USGS

WATER RESOURCES RESEARCH GRANT PROPOSAL

Title: Relative Scales of Hydrodynamic and Geomorphologic Influence on the Hydrologic Response in the Illinois River Basin

Focus Categories: G&G, HYDROL, FL

Keywords: Geomorphology, channels, watershed management, hydrologic models

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Non-Federal Matching Funds: $40,630

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Congressional District: 15th

Statement of Critical Regional or State Water Problems

The Illinois River has been the focus of considerable interest within the state, and one of the main concerns has been the impact of human activity on the hydrological regime of the river [*Kustra*, 1997]. Interest has centered specifically on the effect of altered hydrologic regimes on floodplain ecosystems [*Sparks*, 1992]. Along with the human impacts, the integrated effects of climate, geology, land use, physiography and geomorphology determine the hydrologic regime through the quality and quantity of water, sediment and other constituents transported through the river system. Basin geomorphology along with other controls such as hydraulics, water quality, dams, vegetation and habitat characteristics plays a central role in determining the ecological health of the watershed. Consequently the A1997 Integrated Management Plan@ [*Kustra*, 1997] calls for the evaluation of alternative management strategies, and supports several model studies that consider the integrated impact of multiple watershed factors.

Flow through the river system exhibits different characteristics at various scales from small headwater streams to major rivers. Low order streams near the headwater are typically characterized by moderate to steep slopes and are the primary conduits of water and sediment to higher order streams. In higher order streams, gradient decreases, channels widen, transport of large sediment decreases while total volume of sediment increases. It is increasingly being recognized that addressing the A issue of scale @, i.e., understanding and determining the dominant controlling factors at various scales, is of fundamental importance in developing appropriate policy decisions on watershed management. Recent theories [*Rinaldo et al.*, 1991] have suggested that as basin size increases the river network structure masks the effect of differences in hydrodynamic conditions in individual channel reaches. This effect of network structure, referred to as geomorphologic dispersion, plays an important role in the prediction of transport phenomena. The aim of the proposed work is to determine the relative effects of geomorphological dispersion and hydrodynamic dispersion on the hydrological response of the Illinois River system. A particular area of focus will be to examine the effects of two human actions - modification of network structure via land drainage activities and construction of dams - on contemporary hydrological conditions. The results will provide important information and predictive capabilities for assessing the influence of future management scenarios on the hydrology of the Illinois River.

Statement of Results or Benefits

Modeling of the movement of water and sediment is an essential activity for effective watershed management and decision-making. The mechanisms contributing to the movement of water includes the heterogeneity of flow resistance throughout the channel system (hydrodynamic dispersion) and the topological structure of the channel system (geomorphologic dispersion). Proper assessment of the relative influence of these two mechanisms on hydrological response is important because it allows management efforts at different scales to be directed toward the mechanism that is most influential at these scales. It also provides information on the relative effectiveness of specific management options on the overall hydrological response of the basin. This type of analysis can improve the overall cost efficiency of watershed management.

Objectives of the Research

The objective of the proposed work is to determine the relative effects of geomorphological dispersion and hydrodynamic dispersion on the hydrological response of the Illinois River system as scale increases. The specific hypothesis to be tested is that as basin size increases, the river network structure, as compared to channel hydrodynamic properties, plays an increasingly dominant role in determining the hydrological response The research will also explore the effects of two human actions - modification of network structure via land drainage activities and construction of dams - on contemporary hydrological conditions. Whereas dams have undoubtedly had an important influence on hydrodynamic dispersion, the exact nature of this influence at different scales remains unknown. Moreover, the addition of headwater tributaries through land drainage activity in the late 1800s has undoubtedly greatly modified geomorphological dispersion, but the influence of this activity is also unknown. The results will provide important information and predictive capabilities for assessing the influence of future management scenarios on the hydrology of the Illinois River.

Related Research

Since its development, the unit hydrograph theory for the predictions of streamflow from a basin [*Sherman, 1932*] has played a prominent role in the hydrologic engineering practice for several decades. This linear system response theory holds that basin response to a rainfall input is linear and time invariant. The output of a basin [q(t): discharge at the outlet per unit area] is given by the convolution of the rainfall input [$I(t)$] and the instantaneous unit hydrograph (IUH) [$h(t)$] as [*Dooge, 1959*]:

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Hence the key problem faced by the hydrologists is to determine the IUH of a basin. In engineering practice, this is often determined by numerical deconvolution techniques [*Chow et al., 1988*] using observed streamflow and rainfall data.

