Optimal Element Size Analysis Using the WATFLOOD model

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Abstract

Hydrological models can be classed into various groupings; one such classification involves how the model simulates the spatial domain: distributed models or lumped models. Distributed hydrological models (generally) have much higher data requirements, require more computation time, and require a greater level of expertise for calibration than spatially lumped models. There are a large number of questions regarding the optimal methods of setting up a distributed model (e.g. the optimal discretization scheme, the optimal scheme to account for sub-grid heterogeneity, etc.). As a result, the Distributed Model Intercomparison Project (DMIP) was developed by the Hydrology Lab of the National Weather Service (NWS-HL) to address these questions. One of the main science questions in the DMIP was:

> *What is the optimal choice of computational element size to capture the essential spatial variability of precipitation in runoff generation and of flow in routing runoff to stream channels?*

This paper concerns the results obtained by the distributed hydrological model WATFLOOD, from the University of Waterloo, Waterloo, Canada. WATFLOOD is a distributed hydrological model that subdivides the watershed into grids, allowing both the land cover characteristics and the forcing meteorological data to vary throughout the basin. WATFLOOD uses the Grouped Response Unit methodology to account for land cover in-homogeneity. All areas of similar land cover within a grid (not necessarily contiguous) form a GRU, and runoff is calculated for each GRU separately. The runoff estimates for each GRU are summed to calculate the grid runoff, which is then routed downstream to the basin outlet. The model has been used for a variety of basins within Canada and around the world.

This paper addresses this question by running the WATFLOOD model with six different grid resolutions on the same basins (1 km by 1 km, 2 km by 2 km, 5 km by 5 km, 10 km by 10km, 20 km by 20 km, 40 km by 40 km). These grid resolutions represent the full range of grid sizes that are typically used with the WATFLOOD model. The effect of spatial variability of precipitation was removed by performing the simulations at each resolution with the 40 km precipitation.

The main effect of increasing the grid size was to smooth out the hydrograph peaks (there was greater attenuation for larger grid sizes). This could be corrected by changing the routing parameters of the model. The optimal grid size appeared to depend mainly on the grid size necessary to capture the routing dynamics of the watershed, and therefore depended on the size of the watershed. A minimum number of grid cells of approximately 50 are suggested. The hydrographs were not very sensitive to spatial variation in precipitation.

Keywords

Hydrological modeling, Gridded models, Streamflow routing, Grid size

1.0 Introduction

Table 1 (Singh and Frevert, 2002) lists many of the different types of hydrological models in use today. These can be classed into various groupings; one such classification involves how the model is set up in the spatial domain: distributed models or lumped models. They are both equally capable of forecasting streamflow hydrographs given enough calibration and validation data (Refsgaard and Knudsen, 1996). However, in the particular case where streamflow at an internal, ungauged location is desired, one must turn to distributed models to provide the data.

Distributed hydrological models (generally) have much higher data requirements, require more computational time, and require a greater level of expertise for calibration. Nevertheless, it is generally accepted that distributed models, which account for spatial variation in the watershed and meteorological inputs, may be able to improve the streamflow estimates derived from lumped models. However, a large number of questions remain regarding the optimal methods of setting up a distributed model.

The Distributed Model Intercomparison Project (DMIP) was set up by the Hydrology Lab of the National Weather Service to address these questions. Researchers used data provided by the NWS-HL and calculated streamflow estimates for five basins (each with internal locations). There were 15 different distributed hydrological models used in the study. This paper concerns the results obtained by the distributed hydrological model WATFLOOD, from the University of Waterloo, Waterloo, Canada (Kouwen, et al., 1993).

This paper addresses one of the main "science questions" involved in the DMIP project:

> What is the optimal choice of computational element size to capture the essential spatial variability of precipitation in runoff generation and of flow in routing runoff to stream channels?

This topic has long been recognized as an important research issue with distributed hydrological modeling; Kouwen and Garland (1989) mentioned that the effect of the resolution on the hydrologic modeling response was a topic that should be studied in greater detail. There are two main research issues within this topic: the effect of changing grid resolution on the land surface, runoff calculation, and flow routing; and the effect of averaging precipitation as grid size increases. Singh (1997) has provided a summary of research performed in these two areas, a brief summary of which is outlined below. Various authors have studied the topic, but there does not appear to be any consensus among researchers.

There has been little agreement in the optimal element size or shape to allow for optimal calculation of runoff and flow routing. The optimal element size varies widely according to different authors: 10 m (Zhang and Montgomery, 1994), 1% of the catchment area (Bathurst, 1986), 10 km (Kouwen and Garland, 1989), and at least 5 km^2 (Wolock, 1995). These are just a few examples, but they illustrate the range of optimal element sizes that have been found. There are two main categories for element shape: square grid and subcatchment (Singh, 1997). Some of the variation in element size can be accounted for by the method of calculating landscape parameters at the different resolutions. For instance, for a grid element, many authors use a simple average of the elevation in each pixel of the digital elevation model (DEM) to calculate the elevation for the grid (e.g. Zhang and Montgomery, 1994; Horritt and Bates, 2001; Yang, et al., 2001). This approach tends to smooth the DEM, and may even alter the drainage network. The approach used by Kouwen and Garland (1989) is to use the elevation of the midpoint of the river within each grid as the elevation for the grid. This method tends to maintain the drainage network as the grid size increases and allows for much larger elements, but there may still be difficulties with river slope. Other authors avoid the gridding problem by using subcatchment elements, which are based on the drainage networks. However, the use of subcatchment elements requires that the meteorological input be interpolated to each element. Wood, et al. (1988) used the Representative Elementary Area (REA), defined as the size of subcatchment needed to reduce the variability of the storm response to zero as the element size increased. The WATFLOOD model uses square grids, but a “percent drainage area” parameter is defined for each grid. The percent drainage area parameter can be used to account for basin and subbasin boundaries, where the basin or sub-basin does not cover the entire grid. This greatly improves the calculation of drainage area for the basin or sub-basin, and hence improves streamflow estimates by properly preserving drainage areas at each point along the drainage path. The differences between methods of calculating elements helps to explain the lack of consensus among authors in the area of element size and shape for capture runoff and flow routing characteristics. It would appear that the optimal element size depends on a combination of factors, such as: the underlying assumptions of the hydrological model, the size and characteristics of the catchment, the required level of detail in the solution, and perhaps other factors.

The effect of grid size on the routing component of a hydrological model has not been widely discussed but the grid size does affect the optimal time step for routing. For instance, Woolhiser et al. (1990) incorporate a criterion for the modelling time step in the KINEROS model. However, in KINEROS, it is based on the upland routing and not on the channel routing. For kinematic wave channel routing, the Courant number $\left(\beta V \frac{\Delta t}{\Delta x}\right)$ ideally has a value near 1.0. Here βV is the wave celerity, Δx is the grid size and Δt is the time step. It is not possible to attain this value for all grids if the time step is chosen to properly represent the meteorological variations driving the model. Also, in the gridded model, there is a range of channel slopes and sizes and βV can vary widely from grid to grid. Further, for different grid sizes, βV would remain the same but Δx varies. Thus if Δt is set independently of the grid size or βV, there are obvious inconsistencies in meeting the Courant criteria. Some of the implications of this are discussed by Ponce (1989). This paper addresses this question for the WATFLOOD model using a numerical experiment to show the impact of the routing assumptions on the modelling results.

Another issue in the optimal choice of element size is the problem of spatial averaging of precipitation estimates. As the element size increases, there will be greater averaging of precipitation, and this in turn, may result in a lower hydrograph peak. Singh (1997) summarised various studies of the effects of variations in rainfall on runoff. He concluded that differences in rainstorm direction, duration and intensity affected all parts of the streamflow hydrograph: peak flow, time to peak flow, and streamflow volume. Shah, et al. (1996) performed experiments with average precipitation, and found that runoff prediction errors with wet antecedent conditions were lower than the errors with dry antecedent conditions. Therefore, if a number of precipitation events occur in a short time period, the runoff error resulting from increasing the grid size will be less for the later precipitation events. For this study, the average precipitation was used to predict runoff so that the effect of spatial averaging of precipitation could be removed.

WATFLOOD is a distributed hydrological model that subdivides the watershed into grids. WATFLOOD uses the Grouped Response Unit methodology to account for land cover in-homogeneity. All areas of similar land cover within a grid (not necessarily contiguous) form a GRU, and runoff is calculated for each GRU separately. The runoff estimates for each GRU are summed to calculate the grid runoff, which is then routed downstream to the basin outlet. The model has been used for a variety of basins within Canada and elsewhere.

WATFLOOD was setup for each DMIP basin using six different grid resolutions (1 km by 1 km, 2 km by 2 km, 5 km by 5 km, 10 km by 10 km, 20 km by 20 km, 40 km by 40 km). These grid resolutions represent the full range of grid sizes that may be used with the WATFLOOD model. However, it should be noted that at the larger resolutions, it is not appropriate to attempt to calculate internal streamflow for the basins, since the size of the basins are comparable to the grid resolution and there were very few grids at these resolutions. It was also inappropriate to calculate the outlet streamflow at the larger resolutions, due to limitations in the routing scheme currently implemented in WATFLOOD. This is further examined in this paper.

The remainder of this paper first provides a brief description of the WATFLOOD model, followed by a description of the calibration technique, a description of the study basins and their discretization for the model, and finally a comparison of the results for the range of resolutions. The effect of the routing time step is determined to be the major factor in correctly applying the model consistently for the wide range of grid size used, with the variability of the precipitation field being only a minor factor.

