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Geographic Information Systems and Large Area Hydrology

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Summary

Large area water resources development and management require an understanding of basic hydrologic processes and simulation capabilities at the river basin scale. We define large areas as river basins of thousands or tens of thousands of square kilometers. Current concerns that are motivating the development of large area hydrologic modeling include climate change, management of water supplies in arid regions, large scale flooding, and offsite impacts of land management. Recent advances in computing hardware and software have allowed large area simulation to become feasible and have uncovered current limitations as well as opened up new challenges and opportunities.

A Geographic Information System (GIS) application in large area hydrology requires a finely tuned integration of three major components: a GIS, a database, and a hydrologic model. Databases exist for the entire U.S. that are required for hydrologic assessment such as soils, land use, topography, weather, and streamflow records. These databases all have limitations with regard to hydrologic modeling. A major challenge is to select or formulate a hydrologic model that is compatible with the limitations of existing databases and is consistent with the spatial and temporal resolutions of the available data. GIS are being coupled with hydrologic models to extract model inputs from map layers and to spatially display model outputs. Three categories of GIS and model coupling are: 1) input/output using GIS and an independent model, 2) quasi-coupling with a largely independent model, and 3) complete coupling with hydrology functions imbedded within a GIS framework. Current research is largely focused on GIS coupling for small watersheds and a major challenge is to address coupling issues that are unique to large area modeling.

Major challenges in simulating large river basins include describing micro and mesoscale variability, simulating surface and groundwater interactions, addressing the spatial variability of rainfall, and linking to coarser resolution global circulation models. Current research in large area hydrologic models is focusing on developing continuous time models with finer and more flexible discretization capabilities. Is this the direction to follow, or do we need a new modeling approach for large watersheds? Research suggests that simulation of all microscale processes (.1-1 m) may prove impossible and unnecessary at the basin scale. We need a better understanding of the major hydrologic processes operating at the basin scale, and we need to continue research on integration of GIS, databases, and models.

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Introduction

There are several recent developments in computing hardware and software that are allowing large area hydrologic simulation to become feasible. These advances include:

- *Computer Speed.* Although computer speed has increased dramatically in recent years, so have the computing requirements of large area hydrologic models. Processing large databases and running continuous time, distributed parameter hydrologic models require considerable computer time. Desktop workstations are available that can process programs at 20-200 mips (million instructions per second) with data flow ranging from 30-80 megaflops (floating point instructions per second). Supercomputers are available through many universities and federal national research labs that are several orders of magnitude faster. Also, research is continuing on parallel processing and executing existing models in a parallel system. A parallel processing machine is currently available that contains1024 Sparc-based CPU's , 32 gigabytes of memory and 1 terabyte of quick storage. It can attain peak computational speed near 128 gigaflops (1,000,000,000 floating point operations per second), which is approximately 1000 times faster than a desktop workstation.

- *Computer Storage.* Desktop devices are available that can store over 20 gigabytes of data and compact laser disks are common that can be shared by users that hold up to 650 megabytes. This technology is barely keeping pace with the data generated by satellites.

- *Computer Networking.* The UNIX operating system is being used at many research locations to link scientists within a lab and with Internet access, to allow communication between scientists at research locations around the world. This link can speed multilocation model development and allow databases to be stored at a centralized location and be easily accessible by anyone on the network. A wide range of communication links exist to transfer data ranging from 300 baud using telephone modems to 1 gigabyte per second using Hi-performance Parallel Interface Technology and fiber optics.

- *GIS/Spatial Analysis Software.* The advent of geographic information systems are playing an important role in large area hydrologic simulation. The role of GIS will be discussed in detail later in this paper.

- *Software Debugging Tools.* The recent development of advanced code debugging tools has allowed more rapid development and verification of complex simulation models.

- *Visualization Software Tools.* Large area hydrologic models generate overwhelming volumes of output and software tools are being developed to easily visualize and analyze model inputs and outputs.

