RECENT DEVELOPMENTS IN HYDROSYSTEMS

by

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BACKGROUND

It is truly an honor to be invited as the keynote speaker for the Annual Specialty Conference of the Korean Society of Hydrological Sciences. I would like to thank Drs. Joong Hoon Kim and Yong Nam Yoon of Korea University, Dr. Eun-Tae Lee of Kyung Hee University, the Korea Science and Engineering Foundation, Korea University, the Korean Society of Hydrological Sciences, and others else that are responsible for me being here.

Hydrosystems is a term originally coined by Ven T. Chow to collectively describe the technical areas of hydrology, hydraulics, and water resources, and their interaction with other technical, social and economic factors. Hydrosystems has also been a term used for reference to various types of water projects or systems. My use of the term applies to both definitions (Mays and Tung, 1992). For the purposes of this talk I will concentrate on what I refer to as hydrosystems to include hydrological sciences and water resources.

During the last six decades "the evolution of hydrologic science has been in the direction of ever-increasing space and time scales, from small catchment to large river basins to the earth system, and from storm event to seasonal cycle to climatic trend" (National Research Council (NRC), 1991). The recent NRC study by the Committee on Opportunities in the Hydrologic Sciences state that, "**hydroscience** should be viewed as a geoscience interactive on a wide range of space and time scales with the ocean, atmosphere, and solid earth sciences as well as with plant and animal sciences." This interaction is illustrated in Figure 1.

The United Nations sponsored the International Hydrologic Decade from 1965 to 1974 as a result of the need for international cooperation to effectively use transnational water resources and for broad-scale international cooperation to acquire hydrologic data. A primary benefit of this program was to raise the consciousness of mankind about the regional- and global-scale problems and about the human impact on the hydrologic cycle (Figure 2). The realization of the human impact has evolved into contemporary views of the interactive role of man in the hydrologic cycle as shown in Figure 3. Human activity has become an integral and inseparable part of the hydrologic cycle. The quality of water as it moves through the hydrologic cycle is as important as the quantity, and, in fact the quality of water can influence important quantitative fluxes of the hydrologic cycle (NRC, 1991).

ADVANCES IN RESEARCH AND DEVELOPMENT

I will attempt to define advances in hydrologic (and hydrosystems) research that has helped to advance our field. The areas that I have chosen to cover include:

- Data Collection Systems
- Optimal Control of Hydrosystems
- Global Climate Change:Hydrologic Response
- Operation of River-Reservoir Systems
- Decision Support Systems and GIS

Data Collection Systems

As very well pointed out in the NRC study, "advances in the hydrologic sciences depend on how well investigators can integrate reliable, large-scale, long-term data sets." The sequence of steps commonly followed for hydrologic measurement, for either time series or space series data is shown in Figure 4. A rapidly developing area is the real-time transmission of data through microwave networks, satellites, or telephone lines.

Urban hydrology monitoring systems such as the one illustrated in Figure 5 are used by the U.S. Geological survey for urban stormwater investigation. This system is used to collect storm rainfall and runoff quantity and quality data. The system is specifically designed for flow gaging in underground storm sewers.

Real-time data collection and transmission can be used for flood forecasting on large river-lake systems as shown in Figure 6 for the lower Colorado River in Texas. This system is referred to as a Hydrometeorological Data Acquisition System and provides both water surface elevations and rainfall from a rain gage network.

Flood early warning systems for urban areas such as shown in Figure 7 are real-time event reporting systems that consist of remote gaging sites with radio repeater sites to transmit information to a base station. The overall system is used to collect, transport, and analyze data, and make a flood forecast in order to maximize the warning time for occupants in the flood plain.

The use of radar for precipitation measurement provides the advantage of large areal coverage with high spatial and temporal resolution. Radar can provide rainfall estimates for 5 minute increments and a spatial resolution as small as 1 km^2. Systems of weather radars used for precipitation estimation are either active or planned in the U.S., England, continental Europe and Japan.

In the U.S. the **Next Generation Weather Radar** system (NEXRAD) consists of 120 high-quality radars that will be deployed by 1996. These NEXRAD systems are termed WSR-88D, in which WSR denotes weather surveillance radar and D denotes Doppler. Figure 8 shows the principal components of the NEXRAD system. Each WSR-88D system has a 10 cm radar data acquisition unit as the centerpiece along with a computer processing system for converting radar data to meteorological products and a graphical display system.

The use of remote sensing to applications in hydrology are relatively new but are rapidly becoming an important source of information. Remote sensing uses measurements of the electromagnetic spectrum to characterize the landscape or to interpret properties of the landscape. Basically, remote sensing data are used as a substitute for land cover maps obtained by conventional means. Modern remote sensing is centered around satellite systems which include major commercial satellites, the U.S. NASA Landsat and TM series, the U.S. NOAA satellites, and the French SPOT satellites (Engman, 1993). As an example of the use of remote sensing data, Landsat data have been used to replace conventional land-use data in the SCS curve number procedure, to derive flood frequency parameters, to delineate or map flood plains and areas inundated by floods. A future task will be to merge remote sensing with Geographical Information Systems (GIS). In the U.S. Army Corps of Engineers, Hydrologic Engineering Center, has begun work in this area.

Global Climate Change: Hydrologic Response

Another one of the critical and emerging areas of hydrology is to understand the earth system. Toward this goal, we need to better understand the connection between hydrology processes and the other earth processes. Of particular interest in the past few years is to improve our understanding of the interaction between the hydrologic cycle and the general circulation of the ocean-atmosphere system. Operational tools in these types of studies are the **atmospheric general circulation models** (GCMs) that are being developed to reproduce the basic patterns and processes of atmospheric systems. Climate variables (i.e. precipitation and temperature) are reasonably well simulated by GCM's for broad spatial scales (global, zonal, or continental) and for annual or seasonal temporal scales (Grotch, 1988, U.S. EPA, 1989, 1991). GCM performance is rather poor, however, on regional or local spatial scales and monthly or daily temporal scales (Schlesinger and Mitchell, 1987; Mearns, et al., 1990, Grotch and MacCracken, 1991). This results from the large resolution, on the order of several hundred kilometers, for most current GCMs used for climate studies.

Landscape-scale hydrological models (LSHMs) can be used to evaluate the sensitivity of hydrologic systems to climate change by simulating land-atmosphere interaction on spatial scales of lake basins and watersheds. LSHMs have been used in a one-way coupling with GCMs to investigate the sensitivity of hydrologic systems to climate change (e.g. Gleick, 1987, 1989; McCabe and Ayers, 1989; U.S. EPA, 1989; Crowley, 1990; Lettenmaier and Gan, 1990). Large differences in scale between the models result in poor simulation of daily or monthly streamflow of basins.

