Water Resource Issues in the Namoi Basin

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Abstract

The management of the water resources of the Namoi River system has reached a critical level with regard to both water allocation and quality. The major issues include re-allocating the surface and sub-surface resource to balance both human and environmental needs, as well as implementing key land management practices to reduce adverse effects on water quality. The key water quality issues include reducing nutrient loads, especially phosphorus levels, impacts of rising water tables and subsequent increased dryland salinity and the presence of pesticides in both ground and surface waters above acceptable ecological standards. The response to improving the environmental quality of the Namoi system is being driven by principles and process's as espoused through Integrated Catchment Management. A community taskforce is now developing a catchment plan for the Namoi catchment, which will prioritise actions including allocation of funds for research, extension and monitoring needs. Modelling is playing an increasing role in aiding the community to make more informed decisions to better manage the land and water resources in the Namoi Valley.

1. Introduction

The Namoi River Catchment is located in the Murray Darling Basin system, west of the great dividing range in north west NSW. It covers an area of 41,988 km^2 and stretches westward for over 350 km from the great dividing range between Murrurundi and Walcha in the east to where it joins the Barwon River at Walgett in the west (fig 1).

The catchment produces around $ 600 million from agriculture per annum, with about 20 percent of income coming from irrigated production (DWR, 1992).

In recent years the management of the catchments water resources have come under greater public scrutiny as to the long term sustainability of the resource. A number of major decisions now have to be made concerning the management of the catchment regarding allocation of water for human, agricultural and environmental purposes as well as those concerning declining quality of the resource due to land based activities. This paper overviews how water is allocated in the catchment, the emerging water quality issues and how the catchment community is using ICM approaches to drive the process, to improve the management of the resource.

2. Water Quantity Issues

2.1 Surface Water

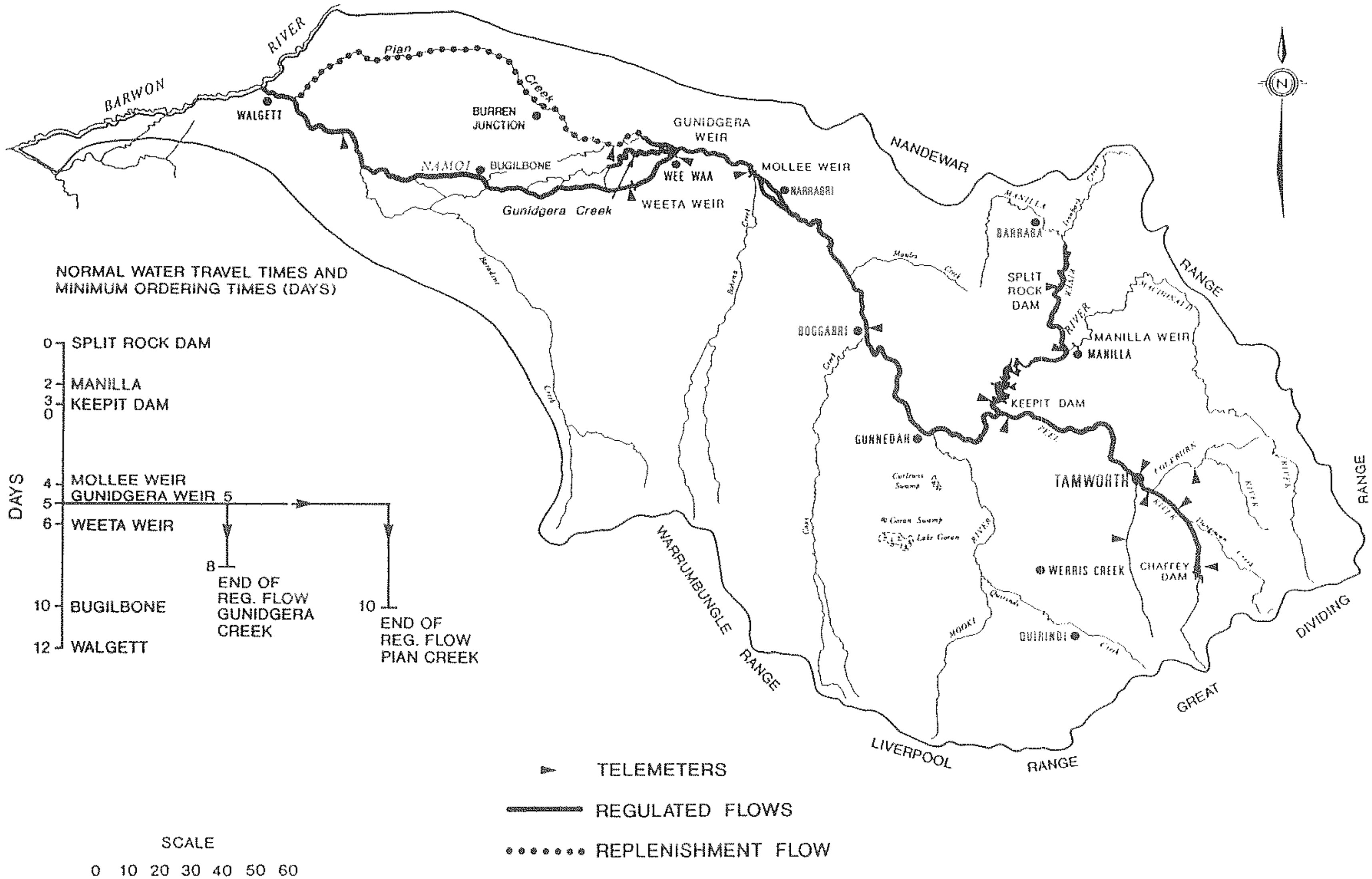
The average yearly flow in the Namoi River is approximately 790,000 megalitres (ML). Of this 280,000 ML is allocated for town, recreation, stock and domestic, industrial and irrigation. Of this irrigation is by far the largest consumer of water using between 70 & 80 percent of allocated water (DWR, 1992).

There are three major headwater storages in the Namoi Valley, in chronological order of construction, they are Keepit Dam-Namoi River, Chaffey Dam- Peel River and Split Rock Dam- Manilla River. These dams when full are capable of storing the entire average annual flow of the river, their storage capacity is 425,000ML, 62,000ML and 397,000ML respectively. In addition three weirs downstream of Narrabri; Mollee, Gunidgera and Weeta Weir ; store a total of 5,500 ML and are used for re-regulating purposes in the irrigation areas. Each weir is fitted with a fishway (DWR, 1992).

Through a combination of past over allocation in some areas and increasing demands by the wider community for increased environmental flows , a total embargo on new irrigation licences is now in place in the Namoi. In July, 1995 a total embargo on new irrigation licences was agreed by all affected state governments through the Murray Darling Basin Agreement, to allow a full audit of water allocation in the Murray Darling Basin to occur.

The NSW government in February, 1994 endorsed the Council of Australian Government (COAG) Agreement on sustainable reform of the water industry. The reforms will have significant ramifications to management of water quantity in the Namoi. The general principles endorsed included a move to full cost recovery, clarification of property rights to water,

FIGURE I



NAMOI RIVER VALLEY
WATER MANAGEMENT SYSTEM

allocation of water to the environment, adoption of water trading rights, institutional and organisational reform and a framework for community participation.

