Working Paper

A RATIONALE, STRUCTURE AND RESEARCH STRATEGY FOR A GLOBAL HYDROLOGICAL MODEL

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INTRODUCTION

Hydrological models deal with the storage and flow of water on the continents, including exchanges of water and energy with the atmosphere and the oceans. Most hydrological models focus on the individual river basin. Basin models have been applied to areas as large as 10^4 km^2 (e.g. Gleick, 1987a, 1987b), about the size of a single grid square in an atmospheric general circulation model (GCM). There is as yet no hydrological model of a whole continent, or of the globe.

A global hydrological model (GHM) would address a different range of issues from conventional hydrological models. Most immediate among these issues is the question of how the geographic distribution of water availability at regional, national and continental scales, will respond to global climatic changes of the kind projected by GCMs as a consequence of the greenhouse effect (e.g. Falkenmark, 1986a; Gleick, 1987c, 1989; Shiklomanov, 1989). A further concern is how changes in the distribution of water at the earth's surface can ameliorate or exacerbate climatic change (cf Walker and Rowntree, 1977; Rind, 1982; Rowntree and Bolton, 1983; Mintz, 1984; Yeh et al., 1984; Eagleson, 1986; Rowntree and Sangster, 1986). To model such feedbacks will ultimately require coupling global atmospheric and hydrological models. All of these issues require the development of hydrological models that are (a) sufficiently mechanistic that they could reasonably be expected to perform reliably in a changed climate, and (b) global from the outset, rather than being assembled from individual river-basin models.

With these considerations in mind, an international, interdisciplinary workshop on Global Hydrology was convened under the auspices of the IIASA Water Resources Project at Sopron, Hungary, 14-18th May 1990. Ten scientists (see Appendix 1) from nine countries met to exchange information about current developments in macroscale hydrology, and to discuss the feasibility of developing a macroscale (continental- to global-scale) hydrological model. It was concluded that the construction of a mechanistic global hydrological model (GHM) within the next five years was highly desirable, and feasible in the context of a sustained international collaboration.

The workshop produced agreement on a rationale, structure and research strategy for the development of a GHM. In this paper we document and amplify these ideas as they emerged from the workshop, with the aim of explicitly demonstrating how a GHM might be constructed and tested. In doing so, we draw on the growing international consensus on the likely structure of a GHM, and on the research strategy required for the development and testing of such a model.

RATIONALE FOR A GLOBAL HYDROLOGICAL MODEL

Water is a resource, a regulator of natural vegetation and crop growth, and a component of the climate system. Changes in climate will undoubtedly lead to changes in the hydrological cycle, with impacts on human populations (Falkenmark, 1986b, 1989; Gleick, 1987b). These impacts include increases or decreases of water availability for crop growth, forests, and pastures, drinking water, irrigation, hydropower and other industrial uses, and changes in the magnitude and frequency of water-related hazards such as soil erosion, salinization and floods.

GCMs provide a rough indication of large-scale changes in climate as a response to forcing, e.g. by changing greenhouse gas concentrations, but the potential effects of such changes on hydrological systems and water resources are not as well understood. Techniques for modelling parts of the hydrological cycle, and global hydrological data bases, are being developed. An international effort is required to integrate these components into mechanistic models of global applicability. Much of the relevant knowledge exists, but not, as yet, the <u>predictive capability</u> that will only come from a sustained model-building effort.

The various components of the hydrological cycle (oceans, ice sheets, groundwater, permafrost, rivers, lakes, soil moisture, biomass) function as both water storages and regulators of water and energy fluxes, and the feedbacks involved in transfers of water and energy between individual components modulate the effects of climatic change on regional water budgets. Individual components integrate changes in climatic variables (e.g. precipitation) on very different temporal and spatial scales. The relatively slow response times (or lags) of some individual components (e.g. groundwater) to change creates the possibility that they may act to buffer the hydrological system as a whole against rapid or short-lived climate changes. These characteristics make it important, ultimately, to model the hydrological cycle <u>as a whole</u>. This ultimately means developing coupled geosphere-biosphere models incorporating three-dimensional hydrology and vegetation dynamics as well as atmospheric water transport. But first, we have to be able to simulate the first-order impacts of specified climate change scenarios on hydrological and vegetation systems; this requires the development of a GHM.

