Characterization of Streamflow Variability Within the Upper Gila River Basin

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Surface Water Hydrology Semester Project
Introduction

As the human population in the American desert southwest continues to grow, its water resources are becoming increasingly taxed. One of the largest suppliers of surface water to this region is the Colorado River. It is managed and operated under many federal laws, compacts, court decisions, decrees, contracts, and regulatory guidelines know as the Colorado River Compact, or “Law of the River”, which was signed into existence in 1922 by Secretary of Commerce, Herbert Hoover (Reclamation, 2007). These documents give a portion of the water in the Colorado River to seven states and one country, Wyoming, Utah, Colorado, New Mexico, Arizona, Nevada, California, and Mexico.

In 1944 Arizona (the last state to sign the Colorado River Compact) finally signed the Colorado River Compact. By signing, Arizona was allotted 2.8 million-acre feet of water per year from the lower Colorado River Basin (CAP, 2007). In 1946, because of its water deficit from pumping groundwater, Arizona began educating its citizens and lobbying congress about the need for the Central Arizona Project, known as CAP (figure 1). CAP is designed to bring Colorado River water to Maricopa, Pima, and Pinal counties through 336 miles of concrete channels, pipelines, tunnels, dams, pumping plants, and siphons (CAP, 2007). This project would also refill the states depleting aquifers (CAP, 2007). A lengthy legal battle between California and Arizona soon took place.

Figure 1 (CAP web site, 2007)
California argued that Arizona could not develop the full 2.8 million acre feet from the Colorado River it was allotted and also develop the water from the Gila River, saying that using Gila River water was an additional amount of water because it was a tributary of the Colorado River and, therefore, was accounted for in their 2.8 million acre feet (Reclamation, 2007; CAP, 2007). In 1968, the U.S. Supreme Court rendered its decision in Arizona vs. California, a 24-year dispute, in favor of Arizona allowing Arizona to develop water from many streams before they reached the Colorado River. However, in times of shortage in the Colorado River, CAP would be subordinate to California’s water allotment (Reclamation, 2007).

In 2004, as part of the Arizona Water Settlement Act in which Tribal water rights were finally acknowledge, Title II allotted New Mexico an additional 14,000 acre feet of water per year beyond the 30,000 acre feet already allotted (Briefing, 2006; Reclamation, 2007). However, many conditions must be met before the water can be developed. One of the many conditions is that a base line investigation of New Mexico’s portion of the watershed be completed. This investigation is not project or activity specific, but will act as a tool to help predict impacts of potential withdrawal scenarios within specific watersheds. This, in turn, will be utilized to meet many of the other conditions of Title II:

- New Mexico diversions cannot exceed 140,000 acre-feet of water during any consecutive 10-year period.
- New Mexico may not consumptively use more than 64,000 acre-feet in any one year.
- New Mexico users cannot divert water unless there is at least 30,000 acre-feet in the downstream San Carlos Reservoir.
- New Mexico must bypass the below amounts to meet the needs of downstream water rights:

<table>
<thead>
<tr>
<th>For NM Diversion Days in the Month</th>
<th>Bypass Amounts (cfs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>January</td>
<td>82.5</td>
</tr>
<tr>
<td>February 1-13</td>
<td>137.5</td>
</tr>
<tr>
<td>February 14-28</td>
<td>215</td>
</tr>
<tr>
<td>March</td>
<td>292.5</td>
</tr>
<tr>
<td>April</td>
<td>432.5</td>
</tr>
<tr>
<td>May</td>
<td>437.5</td>
</tr>
<tr>
<td>June</td>
<td>442.5</td>
</tr>
<tr>
<td>July</td>
<td>442.5</td>
</tr>
<tr>
<td>August</td>
<td>442.5</td>
</tr>
<tr>
<td>September</td>
<td>442.5</td>
</tr>
<tr>
<td>October</td>
<td>267.5</td>
</tr>
<tr>
<td>November</td>
<td>152.5</td>
</tr>
<tr>
<td>December</td>
<td>75.5</td>
</tr>
</tbody>
</table>

Taken from New Mexico Interstate Stream Commission (Briefing, 2006)
There are many more terms and conditions that are listed in Title II of the Arizona Water Settlement Act, but they are beyond the scope of this paper. The question this study is going to try and answer is whether the Gila River produces enough water for New Mexico to develop while meeting the legal obligations for down-stream users. To do this a set of nested USGS gages in the Upper Gila River basin will be analyzed using intraannual and interannual variability in streamflow, flow duration curves, and basin characterization.

