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Raster-Based Streamflow Analysis Applied to the Upper Snake River

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RASTER-BASED STREAMFLOW ANALYSIS APPLIED TO THE UPPER SNAKE RIVER

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Abstract
An innovative approach to streamflow analysis is presented. The raster-based method allows for the quantification and visualization of very large daily streamflow datasets. The technique shows subtle temporal properties not possible with other traditional techniques. This method is extremely flexible, permitting numerous display options depending on the specific research goal.

Dual timescale hydrographs and grid correlograms are applied to the USGS Snake River gaging station at Heise, Idaho and demonstrate how changes to the flow regime are detected and quantified. Also discussed is application of the raster-based approach as a river management tool to target more natural streamflow. This type of streamflow visualization has proved very effective when addressing non-technical audiences such as funding organizations, government/tribal officials, and the public.

Background

Annual, seasonal, and daily patterns of discharge determine many of the physical and biological properties of a channel. The volume of water conveyed by a channel affects water supply, riparian habitat, stream ecosystems, power generation, and recreation. It is also important to know the timing of flow within and between years. Understanding the temporal variability of the hydrologic regime can improve natural and water resources management efforts.

The hydrologic regime

Stanford et al. (1996) discuss how river systems are disturbed and suggest a general protocol for restoration of regulated rivers. They state that human caused perturbations "uncouple" important ecological processes linking ecological components in large rivers. These disturbances are (a) water pollution, (b) food-web manipulation through harvesting, stocking, and exotic invasion, and (c) alteration of water, temperature, and material flux via dams, diversions, and revetment. Short- and long-term dynamics cause the mosaic of flood-plain and channel structures to create a constantly changing habitat. As a result, a patchy distribution of resources needed for different organisms occurs within the heterogeneous landscape. One approach for river restoration is to allow a more natural seasonality of flow. The questions then become "How is a natural flow defined?" and "What guidance can be given to managers to produce a more natural flow?"

Poff et al. (1997) describe a set of discharge characteristics related to ecological integrity and outline an approach where streamflow is a "master variable" correlated to many physical and chemical properties of a river system such as channel morphology, water temperature, and habitat diversity. These factors affect the abundance and distribution of riverine species. They list critical components of the flow regime which include magnitude, frequency, duration, timing, and rate of change. All components vary on time scales of hours, days, seasons, years, and longer.

Data visualization

Access to large datasets is common with online websites such as provided by the U.S. Geological Survey. Haan (2002) states that because of the large amounts of data available to hydrologists, graphical display of the information is a useful initial step in data analysis. The most common graph is a time-series plot of magnitude versus time. However, the graphical technique used will depend on the purpose of the analysis.

Keim and Kreigel (1996) note that visual data mining techniques have proven to be of high value in exploratory data analysis and those techniques have a high potential for mining large datasets. Graphs provide crucial information to the data analyst that is difficult to obtain in any other way. The authors state, "Computing statistical measures without looking at a plot is an invitation to misunderstanding data". Graphs also clarify complex relations between variables and permit detection pattern from noise. Visualization can provide much more information than a table of numbers, which often leads to new understanding and decisions based on more information (Helsel and Hirsch 1991

Pixel-based graphs

A graphing technique that maximizes displayed information uses a pixel or raster-based approach. Each pixel represents a single value of a dataset with an assigned coordinate and a color or shade to create a two-dimensional image. This type of graph is not commonly used in hydrologic analyses.

Keim (2000) notes the basic idea of a pixel-based visualization technique is to represent as many data objects as possible by mapping a value to each pixel and arranging the pixels according to a defined coordinate system. Keim and Kriegel (1996) state that the pixel-based method allows data properties to be determined from overall brightness and color distribution with sharp borders representing discontinuities. Visualization allows identification of similar attributes and associations by similar color and contrast between two data points.

Grid system

Using a two-dimensional grid is central to the raster-based analysis. When data systematically populate the grid, configuration properties of association, adjacency, distribution, timing, and persistence are measurable and observable quantities. Typical hydrologic indices or statistical measurements can only quantify the composition, not the configuration, of daily flows. Patterns that are difficult, or possibly impossible, to identify with linear time-series graphs are recognizable with a raster-based approach.