2.0 Description of WATFLOOD

The model WATFLOOD/SPL is a physically-based simulation model of the hydrologic budget of a watershed. As with all such models, it represents only a small part of the overall physical processes occurring in nature. The model is aimed at both short-term simulations for flood forecasting and long-term water balance simulation, using distributed precipitation data from radar or numerical weather models. The processes modeled include interception, infiltration, evaporation, snow accumulation and ablation, interflow, recharge, baseflow, and overland and channel routing (Kouwen, *et al.*, 1993).

To account for the spatial variability of the hydrological variables, WATFLOOD/SPL uses the Grouped Response Unit (GRU) method to group hydrologically similar response units (Tao and Kouwen, 1989; Kouwen, *et al.*, 1990; Kouwen, *et al.*, 1993). A GRU is a hydrologic computational unit that consists of a grouping of areas that can be expected to react similarly to the same meteorological conditions. Satellite imagery can be used to determine the land cover types. In the GRU method, all similarly vegetated areas (not necessarily contiguous) within a sub-basin element (either a grid or sub-basin area) are grouped into one response unit and called a GRU. Experience to date has shown that five to eight classes are usually sufficient to represent the variability of land cover within a fairly homogeneous physiographic region. More may be needed when the study area includes more distinct hydrological sub groups, such as may happen when a basin includes mountains, prairies and boreal forests. The hydrologic response of each class is computed as if that class covered the whole element but its response (e.g. streamflow) is then weighted according to its percent cover of that element or sub-basin. The size of the element should be chosen to properly reflect meteorological variations and the streamflow system as well as computational requirements.

The meteorological forcing data can vary over the watershed, but are assumed to be uniform within a particular element. It is assumed that all pixels belonging to a land cover group respond in a similar way with respect to infiltration, surface and interflow, evaporation, snowmelt and drainage to ground water, regardless of their location within a grid. Therefore, model parameters are associated with each land cover class and are invariant over the modelled domain. In this way, there are very few “watershed specific parameters,” only parameters pertaining to land cover that are readily transferred to other watersheds. Two parameters associated with the types of rivers in the modelled area and the underlying geology are watershed-specific, although in the future these parameters will be linked to geomorphological features.

The vertical water balance component of the WATFLOOD/SPL model is a conventional hydrological model. Where it differs is in the method that watersheds and regions are subdivided to preserve the hydrological responses of greatly differing surface areas, namely by employing the GRU or pixel grouping approach. Details of the hydrological abstractions in WATFLOOD/SPL are available in previous publications (Kouwen, *et al.*, 1997, Donald, *et al.*, 1995; Kouwen, *et al.*, 1993; Tao and Kouwen, 1989). The time step for the vertical water balance is one hour whenever there is active weather (i.e. precipitation). During dry periods, the time step is allowed to increase to match the river routing time step.

3.0 Calibration technique

The WATFLOOD/SPL model has been calibrated for a number of river basins in a variety of regions across Canada. These include rural southern Ontario (Mousavi and Kouwen, 2003), the Rocky Mountains in British Columbia (Kouwen, *et al.*, 1997), the BOREAS study areas in Northern Saskatchewan and Manitoba (Neff, 1996), and the Mackenzie River basin in northwestern Canada (Seglenieks, *et al.*, 1998). A parameter set that works quite well for these very different domains has been developed (since the parameters depend on land cover, they can apply to multiple basins). The results reflect the flexibility of the model, and the robustness of the parameterization scheme. This section describes the calibration procedure for the Illinois and Blue River basins.

The parameterization schemes in WATFLOOD/SPL have been chosen so that all the parameters have physical interpretations. Although none of the parameters may be measured in the field, all have physically definable limits that have been drawn from textbooks and experience with the model. When parameters remain within these limits, the hydrological processes within WATFLOOD/SPL operate plausibly. In general, the model is calibrated manually until the internal variables (such as evaporation, snow melt, etc.) show that the model physics are operating realistically in all grids.

Manual calibration is accomplished by adjusting parameters to match various components of observed hydrographs. For instance, the base temperature for snowmelt is adjusted so that the initial rise of the computed spring melt hydrograph occurs at the proper time. The river roughness is reduced if computed peaks are consistently late and low throughout the domain. The interflow discharge coefficient is raised if the peaks are late and low only in the smaller watersheds. Recession curves are matched using the lower zone function parameters and the parameter governing recharge, based on logarithmic plots of flow versus time. Evaporation rates are adjusted to ensure annual volumes of runoff are correctly computed. Once these parameters are given these initial values, an automatic optimization scheme can be used. Boyle, *et al.* (2000) reported on a similar approach to match the various segments of the hydrograph that they labelled as “driven”, “nondriven quick”, and “nondriven slow” (corresponding to flow driven by rainfall, the “fast” portion of the recession curve, and the “slow” portion of the recession curve respectively).

Whenever possible, the internal model physics are checked by comparing computed internal parameters (e.g. evaporation, snow water equivalent, soil moisture) against measured values. This was not possible with this analysis, as no internal data were provided for the DMIP.

The above method was used to calibrate the model for the 1 km resolution initially. All of the comparisons were based on two calibrations (one for the Blue River basin, one for the Illinois River basins). In this way, the effect of the grid size on streamflow could be isolated. In the second part of the experiment, the parameters were adjusted so that the hydrographs for different resolutions would match. This was to determine the level of flexibility of the model to adjust for grid size.

4.0 Basin Descriptions

This research was performed on the five DMIP basins listed in Table 2. This paper focuses on the outlet flows only. The flows for the subwatersheds could not be calculated at the lowest resolutions because the drainage areas of the basins were comparable to the area of a single grid at the lowest resolution, and calculation of internal streamflow requires internal grids. The five basins can be divided according to location. Four of the basins, forming part of the Illinois River basin, are located at the borders of Oklahoma, Arkansas, and Missouri (Figure 1a). The Blue River basin (Figure 1b) is located in south-west Oklahoma (south-west of the Illinois River basins). The WATFLOOD model was designed primarily as a regional rather than a watershed model. It is reasonable to assume that modelling units delineated by vegetative characteristics which are are also geographically close to one another behave similarly (due to similar stratigraphy and meteorology). Thus the parameter set applies to a region (which could be very large) rather than a watershed. The data files for WATFLOOD were set up so that the four Illinois basins were calculated with a single simulation, and the Blue River basin was calculated in a second simulation.

The Hydrology Lab of the National Weather Service provided data for the DMIP basins. The WATFLOOD model used the following data: NEXRAD Stage III radar precipitation data, average basin temperature data, streamflow data (for calibration), and the DEM and vegetation data.

The main hydrological feature of the basins is that they are located in a warm, dry climate. The precipitation occurs mainly as rainfall; there are only a few snow events during the eight-year period. Yearly precipitation in the Blue basin ranged from 650 mm to 1500 mm (basin average of 900 mm to 1150 mm) in the period of study. Yearly precipitation in the Illinois basin was somewhat higher, ranging from 600 mm to 1800 mm (basin average of 1050 mm to 1300 mm) in the period of study. The majority of precipitation occurs through the winter months (from September through to May).

In terms of vegetation, the basins have very homogeneous landcover. Deciduous forest covers approximately 97% of the Illinois River basins (Figure 2a), while savannah covers approximately 88% of the Blue River basin (Figure 2b). Since the GRU approach is based on grids with a variety of landcovers, this inhomogeneity in landcover means that there is relatively little benefit in the GRU approach for these watersheds. However, the model may still be applied and the homogeneity of the land cover does reduce the amount of data required to calibrate the model properly.

5.0 File Setup for Multiple Resolutions

One advantage of the WATFLOOD model is that it is easy to set up for multiple resolutions. It is only necessary to re-interpolate the data into the new resolution, and then create new watershed files for the new resolution. The setup of the data files (i.e. precipitation, temperature) for the multiple resolutions used in this analysis was performed by one person and completed in approximately one month, with the largest portion of time allotted to re-interpolation of the radar data. The new watershed information was derived from the DEM by an automatic algorithm, but it was necessary to perform several corrections, as described below.

The first set of corrections fixed the drainage areas calculated by the automatic algorithm. If the drainage area is incorrect, the program will generate streamflow that is either too high or too low in direct proportion to the error in the discrepancy in the watershed size. Incorrect drainage area was a problem mainly for the two largest grid sizes (20 km and 40 km), since there were very few elements to represent the basin outline at these resolutions. The problem was more significant for the Illinois River basins, since there were multiple basins within one watershed information file. The drainage areas were corrected using the “percent drainage area” parameter for each grid in WATFLOOD. Secondly, the WATFLOOD model cannot allow two streamflow stations to be located in the same grid. At the 40 km resolution, the Illinois River at Tahlequah station and the Baron Fork at Eldon station were located in the same grid. Therefore, the Baron Fork at Eldon station was moved east into the next grid, and the watershed information adjusted accordingly. The calculated drainage areas for each basin for the different resolutions are compared in Table 2. All of the errors were less than 10%.

The grid elevations for each resolution are shown in Figure 3 (Illinois River basins) and Figure 4 (Blue River basin). As the resolution decreases, the basin definition becomes less accurate (although drainage area remains consistent).Changing resolution may also cause a problem with the river slope and river length. As the resolution changes, the river (or sections of it) may become flatter or steeper, and/or the river length may increase or decrease (the river length is calculated as the longest sequence of elements within the basin). These change the routing characteristics of the watershed.

A change in river slope alters the shape of the hydrograph significantly. For instance, a flatter slope would generate a more attenuated and longer hydrograph while a change in river length alters the timing of the hydrograph. In general, the 1 km resolution results in a smooth profile while the lower resolutions resemble more a "pool and riffle" type of profile, which is bound to attenuate the hydrograph due to the increased storage in the flat sections.