A GHM could be used to assess hydrological responses (e.g. changes in river discharge and flow regimes, surface water storage in lakes and reservoirs, or groundwater recharge regimes) to natural or man-made changes in climate or land surface conditions. The development of a mechanistic GHM is also vital to other global modelling efforts within the context of the International Geosphere-Biosphere Programme (IGBP), through the impact of changes in regional hydrological budgets on vegetation patterns and productivitity, the role of water in biogeochemical cycling, and the feedbacks of hydrological and vegetation changes on regional climates (Turner and Walker, 1990).

PROPOSED STRUCTURE OF A GLOBAL HYDROLOGICAL MODEL

The proposed GHM is a grid-based model explicitly incorporating vertical water and energy fluxes (soil-vegetation-atmosphere transfers), water storage on the surface and in the soil, and horizontal routing of water on the surface and within the soil. The inputs would consist of mean monthly climate data (most importantly precipitation, temperature and cloudiness) and statistics on the variability of these parameters. Surface boundary conditions would consist of data on the topography, hydrographic base level, soil water holding capacity and certain characteristics of the vegetation cover of each grid cell. Outputs would include evaporation, runoff, changes in the area and volume of surface storage in lakes, rivers, snow, ice and wetlands, and changes in near surface and total soil moisture on each grid cell.

In principle such a model could be designed for a range of spatial and temporal scales depending om the accuracy and resolution required. In practice we envisage that the model would be developed for a spatial grid of approximately 5-10 km spacing and a time step of 1 day. The daily timestep is important for simulating the dependence of surface runoff and infiltration on the rate of precipitation supply, but we envisage that the model would be forced not by actual daily weather data but by a realization of a stochastic process with overall statistical properties similar to those of the real climate.

Grid-based hydrological models have been used by e.g. Solomon et al. (1968). The regular grid format is virtually mandated by the requirement to interface with climate models, since the atmosphere does not respect e.g. the boundaries between catchments. The choice of an appropriate grid size should be determined by the spatial scale of the modelled processes. A secondary (but often decisive) consideration is whether data are available at a particular scale. A consideration of the spatial scales of some important processes in the hydrological cycle (Table 1) suggests that a grid size on the order of 10 km (100 km^2) would allow an adequate representation of key mesoscale processes (e.g. related to the generation of synoptic storms, and to atmospheric mixing). Many other processes operate on a spatial scale of metres, but data limitations preclude global modelling at such a fine scale. Similar considerations (Table 1) motivate the use of a daily time step.

Table 1: The temporal and spatial scales of important processes in the hydrological cycle

Processes	Rationale	Time/space scale
INPUTS		
precipitation	average space/time scale of an average storm:	
	convective storms	30 mins, 1 km^2
	synoptic storms	1 day, 10 km^2
interception[1]		
snowpack melt	dependent on atmospheric conditions (rate & scale of storms); space scale dependent on topography:	
	convective storms	30 mins, 1 km^2
	synoptic storms	1 day, 10 km^2
vegetation partitioning[2]	time scale dependent on scale of average storm:	
	convective storms	30 mins
	synoptic storms	1 day
runoff/infiltration partitioning[3]	dependent on topography & mesoclimatic controls:	
	mountainous areas	1 km^2
	non-mountainous areas	10-50 km^2
OUTPUTS		
evaporation	defined by interception storage and meteorologic forcing	30 mins, 1 km^2 1 day, 10 km^2
transpiration[4]	time scales: diurnal vegetation changes, (equivalent to GCM-scale) and daily & seasonal changes in vegetation	1 hour-1 day
	space scales are limited by the scale of mixing in the atmosphere, and by mesoclimatic controls	10-50 km^2
root-zone partitioning[5,6]	changes in rooting depth and capacity on seasonal or inter-annual scale	1 month-1 year
	space scale reflects vegetation heterogeneity	1 m^2 - 1 km^2

[1] The partitioning of precipitation into snow and rain is of importance in determining the time scale of interest in considering interception. We assume that snowfall enters directly into storage as snowpack, and that it is the timescale on which melting of the snowpack takes place that is of primary interest. The fate of rain, however, is dependent on partitioning by the vegetation.