In an attempt to find a physical basis for the IUH, *Rodriguez-Iturbe and Valdes* [*1979*], using probabilistic arguments, developed a model that relates the geomorphologic structure of a basin to the IUH. The model is relatively parsimonious in data requirements and most parameters can be obtained from topographic maps and/or processing of digital elevation model (DEM) data. Consequently, this theory has undergone several noteworthy developments over the last decade. *Sivaplalan et al*. [*1990*] incorporated the effect of partial contributing areas which recognizes that during a rainfall event, droplets contributing to the runoff are not uniformly distributed throught the basin but are more likely to come from areas that are saturated close to stream channels. The saturated areas can be identified through topographic indices [*Beven and Kirkby, 1979*] which can be easily obtained from DEM data.

van der Tak [*1990*] incorporated hillslope effects in the basic formulation of GIUH by using gamma distributions for the travel time distributions through the flow pathways and introducing a hillslope velocity term. Using the method of moments technique, they found that the hillslope velocities are two orders of magnitude smaller than channel velocities, which has a significant impact on the GIUH. *Lee and Yen* [*1997*] introduced the kinematic wave theory to determine the travel times of overland and channel flows, thus relaxing the linearity restriction of the unit hydrograph theory.

Rinaldo et al. [*1991*] used an advection-dispersion equations to describe the flow through individual streams, which is obtained by introducing a diffusion term in the kinematic wave equation [*Lighthill and Whitman, 1955*] and is given by:

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In the above, y is the normal flow depth, and the D_L is the coefficient of hydrodynamic dispersion. The kinematic wave celerity, c_k, is interpreted as the velocity at which a disturbance travels through the channel network. The diffusion coefficient, D_L, measure the tendency of this disturbance to disperse longitudinally as it travels downstream. Such dispersion is induced by turbulence initiated from the shearing effects of channel boundaries [*Henderson, 1966; Mesa and Mifflin, 1986; Rinaldo et al., 1991*]. The travel time distribution obtained from the solution of the above equation [*Rinaldo et al., 1991*] is

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where *L* is the length of the channel. *Rinaldo et al.* [*1991*] further showed that not only is there a dispersion effect in the individual channels, but the stream network structure itself causes dispersion. They used the term *geomorphologic dispersion* to describe this phenomenon. It captures the fact that raindrops falling at different locations at the same time arrive at an outlet at different times. They showed that the variance of the arrival time *T* at the outlet is given by

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where Install Equation Editor and double-click here to view equation. is the mean path length in the basin of order ©, and D_G is the geomorphologic dispersion coefficient. The geomorphologic dispersion coefficient depends on the first two moments of the flow paths and is given as [*Snell and Sivapalan, 1994*]

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Rinaldo et al. [*1991*] argued that in the event D_G is significantly greater than D_L, which might be the case in larger basins, the network structure may mask the effect of differences in flow conditions in individual channel reaches and will play an important role in the prediction of transport phenomena. The goal of the proposed research is to test the validity of this proposition in the Illinois River Basin and to identify the scales at which the transition from hydrodynamic control on streamflow to geomorphologic control occurs, as well as explore the ways in which two human actions B dam construction and drainage-network modification B have modified D_G and D_L

Methods, Procedures, and Facilities

The coefficient of hydrodynamic dispersion (D_L) depends primarily on the channel roughness, flow depth, and the slope. The geomorphologic dispersion (D_G) depends primarily on the spatial arrangement of the channels comprising the drainage network (i.e., the spatial distribution of the flow paths). Both D_L and D_G increase with increasing distance from the headwaters. The first is due to increasing flow depth, and the second is due to increasing variability in flow paths. To evaluade the relative magnitudes of these two factors, we need to estimate the necessary empirical parameters and perform simulations on basins of increasing size.

The research objective will be accomplished through the following tasks:

1. Estimation of flow path characteristics from DEM and GIS data on the topological structure of the drainage net of the Illinois River system.

It is clear from the above discussion that the structure of the drainage network plays an important role in shaping the streamflow response. Consequently, the arrangement of the flow paths, or channel links, in a basin is of utmost importance. Traditionally, the network structure has been characterized in terms of empirically observed Horton=s ratios or width (area) function [*Shreve, 1969*]. The width (area) function, $W(x)$, of a basin is defined as the proportion of the stream links (contributing area) available at a certain distance from the outlet measured along the river network. It is intrinsically related to runoff response and may also be regarded as the instantaneous unit hydrograph function under the assumption of constant velocity and negligible dispersion.