Figure 5 shows the river slope profiles for each basin (Tahlequah and Watts are combined as they are the same river). These four figures show that the river length increased or decreased for some of the resolutions of each basin. The images also show areas where the slope increased as grid size increased (Baron Fork shows increased river slope), and areas where the slope decreased as grid size increased (Blue River shows decreased river slope). For the latter case, the very flat section at the lower reaches of the Blue River will greatly affect the hydrograph because the peak will be attenuated as if this were a lake. To correct this problem, slopes were manually edited so that the river profile more closely matched the 1 km river profile.

The differing lengths were corrected by setting the "meander" parameter. The meander parameter describes how much a river meanders; it acts as a multiplier on the grid length to represent the "true length" of the river in the grid. The meander parameter is set according to "river type". Each basin (Illinois, Baron Fork, Elk, and Blue) was configured to be a different river type so that the meander could be set independently for each basin. In these ways, the effects of changing resolution on river slope and river length were minimized.

6.0 Comparison Between Resolutions

Careful checking of the watershed information, as described above, can minimize the effect of differing resolutions on the hydrograph. However, there are two other major factors in the hydrograph: the effect of averaging of precipitation, and the effect of changing grid resolution on routing. The first effect may be removed (and was removed for the comparison), but the second effect may not be removed so easily.

The effect of precipitation averaging was removed by using the 40 km precipitation for all resolutions. For small grid sizes, the hourly precipitation derived from the radar data will be very accurate for the grid. However, the hourly precipitation is averaged over 40 km by 40 km at the largest grid size. Small, localized precipitation events will "average out" to near zero precipitation over such a large grid, and there will be very little variation in precipitation across the basin. Therefore, it is necessary to compare the hydrographs using the same precipitation (the lowest resolution) for all resolutions. Unless otherwise stated, all of the hydrographs presented below were calculated using the 40 km precipitation for all resolutions.

6.1 Routing artifacts

The second major factor relates to streamflow routing. Usually, routing is performed (somewhat mindlessly in WATFLOOD) at a maximum time step of 1-hour to coincide with recorded hourly streamflow and the meteorological input data. For a 40 km long river and using a routing time step of one hour, the hydrograph peak will be routed over 40 hours at a 1 km resolution but in only 1 hour at a 40 km resolution. This may result in significant differences in the timing of the peak flow between the resolutions. This problem is inherent in streamflow routing. The limitations of the routing will be presented in this analysis. In this study, all of the differences in the hydrographs were due to streamflow routing, since the vertical budget processes (interception, evaporation, etc.) are scale-independent in WATFLOOD (i.e. the same relative amount of runoff is produced in each grid in each timestep, regardless of resolution).

With the exception of the "meander" parameter to make the rivers have the same length, the first set of simulations used identical parameter sets. A typical hydrograph result is shown in Figure 6 for the Illinois River at Tahlequah location for September 26 to 30, 1996. Generally, as resolution decreases, the peak flow is attenuated, the hydrograph becomes more spread out, and the peak timing is changed. Figure 7 contains charts of the simulated versus observed peaks for the largest events of each watershed. As resolution decreases, the charts generally indicate a drop in peak flow for all watersheds (there are some exceptions for some events). The decrease in peak flow and change in hydrograph shape are streamflow routing issues. At the larger grid sizes, each grid is very long, and therefore the flow experiences attenuation across each grid (greater than a smaller grid size). The attenuation decreases the peak and spreads the hydrograph out. The peak flow timing may also change as a result of streamflow routing. These problems can be partially “fixed” by changing the surface roughness. As the surface becomes smoother, less attenuation will occur as streamflow is routed through grids. However, if the peak flow arrives earlier for larger grid sizes, the surface roughness cannot correct the timing.

A second set of simulations was performed to determine if the attenuation and timing problems could be mitigated more easily than reprogramming the routing module. The surface roughness was decreased until the peak flow and hydrograph shape matched the 1 km peak flow and hydrograph shape. There were no other changes to the parameters. Decreasing the surface roughness caused the peak flow to occur earlier, and there was less attenuation of the water flow. Figure 8 shows the same event as Figure 6, after adjusting the surface roughness to more or less match the peak of the observed hydrograph and improve the timing. Figure 8 shows the negative effects of changing the grid resolution can be compensated for to some extent by adjustments to the river roughness but this can not be done in a consistent or predictable way. As the grid size is enlarged from 1 km, the roughness needed to be gradually decreased to a resolution of 10 km to improve the timing of the peaks. However, for the 20 and 40 km grids, the roughness could be increased to improve the timing but this could also reduce the peak flow by unacceptable amounts. Figure 9 contains charts of the simulated versus observed peaks for the largest events of each watershed, after adjusting the surface roughness. In general, the peak flows for all resolutions are closer. There tended to be more “spread” in the peak flows for the higher peak flows. This may be due to the difficulty of modeling the extremely large flows.

Also, the hydrograph shape becomes less defined as resolution decreases. The observed hydrograph contains a small rise and plateau, a second rise and plateau, and then the final rise and the peak flow, followed by a very fast recession curve. The 1 km resolution reproduces the undulations reasonably well. However, at the 40 km resolution, the model calculated a single rise and recession curve. The peak flow occurred near the observed hydrograph peak for the 1 km resolution, but near the beginning of the event for the 40 km resolution. The early arrival of the peak appeared to be related to the routing timestep of one hour. The lowest resolutions (20 km and 40 km) do not contain enough grid squares to be able to route a multi-part hydrograph successfully. Each of the higher resolutions shows a multi-part hydrograph (to varying degrees of accuracy). This indicates that a minimum number of grid squares is required for a reasonable simulation of the streamflow. These results indicate that it is insufficient to model the different grid sizes simply by changing the river roughness. For this reason, the effect of the routing time step on the attenuation and timing problems was investigated.

6.2 Routing time step

Figure 6 also shows a rather erratic behaviour of the time of the peak. The time to peak is decreased from the 1 to 2 km resolution, then increases from the 2 to 5 and 10 km resolutions and then decreases again from the 10 to 20 to 40 km resolution. Up to the 10 km resolution the timing seems to be affected most by the proper representation of the river length and profile. Beyond this resolution, the lack of compliance with the Courant criteria begins to affect the timing of the peak. In all cases, the routing time step was one hour or less. The detention times (storage/outflow) near the peak of the hydrograph were 3.6 to 16.8 hours at the 10 km resolution, 8.1 to 35.5 hours at the 20 km resolution and 8.1 to 62.5 hours at a resolution of 40 km. As expected, the detention time is roughly proportional to the grid size. This analysis shows that for routing in a watershed model, especially when the river geometry has been **automatically** derived from a DEM, the routing parameters need to be carefully checked by comparing computed with observed hydrographs. Furthermore, it can not be assumed that routing parameters can be transferred from one resolution to another without ensuring that the river profiles and lengths are properly derived and that adjustment in the time step be made to stay in rough compliance with the Courant criteria. The numbers also suggest that even for a given resolution, the same computational time step is not appropriate for all grids of the model because of the range of travel times encountered over the modelled domain. Thus a sub-reach routing method, where reaches are subdivided according to their travel times, would likely lead to more consistent results when hydrographs from a range of resolutions are compared.

Figures 6 to 9 clearly show the effect of a lack Courant compliance. To correct these problems, the simulation was performed again to comply more closely to the Courant criteria. It is not possible with the current implementation of the model to comply with the Courant criteria for all grids. However, it is possible to reduce non-compliance by adjusting the routing time step with the resolution. In Figure 8, the hydrographs for the 10, 20 and 40 km resolutions are well outside an acceptable range of the Courant number. There is little agreement of time to peak and peak flow. For the remaining hydrographs in Figure 8, the compliance with the Courant criteria was almost satisfied for the 1 to 5 km resolutions, and for these, the hydrographs matched more closely.

Figure 10 shows that improved compliance with the Courant criteria improves greatly the timing of the peaks but attenuation of the peak remains a problem with the lower resolutions but can to some extent be made acceptable. For these results, the time step was changed in proportion to the resolution while the river roughness was kept constant. Still, because of range in slopes for the grids, the Courant criteria cannot be satisfied everywhere when the grid size and routing time step is the same for all grids. For the 40 km resolution and 24 hour time step, the peak flow may have been completely missed because of the two data points bracketing the peak flow. The hydrograph is shifted in time by one time step and this may at least partly be due to time resolution.

Figures 8, 9 and 10 show that for a particular watershed, it is possible to obtain very reasonably the same hydrographs for a range of grid sizes. The main requirement of WATFLOOD, or any other gridded model, to determine grid size is that it is necessary to have enough grid cells for a reasonable representation of the routing dynamics. On large basins, a 20 km grid size may be appropriate, while a smaller basin may require a 5 km (or even lower) grid size. For very large watersheds (say larger than 50,000 km^2), the hydrograph is naturally of longer duration and the timing of the peak is not as critical as for watersheds of the size used for this study. For watersheds the size of the Illinois River at Tahlequah, a resolution of 1 to 5 km would be appropriate and in the normal calibration effort, the timing of the peak would be adjusted using the river roughness parameter, although arguably, more attention should be paid to the Courant number.

The results discussed above indicate and the literature on routing suggests that if the Courant criteria is adhered to, a hydraulic or hydrological model should not be sensitive to grid size. Although within a model domain a range of Courant numbers will occur due to variations in grid characteristics, it possible to reduce the negative effects by choosing an appropriate time step for each grid size. This can be further improved by selective sub-grid routing.

