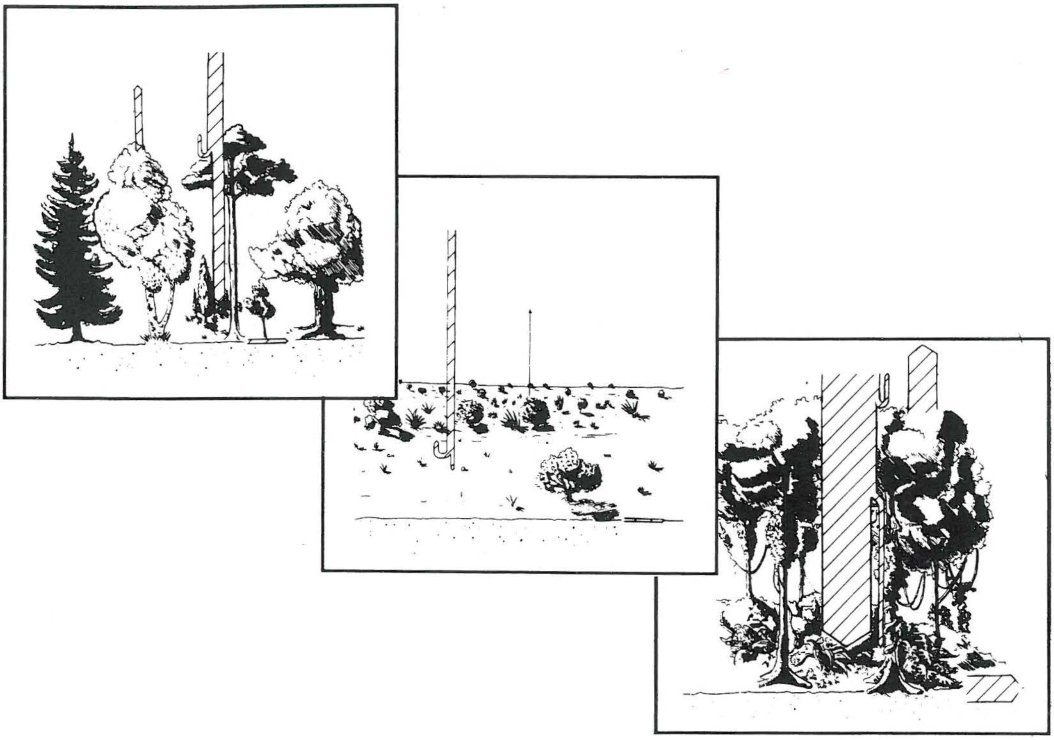
GLOBAL IGBP CHANGE

REPORT No. 17



Plant-Water Interactions in Large-Scale Hydrological Modelling

The International Geosphere-Biosphere Programme: A Study of Global Change (IGBP) of the International Council of Scientific Unions (ICSU)

Stockholm, 1991

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Plant-Water Interactions in Large-Scale Hydrological Modelling

Report of a Workshop in
Vadstena, Sweden, 5-8 June 1990
Organized as a Contribution to the
International Geosphere-Biosphere Programme (IGBP) of ICSU
and the International Hydrological Programme (IHP) of Unesco
by
IGBP, IAHS and IHP

The International Geosphere-Biosphere Programme: A Study of Global Change (IGBP)
of the International Council of Scientific Unions (ICSU)

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1. INTRODUCTION

A thorough understanding of key biological-hydrological interactions of the soil-vegetation-atmosphere system is a prerequisite to predicting impacts of climate change on water resources and on managed and natural ecosystems. Associated with the terrestrial part of the water cycle there is a continuous exchange of energy, water and other substances through the atmosphere, the landscape and inland aquatic systems. The regional variability of surface hydrological processes influences the large-scale patterns of climate. Vegetation cover affects atmospheric composition as well as the energy balance and regional water balance, especially evapotranspiration and runoff components. The dynamics of the hydrological processes and the interaction among soils, vegetation and atmosphere, along with their integrated global effects, are only poorly understood.

The atmospheric, hydrologic, and terrestrial components of the Earth system operate on different time and space scales. Resolving these scaling incongruities is one of the major challenges facing hydrologists, ecologists and atmospheric scientists alike. Integration across these scales cannot be achieved with a simple, additive coupling. Thus, numerical models which describe, simulate or predict behaviour of ecohydrologic processes require explicit linkage to ensure that data flow between the model components contains specific information at the appropriate scale.

In principle, there are three ways of dealing with the scales issue. The first would involve running of the General Circulation Models (GCMs) at higher spatial resolution; the second possibility is to run nested mesoscale models of substantially higher resolution for limited regions of the earth's surface; and the third approach is to disaggregate the climatic information of the GCM at grid resolution into sub-grid scale information using some empirical, statistical relationships derived from knowledge of the real climate system. In practice, some suitable combination of the latter two methods is the most feasible approach.

For at least ten years, the global climate modelers have recognized the importance of incorporating within their models descriptions of hydrological processes at the land surface. The first of the hydrological processes to be included were those that provided the return "flows" to the atmosphere of moisture that had been "rained out" during the previous steps. In these parameterizations, the return flow appeared in an implicit fashion through functions that computed evaporation rates as a function of soil moisture deficit. The fraction of the rain that did not return through the evaporation route but formed groundwater and runoff was not further considered in the model. Subsequently, some other functions of vegetation in the radiation and energy/water budget -- albedo change and pathways for intercepted water -- have been incorporated into the more advanced models but still in a one-dimensional, vertical sense.

Increasingly, both the limitations of the "vertical view" of land-surface processes, and the importance of the role of vegetation and other land-surface characteristics are being recognized. Soil/vegetation feedbacks modify the surface hydroclimatic environment. Terrestrial ecosystems are sources and sinks of most greenhouse gases and their net fluxes are modified by soil moisture status. Nutrients are laterally redistributed. Freshwater is supplied to the ocean, influencing its salinity and circulation. Certain validatory data like runoff are available for spatially integrated regions only. At the heart of all these conceptual improvements and horizontal extensions are plant/water interactions.

To develop an interdisciplinary conceptual framework linking the large-scale interactions between the hydrological cycle and the biosphere, a workshop on "Plant-Water Interactions in Large-Scale Hydroecological Modelling" was organized at Vadstena, Sweden, 5-8 June 1990, as a contribution to the International Geosphere-Biosphere Programme (IGBP) of ICSU, and to the International Hydrological Programme (IHP) of the United Nations Educational, Scientific and Cultural Organization (Unesco) in collaboration with the International Association of Hydrological Sciences (IAHS) and the Swedish National Committees for IGBP and IHP. The workshop discussions were based on the recommendations from a previous IGBP meeting (IGBP, 1990a) and addressed plant-water interrelationships at landscape to continental scales.

