by simple conservative-mixing models have shown repeatedly that stream flow generated during rainfall or snowmelt is derived primarily from water stored in the catchment prior to the event, a surprising insight that has profoundly changed how hydrologists view the runoff process. Use of other isotopes to trace solute sources and reactions has revolutionised the way we view catchment biogeochemical processes.

Hydrometeorology is concerned with the spatial-temporal occurrence of rainfall, the behaviour of water in the atmosphere and at the atmosphere land surface interface. Hydrometeorology is strongly linked with atmospheric science, which is evident from the fact that both hydrologists and atmospheric scientists are active in this field. Research themes within hydrometeorology are the modelling of rainfall time series and rainfall fields using statistical resampling techniques, point processes, multiplicative cascades, and meso-scale atmospheric models and the modelling of measurement of the exchange of heat and water vapour at the land atmosphere interface. Since the advent of weather radar, much research has been performed on the relation between radar reflectivity and rainfall intensity and on the calibration of radar images to rain gauges. Associated with this line of research is the parameterisation of rainfall microstructure based on principles from statistical mechanics. Considerable progress has been made in the last few years in the measurement of evaporation through the use of micrometeorological techniques such as eddy correlation and scintillometry. These developments in measurements techniques have opened new areas in the study of interannual variability in evaporation and interaction of terrestrial ecosystems with the hydrological cycle. Particularly, the availability of large-scale data sets, with full energy and water balances over different types of vegetation, allows detailed investigations into the role of vegetation on the hydrological cycle, and on biogeographical differences in water use of vegetation.

Integrative and auxiliary sub-disciplines

Ecohydrology seeks to understand the interaction between the hydrological cycle and continental terrestrial ecosystems. The key question is: what are the underlying hydrological patterns and causes that determine the apparent enormous diversity of ecological functioning and how do these feed back on the water cycle? Ecohydrology, according to this definition, is a relatively new discipline in hydrology. In a more limited form, ecohydrological research has been around longer. This limited form has mainly concerned the search for non-biotic parameter values (groundwater levels and groundwater quality) that yield optimal circumstances for certain water dependent ecosystems, usually wetlands. More recently, interest has shifted to understanding how plants interact with hydrology. Such interaction not only concerns the way that the hydrological situation limits some species, but also how it favours the development of one species over another (competition) and, more importantly, how certain species may influence the hydrological situation in their favour. Such systems have many positive feedbacks and show self-organised behaviour. To study this behaviour, coupled models of hydrology and space-time vegetation dynamics (including competition and succession) are built. These models are also used to learn about the impact of climatic forcing and human influence on the buffering capacity of ecosystems. Soil moisture content and nutrient availability (C, N, S, P) are key hydrological variables here. On a much larger scale (continental or even global), ecohydrology studies the interaction between the terrestrial hydrological cycle and the biosphere in the context of large-scale water, nutrient and carbon cycles. Obviously, ecohydrology has strong ties with biology and atmospheric science.

Stochastic hydrology aims at an integrated modelling of hydrological processes and the corresponding uncertainty. Uncertainty about the true state of hydrological variables exists due to observation errors, lack of knowledge of boundary and initial conditions, errors in model concepts and errors in parameterisation, i.e. due to unknown spatial and temporal variation of parameters. To deal with such uncertainty, stochastic models are built. Instead of point estimates of the hydrological state, stochastic models consider inputs, parameters, boundary conditions and/or initial conditions as stochastic variables or processes and provide probability distributions of the state. The variance or entropy of such probability distributions then reflects the uncertainty about the true state. Uncertainty can be reduced through observations whereby conditional distributions (with smaller variance) are obtained. In stochastic hydrology, three main research fields have shown significant development. The first field is hydrological statistics that is mainly concerned with estimating the probability of extreme events. These probabilities are obtained from observed time series by fitting probability distributions of yearly maximums or peak over threshold data. A second field is stochastic modelling of hydrological time series. Such methods are mainly used for time series extrapolation or hydrological forecasting. A third field of research that has flourished greatly is stochastic subsurface hydrology. Here, groundwater flow and transport are modelled where porous media properties are described with random fields. Analytical solutions of the statistical moments of head distributions and concentration fields have been derived for certain special cases. Alternatively, Monte Carlo simulations involving geo-statistical methods can be used. Many methods derived in stochastic subsurface hydrology are now being used in other hydrological sub-disciplines to analyse the effect of unknown spatial and temporal heterogeneity on the uncertainty of model outcomes. Stochastic hydrology draws heavily on methods developed in mathematical fields such as statistics, probability theory and the theory of stochastic processes.

Hydrological regionalisation and scaling is related to stochastic hydrology, but its scope is wider. Hydrological regionalisation stands for all methods that aim at translation of process knowledge and parameter values known for a limited number of small areas or small scales to exhaustive process descriptions and parameterisations for large areas and scales. The necessity of developing regionalisation methods arose with both the advent of numerical models where large grids needed to be filled with parameters or boundary processes and the need to predict hydrological behaviour at large scales. Important characteristics of regionalisation methods are the use of various forms of auxiliary information such as digital elevation models and remote sensing images, and explicit accounting for uncertainty due to unknown variability. Regionalisation methods make extensive use of stochastic process theory, geostatistics, GIS analysis, spatial sampling theory, upscaling and downscaling methods, methods of model reduction and model simplification, and data assimilation methods. Hydrological regionalisation is strongly technology driven. So, it is expected that new and better methods will be developed in the wake of better remote sensing techniques (higher spatial and spectral resolutions) and faster computers.

Data assimilation stands for merging observations and model predictions to arrive at physically consistent and (nearly) optimal predictions of state variables. It has been an active field of research for over a decade now in meteorology and oceanography, mainly to keep highly non-linear models on track. In the last few years data-assimilation has found its way to hydrological modelling, especially in land surface modelling. Here, remote sensing data as well as point observations are used to improve model predictions of discharge, soil moisture content and evaporation. Both in the us and in the EU important initiatives are underway to develop land surface data assimilation tools. This is a major scientific challenge as also stated by GEWEX.