6.3 Precipitation effects

All of the above analysis has been performed with the 40 km averaged precipitation for all resolutions. This was done so that the effect of changing grid sizes may be isolated from the effect of changing precipitation resolution. As much as possible, the effects of changing grid size have been removed in the previous analysis. Therefore, the streamflow was calculated for each resolution using the precipitation for that resolution. Figure 11 shows two sample hydrographs for the Illinois River at Tahlequah location with the time step problem resolved by adhering as closely as possible to the Courant criteria while the river roughness was kept constant. Figure 11a (2 km resolution) shows that the averaging of the precipitation results in some smoothing of the hydrograph as expected. However, the major characteristics of the hydrograph are well preserved. On the other hand, Figure 11b shows that for the 10 km grid, the details of the response are completely lost for both the grid averaged and basin averaged precipitation.

7.0 Conclusions

This paper has compared the streamflow estimates from the WATFLOOD hydrological model using six different resolutions for a set of basins. Some general principles were established for choosing a grid resolution.

Firstly, the resolution must be chosen so that the routing dynamics can be satisfied. For instance, in WATFLOOD, it is necessary to have a sufficient number of grid cells to model the characteristics of the hydrograph. Therefore, the optimal grid size will vary according to the basin size and/or response time. For the DMIP basins a grid size of less than 5 km appears to model the streamflow accurately for the standard WATFLOOD one-hour routing time step although some adjustment of the river roughness parameters was required. It is important that the Courant criteria be adhered to in choosing the time step and/or the grid size for any application of WATFLOOD. This finding is based on general hydraulic principles and applies to any model involving routing. A previous study of WATFLOOD's sensitivity to grid size (Kouwen and Garland, 1989) recommended a minimum of 10 grid squares in a basin but this study was of limited scope. The Courant criterion was satisfied by the automatic time step reduction within the standard one-hour time step, which was adequate for the maximum 10 km grid size used.

Secondly, once the resolution is chosen, it is necessary to ensure that the drainage area and slope of the watershed are properly represented and not distorted as a result of the sampling scheme in creating the channel profile. If the channel profile is not accurate, the streamflow hydrographs cannot be expected to be correct.

Finally, the resolution of the watershed grid should be fine enough to capture the variations of the meteorological driving data. If high resolution meteorological data (1 km) is to be used that would incorporate a high degree of time and space variability, Figure 11 shows that the model quickly loses its ability to respond in detail.

Only relatively minor changes in the routing parameters were necessary to accommodate the different resolutions in the WATFLOOD model. This indicates that the WATFLOOD model is flexible and adaptable to multiple resolutions, assuming that there are enough grids in the basin to satisfy routing characteristics and output requirements as well as the appropriate resolution to incorporate the meteorological variability. However, because of this study, it has also become clear that for the common situation of a broad range of Courant numbers within a single gridded model of a watershed, sub-grid routing is needed to satisfy the Courant criteria throughout the modelled domain. For high resolutions, where a model time step of one hour is adequate to preserve the shape of the hydrograph, a reduction of the routing time step is readily accomplished and currently implemented in WATFLOOD. However, for large domains, where larger grid sizes may be desirable but the meteorological data has a time step appreciable shorter than the detention time in the reach, there is a need to perform channel routing on a sub-grid scale while performing the hydrological calculations at the grid scale.

8.0 Footnote

There are clearly situations where the effects of grid size and time step are not important as long as the numerical scheme is such that continuity is not compromised. An example is for very large watersheds where variations in flow occur slowly over periods much longer that the routing time step. For instance, in large rivers where the flow is due to snow melt in high terrain and spans most of the summer, the routing grid size and time step would have little if any effect. Another example is a watershed where flows are damped by large natural lakes, wetlands and/or groundwater reservoirs.

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Table 1 Summary of Routing Methods in Hydrological Models

Model	Routing Method
ARC/EGMO (Becker, et al., 2002, p. 355)	Linear Reservoirs - Cascade Model $C_i = c^* L_i / \gamma_i$
Hydrologic Model System (HMS) (Yu, 2002, p. 394)	Kinematic Wave with a flow-direction algorithm to account for the overland-flow delay and storage in each cell
Macro-scale Hydrologic Model (Ma and Fukushima, 2002, p. 457)	Muskingum
TOPKAPI model (Todini and Ciaparica, 2002, p. 484)	Kinematic
CEQUEAU model (Morin, 2002, p. 536)	Transfer coefficients
LASCAM (Sivapalan, 2002, p. 591)	Stream velocity * time = distance of travel
ARNO (Todini, 2002a, p. 703)	Linear routing – Hillslope to channel, in-channel (within sub-catchment), sub-catchment to sub-catchment
Large Basin Runoff Model (Croley II, 2002, p. 720)	Tank Cascade model
Runoff from Hydrologically Similar Areas (Koivusalo, et al., 2002, p. 789)	Small catchment – single linear store Large catchment – geomorphological instantaneous unit hydrograph
WISTOO (Ozga-Zielinska, et al., 2002, p. 839)	1-D Kinematic wave
CLS Model (Todini, 2002b, p.871-872)	Modified unit hydrographs – one for slow, one for fast response
DHSVM (Wigmosta, et al., 2002, p. 11)	Linear channel reservoirs
SHETRAN (Ewen, et al., 2002, p. 43)	Finite difference approx to governing equations
CASC2D (Ogden and Julien, 2002, p. 84-91)	Explicit diffusive-wave routing (overland or channel) or implicit full-dynamic channel routing
DWSM (Borah, et al., 2002, p. 119)	Kinematic wave routing
SIRG (Yoo, 2002, p. 170)	US SCS double triangle
Modular Kinematic Model for Runoff Simulation (Stephenson, 2002, p. 188)	Kinematic wave – some notes about timestep
WBNM2000 (Boyd, et al., 2002, p. 232)	Nonlinear Lag Relationships between catchments
Geomorphology Based Hydrological Model (Yang, et al., 2002, p. 272)	Hillslopes drain into main channel: Kinematic wave routing

Parched-Thirst (Wyseure, et al., 2002, p. 310)	SCS-synthetic hydrograph – time to peak of the hydrograph is 60% of time of concentration
PSRM – Penn State Runoff Model (Aron, et al., 2002, p. 375)	Kinematic Wave (overland), Muskingum (channel and reservoir)
SCS-CN-Based Hydrologic Simulation Package (Mishra and Singh, 2002, p. 400)	Single Linear Reservoir
SYNHYD (Aron, 2002, p. 470)	Muskingum (in-channel) or Modified Puls (storage routing)
Hydrometeorological models for real time rainfall and flow forecasting (Georgakakos, 2002, p. 610)	Kinematic Wave
NWSRFS (Larson, 2002, p. 697-699)	Dynamic Wave Routing, Lag and K Routing, Muskingum Routing
ANSWERS (Bouraoui, et al., 2002, p. 836)	Explicit backward difference solution of the continuity equation (change in storage=input-output)
CALSM (Pandit, 2002, p. 890)	SCS-CN

Table 2 - List of Basins used in the Study

River Basin	Short form	USGS Number	Drainage Area (km^2)
Illinois River at Watts, OK	Watts	07195500	1,645
Baron Fork at Eldon, OK	Baron	07197000	795
Illinois River at Tahlequah, OK	Tahlequah	07196500	2,484
Elk River at Tiff City, MO	Elk	07189000	2,251
Blue River at Blue, OK	Blue	07332500	1,233

Table 3 - Comparison of Drainage Areas for Different Resolutions

Basin	Drainage Area (km^2)						
	Actual	01 km	02 km	05 km	10 km	20 km	40 km
Watts	1,645	1,629	1,611	1,626	1,656	1,588	1,664
Baron	795	805	802	810	731	820	784
Tahlequah	2,484	2,459	2,430	2,400	2,512	2,460	2,596
Elk	2,251	2,201	2,159	2,152	2,136	2,224	2,176
Blue	1,233	1,232	1,246	1,201	1,223	1,140	1,319