More recently **regional climate models** (RCMs) have been developed that have resolutions on the order of tens of kilometers, or less, over selected watersheads or basins (Dickinson, et al. 1986; Giorgi and Bates, 1989; Giorgi, 1990; Giorgi and Mearns, 1991, Hostetles and Giorgi, 1992, 1993; Giorgi et al, 1993). This resolution is much closer to that of the LSHMs and allows for both one and two-way coupling of RCMs and LSHMs. Future research needs to continue to improve (increase) the resolution of RCMs and to improve the interactive coupling of LSHMs and RCMs.

Optimal Control of Hydrosystems

Over the past two decades there have been many applications of optimization methods to hydrosystems problems. However, the actual use of optimization to solve these problems in practice has been rather limited. There are many reasons for this which is beyond the scope of this presentation. One of the reasons, however, is because of the required simplification of the hydrology and hydraulics of the problems that have been required to solve the hydrosystems problems. On the other hand simulation models have received wide acceptance in the hydrosystem field. During the past five to ten years there have been significant advances in using an **optimal control framework** to interface the use of optimization and simulation to solves these problems.

Many problems for the operation of hydrosystems can be formulated in a general optimization framework in terms of state (or dependent) variables (x) and control (or independent) variables (u)

$$\text{Minimize } f(x, u) \tag{1}$$

subject to process simulation equations

$$G(x, u) = 0 \tag{2}$$

and additional constraints for operation on the dependent (u) and independent (x) variables

$$\underline{w} \geq w(x,u) \leq \overline{w} \tag{3}$$

The process simulation equations for hydrosystems applications basically consist of the governing physical equations (2) that simulate a physical process such as conservation of mass, energy and momentum. These equations are typically large in number, sparse and nonlinear in terms of the state and control variables. In most hydrosystem applications, these governing equations are ordinary or partial differential equations. Conceptually, the simplest approach is to have the optimizer directly solve the above optimization problem by embedding finite differences or finite element equations for the governing process equations. Unfortunately, many of the real-world problems cannot be solved in this manner as a result of their size and nonlinearity.

An alternative approach is to use the appropriate process simulator to solve the constraint process simulation equations (2) each time the constraints need to be evaluated for the optimizer. The major advantage of such an approach is the reduced size of problem seen by the nonlinear optimizer so that only a small subset of the complete set of constraint equations is evaluated by the optimizer.

This class of problems typically have differential equations as part of the constraint set (process simulation equation) making them more complex than the standard type of optimization problem. These optimization problems are referred to as optimal control problems. Recent applications have been made to systems such as groundwater quantity management systems (Wanakule, et al, 1986), river-reservoir systems for flood control (Unver and Mays, 1990), water distribution systems operation (Brion and Mays, 1992), estuary systems for salinity control (Bao and Mays, 1993, a,b), and groundwater remediation (Culver and Shoemaker, 1992).

Operation of Reservoir - River Systems

There have been recent developments and new models for the operation of reservoir and river systems. Both long-term, real-time and forecasting models have been developed. Real-time reservoir operation involves the operation of a reservoir system by making decisions on reservoir releases as information becomes available, with relatively short time intervals which may vary between several minutes to several hours. Real-time operation of multireservoir systems involves various hydrologic, hydraulic, operational, technical, and institutional considerations. In order to make operation decisions for flood control systems in real-time, the operations involved are the decisions on releases from the reservoir(s) in order to control flood waters. For efficient operation, a monitoring system is essential that provides the reservoir operator with the flows and water levels at various points in the river system including upstream extremities, tributaries and major creeks as well as reservoir levels, and precipitation data for the watersheds whose outputs (runoff from rainfall) are not gaged. Many river-reservoir systems in the U.S. and elsewhere in the world now have real-time data collection and transmission systems.

One model developed by Unver et al. (1987) is for real-time operation of the Lower Colorado River - Highland Lakes system in Texas. The overall model structure is shown in Figure 9. Real-time data are input to the model from the data collection network. The **real-time flood control module** includes the following submodule: (1) a DWOPER submodule, that is, the U.S. National Weather Service Dynamic Wave Operational model for unsteady flow routing; (2) a GATES submodule, which determines gate operation information (internal boundary conditions) for DWOPER, such as the gate discharge as a function of the head on the gate; (3) a RAINFALL-RUNOFF submodule which is a rainfall-runoff model based upon the unit hydrograph approach for the ungaged drainage area surrounding the lakes for which stream flow data is not available; (4) a DISPLAY submodule, which contains graphical display software; and (5) an OPERATIONS submodule which is the user-control software that interactively operates the other submodules and data files. The input for this flood forecasting model includes both the real-time data and the physical description of system components that remain unchanged during a flood.

The U.S. Army Corps of Engineers Hydrologic Engineering Center (HEC) is presently developing a generalized **prescriptive reservoir model** referred to as HECPRM. The primary goal of this model is to develop new reservoir system operation rules for monthly operation to improve existing operation and to accommodate new uses. This model utilizes network flow programming to represent a reservoir system as a link-node network. As shown in Figure 10, this model utilizes the HEC-DSS data storage system and utility program, DSPLAY for graphical display system, and DSSUTL and MATHPK.

Decision Support Systems and GIS

I would like to briefly discuss some fairly new concepts and technologies that are rapidly finding their way into the hydrosciences field. These include **geographic information systems** (GIS), **decision support systems** (DSS), and **spatial decision support systems** (SDSS). GIS consists of computer-based programs containing specialized algorithms and associated data-base management structures which are frequently integrated into a package. These systems are designed to store information about the location, topology, and attributes of spatially referenced objects, such as rivers, wetlands, and political boundaries and roads. GIS can also provide analyses of the spatial properties such as length, area, and perimeter of these geographic objects.

GIS has recently been linked with hydrologic models (Ross and Tara, 1993), urban storm water models (Meyer, et al., 1993) and flow models for wellhead protection (Baker, et al., 1993). An example of the hydrologic model linkage is shown in Figure 11 which utilizes four principle components: a GIS; the surface runoff model, HSPF; the groundwater model, MODFLOW; and an evaporation-transpiration code, ET. HSPF calculates surface-water runoff and rainfall losses, above-water table storages, and groundwater recharge. Others (Shea, et al., 1993) have linked the well known U.S. Army Corps of Engineers HEC-1 and HEC-2 programs with GIS. The groundwater code calculates water budget and flow conditions for the water-table aquifer, base flow to streams and potentiometric heads below confirming layers. The ET code computes daily potential evapo-transpiration losses based on daily temperature, land use and available soil moisture conditions. This particular model is capable of both event (storm) hydrologic simulation and continuous (seasonal) hydrologic simulation. Figure 12 illustrates the linkage of GIS to the spatially distributed urban runnoff model RUNOFF for urban storm-water management.

There have been many recent advances in integrating hydrologic models, databases and decision-support functions. Figure 13a illustrates the traditional use of models in which the user had to be an expert and the user became an intermediary between the decision maker and the decision making tool. Figure 13b shows a major departure from the traditional process. Rather than placing the expert in the middle of the process, **advanced decision support systems (ADSS),** linkages blend the key tools (database, simulation model, and decision support systems) into an integrated package (Chapra, et al., 1993). Decision support systems contain the analysis and decision making algorithms needed to support the decision process, i.e., optimization and/or statistical tools. ADSS also includes graphical user interfaces consisting of pre and post processors. The new trend is to make use of object-oriented programming as opposed to earlier modeling systems that relied on algorithmic languages such as FORTRAN.