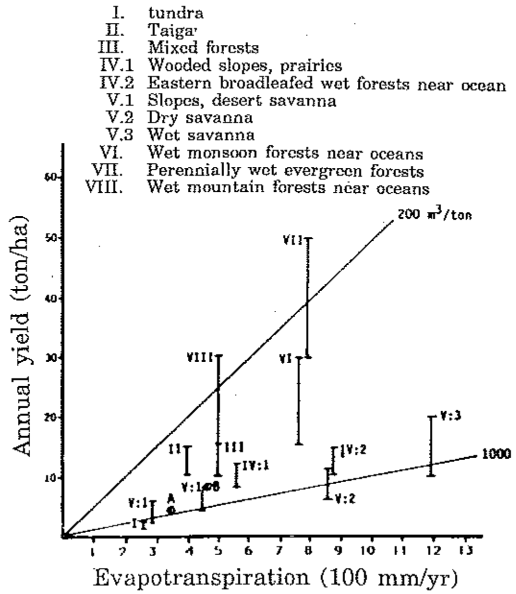
Four topics were focused on during the workshop: (i) The spatial pattern at landscape level of the dynamics of water flows and waterborne fluxes of dissolved and suspended matter; (ii) plant/vegetation characteristics and regolith properties affecting return flow to the atmosphere, in particular, water-use by vegetation; (iii) observational and scaling-up methodological issues to support large-scale modelling and; (iv) plans for focused research in three major hydroclimatic regions: Humid tropical, semi-arid, and temperate zones.

The workshop discussed the first three topics from both hydrological and ecological standpoints. This was followed by three concurrent Working Groups to consider the fourth topic on plant-water interactions in three major zonal divisions: Humid tropics, semi-arid regions, and the temperate regions.

A central issue was the land-surface linkage to climate (a GCM perspective) but an equally important viewpoint concerned the inherent importance of the hydrosphere-biosphere linkage in its own right. The meeting was also concerned with the tools needed for climate impact studies, especially impacts on plant growth that may potentially lead to biome shifts. Thus, the workshop also included mathematical tool-kits that take climate scenarios as inputs, pass their predictions through a numerical weather prediction scheme to establish local boundary conditions, and then utilize plant-water response functions to predict impacts to the vegetative systems and the biogeochemical cycles that are dependent upon them.

The starting position underpinning the workshop was the recognized but poorly quantified synergisms that exist between plants and water -- the regional water balance is in tune with the regional ecosystem that feeds back via the hydrological cycle into the regional climate that generates the regional hydrology, and so on. Such an interrelationship will be manifest in several ways: One that was presented was a putative connection between regional biomass production and evaporative demand (Figure 1).

This report summarizes the scientific issues addressed at the workshop and the recommendations stemming from the Working Group deliberations. It is worthwhile emphasizing that although this report contains many references to plants, vegetation, ecosystems, biomes, etc., such allusions relate not to taxonomic or intrinsic properties, but to the way they interact with hydrological phenomena, especially those implicated in climate or global change processes.



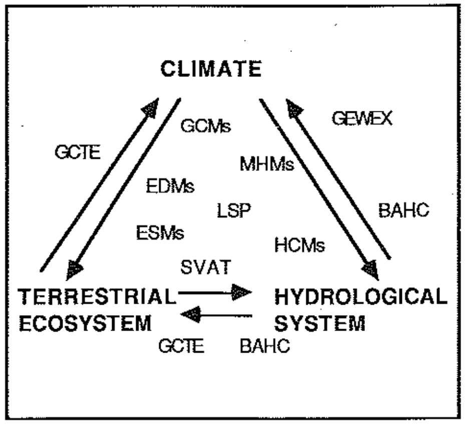


Figure 1. Return flow of water for different regional ecosystems.

Analysis of water-balance components in different world regions has indicated the existence of characteristic zonal patterns in tune with the regional ecosystems. These patterns reflect zonal variations in heat and rainfall but also in soils (permeability, water-holding capacity).

The ecological role of water in the landscape is reflected in the left graph which relates typical values of annual phytomass production (tons/ha) to areal evapotranspiration (mm/yr). The diagram shows vast differences in overall return flow of water to the atmosphere per ton biomass produced: From less than 200 cubic meters per ton biomass to more than 1000. These differences may reflect differences in the water strategies of the plants under water-limited as opposed to non-limited conditions, and differences in the proportions between non-productive return flow (interception loss, evaporation from moist soil surfaces between the plants) as opposed to productive return flow of water to the atmosphere (water used in the photosynthesis). Differences in canopy density, humidity of the boundary layer, etc., would contribute to such proportionality differences. (Falkenmark, 1986).

The SVAT-models in the diagram to the right, relating soil, vegetation and atmosphere, and presently under development within the IGBP, are needed to link climate, terrestrial ecosystems and ecohydrological water flows at the landscape level. Such models will have to correctly reproduce crucial water partitioning processes such as those reflected in the zonal graph to the left.

2. IMPORTANT LAND-SURFACE PROCESSES

The role of plant-water interactions in global climate depends on a particular set of key processes that link hydrological and ecological systems. Much of the modelling now underway attempts to represent these processes in order to simulate current conditions. Successful development of models is a useful tool to evaluate how human activities may affect these systems.

However, we have insufficient understanding of many of the processes to allow us to develop adequately, or use sensibly, models for predicting future changes in the system. Research into the critical processes that govern the fluxes of water, energy, and nutrients between the atmosphere, surface, and subsurface regions, and between biota and the water cycle, is therefore vitally needed. For example, one key issue is the importance of understanding hydrologic pathways and the associated biogeochemistry as they affect the dynamic transfer of water and solutes. This particular area of research, conducted in response to acid-rain-related initiatives, has shown how the chemical environment affects biota. Another critical process for study is the role of atmospheric carbon dioxide in altering plant-water use and stimulating plant growth.

Research into these processes is also urgent, since unexpected or complicated feedback relationships mean that system behaviour may not be predictable from that of single organisms. Several key interface processes not mentioned previously are identified below, and their relative importance illustrated for the case example of semi-arid zones (Table 1).

2.1 Evapotranspiration

From the perspective of atmospheric sciences, evapotranspiration (ET) is the primary linkage between vegetation and hydrology. The water and energy exchanged through ET affect the climate system. The overall sequence of processes affecting ET are strongly influenced by the nature of the vegetation canopy and soils. The canopy structure and leaf area affects albedo, drag, precipitation, interception, and ultimately the ability to fix carbon. Yet our understanding of ET over a region is constrained by uncertainties about the roles of water/vegetation feedbacks and the significant regional differences in the processes governing ET.

