Predicting the Affects of Climate Change on Global Rivers:

A review

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I. Abstract

Climate change is not simply a rising of global average temperature, but will also affect many different processes on the surface of the earth in unknown ways. This review presents two different types of models used to predict changes in river systems in response to climate change. The first model, termed the Climate Forcing Model, uses Global Circulation Models forcing various surface models to predict river hydrology. The second model, termed the River Characterization Model, uses a large global database of many rivers to create predictive relationships among variables. The strengths and weaknesses of these models are discussed including their sensitivity analysis techniques. In conclusion, we find both models to be valuable in different situations and a useful way to check one another.

II. Introduction

Rivers take up an interesting place within the wide study of climate. When investigating the climate as a whole, rivers are mere conduits for runoff to return water to the sea. However, these conduits are some of the most dynamic and complex systems shaping the earth's surface, and are of extreme importance to the human population, which rely on rivers in myriad ways (Nijssen et al. 2001, Vörösmarty et al. 2000). Since climate science is mostly being undertaken to predict the needs of humans in the future, rivers must play both the role of a simplified piece of a model, and a complex subject of study in its own right. This review investigates the methods currently being used to predict river change as forced by climate change.

This review will investigate two different approaches to river prediction. The first approach is to run one or many climate models over a river basin and to force a river as its climatic inputs change. We call this method the Climate Forcing Model. This review will develop this method primarily through the works of Nijssen et al. (2001) and Hamlet and Lettenmaier (1999). This method has been used since the advent of global circulation models, and is a logical step that connects a newly predicted climate with some of the direct impacts it will have on the human population. The second approach seeks to find general relationships between parameters in the hydrology of rivers. It then takes the conclusions from various climate studies and seeks to force a river parameter through its general relationship with a climatic parameter. This approach will be referred to as the River Characterization method and will be developed here along the lines of Syvitski et al. (2003) and Mulder and Syvitski (2006). This review will conduct a detailed investigation into each of these models. A comparison of the two methods will follow, including the strengths and weakness of each method. Finally, conclusions will be drawn from the analysis of these systems and recommendations made for the use of each system.

III. Motivation

One cannot overstate the complexity of the Earth's climate system, but it is as dangerous to assume that rivers are simple in comparison. Rivers have been an object of intense scientific study for the last century. The overarching conclusion of this scientific body of work is that rivers are incredibly dynamic processes incorporating many different processes in their systems (Schumm, 2005). The mere idea of compounding the enormous task of modeling climate with the modeling of a river's consequent actions is daunting. However, this investigation is of utmost importance to the world today.

Since its inception, the study of climate change has been inherently linked to the concept of global warming. Although there is no doubt that average temperatures will rise, it is hardly the most disastrous consequence of climate change. Due to the variability of the atmospheric climate system, it is doubtful that humans will be able to perceive any trend in temperature during their lifetimes. What humans will notice are the myriad ways that this slight change in temperature will affect more tangible parts of their lives. Scientists have predicted the increase in intensity of extreme weather events (IPCC, 2007), the upheaval and migration of entire ecosystems (IPCC, 2007), rises in sea level (IPCC, 2007). Due to the integrated, diverse, and widespread nature of our civilization, virtually every aspect of human life can be seen as somehow dependent on climate and therefore vulnerable to climate change. Rivers are no exception. Because rivers cover the globe as thoroughly as humans do, river change induced by climate change is a sobering prospect (Vörösmarty et al. 2000). Therefore, it a necessary task to predict river change with respect to climate change.