2.2 Ground Water

The Namoi Valley also has significant groundwater reserves. The total volume of groundwater in storage is approximately 285 million ML. Although the availability and quality of this groundwater varies considerably from place to place, an estimated 89 percent of the total is of low salinity ie less then 1000 mg/l TDS (DWR, 1992).

The occurrence of groundwater can be separated into three categories:

. groundwater in unconsolidated sediments eg river alluvium
. groundwater in porous consolidated rocks, eg sandstone and
. groundwater in fractured rocks, eg basalt.

Groundwater in alluvial deposits associated with the Namoi River and tributaries supports extensive irrigation. The volume of water can be extracted under a 'sustainable yield ' management strategy. This yield is currently estimated at 350,000 ML.

In terms of the volume of groundwater and economic return to the valley the alluvial deposits are the most significant groundwater resources pumped. Over half the irrigated cotton in the lower Namoi depends to some extent on groundwater for irrigation. Yields of 200 L/S can be obtained from suitably constructed bores. There are 1639 high yield bores in the alluvium. The extensive development has fully committed groundwater resources in most areas and no new entitlements for high yield bores are being issued. In certain zones entitlements now exceeds sustainable yileds and some pegging back of entitlements will need to occur.

By far the largest store of groundwater is that in the sandstone aquifers of the Great Artesian Basin. An estimated 243,000 million ML of groundwater occurs in the Namoi Basin. Two main aquifers are found between 520 metres to 720 metres and at 810 metres. This water however, is unsuitable for irrigation because of its high proportion of sodium which adversely affects soil structure. However, it is suitable for stock watering, households and town water supplies.

In the GAB because of the large cost of sinking new bores most of the water for stock is delivered from a central bore, controlled by a Bore Trust, to a number of properties using open bore drains. However, this is highly inefficient, with losses of over 90 percent to evaporation common. Due to the waste from the open bore drains and associated land degradation and vermin problems,, a government program called 'Cap and Pipe the Bore' now operates giving graziers incentives to pipe their bores.

3. Water Quality Issues

Water quality issues have recently dominated debate in the Namoi River Catchment. The Namoi contributes large amounts of phosphorus to the Darling system the main causative agent of the recent blue green algae outbreaks, major areas of dryland salinity are now developing on the Liverpool Plains driven by rising water tables and recent monitoring studies have detected an increasing trend of pesticides in surface and ground water.

3.1 Nutrients

Excess nutrients, particularly phosphorus, in the aquatic environment increases the growth of algae and aquatic plants. Total phosphorus concentrations in excess of 0.05 milligrams per litre (for more than 50 percent of the time) have been in recent times found in the waterways of the valley and its storages. This is a level at which algae problems could occur. The frequency and occurrence of algal blooms have increased in the Namoi Valley over the last few years.

Blooms have been particularly bad in the Chaffey Dam the major water supply for Tamworth's population, in excess of 35,000 people. However, research has shown that phosphorus in the dam is largely natural and not, as originally thought, sourced from phosphorus fertiliser added to improved pastures in the catchment (Caitcheon etal, 1995). Aeration equipment is now being installed in the dam with the aim of reducing the blooms.

The Namoi Valley is a major source of phosphorus in the Barwon-Darling River and therefore a major causative factor of the major bloom which occurred in the system in 1991 (MDBC, 1993) . More than 150 tonnes of phosphorus was contributed by the Namoi in 1991/92, 12 tonnes during 1992/93 and 42 tonnes in 1993/94 (DWR, per comms). Recent more detailed monitoring from specific sub-catchments would indicate that certain parts of the catchment may contribute much greater amounts to the bed load along the river. One relatively small flood event in January 1995 from Coxs Creek contributed over 173,000 tonnes of suspended solids, from erosion, which included 58 tonnes of phosphorus and 65 tonnes of nitrogen into the Namoi River over 50 hours (Cooper, 1995).

An associated problem with large amounts of suspended sediment entering the river from soil erosion is turbidity. Councils such as Walgett, at the end of the Namoi have to add large amounts of alum to the towns water supply to remove suspended sediment, as clay, from its drinking water.

While much of the phosphorus in the system is from diffuse sources through soil erosion, the major towns do make significant contributions to the river. Public works data indicates that Tamworth, Gunnedah and Narrabri contribute together about 50 tonnes of phosphorus and 135 tonnes of nitrogen. All these towns are now undertaking public awareness campaigns to reduce use of phosphorus in their towns and are also implementing land disposal programs, with the ultimate aim to stop sewerage disposal to the Namoi.

3.2 Dryland Salinity

The Peel river which originates in the Tamworth district and the Mooki River from the Liverpool Plains have shown rising levels of stream salinity. Both these rivers consistently show levels above 700 uS/cm , with the Mooki at low flow exceeding 2,000 uS/cm. These levels however are reduced from fresher flow's by other tributaries resulting in levels around 450 uS/cm in the lower reaches of the river.

Recent research on the Liverpool Plains (Broughton, 1994) and around Tamworth (Bish and Bradd, 1994) show that water tables are rising in many areas indicating a continuing increase in stream salinity, especially in the Peel River, Mooki River and Coxs Creek system. The problem on the Liverpool Plains is by far the largest with Broughton (1994) finding an area of 195,000 hectares with water levels within 5 metres of the ground surface and 30,000 ha having water levels within two metres of the ground surface, causing soil salinisation and crop yield decline. It is considered that all areas with standing water tables within five metres of the surface are at risk. The Liverpool Plains produces about $200 million from agricultural production per annum, if the worst case scenario were to occur about half of this production could be lost due to dryland salinity within 20 years.

3.3 Pesticides

In the 1994/95 season, four insecticides and six herbicides were detected in surface waters (Dep.Land & Water Con, 1994). Endosulfan is the most widely used insecticide, being used on cotton and other summer grain crops for heliothis control in the valley. In 1994/95 during the cotton season fifty percent of samples collected from river sites in areas of irrigated agriculture exceeded 0.01 μg/L for endosulfan. Levels that exceed more then one hundredth of a microgram of total endosulfan per litre of water (0.01 μg/L) exceeds the guideline established for the protection of Australian aquatic ecosystems (ANZEEC, 1992). However, current testing procedures cannot detect below this level, so whenever endosulfan is detected at all it exceeds this guideline. Current NHMRC (1987) guidelines for drinking water are 3,000- 4,000 times the eco-system level. These levels have never been detected in the Namoi.

In 1991/92, 1992/94 and 1993/94 80 percent of samples taken in irrigated areas for endosulfan exceeded the 0.01 μg/L guideline (DLWC, 1994).

With the exception of atrazine, used as a herbicide in summer grain crops and lucerne, no pesticides were detected upstream of irrigated agriculture. Atrazine continues to be the most widely detected pesticide in both surface and groundwaters. Out of 103 groundwater samples taken in the Namoi for pesticide testing, 8 samples were found to consistently contain atrazine. According to draft guidelines established by the National Health and Medical Research Council, no atrazine levels are acceptable in drinking water.