The newest concepts in this area are the **spatial decision support systems** (SDSS) which combine the technologies of GIS and DSS to aid decision makers with problems that have a spatial dimension. The spatial analysis and display capability of GIS can improve each component of DSS and facilitated the evolution of DSS to SDSS. Figure 14 is a representation of the combining of GIS and DSS into the SDSS (Walsh, 1993). One of the most challenging aspects is that SDSS requires a cross-discipline collaboration to solve the complexities of integrating these technologies.

SCIENTIFIC RESEARCH PRIORITIES IN HYDROLOGIC SCIENCES

NRC Study

The Committee on Opportunities in Hydrologic Sciences of the NRC (1991) developed priority categories of scientific opportunity under the premises that "(1) the largest potential for such contribution lies at the least explored scales and in making the linkages across scales, and (2) hydrologic science is currently data-limited. The unranked research areas of highest priority are:

- Chemical and biological components of the hydrologic cycle
- Scaling of dynamic behavior
- Land surface-atmosphere interaction
- Coordinated global-scale observation of water reservoirs and the fluxes of water and energy
- Hydrologic effects of human activity.

The research area of **chemical and biological components of the hydrologic cycle** includes:

- understanding the interactions between ecosystems and the hydrologic cycle;
- understanding the pathways of water through soil and rock through the use of aqueous geochemistry to reveal the historical states for climate research and to reconstruct the *erosional* history of continents;

- and combining efforts in aquatic chemistry, microbiology and physics of flow to reveal solute transformation, biochemical functioning, and the mechanism for both contamination and purification of soils and water.

Scaling of dynamic behavior involves research:

- to quantify predictions of large-scale hydrologic processes under the three-dimensional heterogeneity of natural systems which are orders of magnitude larger in scale than idealized one-dimensional laboratory conditions and

- to quantify the inverse problem by disaggregating conditions at large scale to obtain small information, e.g. in the parameterization of subgrid-scale processes in climate models;

Understanding **land surface-atmosphere interactions** has become somewhat *urgent* because of the accelerating human-induced changes in land surface characteristics globally on issues ranging from the mesoscale upward to continental scales. A better understanding of the following are needed:

- our knowledge of the time and space distribution of rainfall, soil moisture, groundwater recharge, and evapotranspiration;

- and knowledge of the variability and sensitivity of local and regional climates to alterations in land surface properties.

Coordinated global-scale observation of water reservoir and the fluxes of water and energy is needed for a better understanding of the state and variability of the global water balance. Two programs that will help in this effort are:

- the World Climate Data Program (WCDP) to assemble historical and current data and

- the World Climate Research Program (WCRP) is planning a global experimental program to place future observations on a sound and coordinated effort called the Global Energy and Water Cycle Experiment (GEWEX).

Hydrologic effects of human activity research should focus on the quantitative forecasts of anthropogenic hydrologic change which is largely indistinguishable from the temporal variability of the natural system.

Data requirements for the above research priorities include:

- Maintenance of continuous long-term data sets
- Improved information management
- Interpretation of remote sensing data
- Dissemination of data from multidisciplinary experiments.

GEWEX Program (excerpt from NRC, 1991)

The **Global Energy and Water Cycle Experiment** (GEWEX), proposed to begin in the late 1990s, is designed to verify large-scale hydrologic models and to validate global-scale satellite observations. This initiative of the World Climate Research Program addresses four scientific objectives:

1. Determine water and energy fluxes by global measurements of observable atmospheric and surface properties;
2. Model the hydrologic cycle and its effects on the atmosphere and ocean;
3. Develop the ability to predict variations of global and regional hydrologic processes and water resources and their response to environmental change; and
4. Foster the development of observing techniques, and data management and assimilation systems suitable for operational applications to long-range weather forecasting and to hydrologic and climatic predictions.

A central goal of the GEWEX program is to develop and improve modeling of hydrologic processes, and to integrate surface and ground water processes on the catchment scale into fully interactive global land-atmosphere models. Inadequate representation of hydrology is a major weakness in present climate models. For example, a radical improvement is needed in the treatment of evapotranspiration, which dominates water and heat fluxes from the land surface.

The GEWEX program plans to support hydrologic modeling of continental-scale river catchments encompassing a diversity of terrain and climate conditions. The GEWEX field experiment program would systematically test these models on selected river basins for a minimum of five years, in order to provide the opportunity to compare detailed performances of alternative models under realistic conditions, to ascertain their sensitivity to different estimates of forcing fluxes, and to determine their agreement with observations. The experimental areas must be large enough that the hydrologic processes that contribute to global climate models and large-scale meteorological processes are apparent. The areas should encompass a wide range of soil moisture conditions, vegetation types, and surface topographies. Candidates would include the major river basins of the continents, for example, the basins of the Mississippi, Nile, and Amazon.

Needed Instrumentation

The International Association of Hydraulic Research (IAHR) is concerned with the development, use and maintenance of instrumentation used to evaluate water resources. These need tremendous improvement in developing nations. IAHR (1993) feels that particular efforts are needed to develop instruments for:

- Velocities and discharge in rivers, especially in extreme situations (flash floods, low flows, flows on flood plains).
- Shear stress, there are no instruments or methods available for measuring the distribution of shear stress in an alluvial river.
- Discharges in groundwater flows and storage estimates of aquifers.
- Behavior of flood waves.
- Rain samplers, development of a rain sampler which correctly samples rain during periods of heavy rain accompanied by stormy winds. The motion of the air and the airborne water drops around the sampler also have to be adequately modelled.

Because high-tech solutions developed in industrialized countries are not always appropriate for developing countries, there is a need for **adapted technology of instruments.** In other words, developing countries need robust and low-price instruments that are easy to operate and repair.

SUMMARY

I have briefly described some of the important advances in hydrosystems and to remark on the important scientific research priorities in hydrological sciences. We have concentrated on data collection systems, real-time control of hydrosystems, global climate change and decision support systems and GIS.

In summary, I would like to stress the following points:

- the advances in data collection systems, advanced methodologies for interfacing hydrologic, hydraulic, and optimization models through optimal control approaches; and the advances in decision support systems and GIS will allow the interfacing of all these technologies into some sophisticated and much needed tools for operating hydrosystems;

- the ability to better understand the hydrologic processes and their relationships to other earth processes is important to understanding and modelling of the hydrologic cycle and its interactions with the ocean-atmosphere system;

- and the solution to a better understanding of hydrologic sciences needs to be an international effort such as the GEWEX program briefly discussed above.

I would like to thank each of you for listening to my lecture and to once again thank those responsible for me being here today. Thank you.