Table 1
Characterization of Semi-Arid Systems

Problems/Issues	Spatial Scale [1]	Time to Understand Process (years) [2]	Importance [3]
Hydrology			
Groundwater recharge mode	1,2,3	5	*
Channel behavior-characteristics	1,2	2	**
Shallow groundwater changes	1,2	5	**
Runoff generation	1,2	1-5	**
Horizont. redistribution of soil moisture	1	2	*
Water-balance characteristics (Space, time)	1,2,3	20-50	***
Precipitation processes/character	1,2,3	20-50	***
Soils			
Soil erosion	1,2	1-5	**
Surface soil parameters	1	5	***
Salinity (irrigation, dryland)	1,2	5	***
Soil degradation	1,2,3	20	***
Vegetation-Ecosystems			
Carbon dioxide enrichment	1	5	***
Plant competitive interactions	1	10	***
Length of growing period	2,3	2	**
Above and below ground allocation of carbon	1	5-10	*
Character of canopies	1,2	2	***
Estimating LAI and biomass amounts from remote sensing	1,2,3	2-5	***
Fire regimes	1,2,3	20-50	***
Other			
Human interactions (e.g., grazing)	1,2,3	30-50	***
Character of terrain	1,2	2	***

Spatial Scale Codes [1]

1 Patch (to 1 x 1 km)
2 Small mesoscale (to 10 x 10 km)
3 Intermediate mesoscale (to 100 x 100 km)
4 Continental

Importance Codes [3]

* Desired
** Necessary
*** Urgent

Time to understand processes (years) [2]

The times given reflect the length of time to develop a better understanding and also the time length of the data set. Thus, water-balance characteristics require a data set of 20-50 years, but understanding is within the 7-year time schedule. Research on many of these problems may require transects or multiple research sites.

2.2 Soil Moisture

Soil moisture represents water availability to vegetation. The flux of gases such as CH_4 and N_2O is dependent on the soil moisture content of gas-producing (or consuming) soil layers. The emerging capability of, for example, digital terrain models to predict sites of differing soil moisture is of considerable interest to the ecologist. Other soil moisture modelling problems include the enormous spatial variability in soil and vegetative properties. The spatial and temporal representation of rainfall, as discussed below, also has to be considered. Finally, water movements in the horizontal plane must also be accounted for which calls for information of other soil and surface properties relating to hydraulic conductivity.

2.3 Precipitation

Precipitation is one of the primary determinants of ecosystem structure; a key factor in analyses of ecosystem dynamics at large scales will be the ability to measure and to predict precipitation distributions on a regional basis. This includes translating climate model predictions of grid- and time-averaged precipitation into realistic subgrid distributions of moisture. In addition, the considerable variability in precipitation over space and time complicates the development of satisfactory models for predicting runoff, vegetation distribution, soil moisture, and evapotranspiration.

2.4 Runoff

The nature of runoff-producing mechanisms is important for several aspects of land use change. If, for example, a region is converted from primary forest to grassland or is urbanized, such changes affect the partitioning of water between overland flow, infiltration and subsurface flow. This is generally appreciated by hydrologists and accounted for in catchment models although not all in GCM land-surface descriptions. What is less clearly understood is how different runoff pathways result in the mobilization of the dissolved and particulate materials that eventually constitute the chemical load of rivers. Moreover, differences in mechanisms controlling the amount of runoff in semi-arid tropical and subtropical regions and temperate regions requires the development of different types of models and hence research projects. The regional or continental-scale extrapolation of runoff characteristics is an area of research that deserves further attention.

2.5 Plant Competitive Interactions

The dynamics among plants in an ecosystem are a function of the competitive strategies adopted by members of the community in response to moisture, atmospheric processes, soil conditions, terrain, and other factors. Understanding (and modelling) these dynamic interactions is complicated by the enormous variations between sites, even within one region, by variations in plants, and by soil/plant/water feedbacks. Evaluation of these processes and incorporation of important feedbacks into process models must be done, to understand how anthropogenic changes might affect plant distributions and subsequent changes in the cycling of water. At present, almost all such studies focus on very small-scale ecosystem dynamics. An understanding of large-scale responses is needed for global change studies for which formulations will be needed of how proportions of vegetation of different functional types will alter.

2.6 Human Interactions

The effects of human activities on the hydrologic cycle, on plant cover, and on land surfaces are often more important than natural effects. A better understanding of the implications of these activities is necessary. For example, how does grazing of domestic ruminant animals, grasshoppers, etc., affect plant succession and the cycling of water in semi-arid zones? How do changes in fire regimes alter runoff pathways and revegetation dynamics? How can all such human processes be incorporated into small- and large-scale models of plant/water interactions?

All of these questions must be considered in order to understand better which processes must be incorporated into larger models looking at global change, and which might be safely ignored or incorporated in very simplified form. The following section looks at some of the regional issues that will help define future research agendas.

3. REGIONAL ISSUES

In order to address the interdisciplinary needs of the research projects of the IGBP, the IAHS, and the IHP, a set of regional analyses would be extremely valuable if critical issues can be identified. Toward this end, the workshop participants split into three groups representing the moist tropics, semi-arid regions, and the temperate zone, in an attempt to define our lack of knowledge and to identify research priorities.

In each case, important regional characteristics were identified and the structures, states, and fluxes relevant for looking at the interface between vegetation and hydrology were defined. By doing this, examples of incomplete information and needed research could be identified, and suggestions made for IGBP research projects. These research suggestions are discussed later in this report.

Each of the three regions has unique ecological and hydrological characteristics that determine the nature of the land-surface processes. Indeed, within each region, there are distinct biomes that can be similarly analyzed, and it was recognized that research projects may want to focus within these regions on a representative biome.

Each region is vulnerable to different types of change. For example, tropical rain forests are subject to on-going anthropogenic activities, particularly deforestation. Semi-arid regions are vulnerable to processes that lead to dryland degradation because of the extremely high variability of precipitation, the relatively slow rate of revegetation, damaging land-management practices and poor soil nutrient conditions. Regional research must focus on these individual vulnerabilities.

The group discussing the moist tropics focused primarily on understanding plant-water interactions and processes in the lower Amazon River Basin. This forested region has been a subject of much attention because of the intense rate of land-use changes, the large vertical water fluxes, and the need to understand the associated global impacts in terms of the recycling of moisture, ecosystem changes, loss of biodiversity, etc. Over the past decade, research has been undertaken to study the micrometeorology in the rain forest, basic water budget and the biogeochemical cycling of elements (especially carbon, nutrients, suspended sediments, methane, etc.,) in the Amazon river system.

For the semi-arid regions a set of important characteristics were identified. These include:

Vegetation: low leaf-area-index (LAI)
high woodiness
sparseness
low canopies

Soils: low soil carbon (often as a result of a deliberate policy of burning vegetation)
low soil nutrients
subject to calcification
alkaline

Hydrology: highly variable in space
highly seasonal and subject to long-term fluctuations
low precipitation to potential evapotranspiration ratio (low P/PET)
hydraulic degeneration

Using these regional characteristics, it is possible to identify critical issues for research for any semiarid region or ecosystem. Table 1 describes critical issues and problems that must be understood in order to characterize semi-arid regions, the spatial scale at which those processes operate, the research time needed to resolve the scientific uncertainties, and a simple measure of the importance of each process. The spatial scale at which these problems must be studied may vary from small "patch" scale (1 km^2) to small and intermediate mesoscales (100 to 10 000 km^2). Moreover, for those problems with long-term data needs, such as 20 to 50 years, research must evidently focus on basins from which long-term data are already available if we are to have answers in a reasonable period of time.