4. Addressing the Issues by a Total Catchment Management Approach

Clearly there are major water quantity and quality issues facing the Namoi catchment. To address these a co-ordinated response is occurring where the community, government and industry are using the philosophical guiding principles of Integrated Catchment Management (ICM) to develop solutions.

Mitchell (1987) recognises three dimensions to integrated approaches :

The philosophy- refers to the belief that interactions between natural resources and humans should be viewed in a holistic framework.

The Process- refers to flexible, adaptive, ongoing and dynamic mechanisms, which co-ordinates the activity of many people, both in government and across the wider community.

The product- should be improved quality of natural resources and sustainable economic development and production based on best management practices.

In general the philosophy of ICM is now well accepted in the Namoi Valley. The North West Total Catchment Management Committee, in its new strategic plan 'Managing our Resources the Next Phase' (1995), to deal with issues in the North West in a co-ordinated way is moving towards a process to facilitate development of Catchment Management Plans (CMP's) for the Namoi, Macintyre and Gwydir catchments. These plans will be formed using steering committees representing key stakeholders in the catchments, government agencies and local government. The first of these the Namoi Valley Taskforce is aiming to have an overall situation document prepared for the Namoi in December 1995.

Once the draft situation document is prepared, extensive community consultation will occur across the various sub-catchments to develop the next stage of the plan concentrating on developing key priorities, strategies and actions using a best management practice approach across the catchment. The strategic document will provide the government, community and industry groups with a basis for developing future research, monitoring and extension programs.

Already, the 1.2 million hectare Liverpool Plains region comprising the Mooki River and Coxs Creek catchments, are well advanced in developing a range of best management practice guidelines to address the key natural resource issues in the catchment (Liverpool Plains Land Management Committee, 1995). Here the Liverpool Plains Land Management Committee, which comprises farmer representatives from the 30 plus landcare groups on the plains as well as local government and the state agencies, have already initiated a major research and extension program to develop and support a range of best management practices to address the key issues of nutrients, dryland salinity , floodplain and vegetation management.

Many of the papers in this section of the conference form part of the research teams working on the Liverpool Plains, either as part of the National Dryland Salinity Program, where Liverpool Plains is one of five national focal catchments by LWRRDC for dryland salinity research or through a co-ordinated nutrient research program funded by the Murray Darling Basin Commission and NSW Department of Land and Water Conservation. In addition the Departmant of Land and Water Conservation is developing an Integrated Quality and Quantity Model to determine the interrelationships between water quality and quantity.

The modelling approaches being developed will play a key role in the Namoi Valley and other catchments to allow the community and government to develop strategic responses to the many water issues confronting them.

5. Conclusion

The major water issues in the Namoi Valley relate to both quantity and quality. The key issue with water quantity is that the resource is now totally allocated and in some areas allocation will have to be clawed back to allow greater flows for environmental purposes both down the Namoi and the entire Murray-Darling system. These issues will be of much debate over the next few years as the COAG agreements are implemented.

The major water quality issues relate to the Namoi been a major source of phosphorus to the Barwon- Darling system, development of major dryland salinity problems in the Tamworth - Liverpool Plains area and the resultant impact on farm productivity and water quality and the increasing incidence of pesticide in both surface and ground water.

To address these issues the community and government has chosen to use an ICM response, using catchment planning in the Namoi valley to prioritise issues and ultimately develop and implement a range of best management practices across the catchment.

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INVITED

An Overview of Large Scale Hydrological Modelling

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ABSTRACT The paper presents an overview of large scale hydrological models with a view to identifying their unique features and limitations. We consider three model types: flood forecasting models, long-term water balance models and macroscale hydrological models. The first two have been used for a long time for hydrological applications, while the last one has become important only in recent times for an essentially meteorological application. The three model types are vastly different in their time scales, requiring different parameterisations for the same processes. For example, due to the small time scales used, the explicit inclusion of the effects of spatial heterogeneity (of soil moisture, rainfall and vegetation, and the resulting feedbacks) is critical to the macroscale hydrological models. This is much less critical for water balance and flood forecasting models, which allow a lumped representation of the effects of spatial heterogeneity. This paper also shows how each model can contribute towards the improvement of the others. For example, sophisticated approaches to quantifying spatial heterogeneity in the macroscale hydrological models have the potential to improve the physical bases of the conceptual schemes currently in use in both the water balance and flood forecasting models. Similarly, all three models require some form of soil moisture accounting, which offers an opportunity to combine well-tested, long-term water balance models developed for large catchments, with both flood forecasting and macroscale hydrological models. In the latter case, it provides a natural avenue for utilising measured catchment runoff, which is the only spatially integrated measure of the land surface response available to date.

INTRODUCTION

Hydrologists are increasingly called upon to develop models of the hydrological response of the land surface (and near surface soils) over ever increasing spatial scales [Eagleson, 1986]. These models are required for a variety of purposes: development of flood warning systems, management of land and water resources, modelling the behaviour of large ecological systems, and predicting the effects of projected climate change [Singh, 1995]. Most recently, considerable attention is being given to the issue of "macroscale modelling" to assist in the development of land surface hydrological "parameterisations" for use as boundary conditions in global climate models.

Large scale hydrological models differ from small scale models in that spatial heterogeneities in climatic inputs, such as precipitation, and in land surface properties, such as topography, geology and vegetation cover, are much more important and, in many cases, their effects have to be explicitly included in the modelling. This is not normally a requirement for modelling smaller catchments. Thus, large scale hydrological modelling represents one example of the "scale problem" in that it is not yet clear how our ability to model various hydrological processes at small (and intermediate) scales can be extended to larger scales [Blöschl and Sivapalan, 1995]. The problem is compounded by lack of detailed data to characterise the heterogeneities at various scales, and by limitations of computational power.

Large scale hydrological modelling, therefore, is an exciting area of research as it challenges us to think in more innovative ways than we are hitherto used to, and provides us with the stimulus to look for a deeper understanding of how the hydrologic system operates. Both of these will, in turn, help us to improve our ability to model the hydrological responses at smaller scales as well.

This paper is aimed at presenting an overview of large scale hydrological models, the different model types and their uses, their unique characteristics, and more importantly, to discuss how the experience gained, and the advances made, in developing and applying one type of model can contribute towards the improvement of others.

MODEL FEATURES

(i) Types and Uses of Models

In this paper we will consider three different types of large scale hydrological models (see Table 1). The first type are models commonly used in regional flood forecasting or warning systems. Here we will refer to these as flood forecasting models or FFM. The objective of the FFM is to predict the flood discharge hydrograph, for one event, at a number of nodes within a large river basin. The locations of these nodes are usually governed by the presence of cities or other population centres, and/or hydraulic controls or structures such as bridges and dams. The idea is to use telemetered rainfall information, preferably combined with radar reflectivities, to predict the flood discharges in real time. Examples of flood forecasting systems within which the FFM are used include the U. S. National Weather Service River Forecasting System, NWSRFS [Hudlow, 1988], and the River Flow Forecasting System, RFFS, being used by the U. K. National Rivers Authority for the Yorkshire Region [Moore and Jones, 1991].