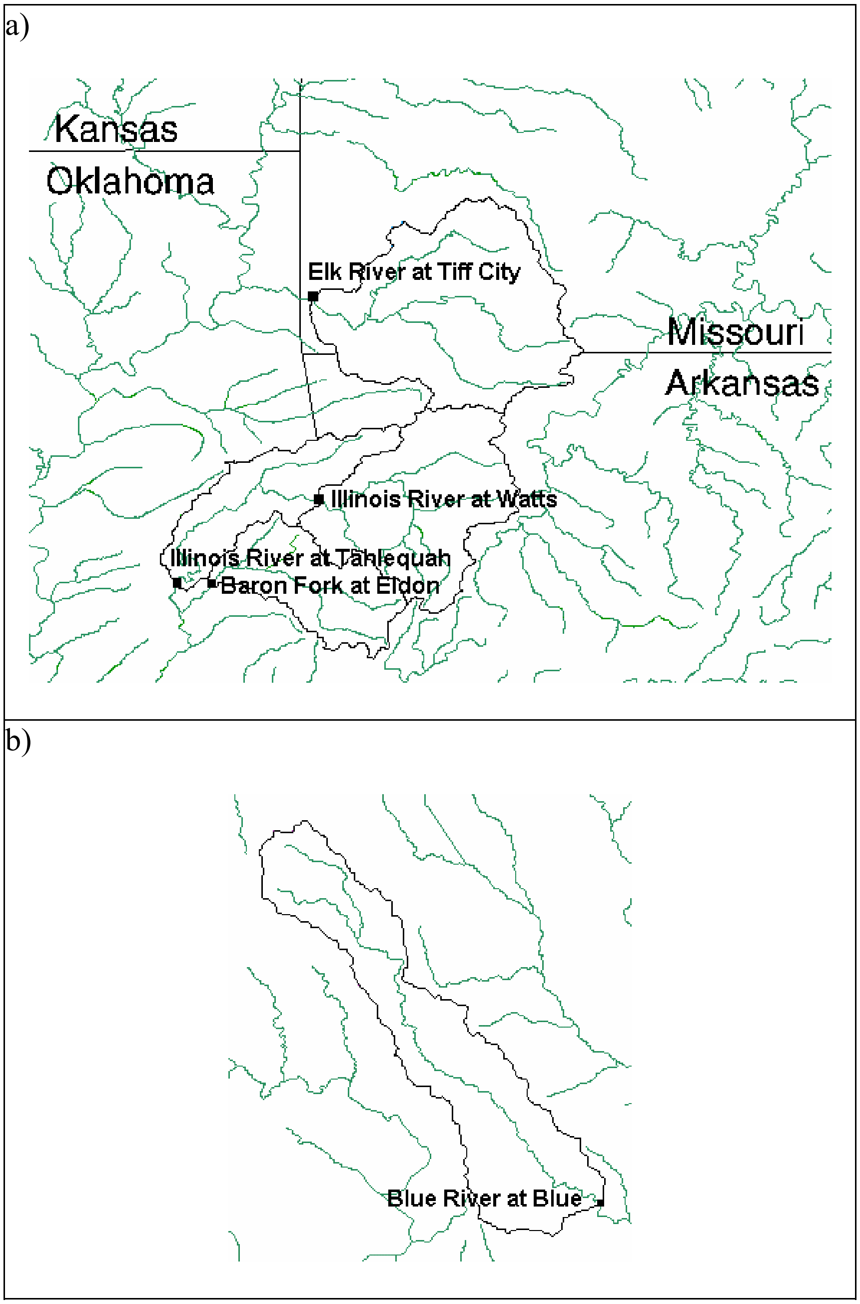


Figure 1 – Outlines of River Basins: a) Illinois River basins, b) Blue River basin

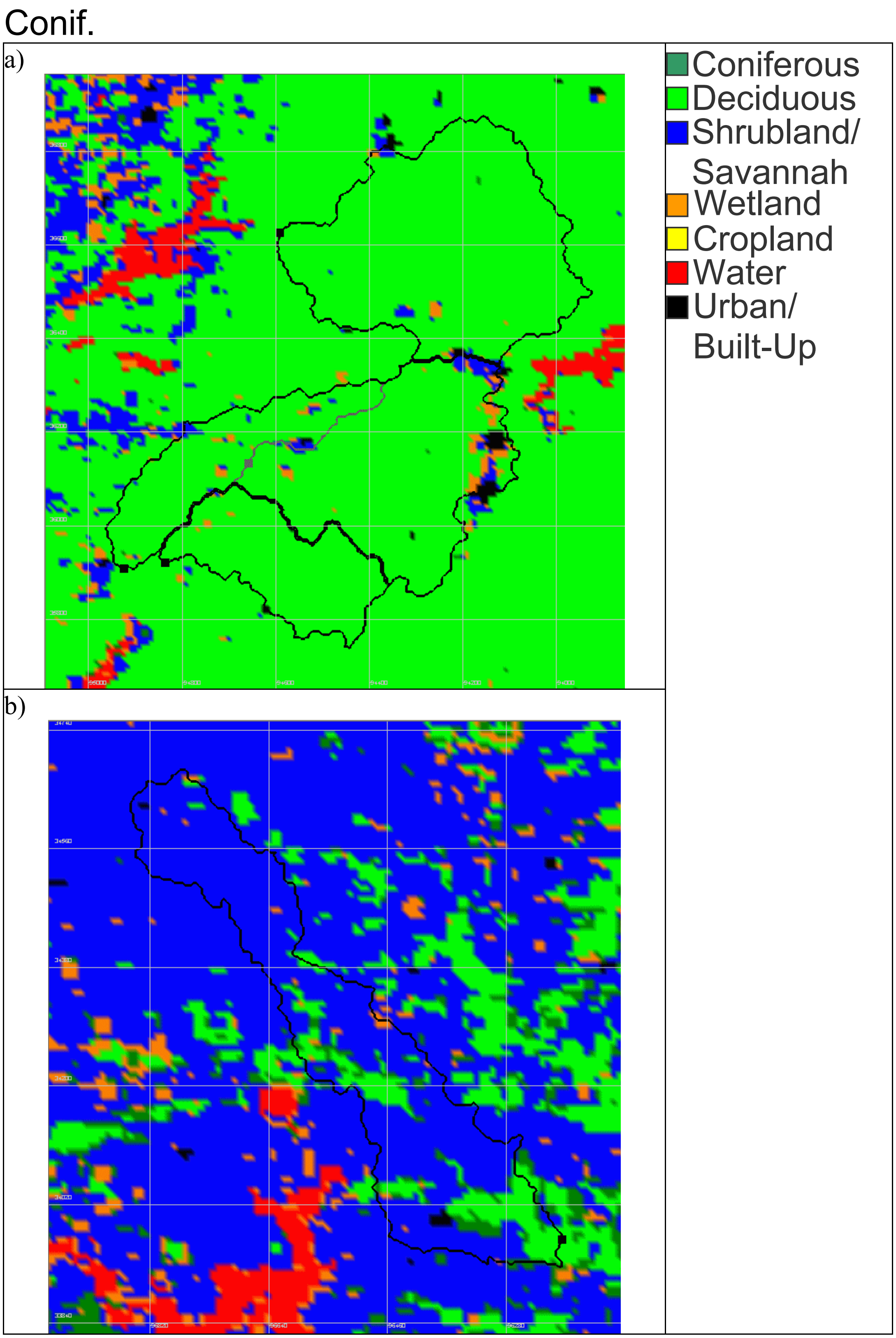


Figure 2 - Landcover images for a) Illinois River Basins and b) Blue River Basin

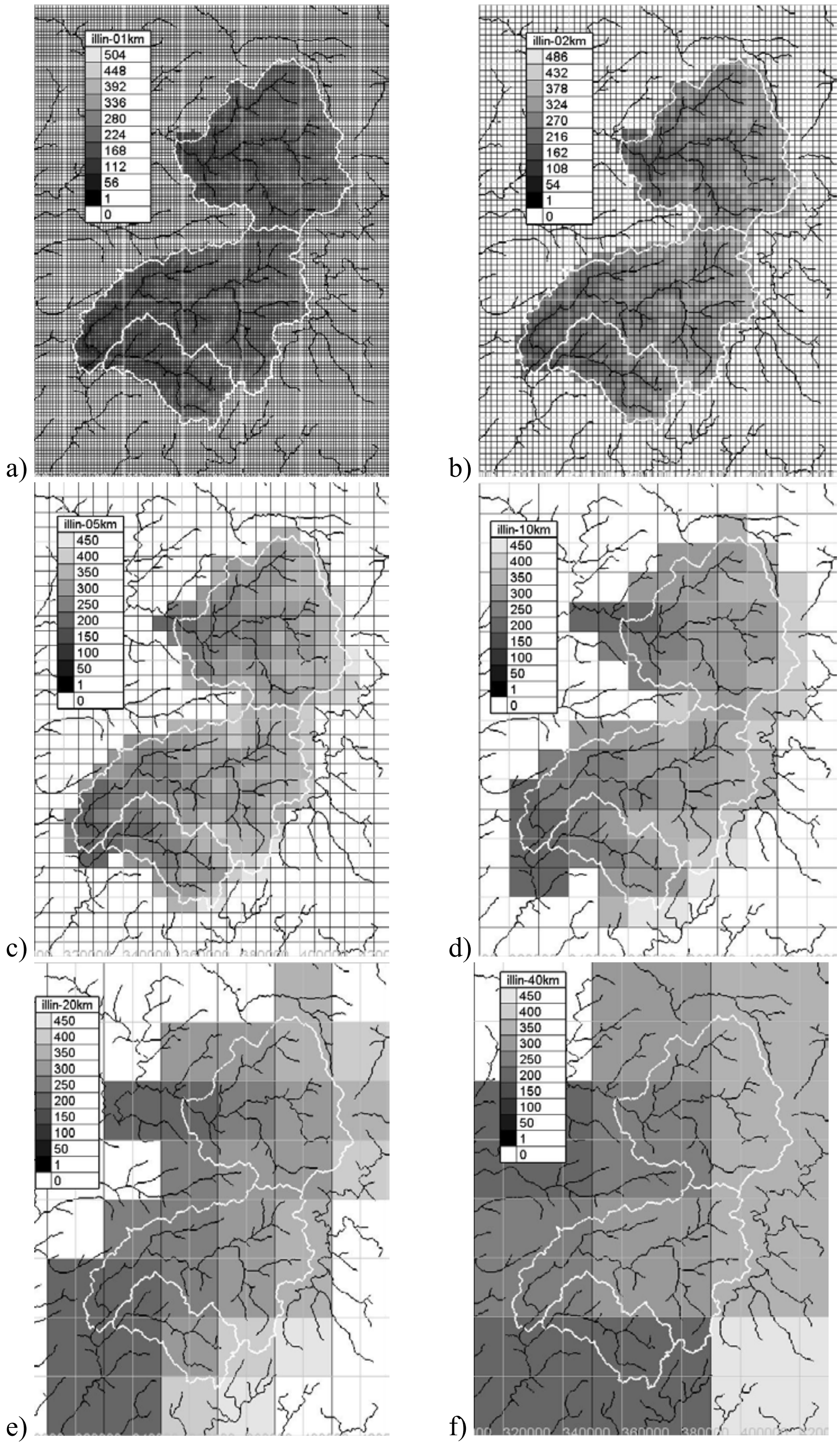
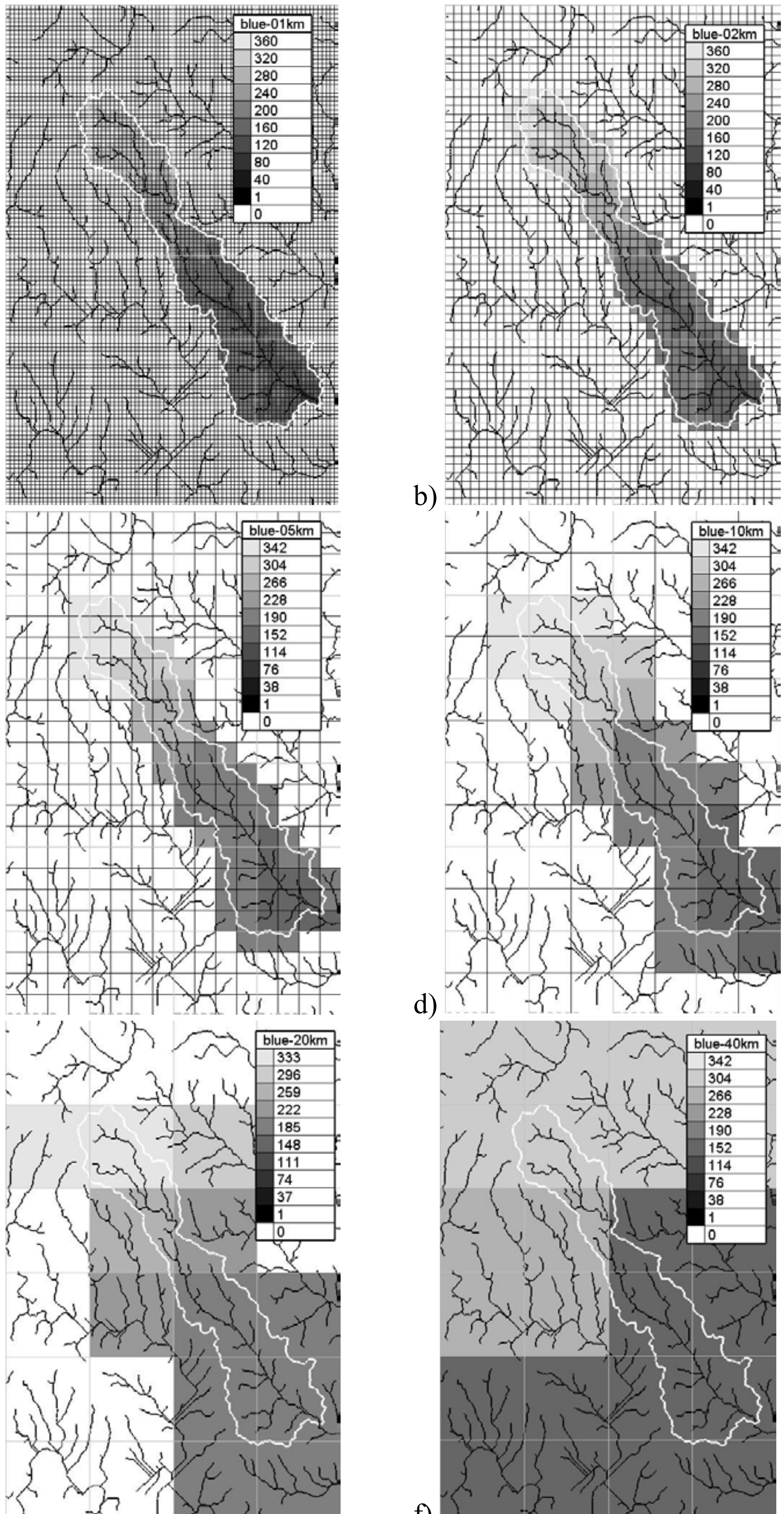