[2] Canopy capacitance is apparently relatively independent of vegetation type. Thus spatial scale is less limiting than temporal scale in considering the partitioning of incoming precipitation by vegetation.

[3] Characteristics such as litter thickness, physical soil characteristics and slope all influence the partitioning between runoff and infiltration. However, these factors change relatively slowly. We therefore assume that the factor which determines the choice of time scale is precipitation rate. The choice of spatial scale is determined primarily by topograpaphy: it is necessary to consider a smaller area in mountainous regions (ca 1 km^2) than in less topographically complex regions (ca 100 km^2). In some circumstances, e.g. shield areas, mesoclimatic considerations may place more rigorous spatial scale limitations (50 km^2) than topography.

[4] From process considerations alone, it is possible to defend two different time scales as being important for transpiration. We suggest that **data availability** may be a consideration in determining the choice of temporal scale. However, we emphasise that the range of scale defined by process considerations is hourly to daily, not monthly. The minimum space scale is limited by the scale of vegetation disturbance (1 km^2). However, the mixing role of the atmosphere must be taken into consideration when considering evapotranspiration fluxes: landscape features with a scale of less than 10 km have no direct influence on the structure of the atmosphere such that observed fluxes represent an area-average of individual contributions, whereas landscape features with scales greater or equal to 10 km trigger atmospheric structures which influence the areal fluxes. The maximum spatial scale of interest is determined by the mesoclimatic control of functional vegetation types, and is of the order of 50 km^2.

[5] This is the point at which non-biological processes (lateral movement of water within the regolith, capillary rise from the deep regolith, and groundwater discharge) become important in determining the availability of water within the rooting zone.

[6] We assume that vegetation heterogeneity must be seen in terms of functional vegetation types; nevertheless, it is still possible to argue for several different spatial scales, depending on whether it is necessary to consider the interaction of individuals of different functional types within a landscape-scale functional unit.

Topographic and Climatic Data Bases

A global topographic data base with explicit information about hydrological base levels is a basic model requirement. The hydrological base level information is necessary in order to be able to route surface runoff correctly. Topographic data exist as digital elevation grids at a global scale (e.g. U.S. Navy topographic data base; Table 2). The spatial resolution varies from continent to continent, from 1.5′ by 1.5′ at best (for Australia) to 10′ by 10′ at worst. Such gridded topographic data are too coarse to generate a realistic hydrological network, which requires additional information to establish local base levels. Local base level can be generated by digitising streamlines and sinks, including lakes, swamps and wetlands from e.g. international aviation charts (ICAO charts) which provide complete global coverage at a scale of 1: 1 million. Digitising the streamlines at this scale would give a maximum possible resolution of 2.5 by 2.5 km in the digital elevation grid.

The minimum set of digitized climate data required to run the GHM consists of grid-based estimates of mean monthly values of temperature, precipitation and cloudiness (or hours of sunshine). There are a number of such climate data bases available (Table 2) but none are entirely adequate. Problems arise because of (a) the spatial uneveness of the original station data used to compile each data base; (b) differences in the length of records available for individual stations; (c) theoretical difficulties in moving from point data to gridded data. The existing IIASA climate data base (Leemans and Cramer, 1990) could provide a starting point, but it should be updated to include a much larger number of weather stations in many areas. And because it is impossible to achieve a weather station density of one station per 100 km^2, for hydrological modelling purposes it is important that precipitation data be interpolated between stations in a realistic way that is sensitive to local elevation effects.

Table 2: Availability of gridded data sets

Variable	Source	Scale	Comments
Topography	US Navy data base	10-20km	does not include hydrologic base level
	ANU, Australia	5km (1/20°)	will include hydrologic base level (coverage limited to Australia and Africa)
Vegetation (actual)	IIASA	1/2°	Olson et al., 1983
Vegetation (NDVI)	NOAA, routinely available	15-40km	
Climate (P, T and cloudiness)	IIASA	1/2°	Leemans and Cramer, 1990
Climate (P, T, ET)	Delaware University	1°	Willmott et al., 1985
Soil (albedo, texture, drainage class)	from authors	1°	Wilson and Henderson-Sellers, 1985
Soil AWC	IIASA	1/2°	Prentice et al., in prep.