Time-series data are typically discrete measurements separated by some time interval Δt. Researchers often confine time to a single axis but others have used dual-axis plots to show inter-annual and intra-annual variation (Poff et al. 1997, Koehler and Ball 1998, Koehler et al. 2002). Each data element has a short- and long-term component for use in a Cartesian coordinate system. The long-term component equals some integer multiple of short-term component measurements. Such a plot shows change in two time-scales simultaneously. By placing the day of year (short-term component) along the x-axis with each successive year (long-term component) above that of the previous year for the y-axis, a grid is created. Figure 1 shows this

concept for November 27, 1985 (day 330 of year 1985). Figure 2 shows a diagram of lagged cells within a grid.

The autocorrelation function for the lagged dataset is the grid covariance divided by the grid variance:

$$r(k_i,k_j) = \frac{\text{grid cov}}{\text{grid var}}$$

The autocorrelation function value is plotted on a grid with coordinates (k_i,k_j). When k_i is 0, the values are the same as a daily correlogram. When k_j is 0, the values are the same as a yearly correlogram (Figure 3).

Raster-based analysis

The raster-based analysis and visualization methods described in this research are applied to selected stations on the middle and upper Snake River in Idaho (ID). Data preparation and patch metric graphs generation used Microsoft EXCEL (Version 2002). Golden Software SURFER (Version 8.00) generated all raster-based hydrographs and grid-correlograms. Golden Software GRAPHER (Version 4.01) was used to prepare flow-duration curves, while MAP VIEWER (Version 5.00) was used to prepare maps. All raster and patch-analysis statistics were computed with the landscape ecology application FRAGSTATS (Version 3.3).

Selection of stations allowed analysis of various hydrologic situations to be analyzed. For the middle and upper Snake River, stations were selected to show less disturbed flow patterns, large reservoir influences and downstream effects, reconstruction of less disturbed flows from regulated discharges, and the effects of surface-water diversions. Within the upper Colorado River, stations were selected to detect influences of "low- impact hydropower" dams, large-reservoir effects, and tributary influences. In all cases, a flow description accompanies the station raster hydrograph and the flow category closest to the flow-duration curve median value is indicated by an open diamond symbol.

Study area physical setting

The middle and upper Snake River and associated tributaries drain parts of southern Idaho, western Wyoming, northern Utah, northeastern Nevada, and eastern Oregon (Figure 4). The upper Snake River from Jackson Lake, Wyoming to Brownlee Dam, on the Idaho-Oregon border, is approximately 1,127 kilometers (km) long. The tributary basins with the east and west sections of the Snake River Plain, drain more than 186,500 km^2 (Lovell and Johnson 1999).

The Snake River at Heise, ID station allows for comparisons before and after Palisades Dam began operation. The streamflow gaging station is 72.5 km downstream of the Irwin gaging station and 74.9 km downstream of Palisades Dam. The USGS station home page notes that diurnal fluctuations due to power-plant operations and electrical production occur during winter. No significant tributaries enter the Snake River between the Irwin and Heise gaging stations (USGS 2001). The IDWR lists 21 surface-water diversions between the Irwin and Heise streamflow gages (IDWR 1999). It is unknown when surface-water diversions began.

Raster-hydrographs
Figure 5 shows a distinct low-flow period for day 40 of water year 1957 (Nov. 1956) and is coincident with the beginning of Palisades Dam operations (USGS 2001). Earlier than 1925, the graph shows that daily data appear consistent on a monthly basis as evidenced by days 1 through 180 that display linear features at monthly intervals. Because of this, grid-correlograms and patch analysis do not use this period of record.