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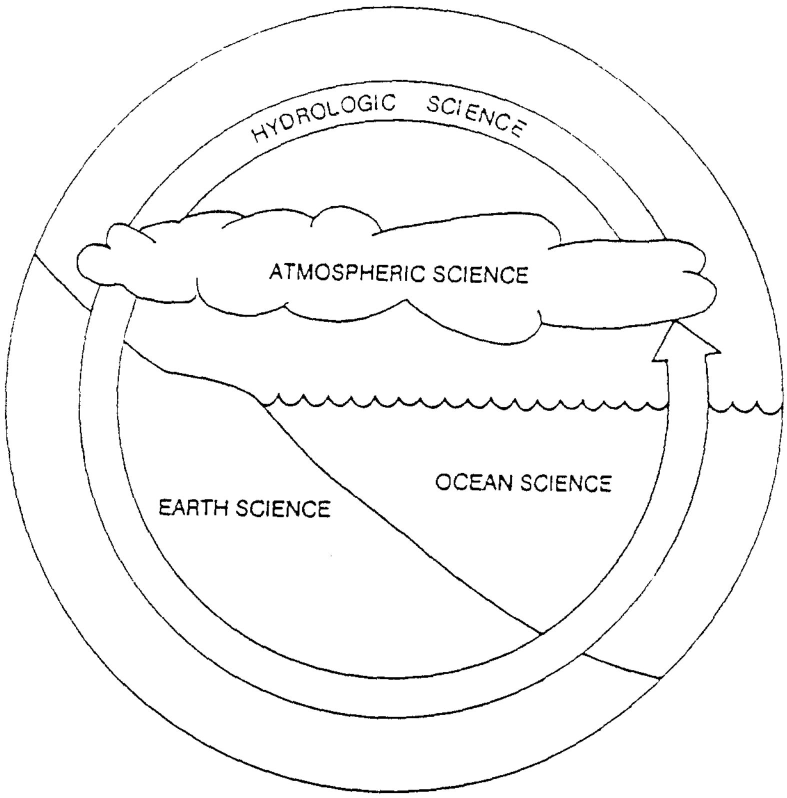


Figure 1. Hydrologic science is a geoscience. (NRC, 1991)

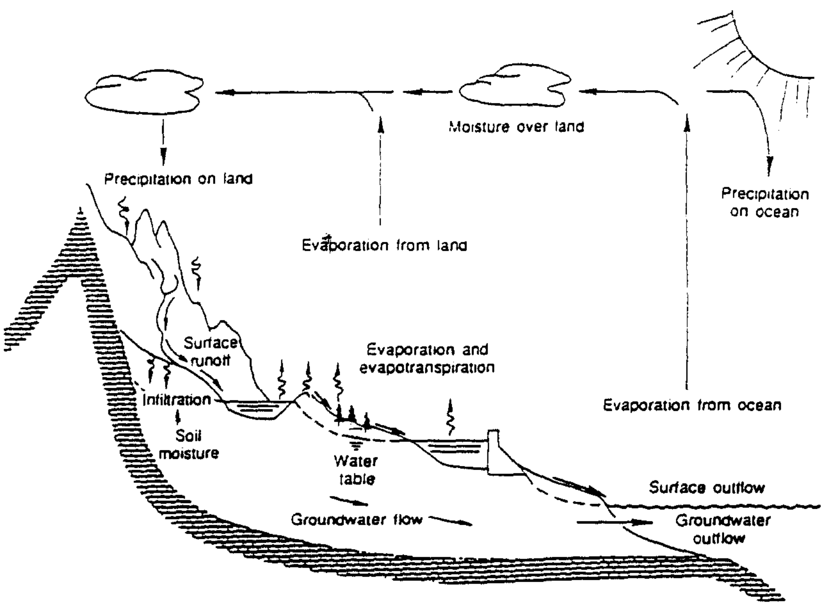


Figure 2. Elements of the hydrologic cycle. (Chow et al. (1988)

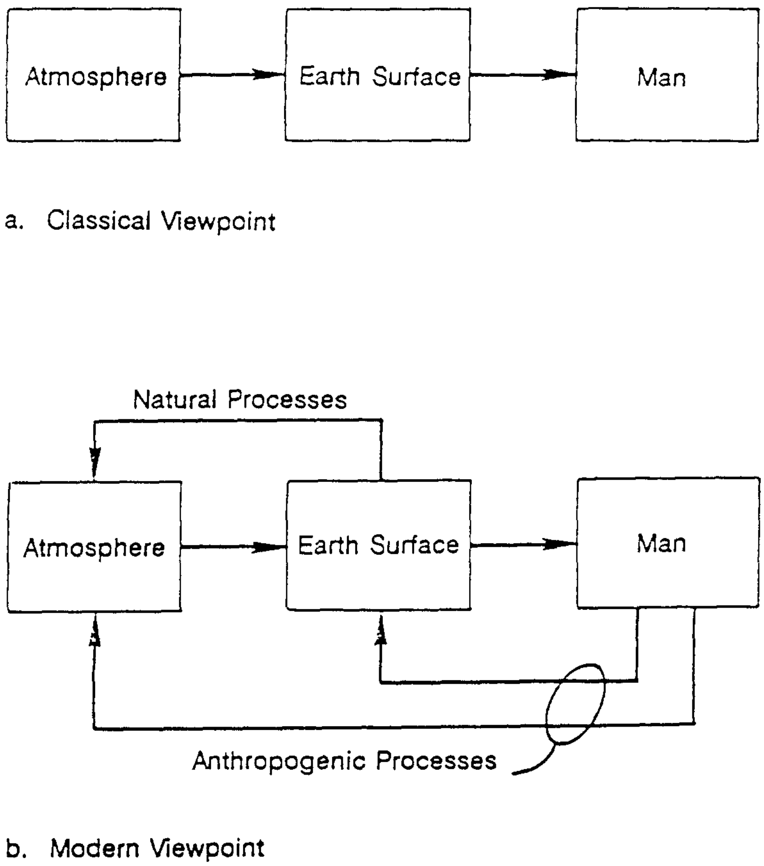


Figure 3. The role of man in the hydrologic cycle. (National Research Council (1982).