Geology

The Gila River basin encompasses about 212,380 km² of the Basin and Range province and covers over half of the lower portion of Arizona and a small portion of southwest New Mexico (Connell et al, 2005). The Upper Gila River basin encompasses roughly 36,000 km² with 14,504 km² of that in New Mexico (NMSU, 2007). The northern boundary is the Mogollon Rim of the Colorado Plateau; southern boundary is along the Arizona/New Mexico, Mexico border; eastern boundary is the Continental Divide along the Black Range in New Mexico; and the western boundary is above Coolidge Dam, AZ, just west of Safford.

The course of the upper Gila River flows through a series of alluviated troughs with broken, elongated, tilted fault-blocks that generally trend north- to northwest and dip steeply 75-80° (Reid, 2004). The river crosses low-lying divides between adjacent mountain ranges (fault Blocks), resulting in the development of bedrock canyons (knickzones), such as those near Safford, Arizona, and near Redrock, New Mexico (Connell, 2004).

There are several subbasins that combine to make the Upper Gila River basin. These subbasins range in elevation from 1,152 – 3,051 m and are surrounded by
mountains (fault blocks) and plateaus that range in elevation from 2,751 m (Black Mountain in the Black Range, NM) to 3,320 m of the Mogollon Mountains, NM, which is the highest point in the Gila River drainage basin (NMSU, 2007).

The basins of the Upper Gila are composed of a wide range of fill, coarse conglomerates to fine-grained lacustrine deposits to alluvial and fluvial gravels. Because the basin fill is relatively thick, 762 m – 1830 m, this makes for a natural aquifer for the entire Gila River basin (NMSU, 2007). In fact, one of the most plentiful deposits in the southern and western portions of Arizona is groundwater. Today, about 67 percent of the water used in Arizona is pumped or otherwise produced from underground reservoirs in the Basin and Range Province (Arizona, 2007). More than 94 percent of Arizona's population, mineral production, agricultural acreage, and volume of water produced are in the Basin and Range Province (Arizona, 2007).

Data Collection and Methodology

Data Collection

United States Geological Survey (USGS) stream gage data was downloaded from the National Water Information website (http://waterdata.usgs.gov/az/nwis/sw). All GIS data was downloaded from the USGS seamless website (http://seamless.usgs.gov/).

Hydrographs

Streamflow hydrographs are observations of stream discharges plotted against time [1]. These plots provide insight into the response of streamflow to forcing characteristics within the basin (i.e. precipitation events, snowmelt); it can also elucidate intraannual and interannual variability of the streamflow at that point. See Appendix A for all the hydrographs constructed for this project. Only complete water years were used from the USGS gage data (i.e. October 1-September 30). Each complete water year is indicated on the x-axis, from the beginning of the individual gage record to its latest record, and day of year on the y-axis. The discharge is represented on the z-axis in cubic feet per second (cfs).

These plots were created using a MATLAB code which extracted gage data from excel files and organized it into complete water years which were then plotted using the mesh function.

Flow Duration Curves

A flow-duration curve (FDC) represents the relationship between the magnitude a frequency of daily, weekly, monthly (or some other time interval) of streamflow for a particular river basin, providing an estimate of the percentage of time a given streamflow was equaled or exceeded over a historical period [2]. This study utilizes the Median Annual Flow Duration Curve (MAFDC) method developed by Vogel and Fennessey in 1994. The MAFDC has several advantages over a traditional period of record FDCs. The first and most important is that they are less sensitivity to interannual fluctuations such as periods of drought. The MAFDC method also allows construction of confidence intervals to expose the uncertainty associated with an FDC. Finally, this method allows one to define annual reliability and the average return-period concept, useful in hydrologic planning and design [2].
To construct MAFDCs all data for each of the USGS gage stations within the Upper Gila Basin were downloaded into a Microsoft Excel workbook. After all header information and column labels were removed a MATLAB code was developed to extract and process the data in the following way:

1. Leap year data is removed so that all water years are 365 day years.
2. Each complete water year is extracted and any incomplete water year is discarded.
3. Individual water year discharges, $q_i$, are ranked from lowest discharge (rank $i = 1$) to highest discharge (rank $i = 365$).
4. The median discharge (rank $i = 182$) is extracted from each water year.
5. Water year median values are ranked from lowest (rank $j = 1$) to highest (rank $j = 365N$), where $N$ is the total number of water years for that set of data.
6. The non-exceedence probability (cumulative distribution function) of each median flow is estimated as $F_q(q_{(j)}) = \frac{j}{365N + 1}$.
7. The exceedence probability is calculated as $EP_q(q_{(j)}) = 1 - F_q(q_{(j)})$.
8. The median water year discharge values are then plotted against their exceedence probability (see Figure 1).