The second type of models are long-term water balance models, or WBM, which are used to predict the effects of projected land use, and/or possible climatic, changes on the water yield, long-term water balance dynamics, of river basins. These are commonly used in water resources planning. Examples of WBM that can be used for water resources planning include the WBM/WTM modelling system for the Zambezi River Basin in Africa [Vörösmarty and Moore III, 1991], the ACRU modelling system developed in South Africa [Tarboton and Schulze, 1991], and simpler approaches for the Danube River Basin [Stancik and Jovanovic *et al.*, 1988].

Finally, we discuss a new generation of models called macroscale hydrological models, or MHM, which are currently being developed with the sole purpose of helping to improve the land surface hydrologic characterisations of global climate models (GCM), regional climate models, and meso-scale meteorological models. A discussion of the various modelling approaches for MHM can be found in Vörösmarty [1993]. Wood [1991] and Wilkinson [1993] present a number of papers which describe the current status of MHM, and the role of experimental data. The inadequate representation of land surface hydrology in current GCMs has provided the motivation for a number of past and present large scale field experiments, e.g., HAPEX, ISLSCP, GEWEX; an overview of these is given by Shuttleworth [1991] and in IGBP/ICSU [1993].

The first two types of models (i.e., FFM and WBM) are hydrological models developed for essentially hydrological applications, whereas the MHM are hydrological models with a predominantly meteorological application.

(ii) Principal Concepts and the Focus of Modelling

As seen above, the three types of models considered have widely different uses. The particular application determines the nature of the hydrological response which is focussed on, and the critical processes which must be captured accurately in the model.

Although the main output variable for both the FFM and the WBM is runoff, the models differ fundamentally in their emphasis. Since FFM are used to predict the flood (runoff) hydrograph for a single event, they concentrate on processes directly relevant to flooding. Other processes such as evaporation and deep drainage are, in most cases, not treated explicitly but, rather, their effects are incorporated through the choice of initial conditions.

On the other hand, the WBM are concerned with the concept of *long-term* water balance. All components of the water balance equation (e.g., runoff, evaporation, recharge etc.) are considered important in the WBM and long-term variations are accounted for. Sub-diurnal variations, or variations internal to specific rainfall events, are deemed less important, and are not explicitly included.

Similar to the WBM, the MHM have to deal with the concept of water balance. However, the dominant motivation of MHM is land surface energy balance at *short time* scales (i.e., sub-diurnal). They are especially concerned with the partitioning of net radiation into sensible and latent heat fluxes and soil heat flux, in the context of atmospheric models. The connection to water balance appears through the latent heat flux term which is directly related to the evapotranspiration term in the water balance equation. Because of the emphasis on *short-term* energy balance, runoff and the concept of *long-term* water balance have, in the past, been considered to be of only secondary importance.

(iii) Main Input and Output Variables

The critical input variable to the FFM is event rainfall specified for all sub-catchments, and the required output is the flood hydrographs at prescribed node(s).

In the case of the WBM, the critical inputs are time series of rainfall and other climatic inputs (e.g., potential evaporation), and more crucially, time series of the land use history for each of the sub-catchments. The output is usually the runoff hydrograph, over long periods of time, for various sub-catchments. Other output variables such as soil moisture storage and surface/sub-surface runoff are sometimes used in the context of applications such as the modelling of sediments, solutes and nutrients.

The main inputs to MHM are GCM generated, grid-averaged values of net radiation, precipitation, air temperature, humidity and wind speed. The outputs are usually grid-square averaged fluxes of sensible and latent heat, and soil heat flux. While runoff and soil moisture are estimated in the course of model operation, they are not key output variables, though being easier to measure in the field than the energy fluxes.

(iv) Spatial Scales of Interest and Modelling Approaches

In the case of FFM and WBM our focus is on the modelling of catchments of area, say, 10,000 to 250,000 km^2, such as the Chao Phraya in Thailand, Murray-Darling in Australia, and Ganges in India. In the case of the MHM the focus is on the current size of the GCM grid-square which is in the range of 200-500 km squared.

While the different model types are designed for land areas of similar size, they differ in the type and size of the spatial discretizations used (rectangular grid vs sub-catchments). The MHM, at present, are based solely on a rectangular grid. The advantage of the rectangular grid, for MHM, is that linkage to the overlying meteorological model is easier, since the latter do not readily recognise catchment boundaries. In the case of the FFM and WBM, both rectangular grids and natural sub-catchments have been used. Sub-catchments are a more natural means of discretization because of the organisation present in real landscapes in the form of stream networks and catchments. Also, discretization into sub-catchments facilitates the use of internal runoff data for calibration and validation. The difficulty to use runoff is a serious drawback of the rectangular grid, especially for MHM.

Deterministic hydrological models are often classified as belonging to either physically-based, conceptual, or empirical (or black-box) approaches. The type and size of discretization have a significant influence on which of the above three modelling approaches can be used.

Physically-based models attempt to solve the underlying, governing partial differential equations of saturated-unsaturated sub-surface flows and overland flows, including channel flows. On the other hand, conceptual models simplify hydrological process representations into that of one or more concentrated water stores, or state variables, reflecting the modeller's understanding of and experience with these processes. The process representations are expressed in terms

TABLE 1: MODEL FEATURES

MODEL TYPE	FLOOD FORECASTING MODELS (FFM)	WATER BALANCE MODELS (WBM)	MACROSCALE HYDROLOGICAL MODELS (MHM)
USE	flood forecasting; flood mitigation	water resources planning and management	global climate modelling
CONCEPT	catchment; event hydrograph	catchment; water balance	surface energy balance
INPUTS	event rainfall	rainfall; pan evaporation; land use	GCM-generated rainfall, radiation, humidity etc
OUTPUTS	flood hydrograph at prescribed nodes	water yield (runoff); soil moisture storage	sensible heat flux latent heat flux
SPATIAL DISCRETIZATION	sub-catchments; river reaches	sub-catchments	rectangular grid
MODELLING APPROACH	empirical/conceptual; physically-based (routing)	conceptual	conceptual towards physically-based
TEMPORAL SCALE (Resolution)	1-6 hours	1 day - 1 month	10-30 minutes
TEMPORAL SCALE (Extent)	1 week	decades	a few years

of intuitive functions whose unknown parameters are then estimated by "calibration". Finally, empirical or black-box models further simplify the process representations, which are constructed without regard to any conceptualisation of the hydrological response; these empirical, input-output relationships are estimated using observed rainfall and runoff data.

There has been considerable debate in the literature on the relative advantages and disadvantages of these modelling approaches. Doubts have been raised about the ability of models based on the traditional and well known governing equations (e.g., Richards equation, St. Venant equations etc.) to predict the hydrological response, even in relatively small catchments. The interested reader is referred, for a more detailed discussion of the difficulties with physically-based models, to Beven [1989], O'Connell [1991], Grayson *et al.* [1993] and Beven [1995]. These difficulties are compounded, several fold, when one considers the application of physically-based models to large, continental scale catchments, or similar-sized land surface areas (e.g., GCM grid-square). Thus, for the large scales considered here, only empirical or conceptual modelling approaches are feasible. This may be a cause of confusion and concern, especially in the case of MHM, since the parent meteorological models are based on physically-based governing equations. However, this does not appear feasible for the hydrological component at this time.

