

# A Retrospective Analysis of Model Uncertainty for Forecasting Hydrologic Change

D.J. Semmens<sup>a</sup>, M. Hernandez<sup>b</sup>, D.C. Goodrich<sup>b</sup>, and W.G. Kepner<sup>a</sup>

<sup>a</sup> U.S. EPA, Office of Research and Development, Las Vegas, NV; [semmens.darius@epa.gov](mailto:semmens.darius@epa.gov)

<sup>b</sup> USDA-ARS Southwest Watershed Research Center, Tucson, AZ

**Abstract:** GIS-based hydrologic modeling offers a convenient means of assessing the impacts associated with land-cover/use change for environmental planning efforts. Alternative future scenarios can be used as input to hydrologic models and compared with existing conditions to evaluate potential environmental impacts as part of this process. Model error, however, can be significant and potentially compounded when projecting future land-cover/use change and management conditions. To address this problem we have utilized repeat observations of land cover/use as a proxy for projected future conditions. A systematic analysis of model efficiency during simulations based on observed land-cover/use change is used to quantify error associated with simulations for a series of known "future" landscape conditions over a 24-year period. Calibrated and uncalibrated assessments of relative change over different lengths of time are also presented to determine the types of information that can reliably be used in planning efforts for which calibration is not possible.

*The United States Environmental Protection Agency through its Office of Research and Development partially funded and collaborated in the research described here under assistance agreement DW12939409 to USDA-ARS. It has been subjected to Agency review and approved for publication. Mention of trade names or commercial products does not constitute endorsement or recommendation for use.*

**Keywords:** Hydrologic modeling; uncertainty; forecasting; alternative futures.

## 1. INTRODUCTION

Integrated, regional planning efforts have begun to use an innovative GIS-based simulation modeling strategy that considers the demographic, economic, physical, and environmental processes of an area and projects the consequences to that area of various land-use planning and management decisions (e.g. Steinitz et al., 2003). The results of such projections, and the approach itself, are known as "alternative futures" and are being used with increasing frequency to favorably guide efforts to shape future landscape change. The results of an alternative futures exercise are represented in terms of land-cover/use maps, which serve as the primary means of relating the consequences of management and policy alternatives to biophysical and socioeconomic systems.

Land-cover/use maps are also a principal input to GIS-based watershed hydrologic models, and the primary means of incorporating anthropogenic impacts into distributed hydrologic assessments. Alternative future land-cover/use grids thus provide a means of incorporating projected growth and development into hydrologic assessments for the purpose of exploring potential environmental impacts associated with future scenarios (e.g. Kepner et al., 2004). This technique holds great promise as a means of providing decision support for planning efforts, but a significant concern is the lack of available information on the uncertainty and appropriate use of physically based hydrologic models in a forecasting mode.

The use of watershed hydrologic models to forecast impacts associated with land-cover/use change is fraught with uncertainty. Even in data rich locations it is not possible to calibrate a model to future

conditions, and it is thus beneficial to have some idea of how model performance varies with time from a baseline, calibrated period. In locations lacking sufficient data for initial model calibration, two additional pieces of information are needed to determine the reliability of predictions derived from distributed hydrologic models. First, it is beneficial to know how well a model performs when it is parameterized entirely by automated processes and default values without calibration. Second, in cases where the objective is to predict hydrologic response to projected future conditions it is necessary to determine if assessments of relative change, derived from a comparison of uncalibrated simulation results, can provide reliable information.

The present study explores model uncertainty in terms of its implications for using model projections as a basis for environmental planning. Using a model developed with historic data, predictive “future” simulations were conducted for time periods with available data to assess model performance for applications typical of a planning exercise. Specifically, we explore the potential for minimizing uncertainty by differencing simulation results between baseline and future time periods to derive relative change. The study focuses on the Soil and Water Assessment Tool (SWAT; Arnold et al., 1994) as implemented through the Automated Geospatial Watershed Assessment (AGWA; Miller et al., in press; [www.tucson.ars.ag.gov/agwa/](http://www.tucson.ars.ag.gov/agwa/)) modeling interface.

## 2. STUDY AREA

AGWA-SWAT was applied to the Upper San Pedro River Basin above the USGS Charleston gauge (Figure 1). The San Pedro River flows north from Sonora, Mexico into southeastern Arizona. The area is a transition zone between the Chihuahuan and Sonoran deserts and has a highly variable climate with significant biodiversity. The study watershed is approximately 3196 km<sup>2</sup> and is dominated by desert shrub-steppe, riparian, grasslands, agriculture, oak and mesquite woodlands, and pine forests. Large changes in the socio-economic framework of the basin have occurred over the past 30 years, with a shift from a rural ranching economy to considerably greater urbanization.