Modeling river transport does not appear to be that complex at first. After all, the water obeys all the laws of continuum mechanics and the Navier-Stokes Equation can characterize flow in rivers as well as flow in the atmosphere. Sediment also moves through river systems, but there is a strong body of literature that characterizes entrainment, transport, and deposition. (e.g. Wiberg and Smith, Exner, 1920). The frustrating thing is that rivers simply do not behave this simply. Stanley Schumm sums up the difficulty in predicting river systems in his book, *River Variability and Complexity* (Schumm, 2005, Preface):

> It must be recognized that rivers differ among themselves, and through time, and one river can vary significantly in a downstream direction. If the morphology and behavior of large alluvial rivers are determined primarily by hydrology and hydraulics, long reaches of alluvial rivers should maintain a characteristic and relatively uniform morphology. In fact, this is not the case, and the variability of large alluvial rivers is an indication that hydraulics and hydrology are not always the dominant controls.

This, of course, is disastrous to the prospect of modeling and is where much of process geomorphology has focused of late (e.g. Jerolmack and Mohrig 2007). In order to get anywhere in the prediction of rivers with respect to climate, one must at first step back from this complexity in rivers. Recently, this has been done in two ways, each described below.

IV. River Models

A. Climate Forcing Model

The climate forcing method of river prediction makes certain key assumptions about flow through a watershed, and then forces the system with a General Circulation Model (GCM). Important recent examples of this work include Hamlet and Lettenmaier (1999) which predicted the effects of climate change on the Columbia River Basin, and Nijssen et al. (2001) which did much the same thing for nine of the world’s largest river systems.

The first major step in the climate forcing method is scaling down a GCM to a size where it is dense enough on the selected watershed to resolve. The way this is normally done is to have a nested, small scale, high grid-density, climate model over the watershed of choice that is surrounded by a standard, low grid-density GCM (Nijssen et al. 2001). The watershed-scale GCM is then forced by the global GCM. This set up is very computationally intensive and must be designed carefully in order to keep downscaling biases small.

The second step in the climate forcing method is to make assumptions about river flow. As explained above, this is inherently difficult. The common method of doing this is to collapse all of the complexities on river systems into a Variable Infiltration Capacity Model (VIC) (Nijssen et al., 1997). VICs have been used in many different climate simulations. These models commonly capture many different things (from Nijssen et al. 2001):

- Subgrid variability in land surface vegetation classes;
- Subgrid variability in the soil moisture storage capacity, which is represented as a spatial probability distribution
- Subgrid variability in topography
- Drainage from the lower moisture zone (baseflow) as a nonlinear recession

- Spatial subgrid variability in precipitation

The moisture fluxes from a VIC are in turn routed down elevation using a separate routing model (e.g. Lohmann et al. 1998).

This approach uses three separate models: Global Circulation Model, the Variable Infiltration Capacity Model and the Flow Routing Model. Because they are independent of one another, different models can be changed in and out. The general consensus is that the average of many GCMs is a more realistic estimate of climate than any single model so it is common to use a few GCMs in this approach. The figure below is from Nijssen et al. 2001.