Many of the characteristics listed in Table 1 are poorly described in current hydrological models because of difficulties in collecting representative data, or because of uncertainties about the processes. Hydraulic degeneration, for example, is the process by which runoff in semi-arid basins disperses into open basins or otherwise rapidly disappears. In contrast, runoff in temperate or tropical regions collects and increases over horizontal distances. This process, unique to arid systems, is poorly represented in current hydrologic models. The process of scaling-up from patch to mesoscale or large region is problematic in semi-arid ecosystems due to the highly variable nature of many factors such as precipitation, plant distribution, and soil characteristics.

The interaction of topography and moisture availability on biological dynamics is another regional-specific property, which is poorly represented in current conceptual models (Figure 2). In New Mexico, this feature can be seen from changing life forms in ecosystem transition areas. A discontinuous behaviour, or "big effect from small causes" is an extremely important ecological phenomenon in semi-arid systems. Threshold phenomena, where the precipitation interacts with subtle differences in soil texture, may be important aspects of this divergent behaviour and may explain the dramatic changes in biological responses in such systems.

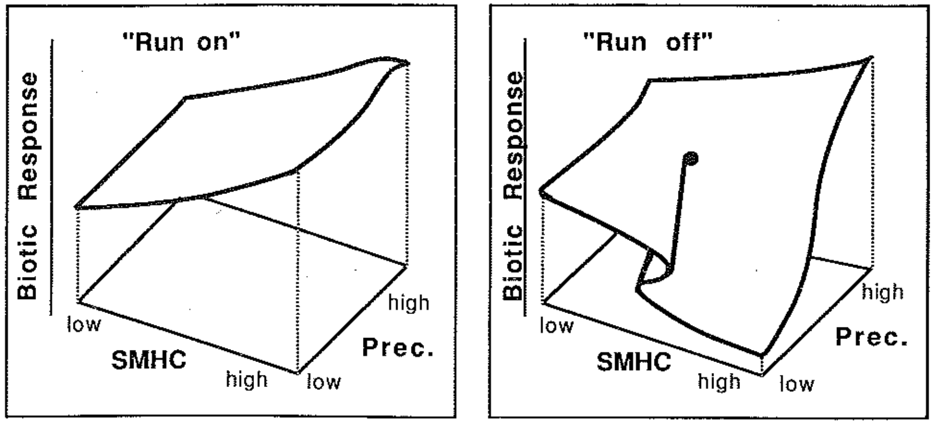


Figure 2. Water-related topography influence in biological response in semi-arid environments.

Topography plays a major role in semi-arid systems. A diverse pattern of high and low soil moisture gradients is formed on the landscape as a consequence of the non-uniformity in runoff generation and infiltration over the heterogeneous patches of rock and soil. In turn, this unevenness in soil moisture distribution affects soil salinity gradients, nutrient distribution, and biotic responses which amplify landscape heterogeneity. The field of topology provides examples of the formulation of system models (three-dimensional response surfaces) rich in ability to capture inherent structure and comprehensive quality properties.

The above conceptual model depicts the role of topography on biological responses (e.g., primary production), a precipitation threshold (Sala et al., 1988), and the inverse texture hypothesis (Noy-Meir, 1973) in a semi-arid environment. The inverse texture hypothesis pertains where annual precipitation fluctuates around 370 mm. Above this threshold, productivity increases with soil moisture holding capacity (SMHC), characteristic of fine-textured soils. Conversely, productivity decreases with SMHC if precipitation is below 370 mm, because coarse soils (low SMHC) allow deeper penetration of scant moisture and reduce evaporation. "Runon" and "runoff" areas have very different response patterns to changes in soil texture and precipitation change. "Runon" areas demonstrate a relatively smooth biological response surface reflecting higher soil moisture and the linear increase in production to increased SMHC or precipitation. "Runoff" areas magnify the influence of low precipitation on soil moisture and may demonstrate complex, non-linear behaviour.

4. SCALE ISSUES

A primary challenge for Global Change programmes is to understand the current status of the Earth system sufficiently well so that reasonable predictions of its response to human activities can be made. Of necessity, this requires numerical models based on the state-of-the-art understanding of the critical processes which govern the fluxes of water, energy, and chemical species between and within the atmosphere, the land and the water bodies. Temporal and spatial scales of study necessary to provide the basic process information vary according to the linkages of interest. For example, hydrologists use basins of various sizes to provide closure of the water balance, whereas ecologists interested in the effect of water on vegetation-community structure need plots or patches of various sizes.

4.1 Linking "Vertical" and "Horizontal" Hydrology

Characteristics of one field of study may vary with changes in scale and this effect is compounded by heterogeneities in other fields. Also, the linkages vary according to scale as differing characteristics of the land, vegetation, and atmosphere at one scale may need to be recharacterized as the scale of study is changed. An example of this is the runoff characteristics in semi-arid regions. Runoff events of high magnitude occur in large basins but their frequency is extremely low, whereas events of smaller magnitude characterize small headwater catchments, but these occur frequently. The primary cause for this is the spotty nature of precipitation in this region. The influence of the distribution of precipitation on ecosystem properties needs to be studied in order to understand how the temporal and spatial characteristics of rainfall influence processes in the region (Figure 3).

In the view of the workshop participants, models fall into several categories, according to the specific issues being addressed. Descriptions of the physical climate system are provided through several levels of resolution. The coupling between the atmosphere and the land surface, as represented in some GCMs, is currently provided through soil-vegetation-atmosphere transfer (SVAT) models, such as Simple Biosphere Model (SiB) (Sellers et al., 1986) and Biosphere-Atmosphere Transfer Scheme (BATS) (Dickinson et al., 1986). These models are conceptually one-dimensional, vertical transfer schemes representing a point in space but parameterized to simulate energy and water transfer over an entire GCM grid cell. At much finer resolution, from patches to landscape, water fluxes are being calculated in digital terrain models (e.g., the TOPOG model) (O'Loughlin, 1990). Other models explicitly represent ecological processes. These models include changes in forest structure and succession (e.g., FORET) (Shugart and West, 1977), with essentially no inclusion of hydrology, to spatially explicitly community dynamics models (the RESCOMP models) (Penridge et al., 1987), which includes soil water dynamics, and models of primary production and water use (Forest BioGeoChemical cycle model (FOREST-BGC)) (Running et al., 1988) and soil organic matter turnover (CENTURY) (Parton et al., 1987; Schimel et al., 1990). At highly aggregated scales are models of the terrestrial portion of the global carbon cycle.

An observation made at the workshop regarding models was that most models have been poorly validated, and it is not known how accurately they reflect even current conditions and dynamics. We have insufficient process-level knowledge of plant-water interactions to use sensibly any of the models for predicting future changes in the system. In the long-term, not only must the individual models be improved, but coupling between them is required. Overcoming one of the most serious obstacles facing this modelling involves a shift from the vertical emphasis of the existing SVAT-models to those which address horizontal water, energy and biogeochemical transfers using two-dimensional or even three-dimensional schemes over large regions.