Satellite data were acquired for the San Pedro basin for a series of dates over a period of 25 years: 1973, 1986, 1992, and 1997. Landsat Multi-Spectral Scanner (MSS) and Thematic Mapper (TM) satellite

images have been reclassified into 10 land-cover types with 60-meter resolution. The most significant changes were large increases in urbanized area, mesquite woodlands, and agricultural communities, and commensurate decreases in grasslands and desert scrub (Kepner et al., 2002).



**Figure 1.** Map showing the location of the Upper San Pedro River Basin and the watershed discretization for SWAT, with 53 subwatersheds.

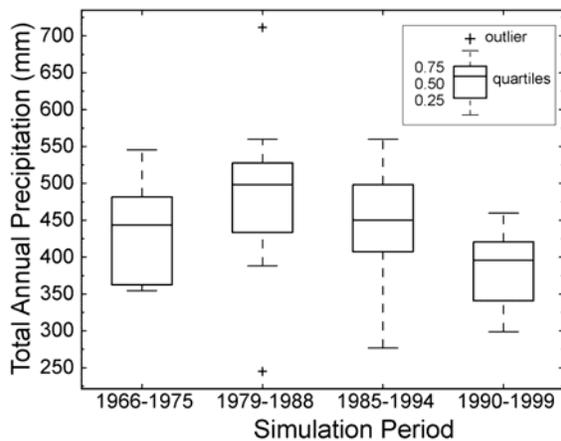
## 3. METHODS

AGWA was used to delineate the Upper San Pedro watershed, subdivide it into model elements (subwatersheds and stream reaches), and derive an initial parameter set and input files for SWAT using the 1973 land cover. Precipitation inputs were derived from a total of seven National Weather Service gauges within the basin, and distributed across the subwatersheds using a Thiessen polygon weighting scheme. Agricultural withdrawals and diversions were incorporated into this default parameter set, and model performance was noted for the period from 1966-1975. The year of 1966 was defined on the basis of utilizing the maximum number of rain gauges with continuous daily rainfall records. A calibration exercise was then carried out for the same period. SWAT was calibrated for base flow, surface runoff, and water yield. Results from the automated base flow separation program (Arnold et al., 1995) were used to identify the groundwater contribution to the total water yield.

Additional “future” simulations based on the 1986, 1992, and 1997 land-cover/use grids were carried out for the equal-length periods of 1979-1988, 1985-1994, and 1990-1999, respectively. They incorporated all known changes to agricultural water

withdrawals and diversions. Management actions such as these are a common component of alternative future scenarios, and considered to be something that can reasonably be projected along with land use. Simulations for the future conditions were carried out in two ways: once with no calibration using the default parameter set derived from AGWA, and once using optimized parameters from the baseline conditions. For the latter, parameters not derived from land-cover datasets were retained in all simulations; parameters derived from land cover were first estimated using each data set and then adjusted in the same way they were during the calibration (e.g. 10% reduction in Curve Number).

Climatic inputs for all simulations were treated in two ways. Simulations were run first using the observed daily precipitation and temperature associated with each simulation period. Figure 2 provides a summary of the total annual precipitation during each of the four 10-year simulation periods. The simulations were then repeated using precipitation and temperature from the 10-year calibration period for the three “future” scenarios (i.e. 1986, 1992, and 1997). The latter treatment of climate is the most practical means of deriving climatic inputs for future simulations, and has the added benefit of eliminating climatic variation from assessments of hydrologic response to landscape change. Together, the two treatments of climatic inputs provide a means of estimating the proportion of model uncertainty in future simulations that is associated with unknown climatic conditions.



**Figure 2.** Box plot showing the spread and distribution of total annual precipitation for each simulation period.

Four simulations were thus carried out for each of the four simulation periods to yield a total of 16

simulations. Results were compared in terms of Nash Sutcliffe model efficiencies relative to observed water yield for each simulation. A second set of comparisons was then carried out to determine how the model fared in terms of predicting change relative to the 1973 baseline condition. Simulation results for the baseline condition were subtracted from those for the three future conditions to compute relative percent change in the average annual water yield according to (1):

$$[\text{future} - \text{baseline}] / \text{baseline} * 100 \quad (1)$$

AGWA incorporates the functionality to do this automatically for each pair of simulation results and for each model element, producing what is effectively a new set of results (percent change) for each model element that can be mapped over the watershed. Although insufficient data are available to evaluate predicted change across the watershed, a visual comparison of distributed results was made to evaluate whether the model was able to qualitatively predict the spatial patterns of hydrologic response when calibration-period (historic) climate inputs were used, and when the model was not initially calibrated. In addition, all results were compared with observed change at the watershed outlet.