State-of-the-Knowledge

Current state-of-the-art in large area hydrology has been significantly influenced by the previously presented advances in computing. In the past, large area models have been limited by the resources (time, personnel, and expense) required in obtaining input data and by the intense computational requirements. Consequently, a trade-off has occurred between spatial and temporal resolution. Distributed parameter models allow a basin to be subdivided into small subbasins. Because of the extreme spatial complexity, these models have until now been limited to single storm events. On the other hand, continuous time models have not allowed the basin to be subdivided as finely and some lumping of inputs is generally required. Advances in computer hardware, combined with spatial data handling systems, such as geographic information systems, are attempting to overcome these limitations. Current research has focused on developing continuous time, distributed parameter models, linking surface and subsurface flow models, developing models that allow greater flexibility in watershed discretization, and developing more modular modeling frameworks.

Geographic Information Systems are designed to store, manipulate, and display geographic information such as maps of soils, topography, landuse, and landcover. There are different ways of describing what a GIS is and what it does. One is to consider it a database (realizing of course that it is much more) that can be utilized by various models and tools. A single GIS for non-point source pollution control can facilitate multiple applications: effectively pinpointing areas where resources are threatened, helping impartially distribute incentives and regulations used for rural land management, providing quality information to decision-makers cost-effectively, and speeding the delivery of conservation services. One function of many of the GIS that have been developed to date is erosion control planning. Simple erosion prediction models such as the USLE are easily implemented within most GIS tools. There has recently been considerable effort in utilizing GIS to extract inputs (soils, land use, and topography) for comprehensive simulation models and spatially display model outputs. Much of the initial research was devoted to linking single-event, grid models with raster-based GIS (Srinivasan and Engel 1991, Rewerts and Engel 1991). Research is also continuing on utilizing GIS as an input/output interface tool for continuous time models using subwatershed boundaries based on natural flow paths (Sasowsky and Gardener 1991, Srinivasan and Arnold 1993).

The new opportunities created by the advances in computing are creating new areas of critical research in large area hydrology. The opportunities have allowed us to see several shortcomings in existing technologies that will be discussed in this paper:

- Adequacy and quality of the databases.

- Limitations and potential of existing hydrologic models to simulate large river basins.

- Limitations and opportunities for coupling GIS to hydrologic models.

Scientific Challenges

Three main areas of large area hydrology are discussed in the following including large area databases, coupling GIS and hydrologic models, and large area models. Limitations, critical gaps, and knowledge deficiences are addressed.

Large Area Databases

Selected data-base related problems in large area hydrologic applications using a GIS are reviewed in this section. For the purpose of this discussion, large area is defined as any watershed exceeding several hundred square kilometers. The practical aspects, necessity and advantages of a GIS as the data preparation, management and display environment are assumed to be known to the reader. The hereafter presented data-base problems are not intended to dispute the capabilities or question the necessity of using a GIS to conduct large area hydrology. They aim to focus on opportunities and challenges in large area hydrology.

A GIS application in large area hydrology requires a finely tuned integration of three major components: a GIS, a data base, and a hydrologic model. Each of these components are briefly reviewed and fundamental problems in their integrated use in large area hydrology, especially with respect to data bases, are discussed thereafter.

Geographic information systems. A GIS is a tool that is primarily used to manage, manipulate, process, overlay and display spatial data. It performs data preparation tasks that were traditionally done manually or by semi-automated procedures and visualizes intermediate and final output data. The GIS can display individual spatial data layers, combine and display a variety of data layers, or perform data processing functions on data layers and display the results. These tasks are performed very efficiently and the colorful graphical displays are highly sophisticated and informative. It should nevertheless be remembered that the quality of the results (display) are not related to the GIS capabilities, but to the quality of the initial data input into the GIS. This aspect is often overshadowed by or even forgotten amid the sophisticated and fanciful GIS manipulations and displays.