Records show droughts occurring 1930 through 1940. Influence of Palisades Reservoir regulation has produced more low flows as compared to the earlier part of the record, seen from day 1 through day 210. Additionally, reduced snowmelt runoff occurred from day 210 through day 300, causing a decrease in snowmelt peak flows while extending the period of snowmelt flows later into the year for water years 1957 through 1960 as to the pre-dam conditions. Also seen is the extension of flows equal to or greater than 170 m^3/s (cms) from day 1 through day 150. The extension of these higher flows happened twice in the 43 years of pre-dam conditions. During the same timeframe (day 1 through day 150) post-dam conditions show flows equal to or greater than 170 m^3/s occurred in 19 of 44 years of record. Drought periods of 1980 and 1987 through 1995 are evident in the raster hydrograph. The grid-correlogram of Figure 6 is for 1911 through 1951 and shows an intact aura with less random fluctuations and zero-correlation lines tracking along the y-axis. Figure 7 is the grid-correlogram for years 1960 through 2000 after Palisades began operations and shows a distorted aura and wavy zero-correlation lines consistent with simulated deterministic streamflow containing random fluctuations. The median flow is 110 m^3/s before Palisades Dam and 149 m^3/s after dam construction. Patch metrics are shown in Figures 9 through 14.

The Heise flow-categories for 1960 through 2000 show a tri-modal distribution in the percent days, percent edge, mean patch size, mean patch shape, and the aggregation index. The Heise flow-categories for the 1911 through 1951 period show a bi-modal distribution of most patch measurements.

Summary
The middle and upper Snake River stations provide an opportunity to apply a raster-based analysis. Pre-Palisades Dam construction flows at Heise display the grid-correlogram from a less disturbed river system. The post-Palisades Dam construction-flow record at Heise shows a distorted grid-correlograms consistent with deterministic flow with random fluctuations. Examination of patch metrics allowed for the quantification of the mosaic patterns present in the raster-hydrograph. Differences between the pre and post palisades Reservoir period are especially evident in the mean patch size and mean patch shape.

Stalnaker (1979) recommends that flow requirements should be dynamic. The raster-based methodology can address this concern. A patch-work or “management mosaic” of flow categories would incorporate the multi-year daily, seasonal, and annual variations not possible with minimum-flow requirements or targeted monthly flows. Different flow regimes for wet years and dry years can be accommodated by different “management-mosaic” scenarios. In all cases, the natural temporal variability of a stream would be included, an element lacking in some current management techniques.

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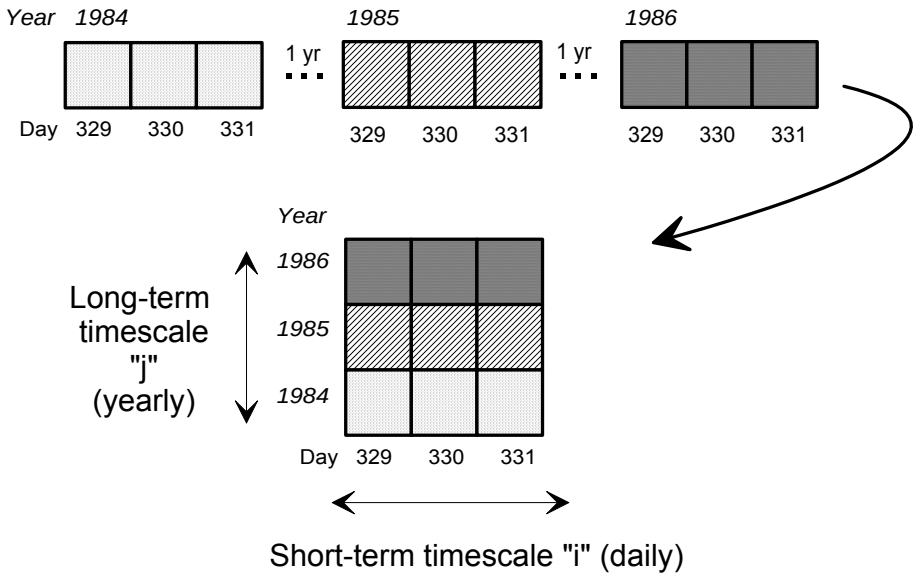

FIGURE 1. Illustration of re-ordering a daily time-series into a raster grid.