Computational hydrology is (and should be) an integral part of hydrological research. Hydrological systems are in general characterised by heterogeneity at different spatial scales, temporal variability at different time scales, and the occurrence of strongly coupled non-linear processes. Modelling these systems will require models with high resolutions in space and time, which can only be accomplished if very efficient and robust numerical methods are employed. That becomes even more important if one considers the problems of data assimilation, parameter estimation (inverse modelling), optimisation, and the quantification of prediction uncertainties of hydrological models. These fields rely on stochastic approaches that will in principle require large numbers of simulations with complicated models. Although computational hydrology relies to a large extent on methods developed in similar fields, such as Computational Fluid Dynamics, many researchers in hydrological science have worked in the last decades on the development of new efficient and dedicated numerical techniques. Obviously, strong ties with (numerical) mathematicians were and are prerequisites for the success of this work.

Remote Sensing. The value of remote sensing data to hydrological research has long been recognised. But only recently significant progress (both in terms of remote sensing technology and image interpretation) has been made to start to fulfil the high expectations that the hydrological community has from remote sensing. Compared to conventional methods of data collection, the main advantages of remote sensing techniques may be summarised as:

- o disturbance of the objects being measured;
- exhaustive distributed measurements instead of point measurements;
- possibly high resolution in space and/or time;
- data available in digital form;
- information possible about remote and inaccessible areas. The main disadvantage is that remote sensors do not directly provide data in a form needed in hydrology. The information acquired by such sensors consists of measurements of electromagnetic signals that have to be converted into hydrological relevant data. Another major problem facing the user of these data is how to effectively incorporate remotely sensed data into hydrological studies. Remote sensing data can be utilised in different ways in hydrological modelling:
- as parametric input data, including land cover data, such as land use classes and soil properties, mainly acquired from passive remote sensing instruments and precipitation data, mainly obtained using ground based weather radar systems;
- as data on initial conditions, such as initial catchment wetness;
- as data on hydrological state variables, such as soil moisture, vegetation status relating to evaporation, and snow cover extent.

While the application of the data of types (1) and (2) in distributed hydrological models is, in principle, quite straightforward, application of type (3) data requires new modelling approaches, such as data assimilation, where uncertainties in both remote-sensing-inferred data and model estimates have to be incorporated. In the accompanying box, a short review of existing and emerging remote sensing techniques for hydrological applications are discussed.

Hydrological science and engineering hydrology

It is important to distinguish between hydrological science and engineering hydrology. Hydrological science aims at understanding the mechanisms of the hydrological cycle and its interaction with the lithosphere, atmosphere and biosphere. In engineering hydrology, the knowledge generated from hydrological science is used in the design and operation of dams, water distribution works, drainage and irrigation systems and drinking water wells, and to direct water management policies.

Over the centuries there has been a shift of interest from one to the other and back. According to

A.K. Biswas (History of Hydrology, North-Holland Pub., Amsterdam, 1970), hydrology started off as an engineering practice during the rise of early civilisations to serve agricultural and military purposes. During the Greek and Roman civilisations, hydrology became a classical science, as philosophers pondered the origins of rivers, springs, and rain; not for the sake of application but solely for the sake of (process) understanding. But, it wasn't until the 17th century that hydrology became a modern (empirical) science when scientists such as Perrault, Mariot and Halley defined and explained the hydrological cycle quantitatively through observations of rain, evaporation, and discharges of rivers and springs. During the 18th century methods for quantification of precipitation, evaporation, and discharge were developed. Also, the first discharge formulas (e.g. Chezy) were derived during the 18th century, while Bernoulli defined his energy equation. The 19th century is characterised by important contributions to the theory of surface water flow (e.g. Navier and Saint-Venant) and the birth of the theory of flow through porous media (with contributions from Darcy, Dupuit, Forcheimer and Boussinesq). Clearly, developments in hydrology seem to be in line with development of natural sciences in general (e.g. Gribbin, J., 2002, Science: a history). See for the history of Dutch (engineering) hydrology annex H.

Despite many advances during the twentieth century, hydrological science also suffered greatly from lack of visibility as a self-contained scientific discipline in earth sciences. This issue was thoroughly discussed in a paper by Klemeš (1986). His basic argument was that hydrology suffers from lack of scientific stature due to the curse of practical model application. Indeed, hydrologists have invested too much effort (with reasonable success) in the development and application of hydrological models in engineering practice. Moreover, for too long, empirical relationships have formed the cornerstone of hydrological models; hydrologists have too quickly chosen to use such relationships for the sake of practical applicability of their models.

These arguments, however, are only partly true as, parallel to hydrological applications, dedicated and systematic studies for the characterisation and explanation of hydrological processes and systems have been carried out for many decades. Thanks to its many achievements and a splendid history, there is currently no doubt about the scientific stature of hydrology. In fact, there has been an increasing interest in a scientific approach to hydrological modelling in the last decades. This is a result of the fact that empirical approaches have proven inadequate in solving the complicated practical problems that we have to solve nowadays. Also, new measuring and monitoring techniques and the huge increase in our computational abilities have greatly facilitated and enhanced these developments. The scientific approach to hydrology strives not only to reduce empiricism in solving engineering problems, but also to address the multitude of non-engineering aspects of hydrology (notably links with climate, biosphere, and water quality) at various scales. The prediction of hydrological stocks and fluxes in a changing environment calls for physically-based models that can be applied to assess the impact of environmental change on hydrological behaviour.

ANNEX E. Current research programmes of Dutch hydrology groups

Delft University of Technology

Main hydrological research activities are carried out under the Chair of Hydrology of the Section of Water Resources and are related to surface water hydrology and geohydrology, within a civil engineering context. Research is a combination of field investigations, laboratory experiments, modelling, and theoretical development. The following fields are distinguished:

– River Basin Hydrology. The focus is on understanding, describing and modelling rainfall-runoff processes, both in terms of runoff production and runoff routing in river basins. The research programme concentrates on the impact of human interventions and of the underlying systems of reticulation. The approach is a combination of physically based and conceptual modelling at different scales. The potential to use gravity observations from space for modelling has special attention
– Hydrology for water management in rural areas. On a local and regional scale in rural areas, research is focused on understanding, describing and modelling the water system in relation to local meteorological conditions, soil conditions and land use
– Hydrology of deltas. The focus is on research into the interaction between estuary shape, river discharge, tides, salt intrusion, groundwater interactions, water quality and ecology
– Hydrology of Groundwater Systems. Groundwater in relation to the different functions and users of groundwater; groundwater-surface water interaction; groundwater-ecosystem interaction; groundwater as a source for drinking water; salt water intrusion in coastal areas; protection of groundwater resources; and time series analysis.