Figure 2

Gila River at Calva

![Gila River at Calva](image-url)
For streams unaffected by diversion, regulation, or land-use modification, the slope of the upper end of the FDC is determined principally by the regional climate and the slope of the lower end by the geology and topography [1]. A flat slope at the upper end (i.e. low exceedence probability) indicates that large flood events are a result of snowmelt or long duration rain events; conversely, if large storm events are intense short duration the slope will be steep [1]. At the lower end of the FDC (i.e. high exceedence probability), a flat slope usually indicates that flows come from significant storage in ground-water aquifers or in large lakes or wetlands; a steep slope indicates an absence of significant storage [1].

GIS

Environmental Systems Research Institute based GIS was used in the processing of spatial data. Surface water catchment areas for each of the USGS stream gages were delineated from a 30 meter digital elevation model (See Appx. B). Delineated basin polygons were then used to delineate other spatial data sets such as the National Land Cover Dataset (NLCD). All processing of raster datasets was performed in ArcINFO. Analysis and display was done in ArcMap and ArcScene version 9.2.

Results

Intraannual Streamflow Variability

The Upper Gila Basin experiences two main periods of runoff. With respect to the water year beginning on October 1, the first period begins in mid November and ends late May early June, and the second begins in early July and tails off mid to late September (Figure 4).

Figure 4
There is a significant difference in the hydrograph shape of runoff events from winter to those in the summer. One explanation is differences in the source of streamflow to the river. The winter period may be dominated by snow melt or long duration storm event, or a combination of both. This region is subject to the short duration monsoonal rains in late summer, as is most of the American Southwest, which explains the nature of the hydrograph in the summer period. However, it is cautioned that effects of evapotranspiration and agricultural diversions during the summer months are not accounted for in these representations and may have a profound effect on the amount of water that reaches the river and becomes streamflow. None the less, the general trend within the Upper Gila Basin is two periods of higher runoff dominated by the longer winter period.

Another interesting trend from the intraannual analysis was a difference in proportionality of the two seasonal high flow periods between the two rivers (San Francisco and Gila). Summer streamflow is more prevalent in the Gila River than it is on the San Francisco relative to their intraannual variability. If we look at two gages that are near the confluence of the San Francisco River and the Gila River this trend is more apparent (Figures 7). Disregarding the scale, the summer period of discharge on the Gila River is more prevalent relative to the intraannual distribution of event peaks then on the San Francisco River.

Figure 7

Interannual Streamflow Variability

The Upper Gila River Basin not only has a good array of USGS gages, but also good periods of record. Most gages have records beginning in the early 20th century to the present day. This allows a good analysis of the interannual variability of streamflow within the Upper Gila River Basin.

All gage hydrographs show an increase in magnitude and frequency of large streamflow events beginning in the late 1970’s through the early 1990’s. This increase seems to have the largest effect on the winter period of larger streamflow events (Figure 8). Some larger events happen during the summer period, but in general the trend only
affects the winter period. One other aspect of this 1970’s-1990’s period is that there is an earlier occurrence of large streamflow events in the time period between the summer and winter high flow periods. This trend in the data is most likely attributed to a global or regional cyclical pattern in climate.

Figure 8
Flow Duration Curves

Two separate FDC’s were constructed, one for the San Francisco River and the other for the Gila River. This was to highlight the differences within these sub basins of the Upper Gila River Basin.

Appendix B shows the location of the three gage stations used for the San Francisco River FDC analysis. The Reserve gage is the furthest upstream followed by Glenwood then Clifton. The FDCs indicate that the San Francisco River is a gaining stream from it’s headwaters in the Mogollon Rim to the USGS gage near Clifton, AZ which is also close to the confluence of the Gila and San Francisco Rivers (Figure 9).

Figure 9

The increase in discharge is nearly uniform throughout the probability distribution between consecutive stations. The upper end of the curve (low exceedence probability) has a low slope for all stations indicating the contribution of snow melt and longer winter rain events. This is supported by the hydrographs for the San Francisco gage stations that show a dominance of winter stream flow to summer. The lower end of the curve (high exceedence probability) also has a low slope that may be due to a large groundwater component.