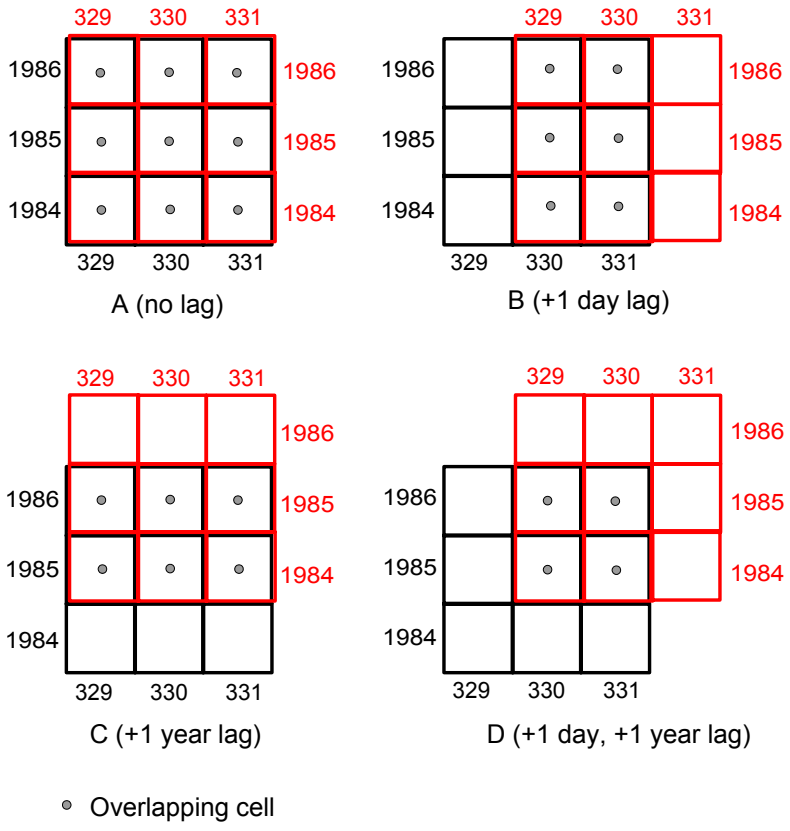

FIGURE 2. Diagrams of lagged cells within a grid.

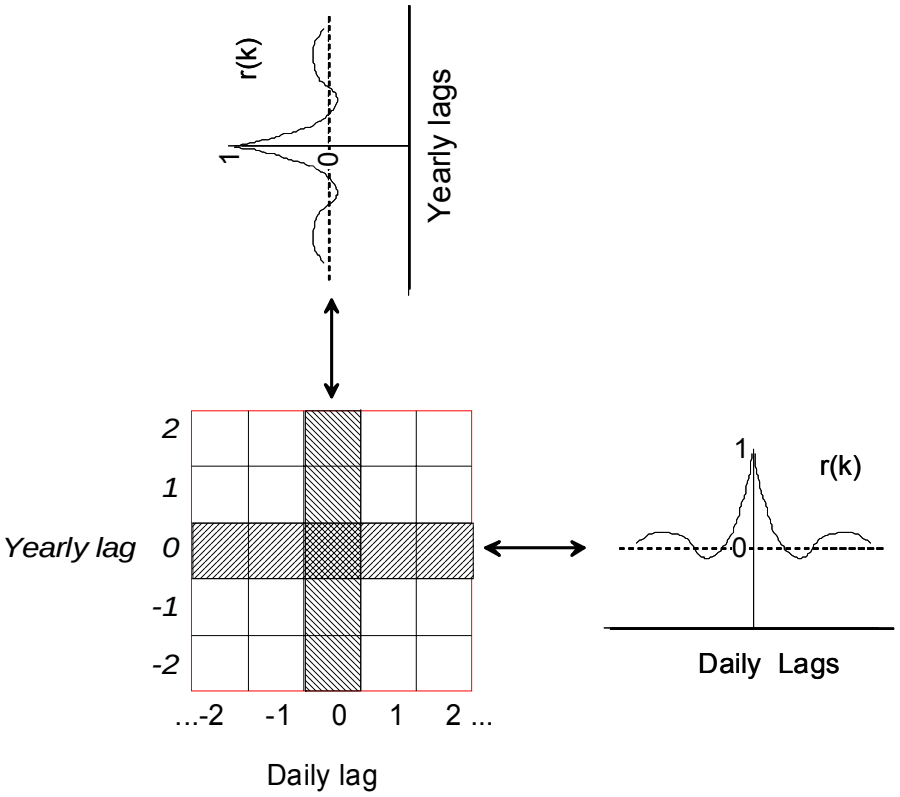

FIGURE 3. Diagram of grid autocorrelation values.