Data-bases. Topography, hydrography, soils, vegetation and climate over the geographic region of interest are basic spatial data needed in large area hydrology. Other data may be also be necessary. However, within the limited framework of this paper, only the ones listed above will be treated. Field collection of this data is generally impractical, if not impossible, and existing data sources are used to the extent available. This USGS Digital Elevation Model (DEM) data is often used for topographic data, mainly because of its extensive and consistent coverage. DEM elevation data are available in 7.5 minute, 15 minute, 30 minute and 1-degree units. USGS digital line graphs (DLG) of elevation contours are also available for different map scales. Hydrographic data are provided by the USGS in DLG format. The data includes streams and water bodies. The DLG data for contours and hydrography are available for 1:24,000-, 1:100'000-, and 1:250,000-scale maps. Drainage boundaries are available in the 1:250,000-scale land use may series only. As an alternative, most hydrographic data can be extracted from DEMs using existing GIS software. Digitized soil survey data are available through the USDA-Soil Conservation Service. Three levels of digitized soils data exist in various levels of completion: 1) national soils map (NATSGO, 1:2,000,000; completed), 2) state general soil maps (STATGO, 1:250,000; mostly completed), and 3) county soil survey maps (SSURGO, 1:24,000; mostly complete). The SCS is in the process of digitizing this SSURGO data. The digitized soil surveys, used in conjunction with a soils attribute data base (Soils-5), define the spatial distribution of soil characteristics. Land use and land cover data show seasonal character, and, particularly in agricultural regions, it may change as a result of human intervention. An up-to-date land use/land cover/albedo data are derived from the AHVRR (Advanced Very High Resolution Radiometer, NOAA-11) 1-km imagery. The data is available at different resolutions (LAG 1 km; GAC 4 km; GVI 16 km). A vegetation index is used to define the land use and cover classes. With two readings a day the dynamics of the vegetation cover in time can be captured (Loveland et al. 1991). Finally, climatic data can be obtained for national weather service stations, and from climate generators, satellite or radar (precipitation only). Even though most fundamental data appears to be available in one form or another, inherent limitations make their use in large area hydrology problematic. A few selected problems are presented in the following.

The USGS 7.5 minute DEM data is obtained by one of four procedures: (1) the Gestalt Photo Mapper II, (2) manual profiling from photogrammetic stereomodels, (3) stereomodel digitizing of contours, and (4) derivation from DLG hypsography and hydrography categories. Three levels of DEM data are available. The higher the level the more accurate the elevation data. The accuracy standards for the three DEM levels can be found in USGS (1990). DEM data acquired by procedure (1) and (2) are restricted to the level 1 category. These procedures were used in the 1970's and early 1980's, and a good portion of the USGS DEM 7.5 minute data falls in this category. This data contains systematic and recognizable errors within stated limits of tolerance that make this data generally unusable for drainage and hydrographic analyses. For example, the manual profiling results in striping along the profiles that can interrupt flow paths, create artificial depressions and alter drainage boundaries. DEM data acquired by procedure (3) falls usually into the level 2 category and represents todays standard procedure. This data has been processed or smoothed for consistency and edited to remove identifiable systematic errors. It is of higher quality then the level 1 data, but its suitability for drainage analyses remains to be tested. Finally, level 3 DEM 7.5 minute data, the highest quality, is not produced on a regularly basis at this time. Therefore, caution should be excerised using the USGS 7.5 minute DEM data for drainage applications, in particular when it is used to derive hydrographic data and for flow routing.

The SCS county soil surveys are generally used as a source for soil classification and spatial distribution. The clear cut boundaries between soil classifications, as shown on the soil surveys, rarely exist in the natural enironment. Spatial transitions between soil characteristics are gradual. It is also noted that soil classification and the determination of the boundaries between soils is not an exact science and depends to some extent on the experience and interpretation of the soil scientist. Given these considerations, inconsistencies in soil classification between counties may exist. In GIS displays, these inconsistencies become particularly apparent along county boundaries. The application of the soil surveys in hydrologic investigations requires that specific soil properties be known. In large area hydrology the number of soils does not lend itself to conduct on-site measurements. The general approach is to access a soils database which contains the parameters for each soil. Soils-5 is the database often used. This data base, however, provides a range of values for each parameter and the appropriate parameter value remains to be determined. Furthermore, it is noted that the soil properties are generally given for the B-horizon, yet the A-horizon may be determining soil horizon for the hydrologic processes. For example, in semi-arid climates the runoff separation for high intensity, short duration, precipitation events is generally controlled by the top soil horizon.