The Stochastic Spatial Weather Generator

Global data bases of climate data generally include only long-term mean monthly values of climate variables. The existing global climate data therefore need to be translated into climatic events on the daily basis required by the GHM. In addition, there are strong spatial correlations in rainfall occurrence and intensity (and other variables), corresponding to e.g. short-lived, small-scale rainfall producing cloud structures. These spatial correlations need to be preserved when generating daily climatic events from the global climate data. In other words, a **stochastic spatial weather generator**, capable of explicitly generating the space-time variation in climatic variables, needs to be developed as part of the GHM.

This is a difficult problem, both from a theoretical standpoint and because of the relative paucity of data with which to establish the spatio-temporal correlations. Relevant contributions in the literature include Rodriguez-Iturbe (1984), Waymire et al. (1984) and Bell (1987). Given the problems of obtaining and analysing detailed daily data for suitably dense networks of stations in different climatic regions, the space-time stochastic model will necessarily draw heavily on a theoretical understanding of the underlying physical climate processes and their interactions. However, we anticipate that considerable guidance about the nature of the outputs of the space-time model will be provided by ongoing research into stochastic models describing temporal variations in climate variables at a single point (e.g. Hutchinson, 1990a, b) and work on the spatial interpolation of point model values.

Thus, although a considerable amount of work is still required to produce a stochastic spatial weather generator, the following steps appear to be necessary stages in its development:

(1) Suitably simple stochastic models of the temporal variation in daily rainfall and other related variables, including temperature, cloudiness and evaporation, at a point will be developed using measured daily climate data at that point (e.g. Hutchinson, 1990a). The parameters of the model will be robustly determined by the observed statistics for each month. Some parameters may be reasonably assumed to be constant throughout the year.

(2) The parameters of the point model will be interpolated across a suitably dense station network, using thin-plate smoothing techniques (Hutchinson and Bischof, 1983). Thin-plate smoothing techniques have been successfully applied to the continent-wide interpolation of monthly climatic means from suitably dense networks, so it is reasonable to expect that they could be successfully applied to the interpolation of point model

parameters. However, the strong spatial correlation in climatic variables means that it is not sufficient to run a spatially extended point model independently over a suitably dense network of points across a catchment, since this would merely give rise to essentially long-term average conditions when the outputs were integrated across the catchment.

(3) Insights gained into the spatial and temporal correlation structures inherent in the climatic data will be used to guide the construction of a stochastic weather model, which will explicitly take account of the space-time variation in climatic variables. The stochastic space-time model will be directly calibrated and validated in terms of detailed daily observations, most of which are likely to be point-based. Remotely-sensed, spatially extended rainfall data may also provide a means of testing the model.

The SVAT Sub-Model

Water- and energy-balances within each grid cell would be calculated using a one-dimensional soil-vegetation-atmosphere transfer scheme (SVAT sub-model) constructed at the appropriate space/time scale and level of complexity. A number of models of the fluxes between the land surface and the atmosphere have been developed, including the Simple Biosphere (SiB) model (Sellers et al., 1986, 1988), the biosphere-atmosphere transfer scheme (BATS) (Dickinson et al., 1986; Wilson et al., 1987), the Noilhan-Planton transfer model (Noilhan and Planton, 1989) and the "Bare Essentials of Surface Transfer" (BEST) model (Cogley et al., 1990). The existing SVAT models make high demands on data, requiring e.g. inputs on solar radiation, atmospheric longwave emittance, precipitation rate, near-surface wind speed, temperature, specific humidity and pressure, and were generally developed with the explicit aim of resolving the diurnal cycle, and are therefore not suitable for direct incorporation into the proposed GHM. We anticipate that they will provide a starting place for the development of a simplified, low-resolution SVAT model. The strength of ongoing research efforts in this field, and the high priority placed on the development of simple SVAT models by IGBP (Turner and Walker, 1990), suggest that the construction of a simplified SVAT model is not likely to be a major hurdle in the development of the GHM.