The workshop participants therefore emphasized that the priority problem relates to the need to translate classic "horizontal" hydrology derived from smaller scale models and analysis to a form suited for use in GCMs. The focus of the ecology and biogeochemistry components is currently structured around models/analysis that have a common linkage to hydrology also through a one dimensional (vertical) analysis. These include, but are not limited to, models dealing with the succession of vegetation community structure, (Shugart and West, 1981; Shugart et al., 1986) primary production including gaseous fluxes, (Running and Coughlan, 1988; Schimel et al., 1990; Box, 1981) and soil processes including decomposition (Parton et al., 1987; Pastor and Post, 1988). Regional models, mesoscale and smaller, are needed to provide a practical bridge between site specific models and global models (Prentice et al., 1989). The process of integrating or aggregating mechanisms from one scale to another is of primary concern and is embedded in the rigorous assessment of the assumptions used in this process.

4.2 Patch-Scale to Landscape-Scale Transpositions

The issue of how findings developed for the patch scale (typically less than 1 km by 1 km) may be transposed to the landscape scale (upwards from 10 km by 10 km) is important. At this larger scale they become available for incorporating into global

hydrological models (GHMs) and integrating up to the scale required by embedded mesoscale models.

Two illustrations of scale transposition were presented. The ecological view drew lessons from the patch-scale variability that exists in the semi-arid region to identify critical variables and landscape characteristics that would become the focus for larger scale modelling. The hydrological modeler's view was based on geomorphological principles, which lead to scaling factors that may be expected to show a predictable gradation through the space scales. In this illustration much depended on expressing the variability in landform through statistical distributions of governing geomorphic variables. However, it was appreciated that other qualities than landform might become critical in other regions. Additional experience in different hydrological regions would be necessary to understand how various processes scale across different catchment areas. Also, because the approach is empirical rather than process based, it may be questionable whether it can provide a solution to water and other transported elements simultaneously.

A step on the path for scaling from an individual patch or unit of landscape to large regions may be through extrapolation from digital terrain models (DTMs). A series of procedures was reported that employed a methodology for aggregating spatial data (Running et al., 1989; Band et al., in press). The system combines a model of forest ecosystem processes with a quasi-distributed hydrologic model, which employs remote-sensing data for estimates of LAI, ET, and photosynthesis, and landscape physiographic information from a DTM. One example (Running et al., 1988) was for coniferous forest basins in Montana (the largest basin was 1600 km^2). A second example was for a 100 km x 55 km transect across forests, woodlands and shrublands in the Murray-Darling Basin in Australia (Pierce et al., 1991).

Non-linearities on system response under current conditions and most likely under altered environmental conditions is an important consideration. A classic example of non-linearity is interception due to threshold and spatial variability of precipitation intensities. Non-linearities present major obstacles in the information transfer between patch- and landscape-scale model parameters. An extreme case occurs when there are discontinuities where, especially in dry regions, the ecosystem response to a climatic forcing depends on the prior history. Ecotones, or transitions between distinct ecosystems, provide a valuable natural laboratory where change can most easily be observed. The current solutions are to make simplifying assumptions and apply non-linear solutions for clearly identifiable regions. These assumptions need thorough validation or testing.

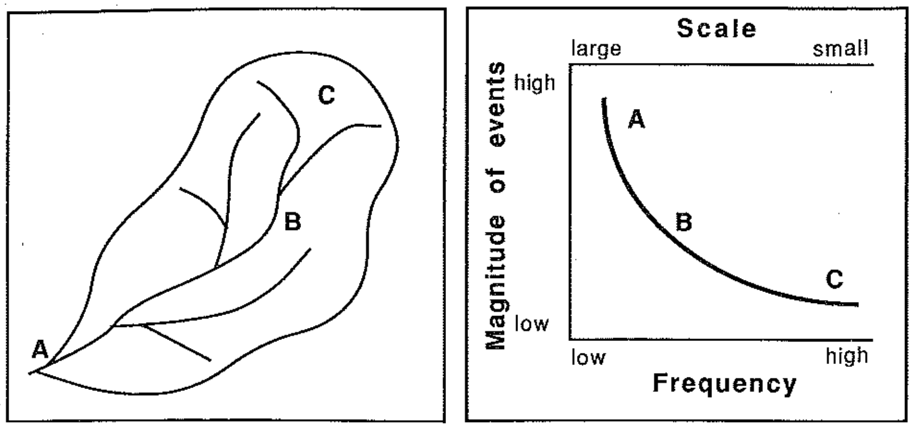


Figure 3. Runoff characteristics in semi-arid regions.

Drainage networks in semi-arid regions (e.g., Rio Grande in New Mexico, USA) have a natural, hierarchial organization related to both size and dynamical behaviour, with small watersheds exhibiting high frequency, low magnitude flows and large watersheds having low frequency, high volume flows (Yair, 1983; Gosz, 1991). These characteristics cause different-sized watersheds in semi-arid areas to be sensitive to qualitatively different "signals" about climatic variation. Different positions within a watershed also "see" different signals. The upper areas (e.g., area C) experience precipitation signals that are predominantly high frequency, low magnitude. In contrast, downstream reaches (e.g., area A) "see" less precipitation, characteristic of lower elevations, and only infrequent but large stream flows characteristic of those rare instances of extremely large storms covering the entire watershed or very high intensity rainfall events.

Species reflect those different "signals" with different rates and locations of establishment and growth. Different life history strategies and growth forms are selected for at different positions in the watershed. Since watersheds in semi-arid environments magnify changes in precipitation (10% precipitation change results in 50-75% change in runoff), species responses to altered runoff patterns and amounts are likely to be amplified.

One way of transferring information across scales and extending characteristics from patches to slopes to landscapes (Band, 1989; Lammers and Band, 1990) uses remote sensing to assess wetness-related landscape similarities. Characteristics are defined that indicate similar hydroecological behaviour (hydrotope) across the landscape. A wetness index was defined that expressed soil-water status from water balance, terrain, and soil properties (slope and transmissivity). It was indicated that the terrain analysis is essential and that scaling up becomes easy if similarity criteria have been defined. These models of surface distribution of water are essential in studies of the interactions between soil moisture distribution, plant growth, etc.

4.3 Scale Aspects of the Evaporation Process

A particular model formulation, evaporative demand, was identified as one particular process that is not well understood. The Penman-Monteith equation for potential evaporation is regarded frequently as state-of-the-art and employed in many models. However, it does not fully reflect the feedback between an evaporating surface and overpassing air. While this in itself is a process level concern, it was emphasized that the Penman concept in dry climates is relevant only for small areas. When applied to large areas, the basic formulation no longer provides adequate prediction due to the advection of moistened air. It is not that the principles underlying the Penman-Monteith formula are invalid, but rather that an extensive evaporating surface necessarily modifies its own atmospheric environment. "Realistic" simulations must take account of the horizontal transports and the internally altered environment.

It was agreed that a major issue to be addressed is the change in stomatal control due to enhanced atmospheric CO_2. Other issues are the differences in response to CO_2-increases between trees and crops and the possible temporal adjustments of the vegetation. In addition, other issues related to changes in litter quality, affecting nutrient availability interacting with photosynthetic response to elevated CO_2 levels, need to be evaluated in the context of water fluxes and ecosystem dynamics. Again, although this appears to be a process-level issue, it was stressed that existing information is based almost exclusively on single species studies in a controlled environment. Problems related to extrapolation to large areas and multiple species remain unsolved. When the effects of temperature increase are added (drying out the soil), scientists no longer agree even on the signs of the resulting change produced. The resolution of this issue must lie in open-air enriched experiments carefully designed to eliminate artifacts and maintained over a sufficient period to observe life-cycle effects.

