*European Water* 57: 109-113, 2017.


# Impact of extreme events on watershed dynamics

J. Kim[1], M. Dwelle[2], A. Warnock[3], V. Ivanov[2] and N. Katopodes[2*]
[1] *Department of Civil and Environmental Engineering, Sejong University, Seoul, Republic of Korea*
[2] *Department of Civil and Environmental Engineering University of Michigan, Ann Arbor, USA*
[3] *SRI International, Menlo Park, CA, USA*
[*] *e-mail: ndk@umich.edu*

**Abstract:** This paper presents the methodology for a quantitative assessment of the impact of extreme events on watershed morphology and dynamics. By linking some key factors of erosion to land morphology and biota, a quantitative measure of the sustainability of aquatic life is also presented. The integrated watershed-morphology model is used to perform a formal sensitivity analysis of land dynamics to various hydrologic changes at the drainage basin level. Finally, by running simulation scenarios over long term periods, it is possible to establish quantitative measures of the trade-offs between the ecosystem services provided by water within a watershed.

**Key words:** Climate change; watershed dynamics; Numerical models; Erosion; Sedimentation

## 1. INTRODUCTION

Long-term effects of land use practices and extreme weather phenomena lead to erosion and sedimentation processes that are responsible for many undesirable changes to the ability of the land to sustain microbial life and produce food. Every isolated event has an irreversible impact on the land due to the potential for erosion that ignites a sequence of events whose scale increases with time. Variations in watershed headwater land use, as well as climate change, directly affect the local runoff and erosion processes, and the related ecosystem services. The process-scale dynamics of hill-slope-channel erosion and streamflow sediment yield are well understood, being strongly affected by the spatial heterogeneity in soil and bedrock, vegetation cover, and topography. The rainfall-runoff mechanism is the primary driver of these dynamics, exhibiting high heterogeneity over a number of spatial and temporal scales and a strong dependence on antecedent conditions. Consequently, changes in watershed headwater land use, as well as changes in key forcing elements of the hydrologic cycle may alter the characteristics of local runoff production and erosion processes. This, in turn, may lead to the adverse effects of excessive sedimentation and unstable hydrology of estuarine and wetland habitats.

Even if alternative scenarios for watershed management were available, it would be impossible to quantitatively assess how long it would take to restore a watershed to its original state and provide relevant uncertainty bounds. Additionally, the transfer of qualitative interpretations from one watershed to another is not meaningful, as most of the information derived is site specific, and the underlying physical and ecological components are difficult to scale. It is therefore clear that physical processes occurring in the headwater drainage basin are critical, and need to be considered for meaningful and robust evaluations. A predictive sensitivity analysis model is needed to quantify each of the processes involved, to explain how past practices have led to the present state, as well as to offer alternative land use approaches for the future. Such a tool would be also capable of interpreting anticipated perturbations in the hydrological cycle as a result of deviations from mean climate.

We present a method that can overcome these difficulties by coupling a high resolution land morphology model with a large scale watershed model. The two models are mathematically compatible, thus there is high confidence that their integrated results will provide a unique method for the investigation of both extreme and long-term changes due to flood and drought.

## 2. MODEL DESCRIPTION

The primary tool used for hydrologic assessment is the tRIBS-OFM model (Kim et al., 2012). The model is also capable of simulating erosion and sedimentation (Kim et al., 2013). The fundamental development for the hydrologic processes is due to Ivanov et al. (2008). The overland flow dynamics was originally developed by Bradford and Katopodes (1999) and later converted to an unstructured grid by Begnudelli and Sanders (2006).

*Figure 1. Computational grid.*

A key feature of the model is the collocation of the computational grids for the hydrologic and hydrodynamic modules. As shown in Fig. 1, the Voronoi cells of the hydrologic model are mapped onto the Delaunay triangles of the overland flow model, thus coupling the two processes by means of the runoff volume at the cell center. This allows a two-way transfer of information from between the erosion and sedimentation module and the precipitation and energy flux input of the integrated model. This represents the precise mechanism by which the sensitivity analysis can be performed by seamless transfer of adjoint data from the downstream end to the headwaters of the watershed.