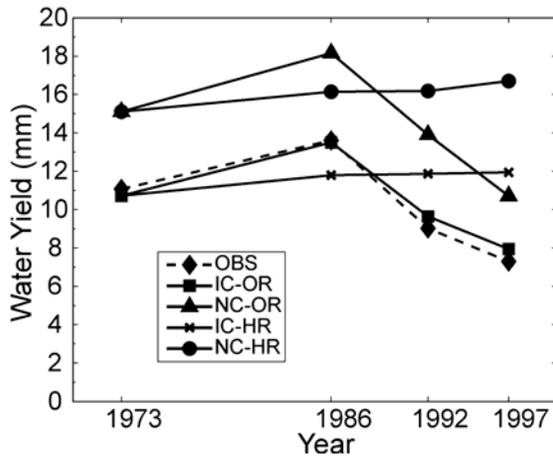
## 4. RESULTS AND DISCUSSION

### 4.1 Model Performance

As expected, results from the initially calibrated simulations using observed climate data best reproduced the observed conditions for all simulation periods (Figure 3). Uncalibrated simulations using observed climate data captured the trends quite well, and although they over-predicted water yield, they did so consistently. Also as expected, simulations based on the historic climate inputs vary considerably from those based on observed inputs. Predicted water yield increases with time reflecting land-cover/use change in the basin, but the much stronger influence of climate renders meaningless projections of water yield at any point in the future. Uncalibrated simulations produce an almost identical trend of increasing water yield with time, consistently over-predicting the initially calibrated simulations.

Model efficiencies for the initially calibrated simulations using observed climate inputs were quite good, although they declined somewhat for the most distant “future” simulation (Table 1). Uncalibrated

simulations using observed climate inputs had much lower efficiencies that declined slightly with time. Simulations based on historic climate inputs had lower model efficiencies that declined over time.



**Figure 3.** Observed and simulated average annual water yield (mm) for the simulation period around each land-cover dataset. Simulations are abbreviated as: initial calibration (IC), no calibration (NC), observed rainfall (OR), and historic rainfall (HR).

**Table 1.** Nash Sutcliffe model efficiencies for the simulation periods around each land-cover dataset

Simulation	1973	1986	1992	1997
Initially calibrated, observed climate	0.89	0.72	0.94	0.5
No calibration, observed climate	0.04	0.25	-1.21	-1.4
Initially calibrated, '66-'75 climate	0.89	0.21	-1.2	-4.69
No calibration, '66-'75 climate	0.04	0.12	-4.65	-13.9

#### 4.2 Relative Change Assessment

Percent change in average annual basin water yield was also dominated by climatic inputs (Table 2). Both sets of simulations using observed climate inputs reasonably predicted the observed change in water yield. Interestingly, the initially calibrated simulations did not yield better predictions of change. Simulations based on historic climate inputs were not able to predict the magnitude of observed changes in water yield.