In order to run the SVAT model, information on certain characteristics of the soil (available water-holding capacity: AWC) and vegetation cover (albedo, leaf area index: LAI) are required for each gridcell. A gridded data set of AWC, based on soil textural characteristics derived from the FAO soil classification is available from IIASA (Table 2). Vegetation characteristics could either be derived from satellite measurements of NDVI or from maps of the ditribution of actual vegetation. A gridded data set of actual vegetation, based on the Olson classification (Olson et al., 1982) is available from IIASA (Table 2).

The Routing Sub-Model

Excess water (surface and subsurface runoff) needs to be explicitly routed from gridcell to gridcell, along an appropriate drainage network determined from the topographic data. This task is conceptually simple (simple electrical analog methods can be used) but the programming will be time-consuming, particularly because of the need to achieve a high computational efficiency. Use of a mechanistic routing procedure based on the grid cell topography will only be justified, however, if the digital elevation model respects at least the major drainage divisions. Our selection of a spatial scale for the GHM was influenced by the fact that Hutchinson and Dowling (in press) have shown that a grid resolution of 5km is sufficient to define major catchment boundaries.

Model Outputs

Possible model outputs would include evaporation, runoff, changes in the area and volume of surface water storage (e.g. in lakes, rivers, snow, ice and wetlands) and changes in near surface and total soil moisture. Since the proposed model operates with a daily time step it would be possible to reconstruct changes in these variables on a daily basis. These values could then be used to reconstruct mean monthly values and to assess inter-monthly and/or inter-annual variability. The preservation of daily values places high demands on storage and seems unjustifiable in the case of some variables (e.g. the area covered by lakes or ice). In order to preserve information on the seasonality of the hydrological response, however, monthly values would be the coarsest level of output aggregation desirable.

A STRATEGY FOR TESTING THE GLOBAL HYDROLOGICAL MODEL

The GHM must be rigorously tested in order to place confidence limits on projections of future hydrological changes (cf Klemes, 1985). The proposed strategy would be to test model performance using both land-based and satellite observational data. We envisage two major sources of test data: **global measurements of near-surface moisture storage** and **the area of surface water storage** (including seasonal inundation of wetlands), derived from satellite data; **monthly mean runoff** data over a period of years for a number of large rivers, obtained from e.g. the Global Runoff Data Centre, Koblenz. It is not currently possible to directly test the predictions of total soil moisture storage, although this is an important output of the GHM model for vegetation models, GCMs, basin hydrology models or crop production models.

Ongoing field experiments of the HAPEX and FIFE type could also provide data suitable for testing purposes (e.g. André et al., 1986; Bolle and Rasool, 1985; Sellers et al., 1988; Hall et al., 1989; Jacquemin and Noilhan, 1990; Noilhan et al., 1990). Further work is required to determine how these data could be incorporated into the proposed testing strategy.

There is a need to ensure the robustness of the GHM under radically different climatic forcings if it is to be used to project the hydrological response to future climatic changes. This cannot be done by testing against modern data alone. Quaternary geological data have proved to be a powerful tool for testing GCMs under a wide range of climatic regimes (e.g. COHMAP Members, 1988), and we envisage that Quaternary palaeohydrological data could be used to test the GHM in a similar way.

The Use of Satellite Data for Testing

Satellite measurements of visible and near-infrared reflectances, surface temperature and microwave emission at various different frequencies can be used to derive a number of hydrological and biospheric parameters (Table 3), including snow cover extent, snow water equivalent, near-surface soil moisture, changes in the extent of surface waters including changes in lake area, seasonal inundation of wetlands and the extent of riverine flooding, fractional vegetation cover, and biomass. The theoretical basis for interpreting the satellite data in terms of hydrological and vegetation parameters is relatively well established (Choudhury, 1989; Nicholson, 1989) and the models have been tested to some extent in specific regions (e.g. Tucker et al., 1985; Choudhury et al., 1987; Choudhury and Golus, 1988; Giddings and Choudhury, 1989). However, a major effort is required to validate the satellite measurements more widely against ground-based data.