(v) Time Scales: Extent and Resolution

The three model types considered differ substantially in their temporal scales - both the extent and resolution. The FFM, being event-based models, use temporal resolutions of one to several hours. This time resolution is necessary for adequately capturing the shape of the flood hydrograph, including the magnitude and timing of the peak. The models are run for the duration of the precipitation event, which can range from a few days to a week.

The WBM normally use a time resolution of one day. This may be up to a month for very large catchments, especially if the sole objective is estimating long-term water yield. However, for some applications, e.g., prediction of sediments and nutrients, which require more process-based descriptions, a time step of one day may have to be used. In most cases, predictions or simulations are expected for a period of 10-50 years.

The MHM operate on very small time scales (e.g., 10-30 minutes) sufficient to capture the diurnal variations of land surface energy fluxes. The small time scales arise from the need of the meteorological models to accomodate "the horizontal propagation of sound and external (or surface) gravity waves: .... a horizontal grid of 200 km demands a time-step of less than 10 minutes" [Pittock *et al.*, 1975: pg. 239]. The MHM are incorporated in global climate models which are usually run for a few years at a time. Distributed versions of MHM may be coupled to regional climate models with a similar temporal extent, or to meso-scale meteorological models which are typically run for periods ranging from a few days to a few weeks.

EFFECT OF TIME SCALES ON MODEL PARAMETERISATIONS

The differences in time scales dictate that different parameterisations may have to be used for the same processes in the three different models. What follows is a discussion of the parameterisations used each model type. These are organised under the headings of: (i) runoff generation, (ii) runoff routing (iii) evapotranspiration, (iv) the effects of spatial heterogeneity, (v) the effect of feedbacks with the atmosphere, and (vi) soil moisture accounting (also see Table 2).

(i) Runoff Generation

A variety of runoff generation models have been used in FFM. The simplest is the ϕ-index (or constant loss) model which estimates runoff generation as $R = P - \phi$, provided $P > \phi$. ϕ is a constant loss rate. Reed [1982] gives an example of the application of ϕ-index model in U. K. catchments in which he related the ϕ-index to the average rainfall intensity and the antecedent runoff. Another runoff generation model is the initial loss-continuing loss model [Inst. of Engrs. Aust., 1987] which is used for flood forecasting in Australia by the Bureau of Meteorology. This model assumes that no runoff is generated until a given initial loss capacity W has been satisfied, irrespective of the rainfall intensity; after that, the continuing rate of loss is assumed a constant, similar to the ϕ-index. Empirical models which allow for the loss rates to vary during the event have been reviewed by Srikanthan *et al.* [1994].

More complex models which generate runoff based on a coupling to conceptual soil moisture accounting schemes, are also being used. These allow for a continuous updating of the loss rates based on changing soil moisture. In general, they are based on $R = R(P, S)$, which is a function relating the rate of runoff generation R to the level of a conceptual soil moisture store S, and the precipitation intensity P. The unknown parameters of this function are estimated prior to the event by calibration with long-term rainfall-runoff data. Two examples of this approach are Boughton and Carroll [1993], who used their AWBM model (a soil moisture accounting model) for estimating the runoff generation, and Ruffini *et al.* [1994], who used the initial and continuing loss model, the parameters of which were updated by relating them to the levels of conceptual soil moisture stores in a modified Sacramento soil moisture accounting model [see Kitanidis and Bras, 1980].

Since the FFM operate during heavy precipitation only (i.e., under wet conditions), and are also heavily dependent on updating procedures, many studies have shown that simple runoff generation models may be adequate (see Srikanthan *et al.* 1994, for a review). However, a WMO study [WMO, 1992] concluded that while simple models may be adequate in small to intermediate-sized catchments, this is not so for very large catchments. In the latter case the study showed that it was necessary to use soil moisture accounting schemes, rather than empirical loss models, to achieve consistently good results for long lead time forecasts. Such models, for improved accuracy, should have a good conceptual basis [Chiew *et al.*, 1993]. In general, it can be stated that models which include partial area runoff generation, where the extent of partial areas can be updated during the storm [e.g., Mein and O'Loughlin, 1991], and can be separated into slow and fast runoff components may be adequate for the purpose.

The WBM also use conceptual soil moisture accounting schemes for estimating runoff generation. Examples of WBM include the Sacramento model, HBV [Bergström, 1992] and LASCAM [Sivapalan *et al.*, 1995a]. The runoff generation routines in these models are similar; they estimate both surface and subsurface runoff, based on the level of water in a number of interconnected soil water stores, and on the rate of precipitation. The more sophisticated models (e.g., LASCAM) include partial area runoff generation explicitly, while in the others it is done implicitly. In LASCAM, for example, total runoff has two components: surface runoff and subsurface runoff. Surface runoff is estimated by $R_s=k_sA^s P$ where k_sA^s refers to the partial area fraction, A is the relative level of soil moisture in one of three soil moisture stores (perched water store), and P is the daily rainfall. Similarly, sub-surface runoff is estimated using $R_b=k_bA^b$. In the above, k_s, k_b, s and b are calibration parameters. Total runoff R is then $R = R_s + R_b$. The value of the soil moisture store A is continually updated, based on contributions due to rainfall, and discharge from a permanent, deep groundwater aquifer, and losses due to evapotranspiration.

In MHM, since the focus of modelling is on the estimation of surface energy balance, simple conceptual soil moisture accounting models have been used to estimate runoff generation. The classic example is the so-called Manabe bucket [Manabe, 1969] which assumes that the runoff produced in a given time step depends on the value of the initial volumetric soil moisture deficit in the bucket (or store). If rainfall depth P is less than D_i, the initial deficit, then $R = 0$, and the deficit at the end of the time step is $D_f = D_i - P$. If $P > D_i$, then $R = P - D_i$, and $D_f = 0$. The value of the deficit D is continuously updated through time

(ii) Catchment Runoff and Flood Routing Models

Routing of the computed volume of runoff generation (i.e., rainfall excess) is critical to the FFM since the objective is to predict the shape of the flood hydrograph at several nodes in the river network. This is usually achieved by a combination of (a) a catchment model and (b) a flood routing model. Catchment models are lumped models which predict the runoff hydrograph at the outlet of a catchment, which is usually the location of the most upstream node in a river network where a prediction is needed. They can be empirical (e.g., unit hydrograph) or conceptual (e.g., multiple linear or non-linear reservoir models such as the Nash cascade, RORB, WBNM and RAFTS; see Inst. Engrs. Aust., 1987). Flood routing models propagate the above computed runoff hydrograph between the various nodes on a river reach, incorporating changes in river cross-section, lateral inflows and the presence of hydraulic controls. These may be conceptual in some cases (e.g., Nash cascade or the Muskingum-Cunge method), or physically-based models solving the governing hydraulic equations of flow in river channels (i.e., St. Venant equations). An example of the latter is the DWOPER model [Fread, 1985] used in the National Weather Service Flood forecasting System in the U. S. [Hudlow, 1988]. The choice of model depends on the accuracy required, the availability of data, and the presence of hydraulic structures or controls. In the latter case hydraulic models are usually preferred.