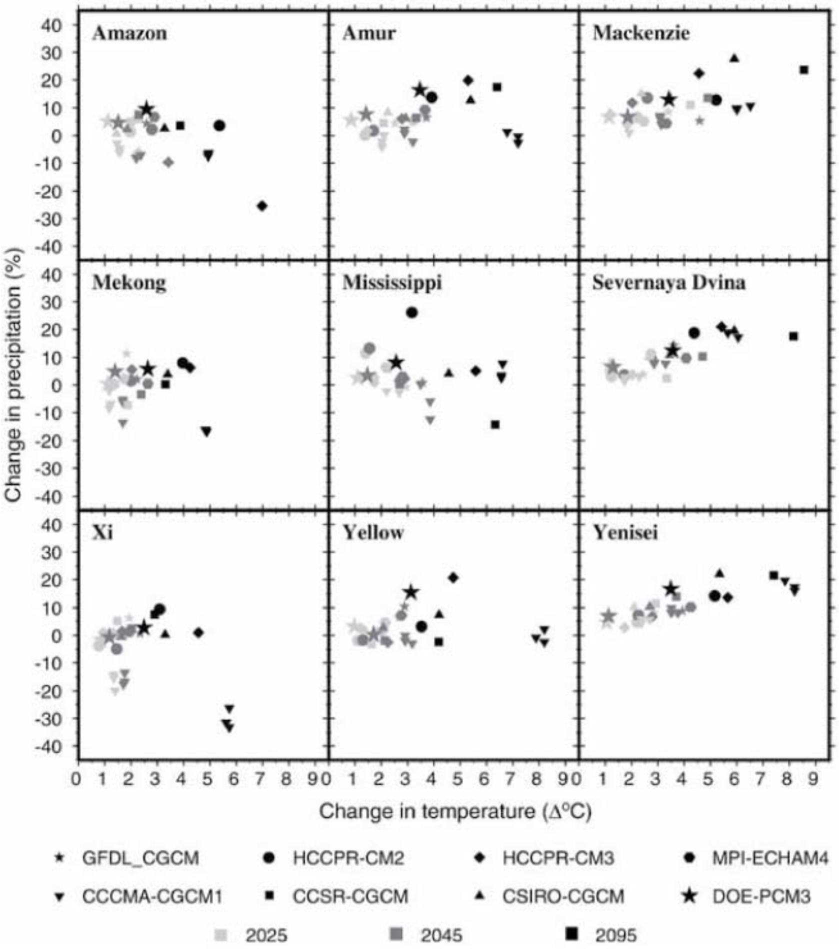


Figure 2. Predicted changes in mean annual temperature and precipitation for each river basin for the decades 2020–2029 (2025), 2040–2049 (2045), and 2090–2099 (2095). Note that climate prediction for 2095 were not available for GFDL-CGCM and MPI-ECHAM4. Also note that the CCCMA-CGCM model provided three ensemble runs, all three of which are plotted.

The figure above shows that there is a wide variability in the predictions of the climate models for each different time horizon.

With the results from the different models and detailed sensitivity analysis, one can begin to predict change in river hydrology. The figure below (from Nijssen et al. 2001) shows the predicted hydrograph for the nine subject basins for the decade 2040-2049.