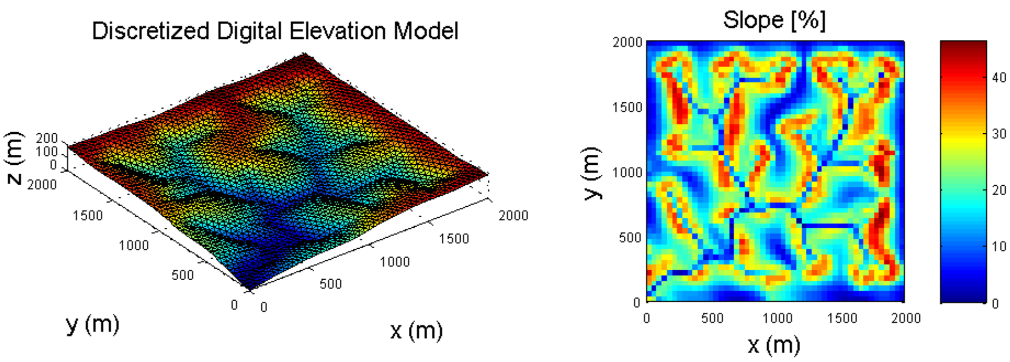


*Figure 2. Watershed model.*

A typical depiction of a watershed is shown in Fig. 2, in which a digital elevation model is used to characterize the morphological elements of the terrain. The soil erosion model was originally proposed by Hairsine and Rose (1992), and later modified by Sander et al. (1996). The current model also includes modules that capture the subgrid effects of land resistance (Kim et al., 2012), and the dynamic switch between dynamic and kinematic waves introduced by Warnock et al. (2014).

The input climate data are introduced using the downscaling approach is due to Fatichi et al. (2015). GCM projections are consistently downscaled using the weather simulator. It generates a hydro-meteorological series with prescribed characteristics in which the interdependencies between key states are preserved, e.g. change in precipitation occurrence will have an effect on cloudiness, incoming short- and longwave radiation, and air temperature. The foregoing projections can be accounted for by modfiying the parameters of the Poisson arrival model and nudging the deterministic temperature component to reflect either positive or negative trends. Seasonal interdependencies can then be further tuned. An atmosphere radiative transfer model is used that treats two shortwave bands, VIS and NIR, separately allowing one to estimate fluxes for clear sky conditions. Cloudy sky conditions are also accounted for by suitable parameterizations. Terrain effects are introduced using geometric information on local topographic aspect and slope.

Air temperature is assumed to be the sum of two variables: a deterministic and a random variate. The deterministic component is determined based on an empirical method that attributes temporal variation of the air temperature to the divergence of radiative and eddy heat fluxes. In essence, the deterministic temperature increment is regressed on several hydro-meteorological variables such as the site Sun position, a factor of cloudiness, and incoming longwave radiation. The random variate is approximated by a first order Markov process. For air humidity, the model converts the minimum daily temperatures to dew point temperature using information on daily potential evaporation and degree of aridity of the region. Since dew point temperatures typically exhibit low variability during the day, daily values suffice for our modeling purposes. Finally, wind speed is introduced as an independent process. Skewed hourly wind speed data are generated using a first order Markov model where the random term forces skewness on the results of the autoregressive model. Using the generated runoff and eroded particles as input, the transport model simulates the redistribution of sediment both as bedload and as suspended load across the basin drainage network. The long-term simulations allow the representation of characteristic hydro-geomorphic seasonal dynamics. Thus, at the framework back-end, this will provide the necessary information for the evaluation of rates of change of stream and estuary morphology that will be translated to changes in aquatic habitat quality.

## 3. SENSITIVITY ANALYSIS

A formal sensitivity analysis is conducted based on the adjoint equation method developed by Sanders and Katopodes (2000). The integrated watershed-estuary-habitat model is used to perform a systematic study of the factors affecting aquatic life in wetlands and estuaries. The precise impact of climatic change or alternative land practices at the watershed level can be quantitatively assessed if one system parameter is varied while all others remain constant. The effect of such variation on a specific target, e.g. habitat component, represents the sensitivity of the habitat to each parameter change.

The proposed model provides the ideal means for performing such an analysis using the best possible physical description of the system. However, in cases where the impact of a parameter variation requires several years to manifest itself in the habitat, tedious computations are needed to obtain the relevant sensitivity information. These must be then repeated for each parameter that can potentially affect the target process. Adjoint sensitivity analysis allows us to compute the same impact information extremely efficiently without repetitive runs of the model. By running the adjoint model in the reverse time direction, all sensitivity data for a given habitat component can be computed by a single simulation of the direct and one of the adjoint model, regardless of the number of parameters affecting the target component. Remarkably rich information can be thus retrieved very efficiently, and parameters that have insignificant impact on the habitat can be securely excluded from further studies.

## 4. DISCUSSION OF RESULTS

The fundamental hypothesis of the present study is that erosion and sedimentation constitute a chain of information that links hydrologic processes to estuarine morphology. Although this is intuitively evident, there is no quantitative estimate of the causes and relative impact of the stressors that cause these changes. Therefore, computational scenarios have been developed to demonstrated the relation between hydrologic inputs and estuarine or wetland changes. The present scenarios have focused on precipitation changes, local temperature, and wind data. Soil properties have also been included in th study, but not as a direct sensitivity indicator.