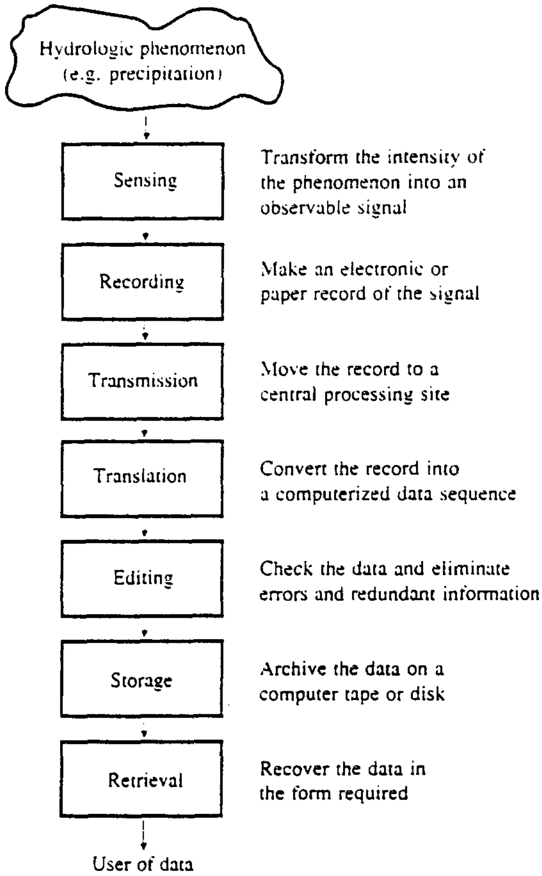


Figure 4. The hydrologic measurement sequence. (Chow, et al. 1988)

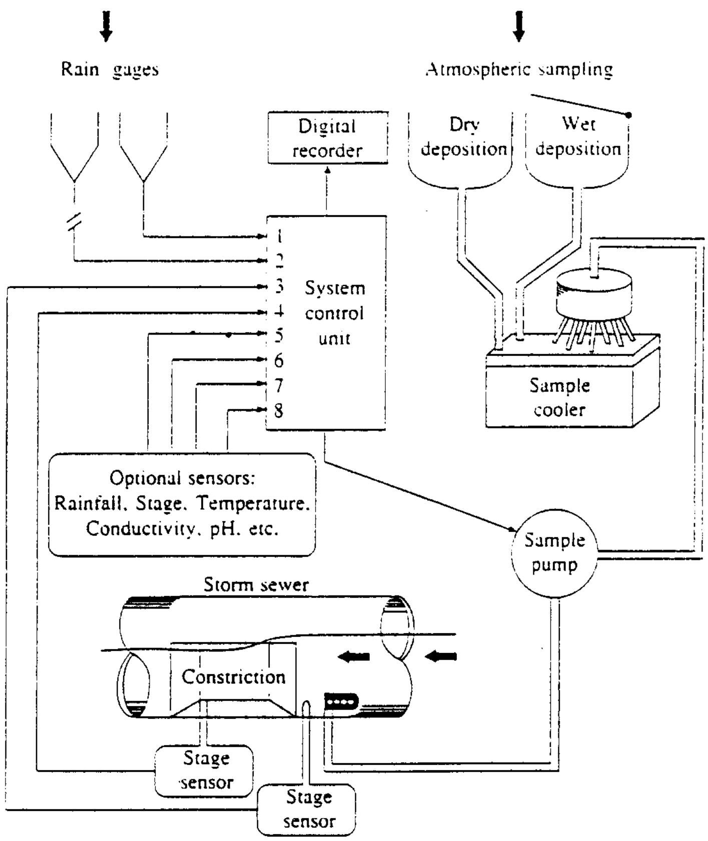


Figure 5. Typical installation of a U. S. Geological Survey urban hydrology monitoring system. (Jennings, 1982)

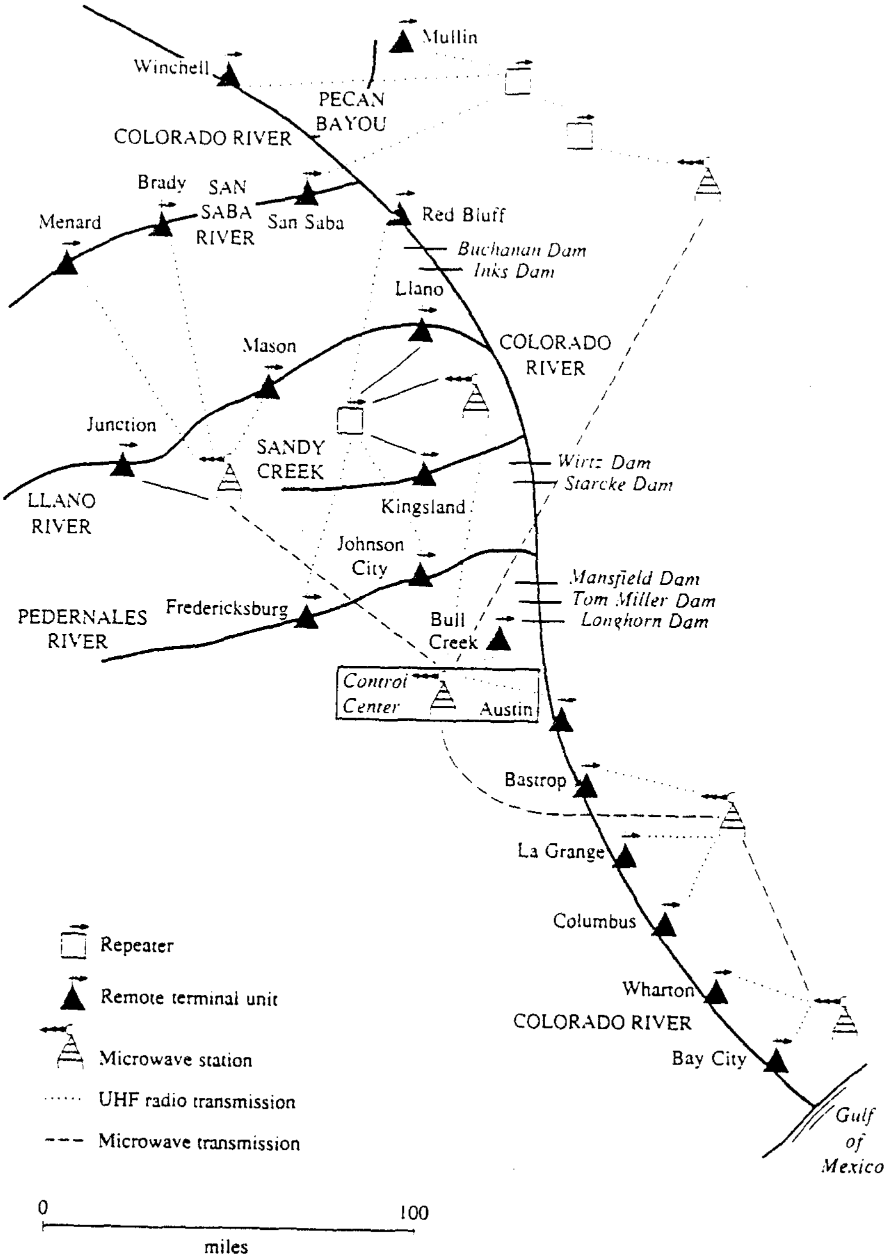


Figure 6. Real-time data transmission network on the lower Colorado River, Texas. Water level and rainfall data are automatically transmitted to the control center in Austin every 3 hours to guide releases from the dams. During floods data are updated every 15 minutes.