Figure 3 - Comparison of different grid resolutions for Illinois River basins: a) 01 km, b) 02 km, c) 05 km, d) 10 km, e) 20 km, f) 40 km



a) b) c) d) e) f)

Figure 4 - Comparison of different grid resolutions for Blue River basins: a) 01 km, b) 02 km, c) 05 km, d) 10 km, e) 20 km, f) 40 km

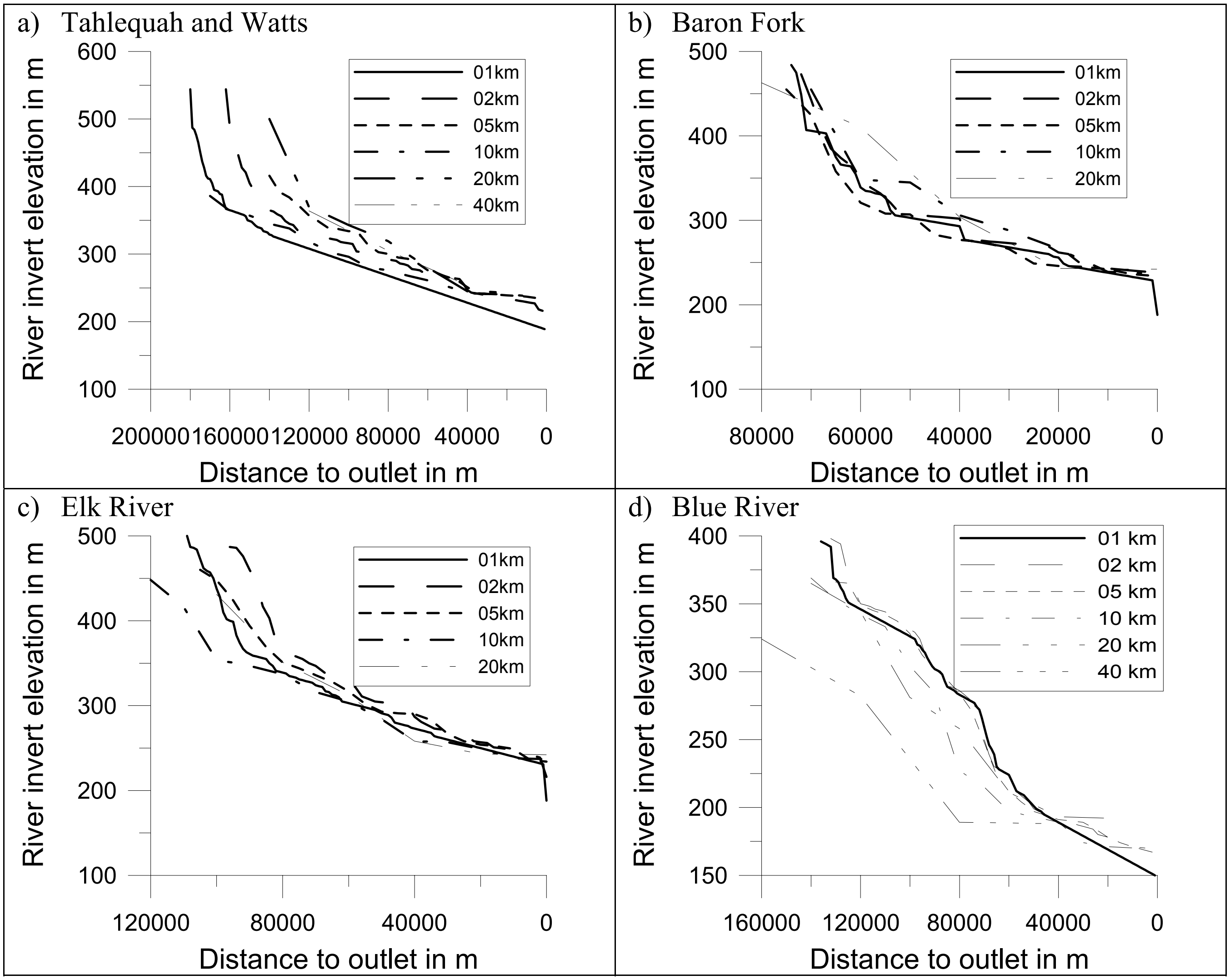


Figure 5 - River slope profiles for a) Tahlequah and Watts, b) Baron Fork, c) Elk River, and d) Blue River

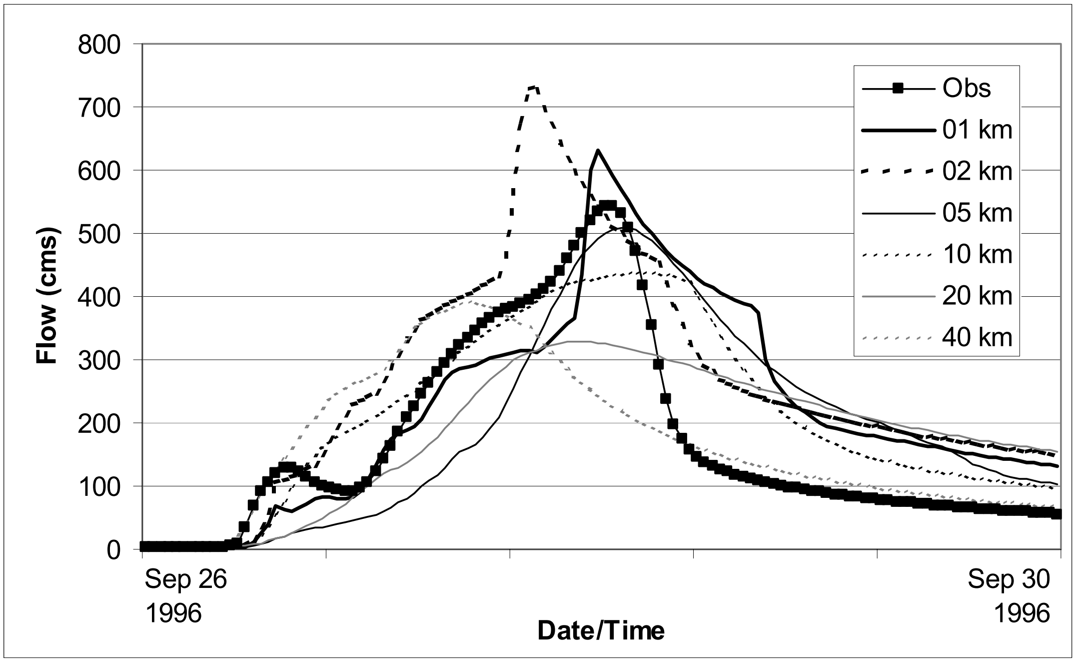


Figure 6 - Typical hydrograph event showing 6 different resolutions calculated with 40 km precipitation (for all resolutions) for Illinois River at Tahlequah Basin