Universiteit van Amsterdam

Universiteit van Amsterdam does not have a formal programme in hydrology. But a small hydrology group (assistant professorship level) exists at the Institute for Biodiversity and Ecosystems Dynamics (IBED) of the Universiteit van Amsterdam.

The hydrological research within the Institute for Biodiversity and Ecosystems Dynamics (IBED) aims at understanding the functioning of landscape ecosystems from a hydrological viewpoint. Studies are carried out by combining field inventories, laboratory experiments, process measurements in the field, remote sensing, geostatistical data analysis, and the development of simulation models. The research focuses on the following aspects:

- The study of soil – water – plant relations including transpiration dynamics and the spatiotemporal distributions of root water uptake.
- The study of mutual relations between vegetation development and hydrogeomorphological processes including the emergence of vegetation patterns in the semi-arid Mediterranean.
- The study of the hydrochemistry of zero to third order catchments with emphasis on interactions between dissolved organic matter – (heavy) metals and dissolved organic matter – nutrients (N, P, S).
- The role of scales in the hydrological and geomorphological process response of catchments incorporating thresholds and hierarchy of spatio-temporal process domains in humid and semiarid geo-ecosystems.
- Development of measuring techniques for hydrological research.
- Development of techniques for identifying model parameters that cannot be measured independently.

University of Twente

A small hydrology group (assistant professorship level and PhD students) exists at the Faculty of Engineering Technology, group of Water Engineering and Management (WEM) at the University of Twente. The hydrological research of WEM focuses on the analysis and modelling of large scale hydrological systems, which may be part of large scale integrated models. These integrated models include river hydraulics, ecology, morphodynamics and socio-economic aspects as well and can be used to support decision makers in water management. The hydrological research focuses on the following aspects:
- Impacts of climate change and variability on floods and droughts.
- Flood forecasting for reservoir operation.
- Development of methodologies and techniques to determine appropriate hydrological models and its components (e.g. spatial and temporal scales, model structures).
- Uncertainty analysis and propagation in large hydrological systems.
- Consistent coupling of hydrological models and models from related fields (e.g. hydraulic and ecological models).

Utrecht University

The Hydrological research at Utrecht University is concentrated in the Faculty of Geosciences, mainly through Departments of Physical Geography and Earth Sciences.

The research at the Department of Physical Geography deals with processes on or just under the earth's surface at scales from a few square centimetres to whole drainage basins (for example the Rhine) or supra-regional basins (like the Mediterranean). The complete programme – in which hydrology collaborates with other disciplines – covers the study of the dynamics of major rivers under climate change, the environmental quality of drainage basins, land degradation in mountainous areas and the Mediterranean at local or continental scales, and the ecohydrology of wetlands. Common to all these themes is the use of geographical information systems (GIS), remote sensing, stochastic methods and geostatistics and computerised tools for dynamic modelling. Specific hydrology topics of interest are:

- Hydrological regionalisation and stochastic hydrology.
- Spatio-temporal soil moisture dynamics: coupled modelling of hydrology and vegetation dynamics .
- Hydrology of upstream areas and hydrology of large river systems subject to climate change .
- Land degradation hydrology: modelling erosion and hydrologyl-induced landslides.

The hydrological research at the Department of Earth Sciences deals with subsurface flow and transport processes as well as surface water quality. Major research issues with emphasis on environmental issues concern soil and groundwater contamination and remediation, storage of matter and energy in the subsurface, reactive transport in marine environments, and study of the role of groundwater in geological processes. Specific hydrology topics of interest are:

- Contaminants and virus transport; chemical reactions, biodegradation, adsorption and clogging processes.
- Density-dependent flow: salt water – fresh water interactions, high-concentration transport, head transport.
- Multiphase flow and transport: unsaturated zone, dissolution processes, migration of organic liquids.
- Rock diagenesis and other large-scale geological transport processes.

In addition to these two main groups, at the Department of Environmental Science, hydrological research is performed within the context of ecosystem modelling and the study of ecosystem deterioration. An important topic is the catastrophic shifts in ecosystems and the positive feedback mechanisms that lead to self-organised vegetation dynamics. Here redistribution of moisture and nutrients through soil moisture and groundwater flow is considered. Another topic is the ecohydrology of wetland ecosystems.

Vrije Universiteit Amsterdam

The Department of Hydrology and Geo-environmental Sciences consists of two active groups in hydrology: Hydrogeology and Ecohydrology.

The research programme of the Hydrogeology Group focuses on 'groundwater and its interaction with lithosphere, atmosphere and biosphere'. Analyses are carried out at different scales and comprise studies of actuo-processes as well as reconstructions of groundwater systems on geological time scales. Both fundamental and applied issues are addressed. Apart from process and system modelling, emphasis is placed on insight gained from dedicated field measurements and integration of different types of observations (hydrochemistry, hydraulics, isotope hydrology, geophysics, microbiology, geology). Current/recent research activities address:

- Organic contaminant biodegradation and istope-fractionation reactive transport modelling.
- Fresh and salt groundwater in coastal areas and the offshore. Dynamics of shallow groundwater systems in the western Netherlands and its role in salinisation of surface waters. Dynamics of seawater intrusion by free convection. The origin of fresh- and brackish paleogroundwater in the offshore and offshore continuation of active groundwater flow systems.
- The role of chemical osmosis in groundwater systems.
- Sustainability/vulnerability of artificial infiltration/bank infiltration systems.
- The impact of faults in unconsolidated sediments on groundwater systems.
- Extraction of climate change and groundwater flow conditions from subsurface temperature.