The land use and land cover data is very important in large area hydrology, particularly when the effect of regional land management changes are being quantified. The AVHRR data which is used to determine land use/cover is evaluated at five different levels of detail. Level 1 land cover data provides the basic grouping of the vegetation (agriculture, range, forest, water barren, etc.). Level 2 data provides subgroups of each vegetation group. Higher levels provide more detailed groupings. To the best knowledge of the authors, level 3, 4, and 5 are not available at this time. It is likely that the currently available data is not sensitive enough to distinguish subtle changes in land use/cover induced by agricultural management, or between different crops having similar reflectivity. Other problems with AVHRR data include the distortions resulting from off-nadir viewing and pixel elongation at the edge of the image, as well as the ground-truthing and interpretation of the data at the available resolutions.

Finally, spatially distributed precipitation datasets for large area hydrology are not easy to obtain. The national weather service stations are generally many miles apart. In mountainous areas the stations density is particularly low, and localized orographic effects generally prevent the data from being applied to a wider area. The overall low station density results in poor interpolation of rainfall fields between stations. Local convective storms between stations remain largely unmeasured. Weather generators are available to estimate daily point precipitation values.

However, practical generators that provide good spatial precipitation distributions over large areas and reproduce the dynamics of frontal movements remain elusive. Satellite data (GOES, NOAA) can be used to determine cloud density and moisture content, but a reliable procedure to infer precipitation on the ground is not available. The best source of precipitation data for large areas is the doppler radar data that will be available in the near future.

The above examples are illustrations of uncertainties and approximations in large area data. Additional problems can be expected when combining the data because of the different resolutions at which individual data items are provided. Little can be done about the quality of the data, and large area hydrology will have to deal with the data limitations.

Hydrologic models. Physically based, conceptual or empirical numerical models are generally used to simulate the hydrologic watershed processes. Physically based models solve equations describing the physical processes. They are complex, yet widely applicable and transferable. They also require detailed input data. Due to date uncertainties and natural variability some calibration may be necessary. Conceptual models are simplified representations of the physical processes. Their widespread use reflects the inherent complexity of the hydrologic processes and the practical inability to account for all aspects of these processes. They are less data intensive then the physically based models and require some calibration. Finally, empirical models are the simplest of all modeling approaches. They emphasize key parameters on which the solution is based. They require calibration and can only be applied over the range of conditions for which they are calibrated. Given today's powerful computers and GIS capabilities, the preferred approach to large area hydrology appears to be distributed modeling using physically based or conceptual models.

Even though a GIS is capable of managing the data and modeling environment, and even though fundamental data and hydrologic models are available, the integration of all three components into one consistent modeling unit for large area hydrology is a significant challenge. For example, the GIS can represent and overlay data and corresponding boundaries with great precision, yet data uncertainties and approximation do not warrant such a precision; or, physically based models can be applied to small subwatershed areas and the GIS can discretize a large area into many subwatersheds, yet data availability and quality limits the resolution of the discretization and the use of this approach. The use of GIS, databases and hydrologic models for large area hydrology must address the issue of compatibility between the three components and must assess the reliability of the modeling results.

Challenges. The challenge is to select or formulate a hydrologic model compatible with the limitations of existing databases and that can be operated at spatial and temporal resolutions that are consistent with the available data. This includes operating the GIS within the range of spatial resolutions dictated by the model and the databases, and to account for the fuzzy nature of many of the data layers. The hydrologic model and the resolution at which they are applied must be sensitive to the dominant processes and spatial variabilities that control the hydrology of large areas.

Research opportunities. 1) Determine of dominant hydrologic processes at the large scale. 2) Determine of the spatial and temporal resolution at which dominant large scale hydrologic processes operate. 3) Formulate a hydrologic model for the dominant hydrologic processes that will operate at the resolution of these processes, that can operate within the limitations of the available data, and that is insensitive to small scale data uncertainties. 4) Modify the GIS to account for fuzzy data layers, and formulate guidelines to operate the GIS at resolutions that are compatible with model and database limitations.