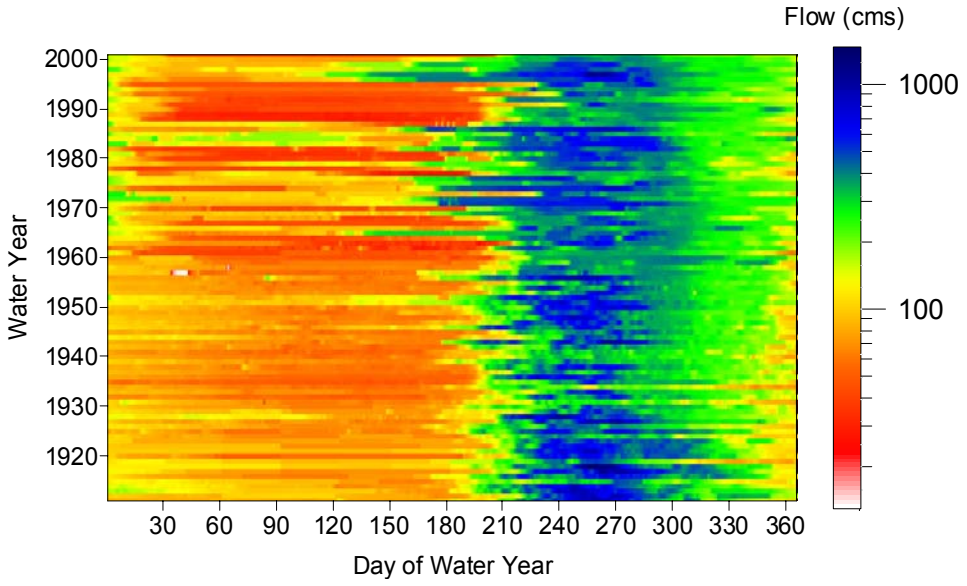

Figure 4. Raster hydrograph, Snake River at Heise, ID

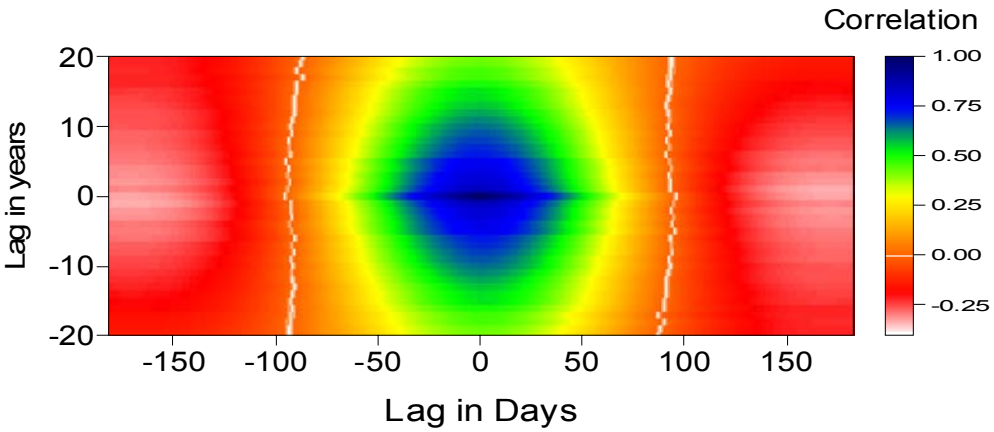

Figure 5. Graph of grid-correlogram, Snake River at Heise, ID (1911 through 1951)