The core theme of the Ecohydrology group is to analyse, quantify and predict the effects of changes in land use and climate on hydrological, meteorological, geomorphological and ecological processes, and their integration on the watershed scale. Changes in land use often occur over short time scales and the effects are often more limited in space than climatic changes. Therefore this research emphasises the land use aspect. The role of water as a transporting agent for dissolved (nutrients, pollution) and in suspension (sediment) and as the key factor in ecosystem functioning is central in this respect. Attention is given to the interaction of vegetation with the hydrological cycle by developing research in the new field of ecohydrology. Further attention is aimed at up-scaling of local processes to larger spatial scales such as watersheds with the aid of physically-based modelling and remote sensing. Research themes are:

- Quantifying effects of changes in local hydrology and water management on carbon fluxes, hydrological functioning and biodiversity in agricultural and natural peat lands and wetlands in the western Netherlands.
- Assimilating and investigating soil moisture, vegetation biomass, and temperature data on a global scale from remotely-sensed passive microwave radiation.
- Quantifying the water and energy balance of grassland and various forest types to predict the effect of lowland deforestation on the hydrology and ecology of higher situated forests in Puerto Rico.
- Studying water and nutrient fluxes in various types of tropical (montage) rain forest to understand their development and importance for water resources. The effects of deforestation, soil conservation, natural re-growth and reforestation in different areas of the world are also studied.
- Understanding and quantifying the Eurasian carbon balance.
- Quantifying the hydrological and carbon balance of taiga and tundra on permafrost in Far Eastern Siberia and assessing the vulnerability to global change.

Wageningen University

The research of the sub-department Water Resources of Wageningen University is focused on the physical and mathematical description of the hydrological cycle and its effect on the biogeochemical cycle at different scales. Two groups are active here:

The Hydrology and Quantitative Water Management Group focuses on catchment-scale hydrological processes and river basin water management. Special emphasis is put on the development of physically-based and conceptual models of surface and subsurface flow processes to examine the hydrological system and its component processes and to study the effects of climate change, land-use change and other human influences on the water and solute balance of catchments. Spatial information technologies, such as remote sensing and geographic information systems, are essential tools in this field. The following topics are covered:

- Hydrological modelling on the catchment scale with applications of remote sensing and data assimilation.
- Floods and droughts (including hydrogeological processes).
- Hydrometeorology, with focus on rainfall radar applications to hydrology.
- Solute transport on the catchment scale .
- Demand and supply of information for decision making on river basin water resources.

The Soil Physics, Agrohydrology and Groundwater Management Group deals with the physical processes of the unsaturated zone, saturated zone and the interaction between the earth surface, atmosphere and plant. These physical processes include the flow of water, heat and gasses and the transport of solutes at various spatial scales (point, field and regional) and temporal scales (seconds to years). Knowledge on physical and hydrological processes at small scale has to be scaled up to larger scales. Research activities of the group:

- Physically based multi-dimensional modelling of water flow and solute transport in heterogeneous soils
- Development of a Soil-Water-Atmosphere-Plant (SWAP) model to simulate water, heat flow and solute transport on field scale
- Physically based characterisation of land use, soil moisture and evaporation by means of optical and microwave remote sensing
- Study of hydrological processes in ecosystems for nature conservation
- Upscaling of the groundwater-surface water interaction in regional groundwater flow models.

Technological Research institutes and Other Research Centres

Alterra

Alterra investigates the use, quality and future prospects of rural areas to promote sound decisions on designation, layout and management of the land. Research focuses on problems of land use, physical planning, environmental protection and water management in rural areas and is implemented in close collaboration with government authorities at different levels. Alterra combines expertise on rural areas and their sustainable use, based on a sound understanding of each of the physical, biological and anthropogene environments. That includes aspects such as water, wildlife, forests, the environment, soils, landscape, climate (-change) and recreation.

The hydrological research at Alterra focuses on the unsaturated zone and the interactions with the surrounding compartments: atmosphere, vegetation, groundwater and surface water. The research aims to describe the physical processes of water and vapour transport, including the involved contaminants and its effects on ecosystems. For this Alterra strongly relies on a combination of experimental (field and laboratory) work, modelling and analysis at scales varying from point/field to regional scale. This hydrological expertise is combined with the other fields of expertise available at Alterra to conduct integrated studies mostly at catchment scale.

Delft Hydraulics (WL)

WL | Delft Hydraulics is an independent research institute and specialist consultancy based in The Netherlands. The Institute has been providing clients, at home and abroad, with expert advice and technical assistance on water-related issues for over 70 years. Their staff of 350 qualified and committed professionals combine an in-depth command of critical details with an across-the-board overview. Their hydrologists are active in water resources assessment, watershed management and climate change studies, often in the framework of strategic planning. Optimal design of flood protection works is supported by flood risk analyses using advanced tools like their state-of-the-art inundation modelling system delft-fls. They have world-wide experience in the implementation of advanced flood early warning systems for major river systems like the Rhine, Danube, Nile and Indus rivers. Water management organisations are supported by them while developing and enhancing their monitoring and information systems.

UNESCO-IHE Institute for Water Education

For almost 50 years, UNESCO-IHE offers post-graduate education in the field of water and environment, in particular to professionals from developing countries. Since 2002, UNESCO-IHE operates as a UNESCO Institute, strengthening and mobilising the global educational and knowledge base for integrated water resources management, and contributing to meeting the water-related capacity building needs of the developing countries and countries in transition.

UNESCO-IHE offers four MSc programmes, which comprise different specialisations, such as a Master's in Water Science and Engineering with, *inter alia,* specialisations in Surface Water Hydrology and Groundwater Hydrology, or a Master's in Water Management with, *inter alia*, specialisation in Water Resources Management.

UNESCO-IHE operates under the Ministry for Education and Science (OCW), which recognises the degrees and quality of education. The 18 months MSc programmes (106 ECTS) are subject to accreditation under the Dutch law.

The institute also offers many short post-graduate courses on water and environment related issues and course that are tailor-made to meet the needs of the client.

UNESCO-IHE is involved in many research programmes in which approximately 50 PhD fellows carry out high-level research. Joint PhD promotions take place with Delft University of Technology, the Vrije Universiteit Amsterdam, the Utrecht University, and the Wageningen University and Research Centre.

ITC

The International Institute for Geo-Information Science and Earth Observation, established in 1950 under the name International Training Centre for Aerial Survey (hence ITC), is an autonomous organisation operating under the aegis of the Ministry of Education, Culture and Science and the Minister for Development Cooperation of The Netherlands and closely linked to Twente University. The knowledge field of ITC is geo-information science and earth observation, which consists of a combination of tools and methods for the collection – through aerospace survey techniques –, storage and processing of geo-spatial data, for the dissemination and use of these data and of services based on these data. The Department of Water Resources (WRS) is ITC's focal point for expertise in water resources and water related environmental studies, concentrating on six, interrelated knowledge nodes: Water resources analysis and management, Satellite hydrology and its application in agricultural production systems, Groundwater management Environmental hydrology, Geo-information for coastal zone management and Information systems for integrated water management.