Coupling GIS and Hydrologic Models

To fully apply the power of GIS to large area hydrologic modeling a fully coupled GIS/Hydrologic modeling system must be developed. Without true coupling our hydrologic modeling efforts will never fully reside within a GIS and a good deal of both computational and research effort will be expended in the back and forth from model to GIS. The move toward coupling is not solely on the shoulders of the hydrologic community as many GIS implementations are already incorporating hydrologically oriented capabilities. It is more likely that the two groups will meet somewhere in the middle. Within this section three classes of GIS and hydrologic model coupling are discussed as are concerns with the use of digital elevation data and large area applications.

Three classes of GIS and hydrologic model coupling can be roughly categorized as: 1) Input/Output using GIS with an independent hydrologic model; 2) Quasi-coupling with a largely independent hydrologic model, and; 3) Complete-coupling with hydrology functions imbedded within a GIS framework. The first class of coupling was alluded to earlier where definition of hydrologic model inputs or parameters for models such as the USLE (or RUSLE) are defined in a largely off-line manner using a GIS. In the case of an independent distributed model, a GIS is often used in the first class of coupling for input and to display and visualize model output. A variety of hydrologically oriented GIS functions are available in the more robust GIS programs to aid the hydrologic modeler in defining typical inputs. They include basin and stream network delineation as well as slope and aspect definition from digital elevation model (DEM) data, and spatial averaging of cover and soil parameters.

In the second class, a quasi-coupled GIS/hydrologic model depends much more heavily on GIS for not only input/output definition but for tracking state variables and parameter updates during the execution of the hydrologic model. The hydrologic model is this class could still be run independently of the GIS. However, substantial programming and database manipulation efforts would be required to organize and keep track of distributed watershed information that a GIS can easily handle. An example of this quasi-coupling is discussed in Gao et al. (1991). They used the GRASS GIS with a 2-D surface/near surface hydrologic model coupled to a 1-D shallow groundwater model. DEM data and associated GIS functions were used extensively in this model as equations of continuity and momentum were solved via finite difference methods. In addition to input/output and data organization typical of the first class of coupling, Gao et al. (1991) used the GIS for real time, distributed water flux visualization and iterative tracking of state variables required for subsequent computations.

Examples of truly coupled, physically based, GIS/hydrologic models are not available. For simple conceptual or regression based hydrologic models, the computations required can be performed within a grid-based GIS using map algebra. Map algebra allows a variety of mathematical operations on a grid-based GIS coverage layer or combination of layers much like a spreadsheet (imagine a grid GIS layer as a spatial spreadsheet). Map algebra continues to become more sophisticated and can even iteratively solve certain nonlinear equations, but it still has difficulty treating feedback from adjacent grid cells that may be encountered in topographically directed flow situations such as backwater.

Maidment (1992) provides a good discussion on methods and attempts to fully couple hydrologic models within a GIS framework. In his report, Maidment discusses important GIS network functions that are typically applied for routing in traffic and street networks in which a *Lagrangian* approach is used to track particles moving through a defined flow field. To couple models such as the KINEROS (Woolhiser et al. 1990) or the HEC series of models (HEC 1990) which simulate flow through linearly connected flow components an *Eulerian* set of GIS network functions must be developed.

To overcome the *Lagrangian-Eulerian* conceptual mismatch Maidment (1993) advocates a hybrid grid-network approach in which a hydrologic modelling network can be imbedded in the 2-D landscape domain of a grid and connected with the 1-D domain of the stream network. In the grid domain, spatially varied processes of precipitation and infiltration can be treated. With basin segmentation provided by the stream network, data structures to get water from the sub-basin tributary areas to the stream network could be generated for a grid-based unit hydrograph or cell based kinematic wave model. Once water is routed into the stream network, more sophisticated reservoir or stream routing techniques could be used if detailed cross-sectional information is available. In summary, a variety of powerful GIS data manipulation and network functions exist to assist hydrologic modeling but additional research must be carried out to fully and efficiently integrate some classes of hydrologic models into GIS.