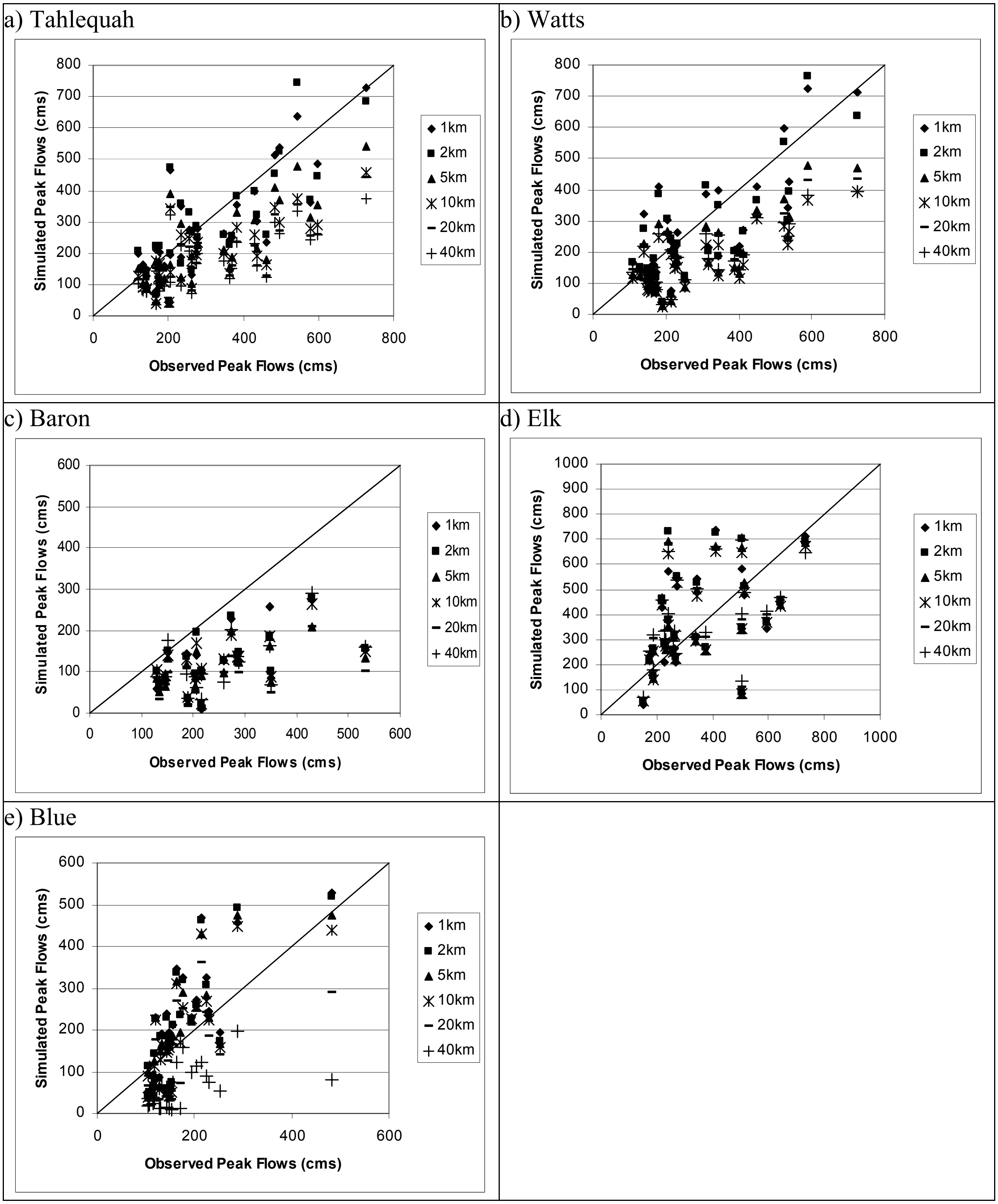


Figure 7 - Comparison of Peak Flows for all six resolutions for each watershed

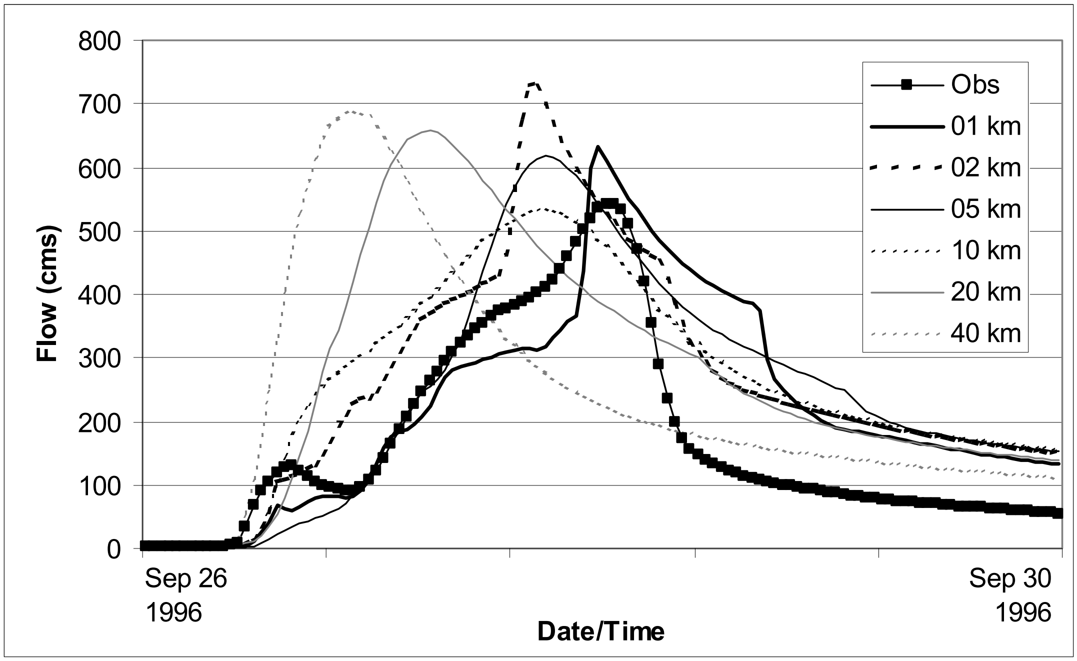


Figure 8 - Typical hydrograph event showing 6 different resolutions calculated with 40 km precipitation for Illinois River at Tahlequah Basin, after adjusting surface roughness parameter