5. TECHNIQUES AND METHODS

Observational data, computational facilities and even manipulative experiments underpin all research activities. The current deficiencies limit the progress that is possible with the scientific issues enumerated above. As a consequence, all the scientific and regional-study sessions made recommendations for enhancing the techniques available for hydro-ecological studies.

5.1 Validation of Models

To a considerable degree the motivation for the Vadstena workshop arose from the lack of clear priorities of which land-surface processes to include in global models and the absolute necessity for satellite remote-sensing data. Even if one had correct algorithms to convert remotely sensed data to ground values, the computational and observational load would far outstrip what is currently available. Hence, the meeting took as one of its starting points the need to develop algorithms which operate at the spatial, conceptual and temporal levels of integration of such models. Such formulations are mostly in the future, and must have sufficient physical and biological reality to be capable of modelling, in a credible way, a changed future world as well as adequately replicating current conditions. Another important criterion is that the algorithms provide opportunities for validation against field data at the module and at the total system level.

The issue of modelling protocols was raised within the meeting. Many felt that a schism had grown between the modelling community and those who used the results or who provided the observations on which models ought to be based. Not all models are in the public domain, i.e., source code made available, exposed to peer review, or used in intercomparison tests -- and this was considered as regrettable and needs to be changed in the IGBP.

Frequent references were made by participants to the need to validate model outputs. Examples were easy to cite where the current generation of GCMs and regional ecological models failed to replicate observed data. The way forward with coupled models was to validate the individual modules within the overall system model. The continuation and strengthening of networks, biosphere reserves, etc, were considered essential to this aspect. It was recognized that one of the most important reasons for spatial aggregation was the opportunity provided to validate models. Examples included water and nutrient budgets in basins such as the Amazon, and its subcatchments. The information contained in the atmosphere itself provides data on gas fluxes as well as on water and energy balance. It also provides a possibility for checking spatial integration but often involves an inverse calculation with consequent uncertainties.

5.2 Remote Sensing and Geographical Information Systems

Remotely sensed data were readily identified as a prime source for many state variable inputs to large-scale models. A move would have to be made from calibrated images to physically-based interpretations using known or measured radiative properties of surface cover. Presently, satellite remotely sensed data provide a good single synoptic view of landscapes and regions. Monitoring land-surface changes or characterizing the structure of vegetation is less successful. Physical models which utilize the components (sunlit crowns, crown shadows, sunlit background etc.,) of satellite scenes are being developed, and of these the geometric optical models hold the most promise. One such model is the HOTSPOT model (a Geometrical Optical model (GO) which utilizes the brightest image of a land surface when the sun and view angle are the same) (Jupp et al., 1986) which enables the structure of the vegetation to be inferred (Walker et al., 1991). To make most use of these models requires side-looking scanners. This facility is on board the Earth Orbiting System (EOS) series. These satellites will also become the major data source for model validation and hypothesis generation in the future. Present models of hydroecological change must, however, press on with the present technology. The variability of precipitation fields was mentioned in several contexts, hydrological and ecological. While satellite and radar are well known, the use of lightning strike data was a novel area introduced at the meeting for semi-arid regions as a proxy record of precipitation measurements. Likewise procedures for sensing large-scale surface soil moisture fields are needed. Calibration and ground truth over a sufficient scale is also needed for satellite-sensed soil moisture fields.

The use of digital terrain models as a visual backcloth for presenting results, for suggesting hypotheses, and for quantifying ground-based characteristics for relating to hydrological and ecological variables is positive. (Figure 4).

Hand in hand with the acquisition of remotely sensed data lies the necessity for developing geographic information systems for handling and sharing these data. The meeting noted that steps were being taken for handling some of the data, especially satellite-derived information, but urged that the problems of storing biological information, especially those from intensive campaigns be looked into.

In the temperate zone especially, there exist several long-term biological data sets the information of which had not been adequately exploited, e.g., herbarium specimens and soil cores. From a methodological point of view such sampling schemes should be extended in time and in space to furnish future scientists with biological time series for the tropical and semi-arid zones.

5.3 Biogeochemical Cycling Studies

Gas fluxes may be a key output from the future generation of joint hydrological ecological models. The problem of methane flux estimation over the Amazon flood plain needs to be addressed. Methane is an important greenhouse gas and methane information is required as part of a biogeochemical balance. Aircraft and ground-based micrometeorological approaches are advocated in support of classical procedures involving cover and chamber work. Another crucial issue seemed to be the definition of source areas by which to scale the unit source strengths, and the accuracy of the preliminary estimate of 5 Gt C per annum was as much limited by land classification accuracy as by flux measurement accuracy.

Hydrologists can learn much about the use of tracers from ecologists, who routinely use them in biogeochemical cycling studies. Hydrochemical models that have successfully reproduced observed behaviors of some solutes have not successfully simulated tracers that are believed to be the most conservative and mobile of any solutes in the system.

5.4 Need for a New Breed of Scientists

A severe rate-limitation to the research needed may well be the availability of sufficient numbers of suitably trained scientists to address these scientific issues. Training courses, which are strongly oriented to individual disciplines such as plant physiology, soil microbiology, or engineering hydrology, do not serve well the increasing needs of global environmental research. Courses need to be defined to provide a true interdisciplinary background. A related issue concerns the needs of developing countries, where many of the most critical changes and pressing difficulties occur.

It is not easy to sum up the diverse recommendations for strengthening technical capacity. Key issues relate to providing data, both satellite and ground-based, for regional extrapolation and for validating models, and the need for information on the carbon fertilization phenomenon at the field scale. Underpinning this is the requirement for increased numbers of trained scientists with the requisite Earth system science skills.

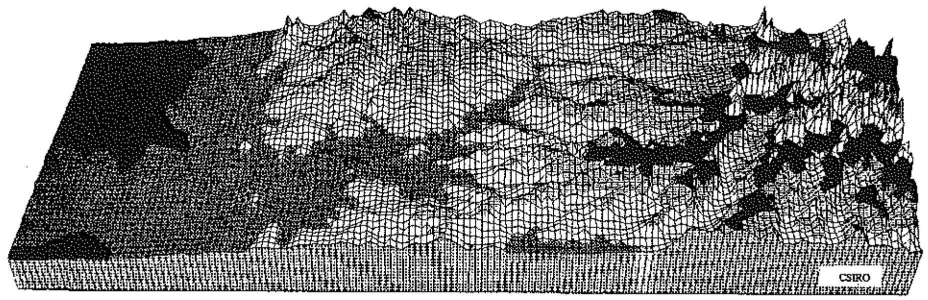


Figure 4a. Use of digital terrain models.