Digital elevation model and length scale considerations. A primary consideration in the complete-coupling class is the type of DEM data representation of the GIS. DEM data is particularly important for derivation of basin boundaries and stream networks within the GIS and for hydrologic models that perform finite difference or finite element based surface or near surface routing. The three primary forms of DEM data are regular grid data, triangular irregular networks (TIN), and contour string (vector) data. Moore et al. (1988b) provides an excellent review of these data types. The most common type of DEM data is regular grid data but some GIS packages allow conversion of various types of DEM data to each of the other forms.

From a GIS data storage and hydraulic routing standpoint, each type of DEM data also has its particular advantages and disadvantages. Regular grid (raster) data, although computationally convenient, suffer from poor definition of flow paths across grid cells, the inability of objective flow partitioning out of a single cell (Moore et al. 1988a), and digital data redundancy in smooth regions. As an advantage, regular grid DEMs are easily interfaced with most forms of remotely sensed and raster based data which are often used to represent soil, vegetation and land use information.

Contour based (vector) data enables the ready definition of streamtubes which allows routing computations to be completed as a series of one-dimensional coupled equations (Tisdale et al. 1986, Moore et al. 1988b). The chief disadvantage of contour based data is the large data storage requirement. Moore et al. (1988b) estimate that approximately one order of magnitude more points are required for comparable surface approximation using contour data than for regular grid data.

Routing on TIN DEM data requires a two dimensional approach due to the arbitrary orientation of TIN facets (Goodrich et al. 1991). This approach overcomes the problems of flow division and convergence when routing on a regular grid DEM. Because TIN DEMs typically require far fewer points to represent topography than regular grid or contour DEMs due to their "coordinate random, but surface specific" character (Peucker et al. 1978), substantial computational economy in routing is also realized. Routing on TIN's therefore represents a compromise between slightly increased computational complexity and the economy of TIN topographic representation.

Another important consideration in the coupling of hydrologic models to GIS is the need to adequately maintain characteristic length scales of the phenomena being modeled. In an attempt to adequately model fluxes represented by partial differential equations, numerical methods must maintain time/length scale ratios representing the characteristic length scale of the hydrologic process being modeled to obtain accurate solutions. This may require imbedded GIS computational layers that have a finer grid resolution than the grid resolution of data layers typically stored in GIS such as soils and topography. Utilizing a very coarse resolution numerical grid may provide solutions after model calibration to observations. However, in this case, the model becomes more conceptual in nature and physically based interpretations will be difficult to justify.

In light of the large area database problems discussed earlier the application of physically based models which utilize conservation of mass and momentum concepts may be quite difficult. In this class of models, a high degree of parameterization and data input resolution is typical and accurate definition of driving gradients is crucial. It may be some time before database resolution and computational resources are available to support this level of model complexity. Improvements in both areas will continue to be made and research should therefore continue in coupling this class of models to GIS. In the near term (5 years) new modeling approaches will be required or it will be necessary to employ a more conceptual, less physically based hydrologic modeling approach to large area problems.

Large Area Hydrologic Models

The recent advances in computing power have initiated a trend in large area hydrologic modeling to discretize a basin into finer and finer subbasins. There is also current research that is allowing more flexibility in how a basin may be discretized (Arnold et al. 1993). Is the trend toward finer discretization the appropriate direction to head or should we develop an entirely new modeling approach? Recent research suggests that a new modeling approach may be required for large area hydrologic modeling.