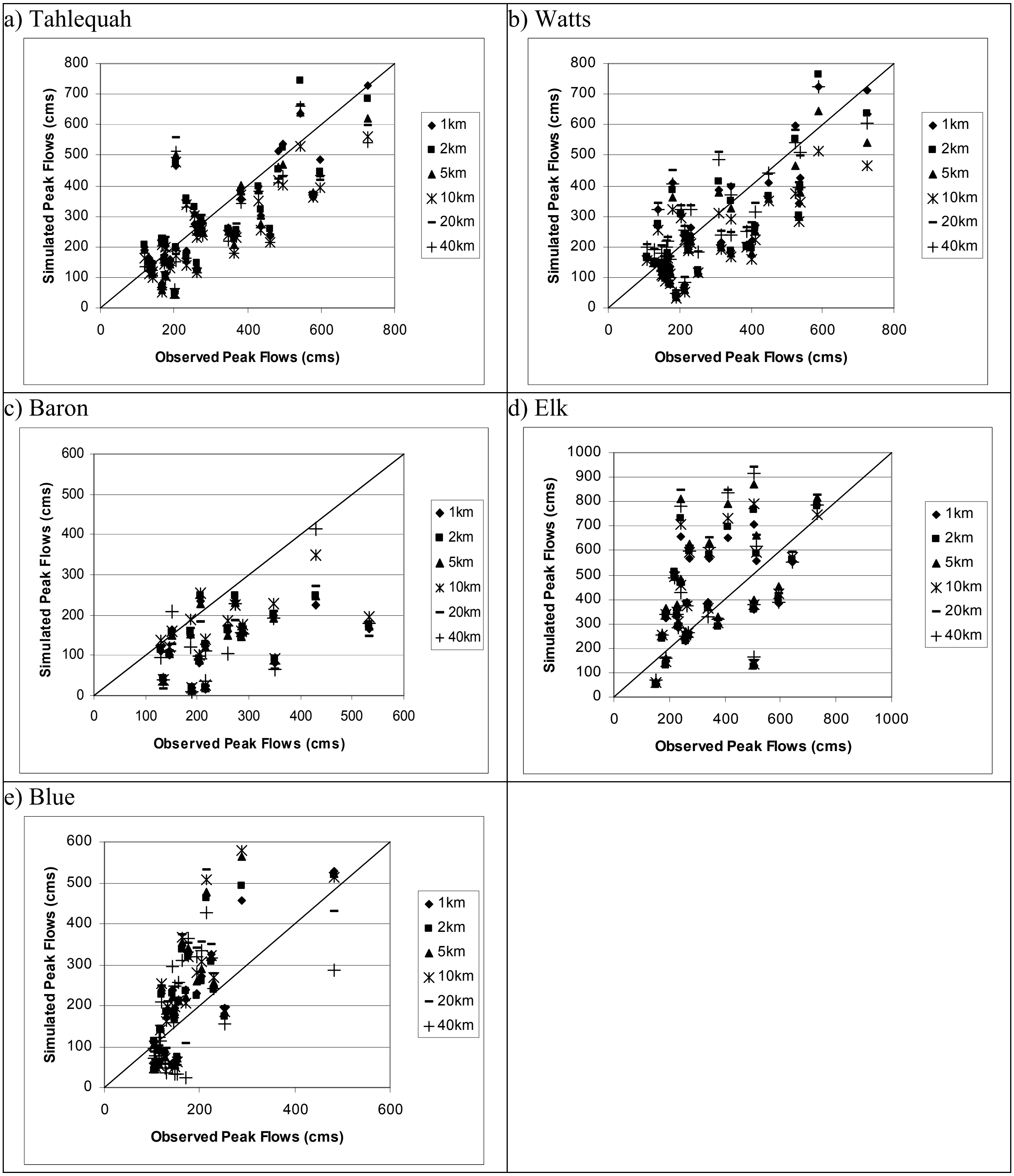


Figure 9 - Comparison of Peak Flows for all six resolutions for each watershed, after adjusting surface roughness parameter

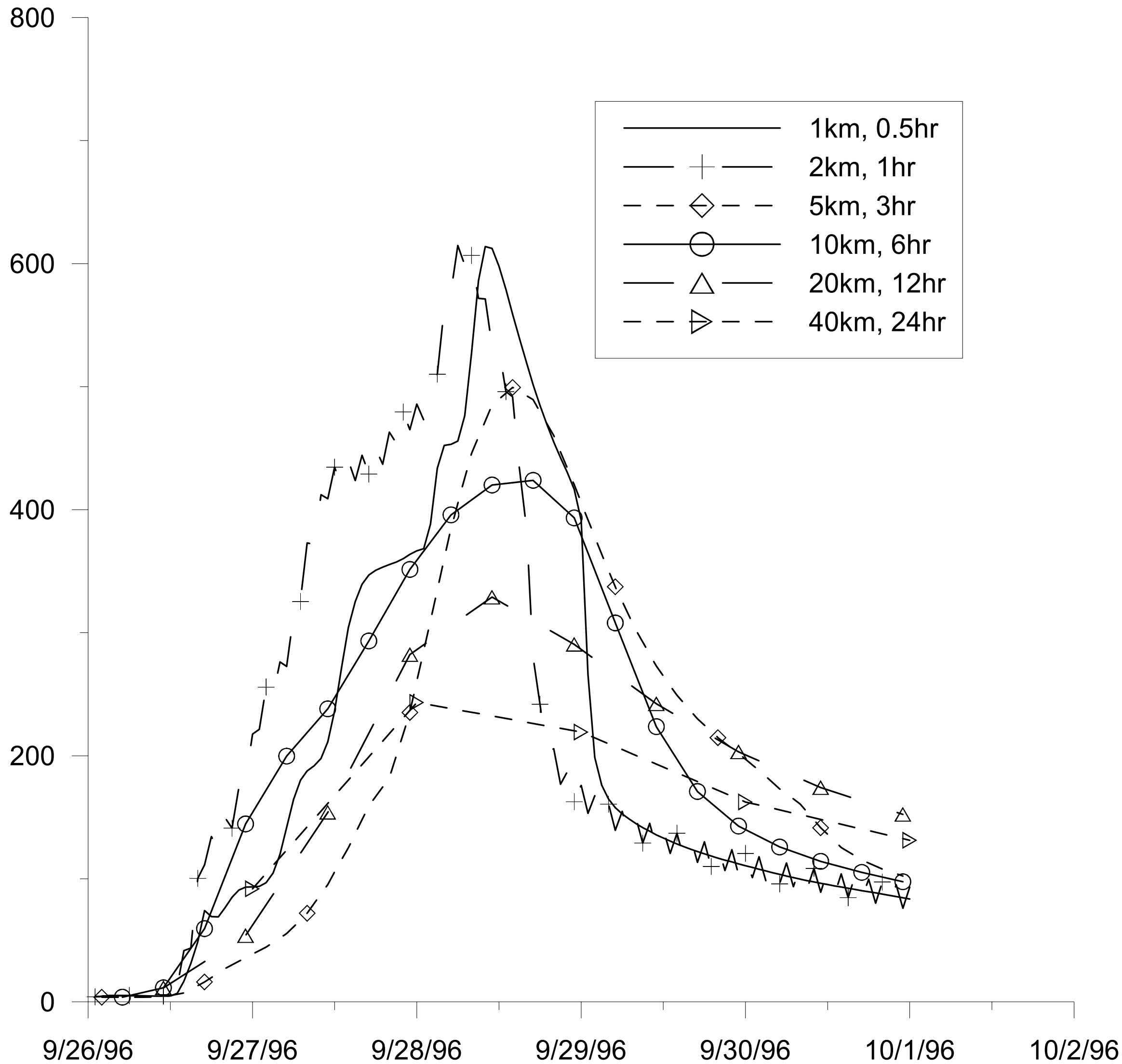


Figure 10 - Sample Hydrograph for Illinois River at Tahlequah using 40-km precipitation and a constant surface roughness parameter for each resolution, but using a different routing timestep for each resolution

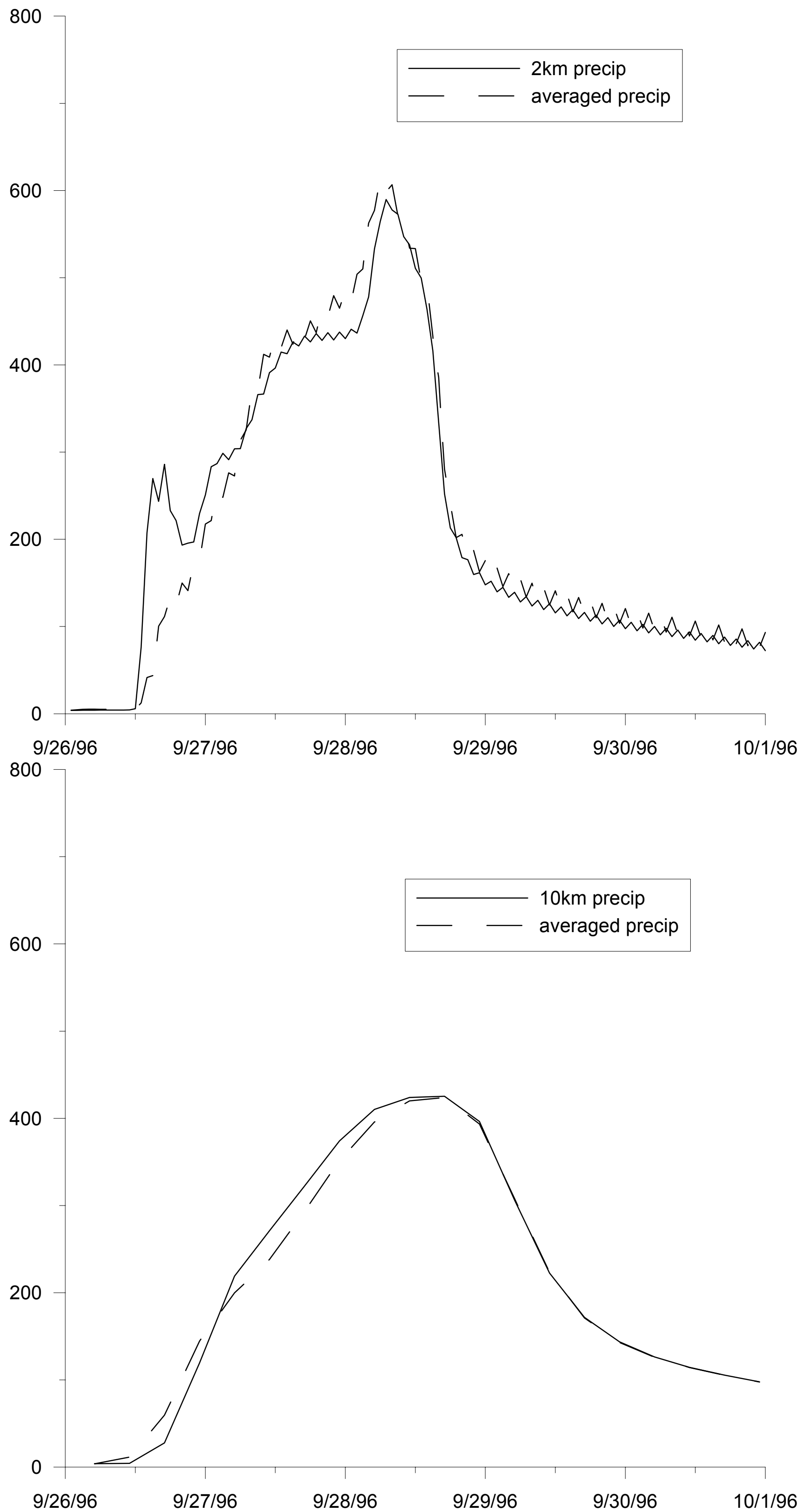


Figure 11 - Comparison of typical hydrograph showing grid-averaged precipitation versus 40-km averaged precipitation a) 2-km resolution, b) 10-km resolution