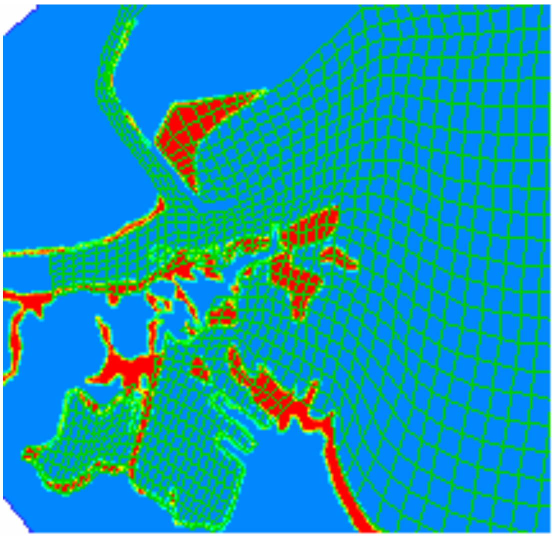

*Figure 3. Sensitivity of Deposition areas in Muskegon River estuary.*

The sensitivity analysis identifies areas of potential deposition in a study area, such as the one shown in Fig. 3. Then, the model tries to identify the individual sensitivities of a unit change in estuarine depth to unit changes in the parameters of the study. Trial runs eliminate parameters with low sensitivity, thus allowing subsequent runs to focus on those parameters that have a larger impact on sedimentation.

The results of this study provide overwhelming evidence that soil moisture conditions, as affected by the infiltration process, subsurface redistribution in the unsaturated-saturated zones, and evapotranspiration are the antecedent conditions with the highest sensitivity. In areas susceptible to erosion, the locally produced event-scale runoff is then translated into sediment yields. Diffusive erosion processes due to rain-splash, freeze-thaw, bioturbation, and wet-dry cycles represent lower frequency phenomena responding to seasonal and long-term dynamics. This extreme drought followed by extreme precipitation is therefore the mechanism with the highest sensitivity to changes in aquatic biota in estuaries and wetlands. The proposed model is capable of providing spatially distributed information on the specific areas of a given watershed that are susceptible to erosion to which estuarine dynamics show high sensitivity. It is believed that this information may be of value to engineers and planners that can then take measures to prevent these changes.

## REFERENCES


Begnudelli, L., and B. F. Sanders (2006). Unstructured grid finite-volume algorithm for shallow-water flow and scalar transport with wetting and drying, Journal of Hydraulic Engineering-ASCE, 132(4), 371-384.

Bradford, S. F., and N. D. Katopodes (1999). Hydrodynamics of turbid underflows. I: Formulation and numerical analysis, Journal of Hydraulic Engineering-ASCE, 125(10), 1006-1015.

Fatichi, S., Rimkus, S., Burlando, P., Bordoy, R., Molnar, P., (2015). High-resolution distributed analysis of climate and nthropogenic changes on the hydrology of an Alpine catchment. J. Hydrol. 525, 362–382.

Hairsine, P. B., and C. W. Rose (1992). Modeling water erosion due to overland flow using physical principles: 1. Sheet flow, Water Resources Research, 28(1), 237-243.

Ivanov, V.Y., R.L. Bras, and E.R. Vivoni, (2008). Vegetation-hydrology dynamics in complex terrain of semiarid areas: 1. A mechanistic approach to modeling dynamic feedbacks. Water Resources Research, 44(3), doi: 10.1029/2006WR005588

Kim, J., Ivanov, V. and Katopodes, N.D., (2013). Modeling erosion and sedimentation coupled with hydrological and overland flow processes at the watershed scale. Water Resources Research, 49(9): 5134-5154

Kim, J., V.Y. Ivanov, and N. Katopodes, (2012). Hydraulic resistance to overland flow over vegetated surfaces. Water Resources

Research, 48(10), doi: 10.1029/2012WR012047

Kim, J, Warnock, A., Ivanov, V. and Katopodes, N.D., (2012). Coupled modeling of hydrologic and hydrodynamic processes including overland and channel flow. Advances in Water Resources, 37, 104-126

Sander, G. C., P. B. Hairsine, C. W. Rose, D. Cassidy, J. Y. Parlange, W. L. Hogarth, and I. G. Lisle (1996). Unsteady soil erosion model, analytical solutions and comparison with experimental results, J. Hydrol., 178(1-4), 351-367.

Sanders, B.F. and Katopodes, N.D., (2000). Sensitivity Analysis of Shallow Water Flow by Adjoint Method. Journal of Engineering Mechanics, 126(9), 909-919.

Warnock, A., Kim, J., Ivanov, V., and Katopodes, N., (2014). Self-Adaptive Kinematic-Dynamic Model for Overland Flow. Journal of Hydraulic Engineering, 140(2), 169-181.