Satellite observations are well suited to testing global models because the data are generally global in coverage and available over a number of years. The interpretation of satellite data, however, is complicated by an number of factors including the spatial heterogeneity of the land surface, atmospheric effects, temporal variations in the sensor calibration constants, the artificial degradation of the spatial resolution of the observations during processing, and changes in the characteristics of the individual sensors installed on different satellites. While these difficulties do not apparently invalidate the use of satellite data, they do suggest that the data need to be adequately calibrated and ground-truthed before they are routinely used for model testing.

A final requirement for model testing is that the derived data are available as gridded global data bases. Digital data on snow cover (Matson and Wiesnet, 1981) and NDVI are available through NOAA. Data on the snow water

Table 3: Satellite Measurement of Hydrological and Biospheric Variables

Sensor	Things measured	Source	Spatial/ Temporal measurement scale	Length of record	Derived variable	Availability of global data sets
AVHRR	visible and near-infrared reflectances and surface temperature	US Dept of Commerce	4km; once per day, once per night; global coverage	1982-	snow cover extent; fractional vegetation cover	snow cover digital data (NOAA); NDVI (NOAA); fractional vegetation cover needs to be derived
SMMR	microwave emission at 6.6, 10, 18, 21 and 37 GHz	NASA/ Goddard	spatial resolution variable, 150km at 6.6 GHz, 25km at 37 GHz; midday and midnight, weekly global coverage	1979-1988	snow water equivalent; near-surface soil moisture; vegetation biomass; seasonal inundation of wetlands; area of surface water	snow water equivalent (NASA); other data has not been compiled yet
SSM/I	microwave emission at 19, 37 and 95 GHz	NASA/ Goddard	spatial resolution variable, 50 km at 19 GHz, 25km at 37 GHz; global coverage	1989-	snow water equivalent; near-surface soil moisture; vegetation biomass; seasonal inundation of wetlands; area of surface water	no data have been compiled

AVHRR: Advanced Very High Resolution Radiometer
SMMR : Scanning Multichannel Microwave Radiometer
SSM/I: Spatial Sensor Microwave Imager

equivalent are available through NASA. However, most of the derived data have not been compiled in a global data base. A considerable effort will be required to ensure that the data required for use with or testing of the GHM is made available as gridded global data bases.

We anticipate that satellite data will be used for testing the model simulations of in particular near surface soil moisture, evapotranspiration and changes in surface water storage.

The Use of Runoff Data for Testing

Observational data on the mean monthly runoff over the period 1978-1983 for a number of large rivers (as published by UNESCO in "Discharges of Selected Rivers of The World") and daily data for ca 1200 stations from 67 countries for 1978-1983 are available through the Global Runoff Data Centre, Koblenz (Infoclima, 1989). The monthly data, in particular, would provide an excellent test of simulated runoff. Flow data from small and medium-sized catchments in northern and western Europe, compiled during the FREND project (Gustard et al., 1989), is also available from the Institute of Hydrology, Wallingford (Arnell, pers. comm., 1989). These data would provide an opportunity to test the accuracy of the GHM predictions of runoff at different scales.

The Use of Palaeohydrological Data for Testing

Quaternary palaeoclimatic and palaeohydrological data have proved to be a powerful tool for testing GCMs under a wide range of climatic regimes (e.g. COHMAP Members, 1988), since they show how individual elements of the system have actually responded to large changes in global boundary conditions, comparable in magnitude to the changes that are likely to occur in the next centuries. A similar approach, using reconstructions of palaeohydrological data on a continental to global scale, could be used test the robustness of the GHM to a range of climatic forcings. Palaeoclimates simulated by GCMs could be used to provide input to hydrological models, whose predictions can be compared with Quaternary palaeohydrological data.

Two kinds of Quaternary data are required for this effort. Data are needed to define the surface <u>boundary conditions</u> for model experiments (e.g. extent and height of ice sheets, and the geographic pattern of sea-surface temperature (SST) anomalies for specified times in the past). Accurate specification of boundary conditions is important for the reliability of the test procedure. Other types of data then provide <u>tests</u>. For example, regional patterns of changes in lake storage, as indicated by geomorphic or stratigraphic evidence, could be compared directly with the predictions of hydrological models of changes in the proportion of the surface area covered by lakes. Similarly, geomorphic and stratigraphic records of changes in river discharge and flood regimes could be compared with model predictions of changes in total runoff and flood frequency.