Generally, runoff routing is not critical to WBM since long-term water balance or yield is the critical issue. However, since the runoff hydrograph is used for model calibration, the match between observed and predicted runoff, and consequently the robustness of the parameter estimates, are improved when routing is included. Nevertheless, fairly simple and parameter-efficient models, such as approaches that use a constant velocity of travel, are usually sufficient [Sivapalan and Viney, 1994]. If needed, for very large catchments, more complex schemes based on a flow dependent travel speed may be used.

Runoff routing is not considered at present for MHM, even though the time scales are small. This is because (a) runoff is not the main output variable and therefore there is no need to estimate its timing, and (b) runoff routing is very difficult to carry out since there are likely to be multiple outlets to the edges of the GCM grid-square.

(iii) Evapotranspiration and Surface Energy Balance

While evapotranspiration during flood events is small it is significant between events. Indeed the between-event evapotranspiration strongly influences the antecedent soil moisture for subsequent storms. Antecedent soil moisture, which is used as the initial condition in FFM, can be estimated in two alternative ways. Firstly, observed runoff at the beginning of the storm event is used as a surrogate for the initial soil moisture status of the catchment. Secondly, FFM is coupled to a continuous soil moisture accounting scheme (i.e., WBM), which updates the soil moisture through the event and inter-event periods.

WBM operate on time steps of one day or more. The common way to model daily evapotranspiration in most WBM is according to $E_a=\alpha(S,G)E_p$, where E_a is actual evapotranspiration (bare soil evaporation + transpiration), E_p is some measure of standard or potential evaporation (e.g., pan evaporation, or an estimate based on the Penman or Priestley-Taylor equation), and $\alpha(S,G)$ ($\alpha < 1$, $G < 1$, $S < 1$) is a function expressing the control of soil moisture availability S, and vegetation cover measured by a greenness index G, on the rate of evapotranspiration [see Shuttleworth, 1993; and, Dyck, 1983]. The function $\alpha(S,G)$ is usually of the form $\alpha(S,G)= G\, k_e S^c$, where k_e and c are calibration parameters. In the limit, evapotranspiration is equal to the potential rate for a fully vegetated surface when there is adequate supply of water to the roots (i.e., $\alpha = 1$), but falls below the potential rate when either the vegetation cover or the soil moisture is reduced below their maximum values.

Interception loss is important for WBM especially for forested
catchments. It is usually estimated using simple models, e.g., $I=a+b\,P$, where I is daily interception loss, P is the daily rainfall input, and a and b are constants which are dependent on the greenness G [Ruprecht, 1990].

The simple models of evapotranspiration and interception used in WBM are no longer adequate for MHM because of the shorter time scales. More sophisticated models, which explicitly include the partitioning of available radiant energy into latent heat and sensible heat fluxes, and into soil heat flux, are required. This partitioning is governed by the processes controlling water vapour diffusion from the soil, through the stems and leaves of plants, and through the air. One concept is to assume that the water (vapour) fluxes through these pathways are proportional to differences in vapour pressure between the bottom and top respectively; the constant of proportionality is called a *resistance*. *Soil surface resistance*, *stomatal resistance* and *aerodynamic resistance* are used to characterise flows in each of these pathways. Stomatal resistance measures the control of evaporation by plants which open or close the stomatal openings in their leaves in response to atmospheric demand and soil moisture availability. The stomatal resistance of the whole plant canopy is termed *canopy resistance*. Empirical relationships exist for the canopy resistance in terms of leaf cover, soil moisture status, and environmental variables such as air temperature, humidity and photosynthetically-active radiation [Jacquemin and Noilhan, 1990]. The aerodynamic resistance controls the rate of water vapour transfer away from the evaporating surface by turbulence, and depends on the wind speed and the height of vegetation (i.e., roughness).

Advanced models of evapotranspiration used in the MHM break up the plant canopies and soil into separate layers, and represent the water vapour and heat flows between them using complex networks of such resistances. A number of models of varying levels of sophistication are now available, the most advanced being BATS [Dickinson *et al.*, 1986] and SiB [Sellers *et al.*, 1986]. A simple resistance-based model is the Penman-Monteith equation which, for example, is used in the TOPLATS model developed by Famiglietti [1993]. These models are examples of so-called *big leaf* models which represent the vegetation within the entire grid-square in a uniform manner as if it were one single leaf.

(iv) Effects of Spatial Heterogeneity

Both FFM and WBM deal with catchment response in a lumped manner. Spatial heterogeneity, other than between sub-catchments, is rarely treated explicitly. Rather, the heterogeneity is absorbed in the lumped representations, such as catchment rainfall which is an areal average.

On the other hand, at the small time scales of interest to MHM, spatial heterogeneities of soil moisture, rainfall and vegetation cover have been found to be of considerable importance [Entekhabi and Eagleson, 1989; Avissar and Pielke, 1989; Famiglietti and Wood, 1990; Sivapalan and Woods, 1995], and the effects of such heterogeneity need to be either explicitly or implicitly included. The remainder of this section is therefore mainly concerned with MHM.

TABLE 2: Effect of Time Scales on Model Parameterisations

MODEL TYPE	FLOOD FORECASTING MODELS (FFM)	WATER BALANCE MODELS (WBM)	MACROSCALE HYDROLOGICAL MODELS (MHM)
TEMPORAL SCALE (Resolution)	1 - 6 hours	1 day - 1 month	10-30 minutes
TEMPORAL SCALE (Extent)	1 week	decades	a few years
RUNOFF GENERATION	loss models	soil moisture accounting models	soil moisture accounting models
CATCHMENT RUNOFF & FLOOD ROUTING	unit hydrograph; reservoir models; St. Venant equations	constant, or variable (flow-dependent) velocity models	not considered
EVAPOTRANSPIRATION	initial conditions	$E_a = \alpha(S,G)\ E_p$	big leaf models (e.g., BATS, SiB, Penman-Monteith)
SPATIAL HETEROGENEITY	not explicitly considered; absorbed in model parameters	not explicitly considered; absorbed in model parameters	pdf approaches; distributed numerical models; effective parameters
ATMOSPHERIC FEEDBACKS	not important	not explicitly considered; absorbed in climatic inputs or model parameters	vertical feedbacks accounted for; horizontal advection effects to be parameterised
SOIL MOISTURE ACCOUNTING	initial conditions or coupled to WBM	multiple-store models	single or multi-store models; multi-layer models
VALIDATION CALIBRATION UPDATING	updating (runoff); calibration	calibration (runoff)	diagnostic analyses jointly with GCMs

- Heterogeneity of Soil Moisture

Most approaches to quantifying soil moisture heterogeneity assume that the probability distribution function (pdf) of soil moisture is sufficient to describe the heterogeneity completely. For example, Entekhabi and Eagleson [1989] used the gamma distribution to characterise the heterogeneity of soil moisture content. The assumption of the gamma distribution allowed the derivation of analytical expressions for the resulting hydrological fluxes. Based on these, Entekhabi and Eagleson demonstrated the critical importance of soil moisture heterogeneity for the estimation of land surface water and energy fluxes. Wood *et al.* [1992] and Liang [1994] also adopted the pdf approach, using the Xinanjiang distribution in their variable infiltration capacity (or VIC) model, which too allowed derivation of analytical expressions for the fluxes. However, in the case of the VIC model, the spatial heterogeneity of soil moisture is coupled to a changing lumped soil moisture store (i.e., from a soil moisture accounting scheme). This allows for the simulation of changing pdfs of the spatial soil moisture patterns. The VIC model thus has the simplicity of a lumped model, while still being able to incorporate changing soil moisture heterogeneity.