KIWA

Kiwa Water Research is the Dutch research and knowledge institute for water and associated ecological and environmental questions. Key aspects of the work of about 120 employees are innovation and knowledge transfer. The focus is the entire process of extraction, treatment, distribution and quality assessment of drinking water, industrial water and domestic water. Kiwa Water Research performs projects concerning the water cycle, varying from drinking water to waste water treatment and all related nature and environmental aspects. In close co-operation with the water supply companies, Kiwa conducts the joint research programme BTO of The Netherlands drinking water sector with a present budget of 6 million Euro annually. Not surprisingly, it is known as a leading knowledge centre of drinking water quality and all related aspects. It distinguishes itself by combining the required disciplines in one project. These disciplines can vary from scientific and technical knowledge to management expertise. Kiwa does not only find solutions by its innovative research but, when required, also implements these solutions. Companies as well as authorities frequently consult Kiwa on water related issues. Knowledge management and knowledge transfer is an essential tool for closing the gap between theory and practice. Through its certification, inspection, research and consultancy activities, Kiwa stimulates the development of people and companies alike.

NCR

The Netherlands Centre for River Studies (NCR) is a co-operation of the major developers and users of expertise in the area of rivers in The Netherlands. The NCR partners are Delft University of Technology (TUD), Utrecht University (UU), Radboud University Nijmegen (RU), University of Twente (UT), Wageningen University (WU), Unesco-UNESCO-IHE Institute for Water education, RIZA (Institute for Inland Water Management and Waste Water treatment), ALTERRA (Dutch centre of expertise on rural areas), Netherlands Institute of Applied Geoscience (TNO-NITG) and WL | Delft Hydraulics. NCR has two key functions:

- network or platform function: this function is reflected in the organisation of meetings at which expertise and experience are exchanged; other parties are very welcome to attend; examples are the yearly NCR-days and the different workshops NCR organises;
- research-oriented and educational co-operation based on a joint research program.

Disciplines of importance for NCR are hydrology (of the river basin), fluvial hydraulics, geomorphology, sedimentology, river ecology, social sciences and spatial planning.
The research program is structured in the themes:
- Living (in harmony) with the River ((Over)leven met de rivier)
- River and Floodplain Management
- Morphology (the Morphological Triangle).
- Genesis of Floods, which is incorporated in the activities of the Hydrological Triangle.

A very important part in the NCR-role as far as research is concerned is the building of a strong international image through international research co-operation. This aim of NCR received a boost by the invitation in 1999 to lead the EU sponsored (INTERREG-IIC) IRMA-SPONGE research program, focused on flood Risk management, including improving flood prediction. Most NCR partners participated in this program together with some 25 other research groups/institutes from Germany, France, Belgium, Luxembourg and Switzerland.

CWE

The Centre for Wetland Ecology is an initiative of The Netherlands Institute of Ecology (NIOO) of the Royal Netherlands Academy of Arts and Sciences, the Faculty of Science, Mathematics and Information Science of the Radboud University of Nijmegen (RU) and the Faculties of Biology and Geo Sciences of the University of Utrecht (UU). The Centre will be open for other institutions and currently negotiations with the Institute for Biodiversity and Ecosystem Dynamics (IBED) of the Universiteit van Amsterdam (UVA) are under way.
By the combination of the proposed groups of the Universities of Nijmegen and Utrecht as well as of the NIOO-KNAW a stronghold will be created in the field of wetland ecology.

Wetlands offer many services to human society. Hence, they deserve ample attention, both from the perspective of scientists as well as of managers. The three partners have a long tradition with respect to the study of freshwater wetlands. These wetlands range from fens, bogs, river floodplains and tidal marshes to shallow lakes and ponds. Each of the partners has excellent contacts with the stakeholders of these ecosystems being the managers responsible for wetland conservation as well as the policy makers.

The Centre for Wetland Ecology aims at:
- Bringing together a significantly critical mass for programming and performing basic and strategic research in the field of wetlands ecology'.
- Creating an excellent base for joint applications for national and international research grants.
- Strengthening the education of master and PhD students in the area of Wetland Ecology.
- Optimising the use of each others infrastructures.
- Bringing together PR activities for informing the general public, policy makers and the stakeholders of freshwater wetlands.

To achieve these goals each partner has committed himself to financing two PhD projects and to supporting the scientific coordination.

NITG-TNO

The Netherlands Institute of Applied Geoscience TNO – National Geological Survey (TNO-NITG) is the central geoscience institute in The Netherlands for information and research to promote the sustainable management and use of the subsurface and its natural resources. The institute has some 340 employees and 40 seconded staff and an annual turnover of more than 33 million Euro. TNO-NITG has an information function and a research function. Its information function consist of archives of borehole and geophysical data, oil production and exploration data, geological layertype models for the deep and shallow subsurface, hydrogeological models of the shallow subsurface, geological maps, groundwater maps and the groundwater archive containing groundwater head and groundwater quality data of some 20.000 locations in The Netherlands. The largest part of this information function is financed by the central Government. The fields of research of TNO-NITG comprise the entire subsoil, including geological modelling and mapping, reservoir engineering, subsoil storage of heat and CO_2, contaminant hydrogeology and groundwater modelling. Hydrogeological research at TNO-NITG is mostly applied or application driven. Specific focus areas are regional scale groundwater modelling for water management, inverse modelling and geostatistical methods for parameter estimation, time series analysis and monitoring design, wetland hydrology, groundwater remediation (including multiphase flow and reactive transport) and density dependent groundwater modelling. More fundamental, application driven, research is financed by the central Government. Contract research is performed for provinces, water boards, drinking water companies and municipalities. TNO-NITG works closely together with several Dutch universities through so-called knowledge centres, in particular with Utrecht University in the Utrecht Centre for Geosciences (UCG).