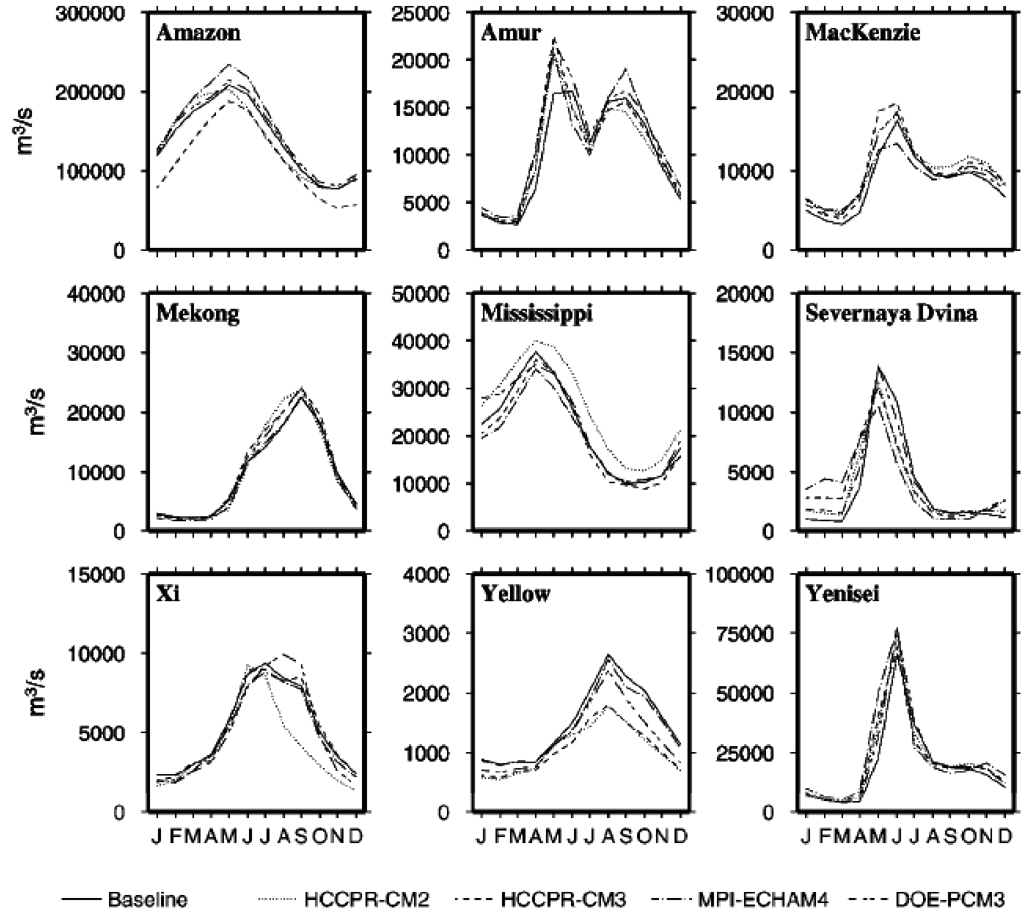


Figure 7. Mean monthly hydrographs for the nine basins for the baseline and climate model simulations in 2040–2049.

After exhaustive analysis of the interaction of the models with the basins, Nijssen et al. (2001) can make a number of conclusions about the rivers:

- All models predict warming in all basins.
- The largest changes in hydrologic cycle occur in the snow dominated basins.

- Different sensitivities manifest at different latitudes
- Overall reduction in mean annual stream flow

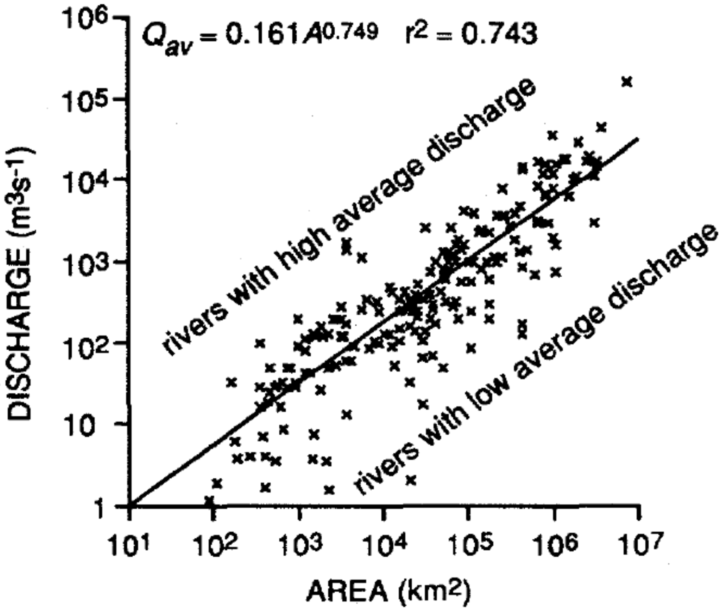
These conclusions are echoed by Hamlet and Lettenmaier (1999), who predict that the Columbia River basin will generally switch its time of high flow from the summer to the winter.

B. River Characterization Method

The River Characterization Method is based on the assumption that rivers across the planet are similar in aggregate, and therefore can be scaled to one another. The goal of the method is to isolate a few river basin parameters that have a large effect on the hydrology of the system, and to express various traits of the system as a function of those important parameters. If a river system can be predicted by-in-large by a few parameters, and climate science predicts that one or more of these parameters are changing, then the river hydrology can be expressed directly as a function of that change.

The River Characterization Method is based on the assumption that all rivers are alike. We have already discussed why this assumption is problematic. However, this method argues that since all rivers are governed by the same equations and force balances, they must be statistically similar on some level. Although this method is useful in a climate science setting, it is unique because it uses no initial assumptions concerning climate. This distinguishes it on a fundamental level from Climate Forcing Method.