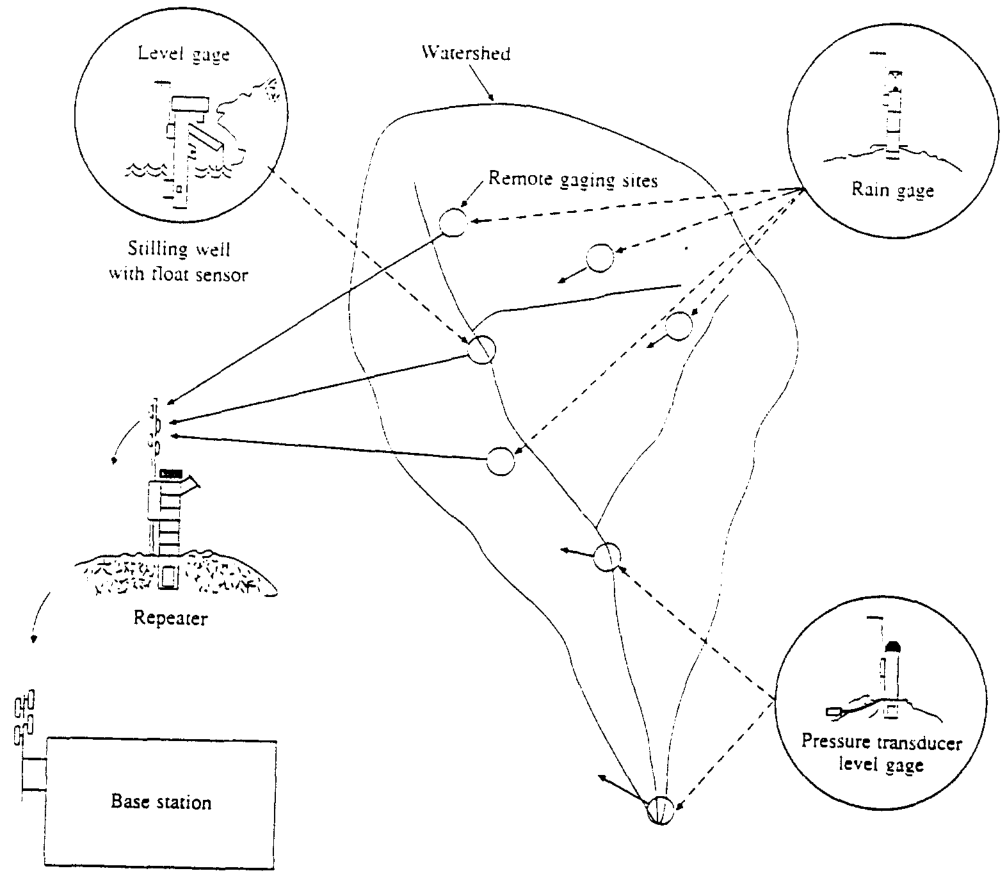


Figure 7. Example of a flood early warning system for urban areas.

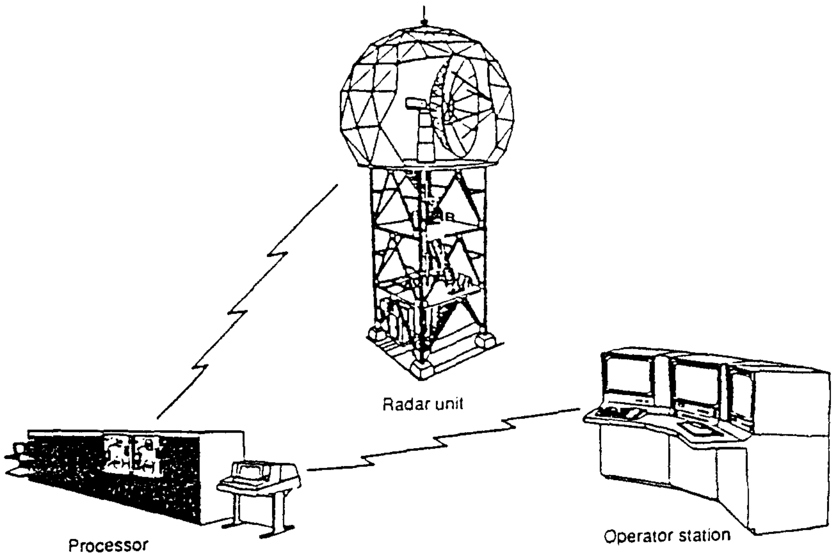


Figure 8. Schematic illustration of a WSR-88D (NEXRAD) system. (Smith, 1993)

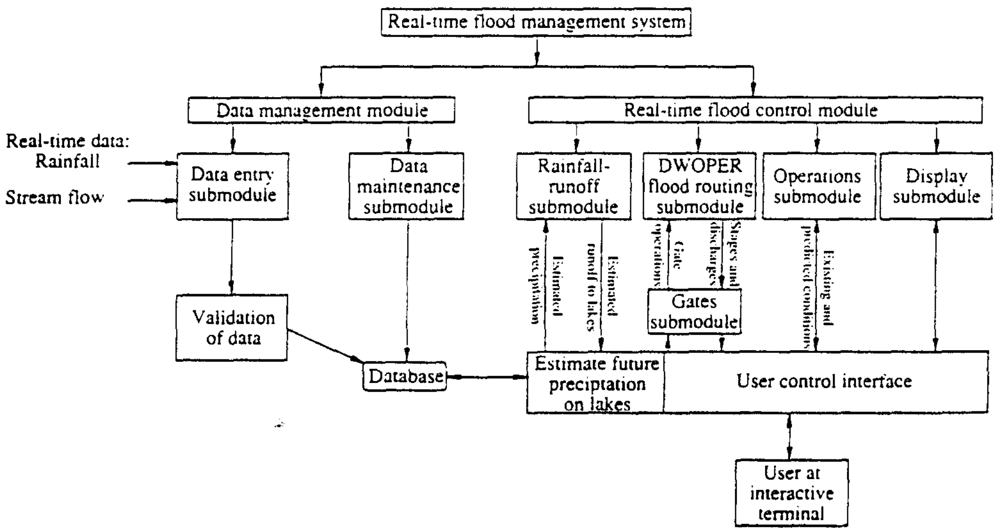


Figure 9. Structure of real-time flood management model. This model is used by the Lower Colorado River Authority to manage the river-lake system. (Unver, Mays, and Lansey, 1987).