STOWA

STOWA (Dutch acronym for the Applied Water Management Research) was founded in 1971. The foundation coordinates and commissions research on behalf of a large number of local water administrations. Among the 76 bodies which contribute to the stowa, there are water boards, provinces and the Ministry of Transport, Public Works and Water Management. stowa provides water managers with scientific knowledge and practical instruments they require for carrying out their jobs sufficiently. Stowa projects cover the following fields: Collection, transport and treatment of waste water, Management of the quality and quantity of surface and groundwater and Prevention against flooding and maintenance of water barriers.

Annex F. University research groups with relations to hydrology: possible research partners for hydrological research

CWI-Amsterdam

Centre for Mathematics and Computer Science, Department Modelling, Analysis and Simulation:
- Applied Analysis
- Numerical Analysis

Delft University of Technology

Delft Institute of Applied Mathematics (DIAM):
- Applied Mathematical Analysis
- Applied Probability and Statistics

Department of Applied Earth Sciences:
- Section of Petroleum Engineering

Department of Water Management:
- Section of Hydrology and Ecology
- Section Water Resources Management

Eindhoven University of Technology

Centre for Analysis, Scientific Computing and Applications (CASA):
- Applied Analysis
- Scientific Computing

Radboud University of Nijmegen

Faculty of Science, Mathematics, and Computing Science:
- Institute for Wetland and Water Research

Utrecht University

Faculty of Geosciences:
- Geochemistry
- Geology
- Coastal and River systems
- Environmental Sciences and hydro-ecology

Science Federation (Biology):
- Environmental Toxicology and Chemistry
- Landscape Ecology
- Plant Ecology

Faculty of Physics and Astronomy, Institute for Marine and Atmospheric Research:
- Atmospheric Dynamics and Boundary Layer Meteorology

University of Groningen

Faculty of Mathematics and Natural Sciences:
- Centre for Isotope Research
- Plant Ecology group
- Microbiological Ecology group

Universiteit van Amsterdam

Faculty of Science, Institute for Biodiversity and Ecosystem Dynamics:
- Abiotic ecosystem processes (especially Computational Bio- and Physical Geography)
- Ecosystem dynamics

Vrije Universiteit Amsterdam

Faculty of Earth and Life Sciences:
- System Ecology
- Quaternary Geology and Geomorphology
- Institute for Environmental Studies

Wageningen University

Department of Environmental Sciences:
- Nature Conservation and Plant Ecology Group
- Aquatic Ecology and Water Quality Management Group
- Erosion and Soil and Water Conservation Group
- Irrigation and Water Engineering Group
- Meteorology and Air Quality Group
- Laboratory of Soil Science and Geology
- Sub-department of Soil Quality

Department of Plant Sciences:
- Fundamental Methodological research

ANNEX G. Hydrology MSc programmes: list of MSc courses and compulsory BSc courses

University	ECTS	BSc Year	MSc Courses	ECTS
Delft University of Technology (TUD):				
Hydrology	3 SP #		Computational modelling flow and transport	3 SP #
Flow in water courses	4 SP #		Water quality management	3 SP #
Groundwater mechanics and flow	3 SP #		Hydrological models	3 SP #
			Hydrological measurements	3 SP #
			Hydrology of catchments, rivers and deltas	3 SP #
			Unsaturated zone hydrogeology	7.5
			Environmental hydrology	7.5
			Hydrology and climate	7.5
Vrije Universiteit Amsterdam (VUA):				
Introduction in hydrology	5	1	Catchment response analysis	6
Hydrology of The Netherlands	6	2	Field Courses Portugal, North Italy	6
			Field Course NL (measurement techniques)	3
			Groundwater flow modelling *	6
			Groundwater hydraulics *	6
			Hydrochemistry	6
			Reg. Hydrogeology and groundw. management.	6
			Unsaturated zone & near surface processes	6
			Ecohydrology *	6
			Soil vegetation atmosphere exchange *	6

TUD has not yet introduced ECTS and uses study points (SP). 42 SP = 60 ECTS.→One ECTS is approximately 0,7 SP.

*) Compulsory for certain MSc specialisations.

Univesity	ECTS	BSc Year	MSc Courses	ECTS
Utrecht University (UU):				
Physical hydrology	5	1	Land surface hydrology	7,5
Soil and water contamination	6	3	Principles of groundwater flow	7.5
			Stochastic hydrology	7.5
			Hydrogeological transport phenomena	7.5
			Reactive transport in hydrosphere	7.5
			Unsaturated zone hydrogeology	7.5
			Environmental hydrology	7.5
			Hydrology and climate	7.5
Wageningen University (WU):				
Hydraulics and hydrometry	5.7	3	Hydraulics and hydrometry *	5.7
Practical hydrology and water quality	5.7	3	Advanced environmental hydraulics *	5.7
Excursions hydrology and water quality	5.7	3	Technical concepts integr. water management	5.7
Hydrogeology	5.7	2	Hydrological modelling; theory and practice	5.7
Soil physics and agrohydrology	5.7	2	Hydrogeology	5.7
Chemical interactions soil-water-sediment *)	5.7	2	Catchment hydrology *	5.7
Catchment hydrology *)	5.7	2	Characterisation regional fluxes by RS, soil physics and ground water modelling *	5.7

*) Compulsory for certain MSc specialisations.

UNESCO-IHE			
MSc courses **Surface Water Hydrology**	**ECTS**	**MSc courses** **Ground Water Hydrology**	**ECTS**
Intro water science and engineering	5	Intro water science and engineering	5
Hydrology and hydraulics	5	Hydrology and hydraulics	5
Hydrogeology	5	Hydrogeology	5
Regional hydrology	5	Regional hydrology	5
Physical hydrology	5	Groundwater chemistry and pollution	5
Hydrological information processing	5	Hydrological information processing	5
Hydrological Data Collection and Monitoring	5	Groundwater exploration and monitoring	5
Environmental hydrology	5	Groundwater systems analysis	5
Hydrological Modelling	5	Groundwater Modelling	5
Water Resources Management and Development	5	Water Resources Management and Development	5
Fieldwork and international excursions	5	Fieldwork and international excursions	5
Groupwork	5	Groupwork	5

Annex H. Institutional and Scientific Developments in Hydrological Research in The Netherlands

Jacobus J. de Vries & Reinder A. Feddes

Water management has always been an indispensable part of life in the Netherlands. Protection against floods, the drainage of surplus water, and the struggle against encroaching sea remained the most important control activities for more than 1000 years. Land subsidence due to drainage of peat and clayey marshland as well as reclamation of lakes and sea-embayments, brought the coastal area below sea level. This process, which began in medieval times, resulted in a complex land and water topography. Separation of more or less homogeneous water management units by dikes, dams and sluices, subsequently led to the creation of a system of polders. Reclamation works, flood protection and river-harnessing are connected with a large number of famous hydraulic engineers and surveyors, who carried out projects in the Netherlands as well as abroad.