The River Characterization Model requires assembling a suite of characteristics of a statistically large number of rivers (typically hundreds to thousands). It is important that the database has rivers found in all environments that the model is trying to predict (Syvitski, 2002). The next step is to find the most important factors that predict the hydrology of a river. For instance, Mulder and Syvitski (1996) find a relationship between river basin area and discharge:



According to these data, there is a power law relationship between Average Discharge and Area. The r^2 value means that approximately 75% of the system's variability can be attributed to basin area. Syvitski et al. (2003) used similar techniques to find

$$Qs=\alpha R^{1.5}A^{0.5}e^{kT},$$

where Qs is average river sediment flux, *R* is basin relief (i.e. difference between highest point in the basin and gauging station), *A* is basin area, *T* is average basin temperature, and *k* and α are constants. This equation successfully predicts pre-anthropogenic sediment flux to within a factor of two for 75% of global rivers spanning five orders of magnitude in basin area and discharge. The figure below compares the observed value of Sediment Load and the value predicted by the model (from Syvitski et al. 2003).

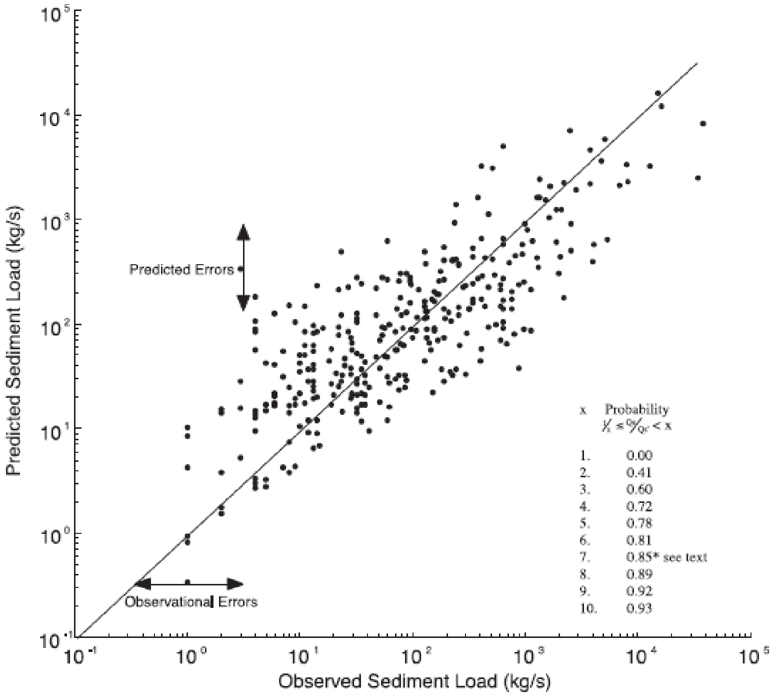


Fig. 7. Sediment load prediction based on predicted basin temperature, reported drainage area, DEM relief using $Qs = \alpha_3 A^{\alpha_4} R^{\alpha_5} e^{kT}$ and coefficients listed in Table 4. Observational errors include loads estimated from too few samples; samples collected over too few years, monitoring that does not capture the high-energy events, measurement techniques, and human impacts. Predicted errors include those related to input variables, and impact of local geography (e.g. lakes) or local geology (highly erodible rocks).

Because this model shows Sediment flux to be dependent on basin temperature, we can see that it will be affected by the temperature increases predicted globally by climate science. When this equation was applied to the Colville River (an Alaskan river with an arctic climate), Syvitski et al. (2003) predict a 22% increase in sediment flux for every 2˚C in average basin temperature.

V. Discussion of Models

A. Assumptions, Strengths & Weaknesses

Two models of river hydrology prediction developed above are founded on different assumptions, and as a result they produce predictions in extremely different ways. Having this plurality in modeling approaches is beneficial to studying changes in river hydrology because it is more productive to evaluate a model by comparing it another.