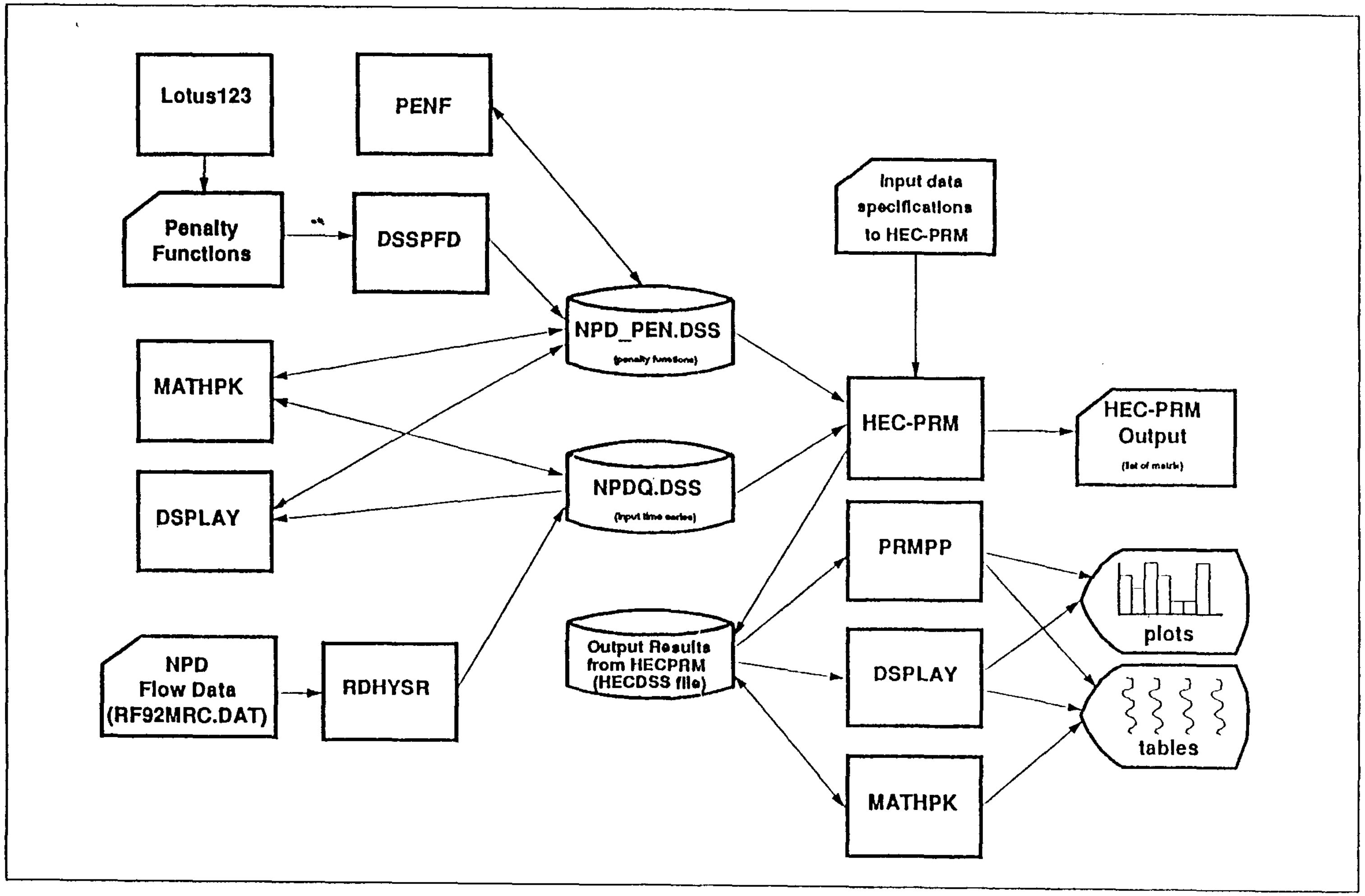


Figure 10. U.S. Army Corps of Engineers, Hydrologic Engineering Center Prescriptive Reservoir Model (HEC-PRM) (Carl, 1993)

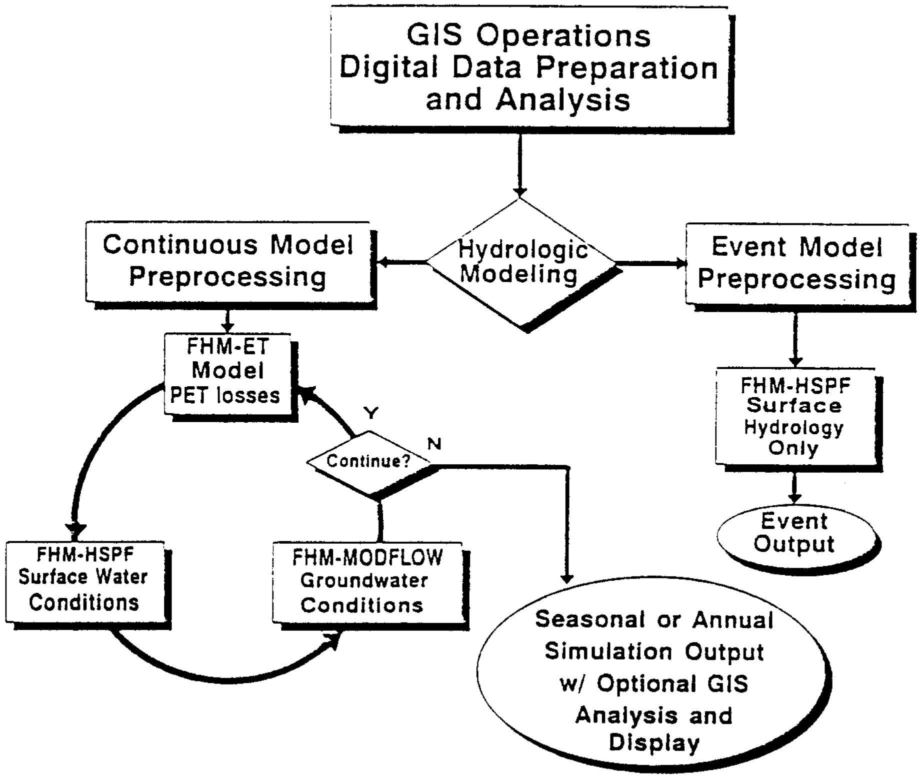


Figure 11. Schematic of FHM Components and Operation (Ross and Tara, 1993).