This analysis however assumes that the entire basin contributes to the streamflow at any time. If topographic index ln *a*/ tan _² [*Beven and Kirkby, 1979*] is used to identify the convergent areas near stream channels contributing to flow, then one can examine the properties of the *saturated area width function* which is simply the fraction of saturated area at a certain flow distance measured along the network. The saturated areas are determined as locations whose topographic index is above a threshold, where the threshold depends on the antecedent moisture conditions and rainfall intensities.

As part of this research, we will extract the geomorphological path properties using 90m DEM data. We have the capability to stitch together several 1E H 1E DEM patches, provided by USGS, and obtain stream networks and topographic indices for basins of the order of 10^4 km^2 using RiverTools software [*http://cires.colorado.edu/people/peckham.scott/RT.html*] developed by Peckham. For example, Figure 1 shows the network structure of the Illinois River Basin and the width function extracted using this software. Such capability gives a unique opportunity to study scale issues for this basin.

Under this task geomorphologic characteristics for several sub-basins of different orders embedded within the Illinois River Basin will be extracted using the digital elevation data. Studying basins of different orders is a natural way to study the scaling up issues. Horton=s ratios, width functions and saturated area width functions for different thresholds of topographic index will be used for simulation as explained under Task 3.

We will also use digital stream data available from the Illinois State Geological Survey to determine network structure. These data have been derived from 7.5 minute topographical maps and can be manipulated using ARCINFO and ARCVIEW software which is available in the PI=s research group. Information on Horton=s ratios, width functions and saturated area width functions derived from the map-based stream data will be compared with the DEM derived information to evaluate the influence of the type of data source on network properties.

2. Estimation of hydrodynamic properties.

The dispersion coefficient D_L depends on the characteristics of the channel and flow in the watershed. The hydrodynamic properties of the slope, cross section and channel patterns will be estimated using data from available field surveys from Illinois State Water Survey, the Illinois state office of the U.S. Geological Survey, from published relations on the hydraulic geometry of streams in Illinois(e.g. Stall and Fok, 1968), topographic maps and back calculations from modeling of observed stream flows. The stream flow data will be obtained from the USGS (United State Geological Survey) or the Illinois State Water Survey. Modeling of observed stream flow for computing the hydrodynamic dispersion will be done using a physical process based watershed and runoff model. Depending upon the accuracy required, kinematic, diffusion wave or full dynamic wave model will be used. The influence of dams on hydrodynamic dispersion will be evaluated by examining changes in hydrograph characteristics at gaging stations upstream and downstream of major reserviors during individual hydrological events. Data will be entered into a GIS database on channel network structure to map spatial variation in hydrodynamic dispersion throughout the Illinois River basin. This information will provide the basis for evaluating the effects of spatial variation in travel time distribution on hydrological response at different spatial scales.

3. Simulation studies to assess the relative roles of hydrodynamic and geomorphologic controls at different scales.

This task will mainly consist of controlled simulations to evaluate the impact each of the two factors have as basin size increases. The width function formulation of the hydrologic response, using the travel time distribution given in equation (3), is given as [*Rinaldo et al., 1991*]:

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Notice that $W(l_j)$ can be the width function or the saturated area width function. Results will be compared with actual hydrological information for the Illinois River basin to assess the overall accuracy of the model at predicting hydrological response. Hydrological records for the watershed are available from the U.S. Geological Survey.

4. Evaluation of changes in network structure on the hydrological reponse of the Illinois River system.

Previous work [*Rhoads and Herricks, 1996*] suggests that the contemporary structure of the Illinois River drainage network is radically different than the structure that existed prior to European settlement of Illinois. Most of this change has occurred through the addition of numerous headwater tributaries by land-drainage activities in the late 1800s. Land-office survey records and maps of the state from the early 1800s provide a valuable record of drainage-network structure at the time of settlement [*Rhoads and Herricks, 1996*]. These records can be used to reconstruct the original structure of the network and to compute network properties (Horton=s ratios, network width function, saturated network width function). This information will be used to estimate the relative roles of hydrodynamic and geomorphological controls at different scales on the hydrological response of the basin in the absence of dams and for the original network structure. The results will illustrate the influence of two types of human activity B dam construction and network modification Bon the hydrological response of the Illinois River system at different scales.

Training Potential: The proposal will support one graduate student for two years for M.S. in Civil and Environmental Engineering with specialization in Environmental Hydrology and Hydraulic Engineering. The proposed research will form the thesis research of the student.

Information Transfer Plan: Journal and conference papers will be published via appropriate avenues throughout the project period. We expect that at the end of two years of the project we will publish one peer reviewed and one conference paper. Cost of travel to a conference is included in the budget.

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