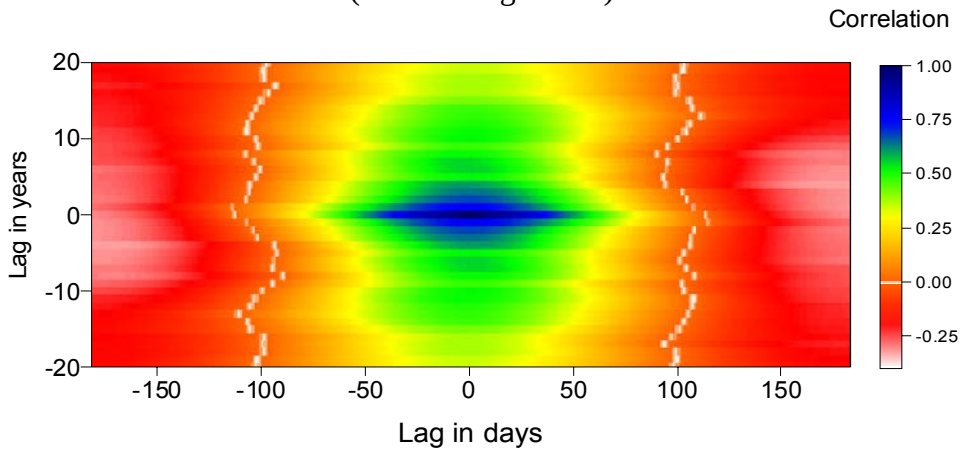

Figure 6. Graph of grid-correlogram, Snake River at Heise, ID (1960 through 2000)