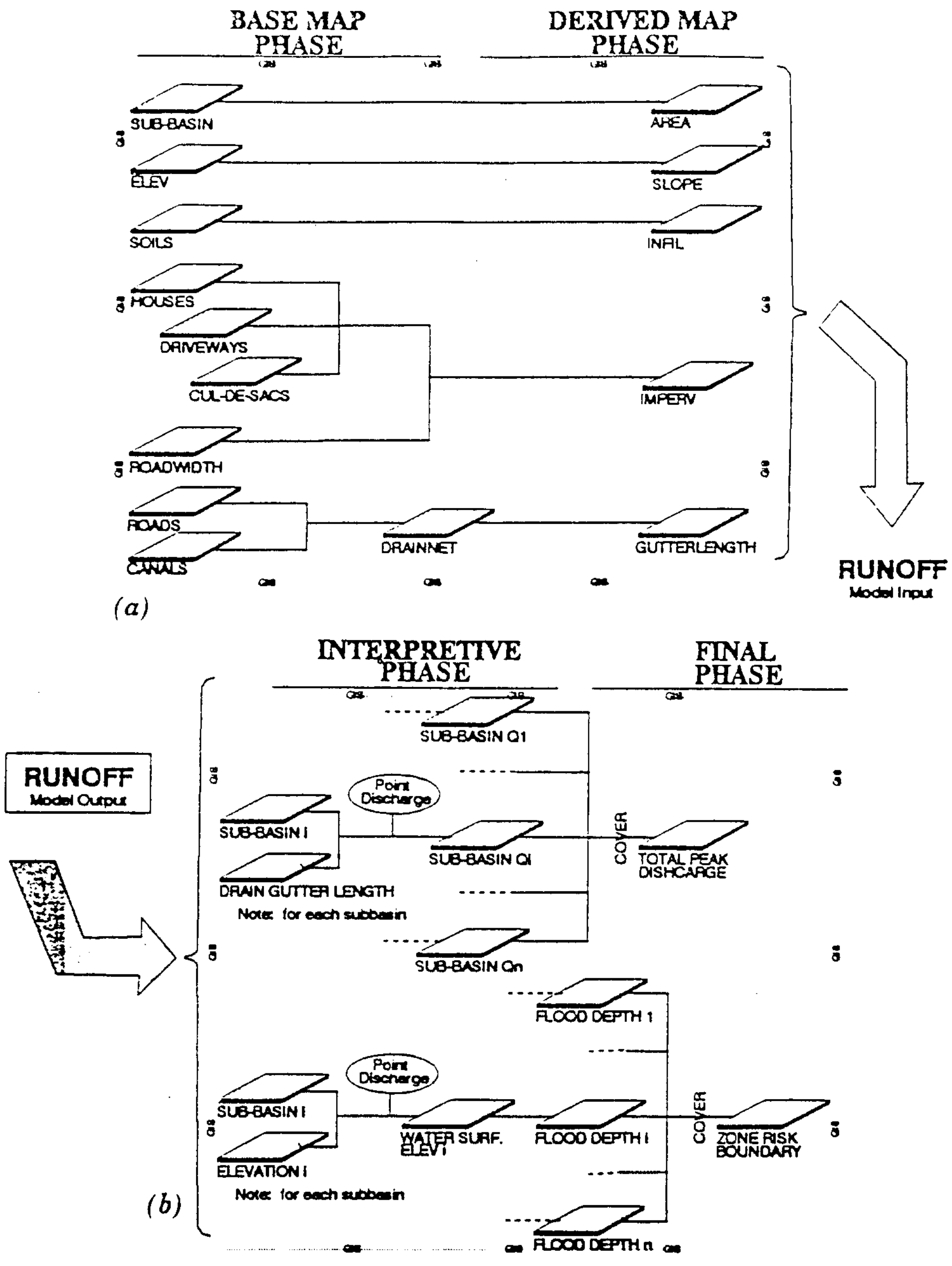


Figure 12. (a) Procedure for GIS/Urban Runoff Model Linkage; (b) Procedure for GIS/Urban Runoff Model Linkage (Meyer, et al. 1993).

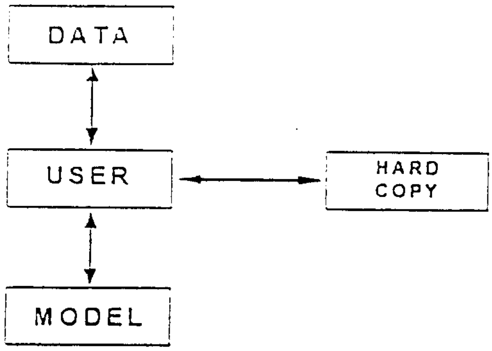


Figure 13a. Traditional water-quality modeling placed the user at the center of the model development/ application process. (Chapra, et al., 1993)

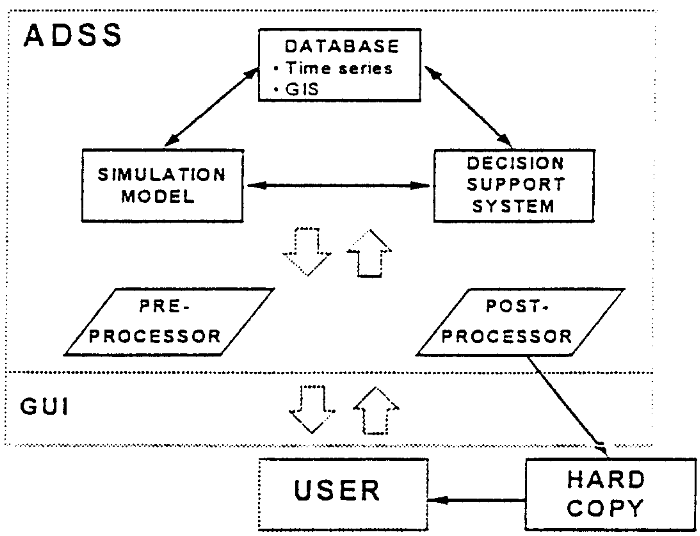
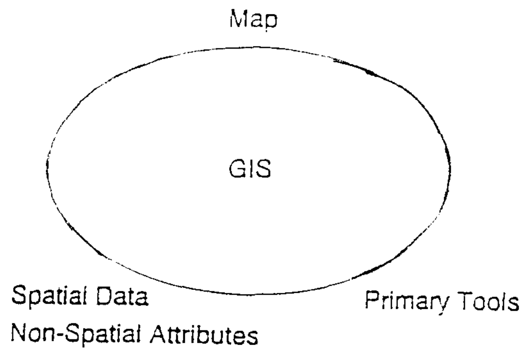
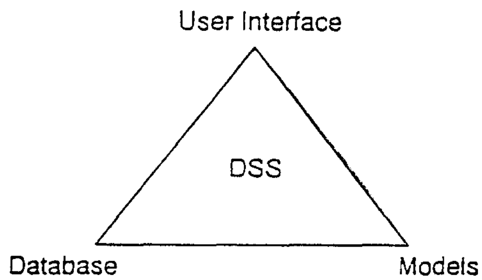


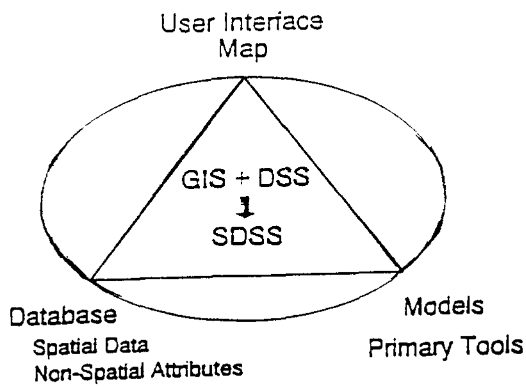
Figure 13b. An advanced decision-support system integrates several tools so that users can automate aspects of the management and planning process that were traditionally in the hands of experts. (Chapra et al., 1993)



(a) Representation of Major Parts of GIS (Walsh, 1993)



(b) Representation of Major Parts of DSS (Walsh, 1993)



(c) Representation of SDSS as Combination of GIS and DSS

Figure 14. Spatial Decision Support System (Walsh, 1993).