Famiglietti and Wood [1990] and Famiglietti [1993], on the other hand, related soil moisture patterns to those of a surrogate, namely, the topographic index, $ln(a/tan\beta)$, of Beven and Kirkby [1979], which was then the basis for a distributed model (based on patterns of soil moisture), and a quasi-distributed numerical model (based on the pdf approach). While these models do not allow analytical solutions for the fluxes, Sivapalan *et al.* [1995b] proposed a variable bucket capacity model, which is also based on the topographic index $ln(a/tan\beta)$, but does permit analytical solutions.

- Heterogeneity of Rainfall

Heterogeneity of rainfall can have a significant impact on land surface energy and water balances at both short [Entekhabi and Eagleson, 1989; Liang, 1994; Sivapalan *et al.*, 1995b] and long [Sivapalan and Woods, 1995] time scales. Handling rainfall heterogeneity in MHM presents two main difficulties.

Firstly, the actual spatial distribution of rainfall within the grid cell for a particular event will never be available from the GCM. All that will be available is the GCM-generated rainfall for the previous time-step which is an average value for the entire grid-square (the so-called GCM drizzle). In view of the size of the GCM grid-square (e.g., 500 km x 500 km), the assumption of uniform rainfall across the grid-square will underestimate the volume of runoff, and consequently, will overestimate the land surface wetness [Sivapalan and Woods, 1995]. Therefore, most models use a probability distribution function approach which includes partial areal coverage [Thomas and Henderson-Sellers, 1991]. The parameters of this distribution may be estimated based on long-term climatic data.

Secondly, unlike in the WBM or FFM, the parameters of MHM are usually not estimated by "calibration", and it is not possible to absorb the effects of sub-grid rainfall heterogeneity into the model parameters. In other words, the effects of rainfall heterogeneity need to be explicitly modelled.

- Heterogeneity of Vegetation

Approaches to quantify vegetation heterogeneity include the use of parameters corresponding to the dominant vegetation only, and (areally weighted) average vegetation parameters. However, since the land surface responds non-linearly to the type of vegetation cover, both of the above approaches tend to be unsatisfactory [Avissar, 1995; Pitman, 1995]. Avissar and Pielke [1989] and Koster and Suarez [1992] suggested an alternative approach which divides the heterogeneous land surface into a "mosaic" of uniform vegetation "patches" to each of which a *big leaf* model is applied, which act in parallel, and respond to a common atmospheric boundary layer. A similar approach has been used for sub-catchments by Silberstein and Sivapalan [1995].

(v) Feedbacks with the Atmosphere

Changes in the surface energy exchange over large areas alter the atmosphere above, and the properties of the air which control surface evaporation. A feedback thus may occur to moderate the influence of changes in surface cover. In the case of FFM and WBM, the longer-term feedbacks between the atmosphere may still be important; however, these are partly included in the seasonal variations of atmospheric inputs such as the pan evaporation, and partly absorbed in the model calibration. The short-term, diurnal feedbacks, on the other hand, do not seem to be important enough to warrant explicit inclusion.

However, due to the small time scales associated with MHM, there is a need for explicit inclusion of such feedbacks. In addition, the spatial heterogeneities of soil moisture, rainfall, and vegetation, can trigger feedbacks between neighbouring, down-wind surfaces, in the form of small-scale advection, and may even cause meso-scale circulations in the presence of large-scale heterogeneities. While the small-scale advection effects may be parameterised using the approaches cited above [e.g., Koster and Suarez, 1992], the meso-scale circulations may need to be explicitly resolved [Avissar, 1995].

(vi) Soil Moisture Accounting

FFM, generally, do not explicitly account for soil moisture. For WBM, however, the soil moisture accounting scheme is the central point of the model. In the conceptual schemes used, most of the input and output fluxes to the catchment system are directly dependent on the level of soil moisture. In addition, long-term temporal trends in water balance dynamics, such as prolonged droughts, cannot be realistically modelled without a suitable soil moisture accounting scheme. In the case of the MHM, the soil moisture governs the temporal variation of the stomatal resistance which, in turn, controls the land surface energy balance.

The soil moisture accounting schemes used in WBM and MHM differ only in the level of complexity. Essentially, they consist of a number of soil moisture stores (or compartments), representing soil moisture in the hydrologic system in a lumped way. Typically, they include one store to represent the deep permanent groundwater aquifer, and one store to represent the unsaturated, near-surface zone. Some models include a near-stream saturated store to simulate the shallow, perched water table. The models then allocate the incoming rainfall to these stores through various pathways such as infiltration, deep percolation, subsurface stormflow and baseflow. Examples of such soil moisture accounting schemes can be found in many traditional WBM (e.g., HBV of Bergström; the Sacramento model used by Kitanidis and Bras, 1980; and LASCAM of Sivapalan et al., 1995].

The soil moisture accounting schemes in MHM, to date, have been relatively simple. Examples include the Manabe "bucket" bucket model [Manabe, 1969] discussed previously which uses a single leaky store. Some of the slightly more complex models are the VIC model of Wood et al. [1992], and the variable bucket capacity model of Sivapalan *et al.* [1995b] which are equivalent to using a distribution of bucket sizes, in which the runoff generation, evaporation and subsurface flow (base flow) are estimated as functions of the total volume of soil moisture in the bucket. Liang [1994] extended the VIC model to add a deeper soil moisture store. In this way, the longer-term variations of soil moisture could be modelled.

MODEL CALIBRATION, VALIDATION AND UPDATING

The WBM and FFM depend critically on "calibration" and "updating" for the estimation of their model parameters. Calibration or updating is performed on the basis of the observed runoff. Most WBM have routines within them that help estimate their unknown parameters by minimising, in some objective sense, the differences between the observed and model predicted runoff. Similarly, updating procedures have been developed which take into account the errors between the computed and observed runoff. Updating is important for increasing the accuracy of real-time flood forecasting, and should be included in all such models [WMO, 1992]. Four different approaches can be used: updating inputs, updating outputs, updating state variables and updating model parameters [Serban and Askew, 1991; Gutknecht, 1991].