Recent advances in palaeohydrology have produced a battery of techniques for reconstructing Late Quaternary changes in individual elements of the hydrological cycle (e.g. lake levels, river discharge, groundwater recharage regimes, glacier and ice cap extent, soil and biospheric moisture storages). Regional to global scale compilations have been made of some types of data (e.g. pollen, lake-levels) as a consequence of projects such as the Cooperative Holocene Mapping Project (COHMAP), and the International Geological Correlation Programme (IGCP) project 158 on "Palaeohydrological changes in the temperate zone during the last 15 000 years" (e.g. Street-Perrott et al., 1989; COHMAP Members, 1990; Berglund et al., in prep.). However, further work is required to determine how these syntheses of Quaternary data could be used to provide an alternative mode for testing the GHM, and links with groups such as COHMAP need to be established at an early stage.

LINKING THE GHM TO GLOBAL MODELS OF THE CLIMATE SYSTEM AND THE BIOSPHERE

Complex feedbacks exist between the climate system, the hydrological cycle and the biosphere. Characteristically, global models of any one of these sub-systems incorporate the others only in a limited and simplified way. Thus, general circulation models treat surface hydrological processes only in terms of water storage in a grid-cell "bucket" and do not incorporate either the complex role of vegetation in the hydrological cycle or allow for the possibility of inter-cell transfer of water. While it is possible that the treatment of other sub-systems could be made more realistic, a more manageable goal is to find ways of linking global models of the three sub-systems, such that outputs from one model could be used as inputs to another. For example, a GHM could be interactively coupled to a global vegetation model, thus allowing changes in climate (ultimately derived from a general circulation model) to be translated into changes in regional hydrology, which would in turn affect regional vegetation through e.g. changes in soil moisture. These changes in regional vegetation would in turn have feedback effects on the hydrology through their effects on the evapotranspiration regime.

We envisage that the GHM would initially be a free-standing model, but that it would be constructed in such a way as to ultimately allow coupling with general circulation models (GCMs) or global vegetation models (GVMs: Prentice et al., 1989). The use of a grid-based model will facilitate such a linkage.

RESEARCH PRIORITY AREAS: WHAT NEEDS TO BE DONE ?

In principle, the proposed GHM could be operational within the next 3-5 years, since many individual components are being actively developed already or are elements of ongoing research projects. However, there are four areas which require urgent consideration:

(1) **the construction of improved global climate and hydrological data bases**, including dense networks of precipitation and runoff data and optimal three-dimensional interpolation of data;

(2) **the estimation of hydrological and biospheric parameters from satellite data** for global-scale model validation;

(3) **the development of efficient hydrological routing models**, appropriate to grid-based modelling at a global scale;

(4) **the development of spatial stochastic weather models**, to simulate temperature, solar radiation and precipitation patterns from frequency distributions derived from climate data and GCM scenarios.

CONCLUSIONS

(1) The construction of a mechanistic global hydrological model within the next five years is both highly desirable and feasible given the existing state of knowledge and modelling expertise.

(2) Techniques for modelling certain parts of the hydrological cycle are already being developed. New research efforts should be concentrated on less well conceptualised areas, notably (a) stochastic weather simulation and (b) surface and sub-surface routing.

(3) Topographic, climatic and hydrological information is required both for initialising and testing the global hydrological model. Some of the relevant data bases are being developed, but a co-ordinated international effort is required to ensure that (a) the necessary data continue to be collected, and (b) adequate, open-access data bases are developed. In those areas where existing information is inadequate, for example on the hydrological characteristics of the regolith, an effort to collect the relevant data is required.

(4) The construction and testing of a global hydrological model is currently beyond the scope of any individual or research institute. Many individual components are being actively developed already or are elements of ongoing research projects. There is an urgent need for co-ordination of such research efforts if a global hydrological model is to be operational within a reasonable time frame.

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