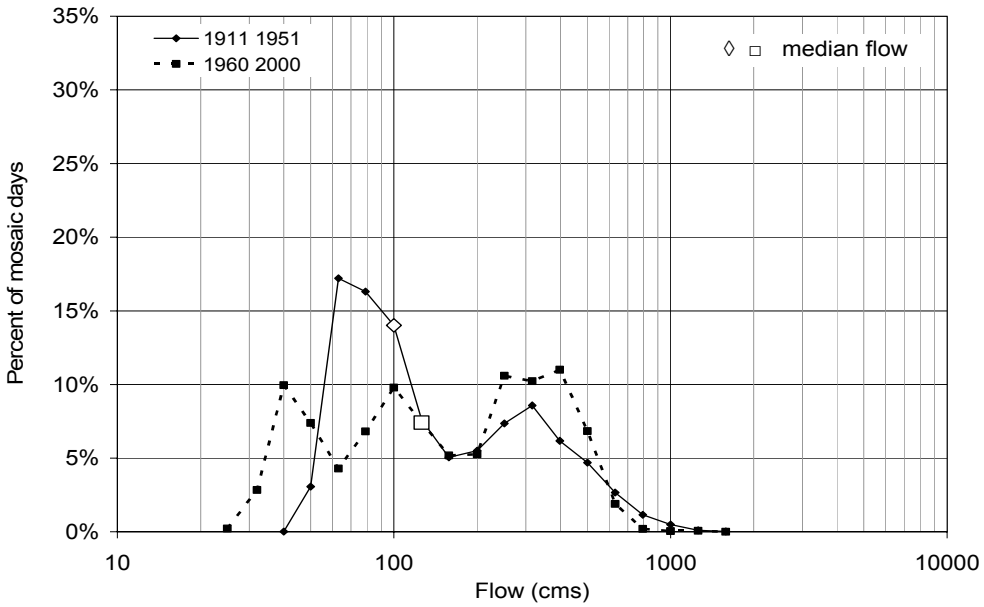

Figure 7. Graph of percent of mosaic days, Snake River at Heise, ID

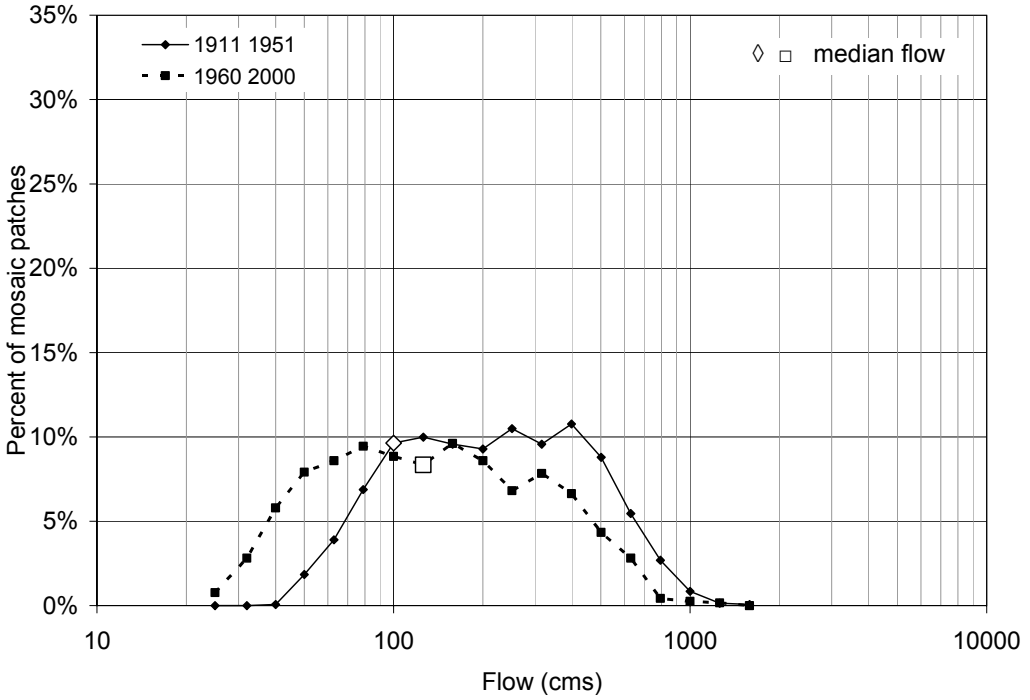

Figure 8. Graph of percent of mosaic patches, Snake River at Heise, ID

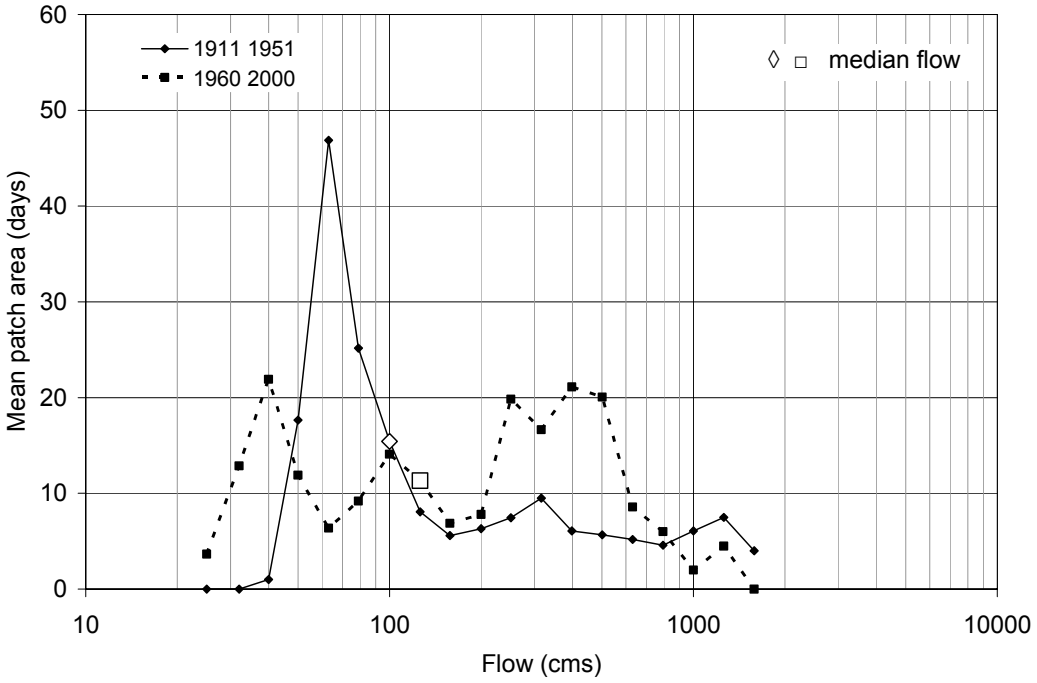