The calibration or validation of MHM presents two main difficulties. Firstly, the models are intimately coupled to a GCM, and as a result it is difficult to separately validate or calibrate MHM. Secondly, calibration or validation is complicated by the fact that while the main output of MHM are estimates of sensible and latent heat fluxes, reliable measurements of these fluxes over large areas are not available at present. A series of large scale experiments are in

TABLE 3: HOW DIFFERENT MODEL TYPES CAN CONTRIBUTE TO EACH OTHER

MODEL TYPE	FLOOD FORECASTING MODELS (FFM)	WATER BALANCE MODELS (WBM)	MACROSCALE HYDROLOGICAL MODELS (MHM)
CONTRIBUTING CONCEPTS		(catchment; |→→→→→→	water balance) →→→→→→
		(quantifying ←←←←←←	heterogeneity) ←←←←←←|
		(process-based ←←←←←←←	models, e.g., BATS, SiB) ←←←←←←←|
COUPLING OF MODELS		(soil moisture |→→→→→→	accounting) →→→→→→
	(soil moisture ←←←←←←←	accounting) ←←←←←←|	
CONTRIBUTING DATASETS		(standard hydromet. |→→→→→→	datasets; runoff etc.) →→→→→→
	←←←←←←←	(new datasets - remote sensing, ←←←←←← ←←←←←←←←←←←←←←←	large-scale experiments) ←←←←←←| ←←←←←←|

progress in various parts of the world, as part of the Global Water and Energy Experiment (GEWEX) of the World Climate Research Programme (WCRP), to assemble short-period observations of land surface energy fluxes and long-term rainfall-runoff data, with a view to validating MHM. These include projects such as GCIP in the Mississippi river basin [WMO, 1992], and GAME in the monsoon regions of Asia and Australia [Yasunari, 1994].

HOW EACH MODEL TYPE CAN CONTRIBUTE TO THE IMPROVEMENT OF OTHERS

FFM and WBM models have been used by hydrologists for a long time, and there is a wealth of experience and expertise in using these. MHM are relatively new. Therefore, there are opportunities for each modelling type to contribute towards the improvement of the others. These are discussed below, along with related research questions (also see Table 3). The discussion is organised under the headings of: (i) exchange of concepts, (ii) coupling of models, and (iii) exchange of data.

(i) Contributing Concepts

WBM towards MHM: Catchment and Water Balance Concepts

Utilising the concepts of a catchment and water balance offers two opportunities for improving MHM. Firstly, if catchments are used, runoff data can be used as an additional means for validating the models.

Secondly, the physical realism of climate models, especially the ability to simulate systematic long-term variations, will be significantly enhanced if the concept of water balance can be integrated naturally with MHM. This can only be achieved if the MHM can use catchment organisation. Algorithms which allow the transformation of land surface properties and state variables between sub-catchments and a rectangular grid are needed to facilitate such an integration.

MHM towards WBM: Quantifying Heterogeneity

While spatial heterogeneity is represented in a lumped way in WBM, it is represented explicitly in MHM. Clearly, the latter are more process-oriented. The process concepts used therefore offer an opportunity for improving the physical basis of traditional conceptual schemes used in WBM.

MHM towards WBM: Better Models of Evapotranspiration

Similarly, the representation of evapotranspiration used in MHM can improve those used in WBM. This seems particularly important for applications such as predicting the effects of land use changes. The evapotranspiration model components in MHM are more advanced in terms of their physical realism (e.g., BATS, SiB). These are continually being improved with increased understanding of the process in a variety of environments.

(ii) Coupling of Models

WBM towards MHM and FFM: soil moisture accounting schemes

Some form of soil moisture accounting is needed in MHM since soil moisture significantly influences the partitioning of available radiant energy into latent and sensible heat fluxes through its control of evapotranspiration. Similarly, soil moisture accounting can improve the accuracy of long lead time forecasts of FFM in large catchments.

Since soil moisture accounting is the central issue in WBM, the latter can be coupled to FFM or MHM, and used as the main soil moisture accounting scheme. The response of soil moisture, generally, is slower than the primary processes of runoff (in FFM) and surface energy fluxes (in MHM). This means that the soil moisture accounting can be performed at coarser time scales than are necessary to model the primary processes of FFM and MHM. This is what makes the WBM a natural soil moisture accounting component for both FFM and WBM.

(iii) Contributing Data

WBM towards MHM: model validation using standard hydrological data networks

WBM are usually calibrated using all available runoff data within large catchments. They also incorporate the effects of land use changes that have occurred within the catchment. Therefore, the use of WBM, as the soil moisture component in MHM, naturally allows the use of both long-term runoff and information on land use history. This is significant not only because runoff is the only available spatially-integrated measure of hydrologic response, but also because it enhances the ability of the MHM to handle or simulate natural long-term trends in climate and water balance. This is important for confidence to be placed in climate model predictions.

In addition, in various parts of the world, there is a wealth of hydrological data, and much insight has been gained from systematic analysis of such data over long periods of time, in some cases longer than 100 years. An example is the Danube River Basin [e.g., Stancik and Jovanovic *et al.*, 1988; Behr, 1991]. These data sets can be extremely valuable for a diagnostic check on joint MHM/GCM predictions as they provide realistic large-scale patterns in space and time.

MHM towards WBM and FFM:
model development/validation using data from remote sensing and from large scale field experiments

Both WBM and FFM can benefit from the significant advances that are being made in measurement technology in general, and remote sensing technology in particular, as part of the general push towards improvements of MHM. These especially include remotely sensed information on vegetation cover, soil moisture and precipitation (ISLSCP, ERS1 etc.), and similar data sets obtained through large scale field experiments (ISLCP, GEWEX etc.). While, these are designed to help develop and validate MHM, they have the potential to provide spatial datasets for improving process representations in WBM and FFM as well.

CONCLUSIONS

In this overview paper we presented a discussion of the characteristics and limitations of three types of large scale hydrological models, namely flood forecasting models, water balance models and macroscale hydrological models.

The models differ substantially in terms of the main modelling concept, and in terms of model time scales (both resolution and extent). The differences in the time scales have a significant influence on the process representations used. Different parameterisations may be used to describe the same process in different models. In general, the parameterisations tend to increase in complexity, from empirical (in flood forecasting models), to conceptual (in water balance models), and to more process-based (in macroscale hydrological models).

Spatial heterogeneities of, for example, soil moisture, rainfall, and vegetation cover (both vertical and horizontal), are particulary important in macroscale hydrological models, and need to be incorporated, either explicitly or implicitly. These are much less important in water balance models and in flood forecasting models, as they are usually absorbed in the model parameters. However, research to date on the effects of heterogeneities in MHMs have tended to treat each heterogeneity in isolation, e.g., vertical heterogeneity of vegetation separate from horizontal heterogeneity, vegetation heterogeneity separate from soil moisture heterogeneity etc. Substantial effort is required to combine these effects in a single model which combines physical realism, simplicity and parameter efficiency.

Finally, the paper discusses opportunities for each model type to contribute to the improvement of others. These were organised under the headings of contributing concepts, coupling of models and contributing data resources.

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