Four stations were used for the FDC analysis on the Gila River. The stations were spread out from it’s headwaters to Calva, AZ (Appx. B). The Gila gage is the furthest upstream followed by Virden, Clifton and finally Calva. Unlike the San Francisco River the FDCs for the Gila River show it to be a losing river from the Gila gage down to the Calva gage (Figure 10). All the curves, except for the Gila gage, are quite different from
the San Francisco River FDC’s. They have steeper slopes at both ends of the probability distribution. This shows the Gila River (below Gila, NM) is more sensitive to the summer high flow events and that there is less contribution of groundwater to the low flows. This is again supported by the hydrographs which indicate a greater influence on large flow from summer monsoon events than snow melt or winter storms.

Figure 10

Discussion

One important question arises when comparing, not only the hydrographs between the Gila and San Francisco Rivers, but also the FDC’s. What is the reason for the major differences in streamflow variability between the two rivers? This is not an easy question to answer and it should be cautioned that only a very first approximation can be made from these analyses and the data collected. The description of the geology gives a good clue to many of the differences between the river FDC’s. Both rivers start in the relatively high mountains of the Black Range, in New Mexico, and the Mogollon Rim, of Arizona. Once the Gila River has past Gila, New Mexico, it flows out into the southern extension of the Basin and Range Province (Appx. B). Here the Gila River flows across large deep alluvial filled basins. The San Francisco River, on the other hand, never flows out into the Basin and Range Province. A likely scenario is that the Gila River loses substantial flow to the large alluvial basins once out of the Black Mountains. This is supported by the fact that the FDC for the Gila gage station is similar to those of the San Francisco River. The Gila gage is located where the Gila River flows
out of the Black Mountains which is similar to the topography which the San Francisco River flows.

Analysis was done on the 2001 National Land Cover Dataset in comparing the two sub basins in the Upper Gila River Basin. However, this provided no conclusive results. This was because the sub basins were dominated by one of two types of land cover. The San Francisco was dominated (over 97%) by conifer forest, whereas the Gila was dominated (over 95%) by shrub and scrub land. More detailed analysis on both the Gila River and the San Francisco River must be conducted to better constrain the streamflow variability within the Upper Gila River Basin.

Conclusions

The goal of this study was to understand the variability of streamflow in the Upper Gila Basin and to estimate the available streamflow that could be potentially developed by the State of New Mexico. To a first order approximation, the variability of the streamflow was described. As for the potential amount of developable water a realistic value for the Upper Gila River Basin is the flow that is exceeded 95% of the time [1]. This value can be determined from the FDC’s. Since there are no USGS stream gages at the border of Arizona and New Mexico the gages closest upstream from the border are used, Virden on the Gila River and Glenwood on the San Francisco River. Based on the 95% exceedence probability discharges for those two gages an estimate of 50,700 acre feet per year of water is flowing into Arizona from New Mexico. This is well above the extra 14,000 acre feet per year New Mexico is allotted. However, this is a very simple approximation based on very little data. As stated in the discussion section there is much more analysis to be done before decisions can be made about the development of the allotted Gila River water.

Future Work

Flow Duration Curves

A more rigorous statistical analysis should be employed on the FDC’s. Vogal and Fennessey provide more robust methods of calculating the Median Annual Flow Duration Curves. The method used in this study was the simplest of the methods. Also confidence intervals should be calculated so as to provide a better estimate of available water to potentially develop. Flood frequency analysis would complement the FDC’s as well as the hydrograph analysis.

Basin Characterization

The Hydrogeology needs to be investigated for both the highlands (Black Mountains, Mogollon Rim) and the Basin and Range Province in southeastern Arizona. Groundwater monitoring in close proximity to the rivers should be done to understand the groundwater surface water interactions throughout the Upper Gila River Basin. Geochemistry would also be useful in understanding groundwater residence times, delineating recharge, and flow paths.
Precipitation

Precipitation data, especially historical, would be very useful in better understanding the hydrographs and the response time of the basin to storm events.
Bibliography


Appendix A

USGS Gage Hydrographs

Gila River Calva Gage 1928-2007

Gila River Clifton Gage 1910-2007
Example of a delineated catchment for a USGS stream gage in the Upper Gila River Basin
Locations of USGS gages used in FDC analysis for the San Francisco River
Locations of USGS gages used in FDC analysis for the Gila River
Study area and USGS gages used in analysis
Three dimensional rendition of the Gila River delineated from the Clifton gage. This view is looking W-NW. Green dots are gage locations.
Three dimensional rendition of the San Francisco River delineated from the Clifton gage. View is looking NE.