The Climate Forcing Model of river prediction is based on the fundamental assumption that the models it uses (Global Circulation, Variable Infiltration Capacity, and Runoff) are reasonable models. It is beyond the scope of this review to fully evaluate such an assumption, but the truth is that models are simplifications by definition and therefore will always have their limitations.

Models as simplifications are beneficial to models such as the Climate Forcing Model because it is so easy to exchange one GCM for another. This makes the model equally as robust for any scenario. That models fall short of reality works both for and against the validity of the Climate Forcing Model. Because of the interconnected and coupled nature of the physical world, the more complete a GCM is, the more difficult it would be to substitute in and out of the Climate Forcing Model.

One of the major problems with this method is the downscaling associated with projecting climate data for river basins. Global Circulation Models are constantly improving their resolution in both space and time, but the biases involved in downscaling data are still dangerously close to being too large to draw conclusions from (Doherty and Mearns, 1999). This means that the Climate Forcing Model will behave well for large river basins (e.g. Nijssen et al 2001, Hamlet and Lettenmaier, 1999), but will accrue more error as the basin area decreases. This limits the usefulness of the method only to large basins, and will only overcome this as models improve their resolutions and downscaling techniques.

The River Characterization Method is based on two assumptions. The first assumption is that rivers are statistically similar in aggregate. The second assumption is that data about the truly important parameters can be taken. The first assumption seems to contradict the discussion above about the complexities or rivers. This is not the case. Instead, it argues that if enough rivers are analyzed, then if a change affects a river basin, it will simply become similar to another analyzed basin somewhere else in the world. Data analysis shows that predicted values match observed values quite well in many cases. However, this assumption will not perform well if there are global trends that are not logged in the database. If, for instance, anthropogenic modification covaried with latitude (Syvitski et al, 2005), then this method would falsely ascribe variance due to humans as variance due to latitude, and the model would not perform well when anthropogenic modification was abnormally high for a certain latitude.

The second assumption relies on our ability to assemble a robust database. Both quality and quantity are an issue here. These studies would be meaningless if the size of the dataset is not statistically significant. The more difficult problem lies in confirming the quality of the data collected. Syvitski et al. (2005) think that the largest unquantified sources of error in their databases come from anthropogenic modification and from not gauging long enough to capture the largest (lowest frequency) floods.

The indisputable benefit of the River Characterization Model is that it is scale independent. Syvitski et al. (2003) shows that its model for characterizing sediment load works to within a factor of two for 75% of rivers with loads between 10^0 kg/s and 10^5 kg/s. This is certainly a valuable tool for river engineers to predict river changes due to climate change.

The main drawback to the River Characterization model is that it yields no information about the dynamics of the river change. That the Coleville River (Alaska) will grow by 22% for every 2˚ C of warming is valuable information, but difficult to evaluate if there is no information concerning how fast the change will occur. Syvitski et al. (2003) claim that because the predictive equation "is a function of twentieth century basin temperature, and even larger temperatures have occurred during the last 100 years since the Little Ice Age (Syvitski, 2002), change in sediment load due to climate warming would likely occur within decades. (Syviteki et al. 2003)" More research needs to be done before this inference can be confirmed. There is also no way of know if current global rivers are in equilibrium. If they are not, then they cannot be used to predict equilibrium conditions in the future.

B. Sensitivity Analysis

The best way of assessing change with a model is through sensitivity analysis, and both of the models examined in this review use it. The Climate Forcing Model is a concatenated group of models, so its sensitivity is assessed by perturbing the forcing slightly and seeing how the system changes. The River Characterization Model is simply an equation, so the calculus of related rates can be used.