Digital elevation models (DEMs) translate topographic surfaces from maps into a digital form suitable for computer analyses. At the regional and catchment scales, DEMs are being combined with spatial information regarding climate, soils, geology, and vegetation into a form suitable as input into hydroecological models. In turn, results from these models can be displayed against this topographic background.

In the above example, an area 150 x 150 km utilizes a DEM to present information regarding elevation (scale not presented). Such information is combined by means of a Geographic Information System (GIS) with other spatial data for this region. For hydroecological modelling, the additional data are soil water holding capacity, radiation, rainfall, temperature, and leaf area index. (Figure from Dr. J. Walker, CSIRO, Australia).

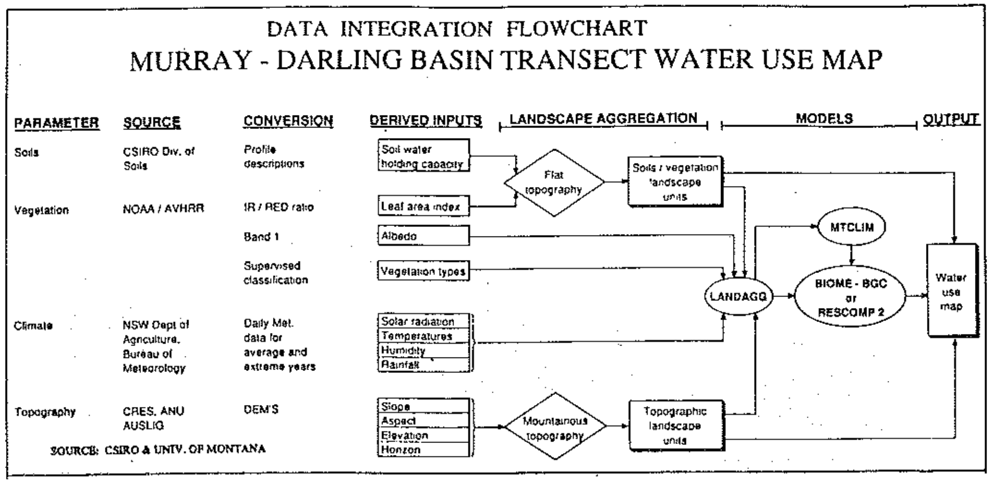


Figure 4b. Use of digital terrain models.

At a more local scale, a DEM combined with other spatial information, can provide a framework for modelling how water moves through complex terrain. The Commonwealth Scientific and Industrial Research Organization (CSIRO) model TOPOG answers questions about the effects of various land uses and climate change on water-related issues. TOPOG is a "distributed parameter" modelling package that can be applied in complex landscapes where spatially variable properties of soil or vegetation are important. A valuable application in the scientific sense is the physical framework that this type of package provides for sound interpretation of historic data on rainfall/runoff relationships from experimental catchments, and how these might change under altered climates.

The essential advance in exploiting the utility of DEMs is the incorporation of dynamic models of soil-water movement (CSIRO-TOPOG) and land cover/vegetation water use (CSIRO-RESCOMP) and University of Montana (FOREST-BGC). (Figure from Dr. J. Walker, CSIRO, Australia and Dr. S. Running, University of Montana, USA and colleagues).

6. RESEARCH REQUIREMENTS

One main problem that must be addressed with respect to the objectives of the IGBP is how hydrologists and ecologists could cooperate in improving the representation of plant-water interactions in the large-scale GCM and GHM models. Philosophically, the question becomes how to provide the essential information relating process-level studies with model studies.

The focus for the Biospheric Aspects of the Hydrological Cycle (BAHC) Core Project of the IGBP, according to the draft scientific programme (IGBP, 1990b), is to evaluate "how plant communities and ecosystems in combination with topographic structure of the land surface affect the cycle of water on earth". This question was deemed by the workshop participants to be an inadequate formulation of the problem for purposes of studying global change. The preoccupations of BAHC on evapotranspiration, though important to atmospheric modelling, was thought to be too narrow, given other equally important and unresolved hydrologic and biotic questions. In particular, the interactions of plants, soils, ecosystems, topography and atmosphere must be considered. In order to address wider issues, all working groups generated suggestions for actions. In essence, these extensions lend a much enhanced importance to studies of horizontal aspects of hydrology at the surface instead of the inherently more vertical view implicit in the current BAHC science plan. In addition, several questions were raised that did not have apparent solutions, but they were to be presented to the IGBP Scientific Committee for further consideration.

6.1 Field Experiments

Moist Tropics

The IGBP Scientific Committee was urged to implement the field experiment to study plant-water interactions in Amazonia as recommended by the Joint IGBP/World Climate Research Programme (WCRP) Working Group on Land Surface Experiments (IGBP, 1990b). The Working Group also identified several additional key issues deserving attention during implementation of the field experiments. These are:

(i) *Enhance* the field experiments by specifically including measurements of biogeochemical elements, designed to understand the cycling of these elements through the soil-vegetation-atmosphere pathway via the water medium; (ii) *develop* observation/modelling strategies to include *horizontal* movement of water and important chemical elements at the continental scale; (iii) *support* upgrading/maintenance of routine networks for hydrological and biogeochemical measurements; (iv) *apply* SVAT models developed for the Amazon basin to other humid tropical regions to investigate the differences in plant-water interactions at patch-to-regional scales in the moist tropical forest zones affected by either maritime or mountain climates; (v) *attempt to incorporate* biological diversity issues into considerations of natural and anthropogenic hydroclimatic changes and; (vi) *carry-out* at least one suite of intensive field measurements in conjunction with instituting longer-term routine measurements in Amazonia before the deployment of the EOS of satellite instruments. Patch and larger scale SVAT models should be developed for the region and their range of sensitivity investigated for differing tropical humid forest regions. However, the study sites should be revisited post-deployment of the EOS with the aim of conducting repeat intensive field campaigns to refine further the suite of SVAT models.

Temperate Zone

The Vadstena workshop identified the following issues deserving attention within the BAHC Core Project of the IGBP: (i) *Determine* areal evapotranspiration emphasizing the advection process. Experiments would be most beneficial in forested complex terrain, but may also be important for edge effects as observed in cropland areas; (ii) *evaluate* remote-sensing techniques at several scales and for different types of vegetation to estimate properties such as albedo, surface temperature, LAI, and soil moisture that could be used to compute evapotranspiration; (iii) *support* research on the availability and content of old data-sets and make this information available in an IGBP publication and maintain a current listing in a computer database; (iv) *convene* workshops for the purpose of comparing plant-water interactions for selected variables. Data-sets exist for many plot, catchment, and basin scales that cover ranges in temperature and precipitation for similar vegetation types. A comparative analysis of some plant characteristics for specific or similar vegetation type(s), such as primary productivity or LAI, across a gradient may yield some knowledge regarding the functional relations, which are currently lacking in all scales of modelling.

6.2 General Recommendations

The workshop proposed attention be given to the following issues:

(i) *Develop* an automatic objective procedure for classifying atmospheric pressure fields derived from GCM output into weather types and develop coupling mechanisms to scale down the GCM output to get a high spatial resolution in the precipitation and temperature distribution. This information would be used as an input for regional and local scale hydro-ecological models.