A scientific approach in water management and hydrology only began in the 19th century when the basic laws of hydrodynamics and hydraulics evolved. Investigations in connection with the study of the behaviour of the large rivers and canals were mainly done in the framework of hydraulic engineering and will not be considered here. Hydrology in the sense of the study of processes within the hydrologic cycle has in the Netherlands always been predominantly based on groundwater hydrology, because of the strong interaction between groundwater and surface water in this flat country with a shallow groundwater table in a permeable subsurface.

Scientific groundwater hydrology in the Netherlands emerged in the second half of the 19th century in close association with the growing demand of groundwater for public water supply. Suitable fresh groundwater resources in the western, and most densely populated part of the country, were mainly restricted to the belt of coastal dunes, and were accordingly prone to depletion and salinisation. A proper and sustainable exploitation, thus, required a sound knowledge of the origin and replenishment of the fresh water reserves as well as understanding of the dynamics of the fresh/salt water interface and the flow towards the extraction means. It took a period of more than half a century of speculations, observations and theoretical considerations before a proper understanding on the basis of an adequate physical theory emerged. The scientific debates often led to strong personal controversies, sometimes with political implications because of the societal relevance of the subject. Several Dutch pioneers performed trail-blazing and outstanding work during the inception period before World War I.

Petrus Harting (1812-1885) systematically investigated the subsurface and performed already in the mid-19th century the first percolation measurements on soil columns to determine the permeability of different sediments. His work was stimulated by the search for drinking water and by the question of the expected (and feared!) upward seepage in the planned Zuiderzee reclamation. Well known are W. Badon Ghijben (1845-1907) with his theory on the depth of the fresh/salt water interface below the dunes, and J.M.K. Pennink (1853-1936), who confirmed Badon Ghijben's theory with viscous plate models and investigated the problem of salinisation. Pennink furthermore advanced the understanding of groundwater flow by his study of the radial flow pattern in a horizontal section between areas of groundwater recharge and discharge (drainage channels) by field measurements with piezometers at different depths.

The basic groundwater flow theory evolved at the turn of the century by combining Darcy's flow formula with the Laplace continuity equation. This theory made possible to simulate groundwater flow with mathematical equations and to solve a groundwater flow problem as a boundary-value problem. The Dutch hydrogeological conditions, which are characterised by relatively homogeneous aquifers and simple and artificially maintained boundary conditions, proved very suitable for application of mathematical models. A number of problems related to groundwater extraction, groundwater level control, land reclamation and civil engineering works were theoretically solved in the period following World War I. This has led to several original Dutch contributions to the theory of groundwater flow in situations were groundwater and surface water are closely related under phreatic as well as leaky aquifer conditions. This development was stimulated by large hydraulic infra-structure works and a nation-wide establishment of public water supply, particularly based on groundwater extraction. The National Institute for Drinking Water Supply (RID), founded in 1913, has played a major role in this development. This institute remained the central organisation for groundwater exploration and research for both drinking water supply and groundwater management connected with infrastructure works, for more than half a century.

J. Kooper (1914) was the first to develop a solution for the steady flow to a well or a large-diameter polder in a leaky aquifer. His work was elaborated and made accessible through the dissertation of G.J. de Glee (1930). J. Versluys (1916) was the first to explain the occurrence of $NaHCO_3$ in groundwater as a product of cation-exchange during a process of freshening of the aquifer. Since then, this water type has become an important tracer in the reconstruction of the hydrogeological evolution of the coastal area through sea level rise and human interference.

C.G.J. Vreedenburgh (1929, 1936) contributed to the theory of groundwater flow by deriving the exact solution of the Dupuit flow case. He furthermore explained how to approach anisotropy by transformation of the coordinate system, and he introduced electrolyte models. J.H. Steggewentz (1933) was the first who developed a mathematical analysis of tidal influence on adjacent aquifers and a methodology to determine aquifer parameters from the pressure propagation in confined and phreatic aquifers. It is particularly noteworthy that he took into consideration the delayed response of the groundwater table. J.H. Edelman (1947) derived theoretical solutions for transient flow near infiltration and drainage channels by an instantaneous water level change. He moreover provided a finite difference network calculation for determination of the optimal distribution of dune water extraction from the upper and lower aquifers.

Scientific research on land drainage was stimulated by the wish to reclaim and develop the new Zuiderzee polders in a rational manner. This successful research programme began in the 1930s at the Experimental Station and Soil Science Institute in Groningen by S.B. Hooghoudt (1901-1953). This led to a basic understanding of the drainage process, and the emergence of extensive basin-scale studies of groundwater discharge regimes and the related drainage requirements for different hydrologic and topographical conditions in connection to improvement of land and water management. He carried out extensive field plot experiments to investigate the optimal groundwater depth in connection with crop production.

Until the end of World War II, groundwater research and its application in water management in the Netherlands developed mainly along various sector lines with separate solutions for problems related to public water supply, agriculture and general water management infrastructure, including flood protection and salt encroachment. After the war, it became clear that an integrated approach was required to deal adequately with conflicting interests and particularly to resolve environmental problems related to water. To coordinate and stimulate research, the Committee for Hydrologic Research (CHO-TNO) was established under the umbrella of the National Organisation of Applied Scientific Research (TNO). This, among other efforts, led to integrated regional surveys, which not only focussed on a more balanced water management but also encouraged fundamental research on the interaction of surface water, groundwater, soil water, and evaporation.