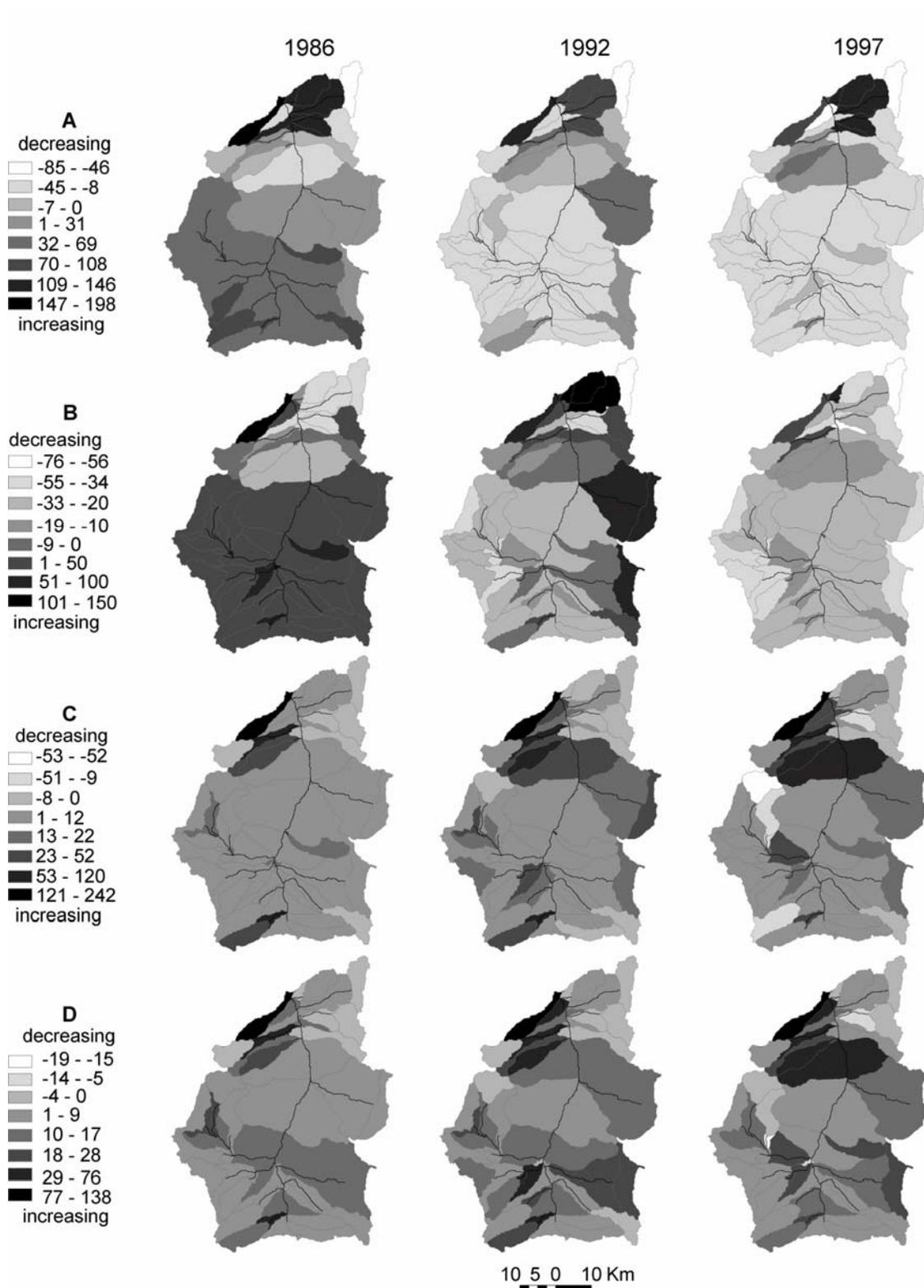
Although no data are available to confirm the spatial patterns of change, values predicted by the initially calibrated simulations using observed climate data are the best available means of estimating them.

Figure 4 presents maps of the percent change in water yield predicted by the four simulation methods for each of the three “future” conditions. Although the values in the legends indicate a substantially different range of values between the sets of simulations, it is noted that some of the major spatial patterns of predicted change are reasonably similar despite the different, distributed precipitation inputs used. Subwatersheds exhibiting the greatest change (positive and negative – lightest and darkest colors) in water yield match well between all four sets of simulations. Despite the dominant influence of climate on hydrologic response at the basin scale, it appears that land-cover changes are locally significant enough to be the dominant influence on relative water-yield changes. This effect is more pronounced (i.e. change assessments match more closely) during the drier 1992 and 1997 simulation periods.

**Table 2.** Observed and simulated percent change in average annual water yield from the 1973 baseline condition

Simulation	1986	1992	1997
Observed change	22.85	-18.52	-34.15
Initially calibrated, observed climate	25.93	-10.07	-25.93
No calibration, observed climate	20.2	-7.95	-29.07
Initially calibrated, '66-'75 climate	9.98	10.63	11.38
No calibration, '66-'75 climate	6.85	7.15	10.6

A quantitative comparison of the predicted hydrologic response to landscape change was performed by computing the correlation coefficients between the water-yield change results for individual subwatersheds in each simulation period (Table 3). Results show strong correlations between the spatial change predicted by the A simulations and that predicted by the B, C, and D simulations. Correlations are highest between the A and B simulations based on observed climate data, and lowest between the A and D simulations, which differ in terms of calibration and climate inputs. Correlations are lowest for 1986, which is the wettest of the four simulation periods. This result supports the interpretation of the previous paragraph; during periods characterized by higher precipitation, climate is more likely to dominate hydrologic response.