In Nijssen et al. (2001), the sensitivity of the Climate Forcing Model was tested by forcing a 2˚ C change in temperature for each of the nine subject river basins for each of the four seasons (DJF, MAM, JJA, SON). This forcing was propagated through their models, and changes in various aspects of the model river system could be measured. Below is a chart of relative changes in seasonal runoff (from Nijssen et al. 2001):

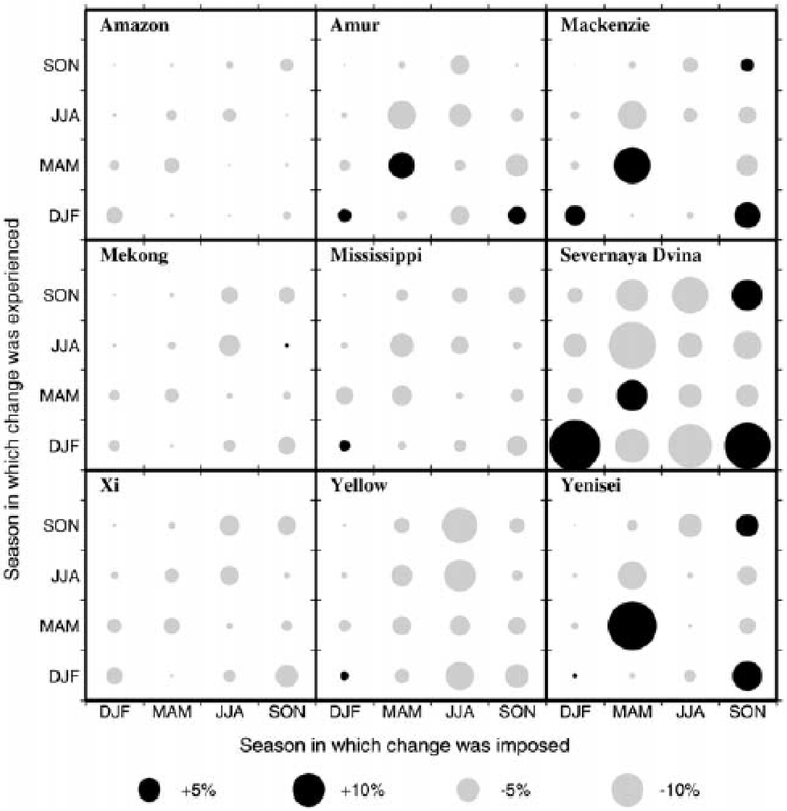


Figure 11. Relative change in seasonal runoff due to an increase in mean monthly temperature of 2 °C. For details see Figure 10 and the text.

It is obvious that seasonal runoff in the Severnaya Dvina (Russia, arctic) is much more sensitive to climate change than other rivers. It is also interesting to note that an increase in summer (JJA) temperature in the Yellow River basin (China, temperate) will decrease seasonal runoff for the entire year by a great deal, but a winter increase in temperature will do little to affect seasonal runoff.

Sensitivity analysis for the River Characterization Method is a simple study of relative rates of change. Once again, the equation for sediment load is:

$$Qs=\alpha R^{1.5}A^{0.5}e^{kT}$$

Using calculus, the change in sediment load with respect to change in temperature is:

$$dQs/dT=\alpha kR^{1.5}A^{0.5}e^{kT}$$

This is the method in which all river change estimates are calculated for the River Characterization Model.

VI. Conclusions

This review focused on two models for predicting river change as affected by climate change. The first model, termed here the Climate Forcing Model is examined via Nijssen et al. (2001). It uses a concatenation of a Global Circulation Model, a Variable Infiltration Capacity Model, and a flow routing model. The Global Circulation Model is run, using a high density grid over the watershed. The precipitation from the GCM is then routed through the VIC and the flow routing model. Rivers are predicted by the outputs of the flow routing model for various time horizons. The model used to make conclusions concerning intra-annual changes in hydrograph, and the differences in sensitivity depending on latitude.