Meanwhile, the government strongly stimulated reactivation and improvement of agriculture. The focus of groundwater hydrology shifted to the unsaturated zone, crop water requirement and water table control. This research became concentrated in the Institute for Land and Water Management Research (ICW), which also took over and extended the land drainage studies of Hooghoudt. This Institute was strongly involved in the water management and land improvement projects for reconstruction of the rural areas. Analysis of the drainage process led to the transient formulas of De Zeeuw & Hellinga (1958) and Kraijenhoff van de Leur (1958), in which the transformation of rainfall into groundwater discharge is characterised by a reservoir factor. This factor includes the hydrological properties of the subsurface and the geometry of the drainage system. These formulas formed the foundation for the design of a drainage scheme on the basis of the required groundwater depth. The optimal groundwater depth was subsequently determined – for various crops and soils – by study of the flow of water in the unsaturated zone, and notably of the water supply by capillary rise. Wind (1955) and Wesseling (1957) were the first to give an analytical description for the relationship between unsaturated soil hydraulic conductivity and the soil water pressure head. Wind (1972) built a unique hydraulic analogon, consisting of a number of vessels - each simulating a layer of soil with its moisture characteristics – and connected by tubes, simulating the hydraulic conductivity. L.F. Ernst (1962) developed solutions for non-linear flow processes towards drains, thereby including the geometry of the drainage channels and the influence of heterogeneous subsoil. Both the solutions of Hooghoudt and Ernst have been applied worldwide. P.E. Rijtema (1969) developed - based on Penman's equation and independent of Monteith (1969) – a physical formulation for the potential evaporation (consumptive use) by introducing a crop resistance factor.

Another important development was the establishment of the Institute for Groundwater Survey (DGV-TNO) in 1968, with the main task of carrying out a regional inventory and monitoring of groundwater data and producing a groundwater map at a scale of 1:50,000, with explanatory reports. Ernst, de Ridder & de Vries (1970) developed - in the framework of regional studies - the first regional computer-simulation model for East Gelderland. De Vries (1974) explained the initiation and evolution of streams under shallow aquifer condition by groundwater sapping erosion at the intersect of the groundwater table. He further studied the influence of climate, morphology and vegetation on groundwater recharge. J.C. van Dam (1967) initiated a programme for the development of analytical solutions for the movement of the fresh/salt water interface in the coastal area, with respect to expected future salinisation processes. R.A. Feddes et al., 1978, developed an expression (sink term) for water uptake by roots within the continuity equation for unsaturated groundwater flow. This equation formed the basis for a general numerical soil-water-atmosphere-plant (SWAP) model, to describe transient water and solute flow in heterogeneous soil-root systems. This model is presently used worldwide.

Awareness of pollution and environmental degradation arose in the 1970s, and water became increasingly considered as an environmental component, requiring an integrated approach of quantity as well as quality of surface water and groundwater, and their interaction with the geological environment. This resulted in broadening of the activities in which hydrologists were involved, notably the hydrogeochemical and biological aspects. This meant an increasing involvement of earth- and environmental scientists in hydrogeological research and exploration, which until then had mainly been dominated by engineers.

Brutsaert and Stricker (1979) combined the potential evaporation under equilibrium with the PET given by Penman's equation (using measured current values of the meteorological variables) to derive the advection-aridity interpretation of Bouchet's (1963) complementary approach, which compares well with estimates of daily evaporation obtained via an energy-budget method (Dnigman, 1993). C.A.J. Appelo (1993) combined hydrochemical transport and process modelling with laboratory experiments to simulate the evolution of the chemical character of groundwater along its flow trajectory. The application of isotope techniques in tracing groundwater and runoff processes and in determination of the age and origin of water, was introduced by W.G. Mook at the Groningen Centre for Isotope Research.

The shift of interest from agriculture to environment and the associated need to adapt the water management-infrastructure accordingly, became notably manifest in the 1980s. In line with this evolution, the RID merged with the National Institute of Public Health and Environment (RIVM) and the ICW became part of a larger organisation for agriculture and environment (initially the Staring Centre and subsequently the Alterra Research Centre). Concurrently, the DGV-TNO was transformed into the Netherlands Institute for Applied Geosciences (TNO-NITG) with a broader mission. This institute became the central organisation for groundwater investigations, monitoring and data management from the mid-1980's. Their position strengthened considerably when the National Geological Survey joined this organisation in the 1990's. This means that earth scientists, in general, became increasingly involved in hydrogeology and associated subsurface engineering problems.

List of acronyms

ABL	Atmospheric Boundary Layer
ALTERRA	Dutch centre of expertise on rural areas
ALW	Earth and Life Sciences NWO
CASA	Centre for Analysis Scientific Computing and Applications
CTG	Centre for Technical Geosciences
CWE	Centre for Wetland Ecology
EGU	European Geosciences Union
GABLES	GEWEX Atmospheric Boundary Layer Study
GEWEX	Global Energy and Water Experiment
GIS	Geographical Information Systems
GPM	Global Precipitation Mission
GRACE	Gravity Recovery and Climate Experiment
IBED	Institute for Biodiversity and Ecosystems Dynamics
ICG	Centre for Geo-ecological Research
IGBP	International Geosphere-Biosphere Programme
IHE	Institute for Water Education
IPCC	Intergovernmental Panel on Climate Change
ITC	International Institute for Geo-Information Science and Earth Observation
KNAW	Royal Netherlands Academy of Arts and Sciences
KNMI	Royal Netherlands Meteorological Institute
LS	Land-Surface
NCR	Netherlands Centre for River Studies
NHP	Netherlands Hydrological Platform
NHV	Netherlands Hydrological Society
NITG-TNO	Netherlands Institute of Applied Geosciences - TNO
NSG	Netherlands Research School of Sedimentary Geology
NWO	Netherlands Organisation for Scientific Research
RAK	Earth and Climate Council KNAW
RBDMC	River Basin Data and Modelling Centre
RH	Relative Humidity
RIVM	Research for Man and Environment
RIZA	Institute for Inland Water Management and Waste Water treatment
RU	Radboud University Nijmegen
RUG	*University* of Groningen
SENSE	Netherlands Research School for Socio-Economic and Natural Sciences of the Environment

STOWA	Applied Water Management Research
TUD	Delft University of Technology
TUE	Technische Universiteit Eindhoven (Technical University of Eindhoven)
UT	University of Twente
UU	Utrecht University
UVA	Universiteit van Amsterdam
VU	Vrije Universiteit Amsterdam
VCH	Foresight Committee Hydrology
VHL	Virtual Hydrological Laboratory
WCRP	World Climate Research Programme
WEM	Water Engineering and Management
WL	Delft Hydraulics
WUR	Wageningen University and Research Centre