**Figure 4.** Maps showing change in water yield relative to 1973 baseline for: A) initially calibrated simulations using observed climate, B) uncalibrated simulations using observed climate, C) initially calibrated simulations using historic climate, and D) uncalibrated simulations using historic climate.

**Table 3.** Correlation coefficients relating the spatial predictions of water-yield change from the A simulations to those from B, C, and D for each “future” landscape condition.

Correlation	1986	1992	1997
A-B	0.812	0.834	0.830
A-C	0.481	0.784	0.815
A-D	0.478	0.732	0.715

## 5. CONCLUSIONS

This paper explores some of the difficulties associated with the use of a GIS-based hydrologic model as a predictive tool to guide planning-related decision support. Results demonstrate that if future land-use/cover and climate conditions are known precisely, the model does a satisfactory job of predicting observed conditions almost 25 years into the future. With initial calibration to baseline conditions, the model was able to provide reliable, quantitative estimates of average annual water yield. Significant performance declines were not observed until somewhere between 19 and 24 years into the future. Without calibration to a baseline condition the model was unable to provide quantitative estimates of average annual water yield, but was able to predict changes over time just as well as it did with initial calibration.

Unfortunately, future land-use/cover and climate conditions can never be known with certitude. The goal of regional planning efforts is to explore desired outcomes, and it is assumed that policy can be used to shape future change and guide it towards a particular outcome. As a result, climate conditions are the primary unknown in projecting future hydrologic response. Results of the present study indicate that by holding climate constant, it is possible to evaluate qualitatively the broad spatial patterns of hydrologic response to landscape change within a basin. Even when calibration for baseline conditions is not possible (i.e. for an ungauged basin), it is still possible to identify a significant portion of areas that are likely to experience the greatest amount of change, both positive and negative, and provide useful, qualitative information for planning-related decision support.

Given the sensitivity of hydrologic response to climatic conditions, future research will focus more attention on the use of climate scenarios to characterize hydrologic response for a range of climatic conditions. With a suitable weather

generator it may be possible to partition predicted hydrologic response into the portions derived from land-cover/use and climate change for a range of climatic conditions. If successful, this methodology could provide a means of deriving quantitative estimates of hydrologic response for various future land-cover/use scenarios.

## 6. REFERENCES

- Arnold, J.G., Williams, J.R., Srinivasan, R., King, K.W. and Griggs, R.H., 1994, SWAT-Soil Water Assessment Tool. USDA, ARS, Grassland, Soil and Water Research Laboratory, Temple, Texas. (<http://www.brc.tamus.edu/swat/>)
- Arnold, J. G., Allen, P. M., Mutiah, R., Bernhardt, G., 1995. Automated Base Flow Separation and Recession Analysis Techniques. *Ground Water*, 33(6): 1010-1018
- Kepner, W.G., Edmonds, C.M. and Watts, C.J. 2002. Remote Sensing and Geographic Information Systems for Decision Analysis in Public Resource Administration: A Case Study of 25 Years of Landscape Change in a Southwestern Watershed. EPA/600/R-02/039
- Kepner, W.G., Semmens, D.J., Basset, S.D., Mouat, D.A., Goodrich, D.C., 2004, Scenario analysis for the San Pedro River, analyzing hydrological consequences for a future environment. *Environmental Modeling and Assessment*, v. 94, p. 115-127.
- Miller, S.N., D.J. Semmens, D.C. Goodrich, M. Hernandez, R.C. Miller, W.G. Kepner, and D.P. Guertin., *In Press*, The Automated Geospatial Watershed Assessment Tool (AGWA); *Environmental Modeling and Software*.
- Smith, R.E., Goodrich, D.C., Woolhiser, D.A., and Unkrich, C.L., 1995, KINEROS - A kinematic runoff and erosion model. Chap. 20 of *Computer Models of Watershed Hydrology*, Singh, V. J., Ed., Water Resources Pub., Highlands Ranch, Colo., pp. 697-732.
- Steinitz, C., H. Arias, S. Bassett, M. Flaxman, T. Goode, T. Maddock III, D. Mouat, R. Peiser, and A. Shearer, 2003, Alternative Futures for Changing Landscapes: The Upper San Pedro River Basin in Arizona and Sonora; Island Press, Washington, 202 pp.