Microscale vs. mesoscale. Woolhiser et al. (1990) describe two spatial scales. The first is the microscale with a characteristic length of 0.01 to 1.0 m. Microscale variability includes surface microtopography, micro areas of ponding, variation in hydraulic conductivity, and distribution of chemicals in the soil. The complexity of microscale processes related to field transport of dissolved materials suggest that solute movement over basin scale distances are best described as random (Rodriguez-Iturbe and Valdes 1979, Gupta et al. 1980, Gupta and Waymire 1983). Rinaldo and Marani (1987) concluded that large scale simulation of all microscale processes may prove impossible and may also be unnecessary. Mesoscale distributions (10 to 10000 m) relevant to basin scale response are independent of the detailed form of the interactions operating at the microscale. Woolhiser and Goodrich (1988) used a kinematic cascade model to account for microscale and mesoscale spatial variations. Mesoscale variations were accounted for by subdividing the watershed into planes with each plane having a mean and coefficient of variation of saturated hydraulic conductivity (K_s) values. To account for microscale variations, they also subdivided the planes into subareas with K_s equal to the median value of equal probability intervals of the cumulative K_s distribution which was assumed to be lognormal. The analogy is that each plane element in a catchment consists of independent parallel planes with different K_s. They concluded that both spatial scales appear to be important.

Surface water groundwater interation. Basin scale water resources development and management plans require quantification of the major components of the hydrologic balance including surface runoff, groundwater flow, impoundment storage, plant uptake, consumptive use, and depletion of groundwater by pumping wells. In most previous groundwater modeling applications, recharge is estimated by empirical methods which have limited application to the impact of surface management. Also, most surface modeling applications assume percolation from the soil profile is lost from the system and ignored. Several attempts have recently been made to link surface and subsurface models (Chiew and McMahon 1984, Prakash and Jafari 1987). However, most attempts have not included the ability to simulate management impacts such as cropping systems, tillage, reservoirs, and climate changes.

In order to achieve a complete coupled description of water movement in surface and groundwater flow, a series of information is needed for the surface, the soil profile, and various subsurface strata. It is possible that these layers can be constructed in 2-D but arranged vertically above one another using a terrain network that has a common set of x,y coordinates for all layers, but each layer has a vertical location and descriptive attributes (Maidment 1992). If surface and groundwater models are to be linked, a true 3-D representation is the ultimate configuration. Although this may be technically feasible, the detailed spatial data bases needed to drive a 3-D model for large basins is not available. Detailed soils, geology and vadoze zone maps and related properties are not readily available for large river basins and simplier models of surface-groundwater interactions will need to be developed (Arnold et al. 1993).

Rainfall spatial variability. One of the major limitations to large area hydrologic modeling is the spatial variability associated with precipitation. There are over 8000 raingage locations in the U.S. with over 30 years of daily precipitation data. There are on average two or three gages per county which leaves several kilometes between gages. This can cause considerable errors in runoff estimation if one gage is used to represent an entire subwatershed or even if an attempt is made to "spatially weight" precipitation for a subwatershed. Also, the data files are difficult to manipulate and contain considerable days of missing records.

Weather generators can be extremely useful when measured data is unavailable and management scenarios are being compared. Daily weather generator parameters are available for generating weather sequences at a point, however, spatially correlated generators required for large area hydrologic simulation have not been developed. The physical processes driving large area weather phenomenon are not fully understood and many technical obstacles need to be overcome before spatially correlated rainfall generation is possible.

Another possibility is to utilize the WSR-88D radar technology (formerly called NEXRAD - Next Generation Weather Radar) to measure aerial precipitation rates needed to drive large area hydrologic models. ARS researchers at Durant, Oklahoma are currently testing WSR-88D and are simulating runoff based on WSR-88D estimates of precipitation.

Linking to global climate change models. Several global climate models exist and the predictions of these models on global warming concern hydrologists that such warming may impact the hydrologic balance. Of particular concern are droughts, flooding, and the possibility of rising sea water levels that could inundate coastal lowlands. Global circulation models are built on a square grid with each cell side hundreds of kilometers long while modeling subareas for hydrologic models are much smaller. One way to overcome this may be to aggregate fine-scale components up to some optimum level where interaction between fine and course scale information can occur (Rastetter et al. 1992). Recent research in this area is encouraging in that it appears that complex spatial patterns in plant physiology and in hydrologic processes may be explained by simple models based on a few principals (Schimel et al. 1991, Running and Nemani 1992).

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