Figure 9. Graph of mean patch size, Snake River at Heise, ID

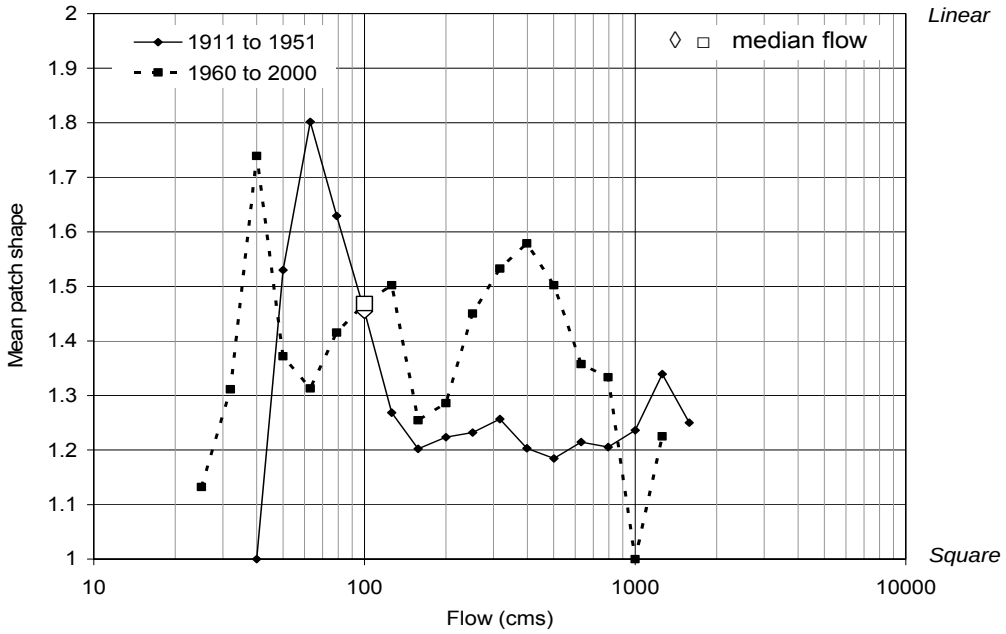

Figure 10. Graph of mean patch shape, Snake River at Heise, ID

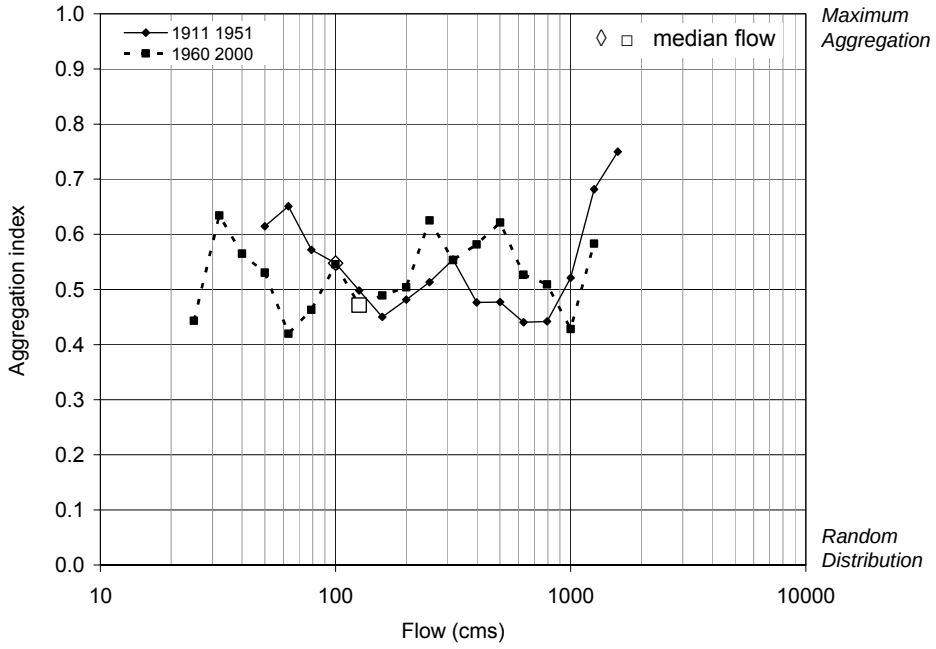

Figure 11. Graph of aggregation index, Snake River at Heise, ID

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