(ii) *Improve* measurements (instrumentation) of net radiation.

(iii) Give more *emphasis* to studies in agricultural areas. Managed ecosystem types, especially agricultural, cover a larger percentage of the total land area in temperate zones than in tropical or semi-arid zones. Man will react to possible global changes by changing land-use management.

(iv) *Investigate* the causes for discrepancies between spatial and temporal patterns of hydroecological characteristics that are derived from remote-sensing data and those from field measurements.

(v) *Investigate and develop* methods for describing the distribution of precipitation and analyze the effect from a modeling perspective on biota and landscape hydrology.

(vi) *Encourage* interdisciplinary teams of scientists to work together on understanding processes by launching parallel experiments at the same field sites.

7. CONCLUSION

There is a general consensus that significant improvements are necessary in GCMs for land surface-atmosphere couplings. A major issue is the linking of vertical hydrology in GCMs and horizontal hydrology derived from smaller scale models and analysis. The role of plant-water interactions in studies of global change depends on a particular set of key processes that link ecological and hydrological systems. These processes were the focus of the Vadstena Workshop.

The Vadstena dialogue included the following experiences: (i) Importance of the runoff-runon phenomenon of lateral flow and moisture accumulation in shaping local ecosystems under semi-arid climate; (ii) use of wetness index based on water balance in combination with digital elevation model analysis to assess hydroecological patch similarities, and exploring the possibilities of scaling up from patch to GCM grid scales; (iii) the use of digital terrain models to predict sites of differing soil moisture, as a base for contributing-area-based simulation of runoff production and; (iv) the linking of vegetation and water-related phenomena across scales for a temperate forest basin in Montana, and a semi-arid basin in Australia where wetness changes arising from alterations in large-scale vegetation patterns were simulated.

During the workshop, stress was put on regional differences and the identification of critical issues. Each of the three regions considered (temperate, humid tropics, semi-arid tropics and sub-tropics) is vulnerable to different types of change and has unique hydrological and ecological characteristics that define the nature of land-surface processes. In the humid tropics, dominating problems include changes in the vertical/horizontal partitioning of the atmospheric input related to large-scale clearing of vegetation and production of trace gases such as methane and nitrous oxide. These gases critically depend on the moisture conditions of the gas-producing soil zone. In the semi-arid tropics, the process of scaling-up is more uncertain due to high spatial and temporal variability of many factors. The dispersive character of semi-arid zone runoff (in contrast to the integrative character of humid region runoff) is not represented in present hydrological models and GCMs.

The workshop concluded that: (i) The focus of the BAHC Core Project on evapotranspiration was too narrow and should be enhanced to include other equally important hydrologic and biotic processes, including biogeochemical cycling of elements; (ii) in the field studies planned for the humid tropics additional key issues deserving attention include soil-vegetation-atmosphere pathways of biogeochemical elements, differences between maritime and mountain climates, biodiversity as related to hydroclimatic change, and range of sensitivity of patch and larger scale SVAT models and; (iii) in the field studies of temperate zones, issues deserving attention include the advective component of evapotranspiration processes, remote sensing of surface properties that could be used as determinants of evapotranspiration, the large asset represented by the long-term data sets available in this zone, and comparative analysis of plant characteristics across a gradient in order to improve functional understanding.

The Workshop highlighted the following key issues to be addressed in future research: (i) Changes in plant-water use due to carbon dioxide enrichment and stomatal control, and the additional effect of anticipated future temperature increases; (ii) hydrological pathways (especially subsurface) and the associated biogeochemistry as they affect the dynamic transfer of water and solutes; (iii) plant competitive interactions to simulate the dynamics of vegetation cover and consequent changes in hydrological phenomena and; (iv) methods for validation of models capable of credibly simulating a changed future.

In addition, the following set of additional issues were highlighted as deserving attention: (i) Automatic classification of atmospheric pressure fields from GCM-outputs as a means of improving the input to regional hydrological modelling; (ii) improved understanding and measurements of net radiation; (iii) more emphasis to studies in agricultural areas; (iv) improved storage of biological information (intensive campaigns, herbarium specimens, soil cores, etc.); (v) resolving discrepancies between hydroecological characteristics derived from remote sensing and from field measurements; (vi) the need for interdisciplinary teams to work together on parallel experiments in the same area; (vii) the need for interdisciplinary scientists and; (viii) the need for exposing models to frequent peer review and/or intercomparison tests.

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APPENDICES

1. Participant List of the IGBP/IAHS/IHP Workshop
2. IGBP Reports

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3. IGBP REPORTS

No. 1. The International Geosphere-Biosphere Programme: A Study of Global Change. Final Report of the *Ad Hoc* Planning Group, ICSU 21st General Assembly, Berne, Switzerland 14-19 September, 1986 (1986)

No. 2. A Document Prepared by the First Meeting of the Special Committee, ICSU Secretariat, Paris 16-19 July, 1987 (1987)

No. 3. A Report from the Second Meeting of the Special Committee, Harvard University, Cambridge, MA, USA 8-11 February, 1988 (1988)

No. 4. The International Geosphere-Biosphere Programme. A Study of Global Change (IGBP). A Plan for Action. A Report Prepared by the Special Committee for the IGBP for Discussion at the First Meeting of the Scientific Advisory Council for the IGBP, Stockholm, Sweden 24-28 October, 1988 (1988)

No. 5. Effects of Atmospheric and Climate Change on Terrestrial Ecosystems. Report of a Workshop Organized by the IGBP Coordinating Panel on Effects of Climate Change on Terrestrial Ecosystems at CSIRO, Division of Wildlife and Ecology, Canberra, Australia 29 February - 2 March, 1988. Compiled by B. H. Walker and R. D. Graetz (1989)

No. 6. Global Changes of the Past. Report of a Meeting of the IGBP Working Group on Techniques for Extracting Environmental Data of the Past held at the University of Berne, Switzerland 6-8 July, 1988. Compiled by H. Oeschger and J. A. Eddy (1989)

No. 7. A Report from the First Meeting of the Scientific Advisory Council for the IGBP. Volumes I and II. (1989)

No. 8. Pilot Studies for Remote Sensing and Data Management. Report from Working Group Workshop held in Geneva, Switzerland 11-13 January 1989. Edited by S. I. Rasool and D. S. Ojima (1989)

No. 9. Southern Hemisphere Perspectives of Global Change. Scientific Issues, Research Needs and Proposed Activities. Report from a Workshop held in Mbabane, Swaziland 11-16 December, 1988. Edited by B. H. Walker and R. G. Dickson (1989)

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No. 13. Terrestrial Biosphere Exchange with Global Atmospheric Chemistry. Terrestrial Biosphere Perspective of the IGAC Project: Companion to the Dookie Report. Report on the Recommendations from the SCOPE/IGBP Workshop on Trace-Gas Exchange in a Global Perspective. Sigtuna, Sweden, 19-23 February, 1990. Edited by P. A. Matson and D. S. Ojima (1990)

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