The second model is termed the River Characterization Model and is examined primarily through Syvitski et al. (2003). It is based on a database containing a wide range of parameters for a global and statistically large set of rivers. The model uses data analysis techniques to find which variables are the most predictive. For sediment load, these parameters are basin area, basin relief, and average basin temperature. A predictive equation is then formed, and rates of change of sediment load dependent on changes in temperature are calculated.

Both methods are valuable, because they allow an independent check upon one another. The Climate Forcing Model is a strong method for predicting the dynamics of large rivers, and can shed light on the time it will take for a river to change. However, it does not perform well for small river basins and cannot deal with the inherent complexity of rivers. The River Characterization Model's strength lies in how robust it is for rivers on a large range of scales and includes the complexity of rivers. The weakness of the model is that it is static, and gives no information regarding how long it will take for river changes to take place. Each model has fundamental assumptions which are generally sound, but can lead to bias. The Climate Forcing Model is tied to the assumption that the models it uses are valid. The River Characterization Model assumes that all rivers are statistically similar. Global river databases and Global Circulation Models will continue to improve, and they will continue to improve the ability to predict changes in rivers.

VII. References

Doherty, R. and Mearns, L.: 1999, *A Comparison of Simulations of Current Climate from Two Coupled Atmosphere-Ocean Global Climate Models against Observations and Evaluation of their Future Climates*, Report to the National Institute for Global Environmental Change, Technical Report, NCAR.

Exner, F. M. 1920, Zur Physik der Dunen, *Sitzber. Akad. Wiss Wien*, Part IIa, Bd. 129 (in German).

Hamlet A.F., Lettenmaier, D.P.: 1999 'Effects of Climate Change on Hydrology and Water Resources of the Columbia River Basin', *J. Amer. Water Resour. Assoc.* **35**, 1597-1623.

IPCC, 2007: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 996 pp.

Jerolmack, D.J., Mohrig, D.: 2007 'Conditions for branching in depositional rivers', *Geology*, **35**, 463-466.

Lohmann, D., Raschke, E., Nijssen, B., and Lettenmaier, D. P.: 1998a, 'Regional Scale Hydrology: I. Formulation of the VIC-2L Model Coupled to a Routing Model', *Hydrol. Sci. J.* **43**, 131–141.

Mulder, T. and Syvitski, J.P.M.: 1996, 'Climatic and Morphological Relationships of Rivers: Implications of Sea Level Fluctuations on River Loads', *Geology*, **104**, 509-523.

Nijssen, B., Lettenmaier, D. P., Liang, X., Wetzel, S. W., and Wood, E. F.: 1997, 'Streamflow Simulation for Continental-Scale River Basins', *Water Resour. Res.* **33**, 711–724.

Nijssen, B., O'Donnell, G.M., Hamlet, A.F., and Lettenmaier, D.P.: 2001 'Hydrologic Sensitivity of Global Rivers to Climate Change', *Climatic Change*. **50**, 143-175.

Schumm, 2005: S.A., *River Variability and Complexity*, Cambridge University Press, Cambridge, UK.

Syvitski, J.P.M.: 2002 'Sediment Discharge Variability in Arctic Rivers', *Polar Research*. **21**, 323-330.

Syvitski, J.P.M., Peckham, S.D., Hilberman, R., Mulder, T.: 2003 'Predicting the terrestrial flux of sediment to the global ocean: a planetary perspective', *Science*. **162**, 5-24.

Syvitski, J.P.M., Vörösmarty, C.J., Kettner, A.J., Green, P, 2005 'Impact of Humans on the Flux of Terrestrial Sediment to the Global Coastal Ocean' *Science*. **308**, 376-380.

Vörösmarty, C.J., Green, P., Salisbury, J., Lammers, R.B.: 2000 'Global Water Resources: Vulnerability from Climate Change and Growth' , *Science*. **289**, 284-288.

Wiberg, P.L., Smith, J.D.: 1987 'Calculations of the critical shear stress for motion of uniform and heterogeneous sediments', *Water Resour. Res.***23,** 1471-1480