Using GIS to determine appropriate pulse flows and emblematic locations for restoration along the Lower Colorado River From Hoover Dam to the Sea of Cortéz

Problem Statement:

The landscape of the Lower Colorado River has been seemingly permanently altered through the addition of monumental dams for the production of hydropower, control of floods, and use of water for agriculture. The damming of rivers has been compared to the clogging of arteries, where the human system stops working in a healthy way. Being one of, if not the, most dammed rivers, the Colorado River has been transformed such that evidence of the historical volatility that engendered its formerly rich ecosystem has disappeared and is now remembered only by the famous literary works it inspired (Figure 1).

The political and economic climate along the entire Colorado River poses bureaucratic challenges in addition to the formidable structural challenges that make returning to this lush natural system a difficult feat. This study seeks to address those challenges by proposing a long-term plan using mimic pulse flows. Pulse flows are essentially induced floods, which mimic the irregular yet frequent floods that occurred in the area historically, although unlikely of the same magnitude. Because of the rigid flood control of the dams, however, developments have been
constructed directly adjacent to the river, and are at risk of being flooded during pulse flows. In order to circumvent man-made disasters, the first step in implicating pulse flows should be to hydraulically model water stages with different discharges from the sequential dams along the stretch of the Lower Colorado River from Hoover Dam to the Sea of Cortéz (or Gulf of California), the study area I will ultimately focus on. For this study, however, a small portion of the river will be most feasible to test the software, discussed further in a following section. The model described in this paper will be used to determine what amount of flow would be most practical and beneficial, as well as identify key sites of restoration to be examined at a smaller scale.

The model utilizes HEC-RAS, a hydraulic modeling system developed by the Army Corps of Engineers, to visualize the extent of water inundation at different locations along the Lower Colorado River with various discharges. Although, the elevation data of the area is somewhat coarse (1/3 arc second), an idea of the developments and areas that are likely to be most affected by mimic pulse flows is nonetheless obtainable. Furthermore, since 1/3 arc second DEMs are ubiquitous for the entire United States, this model can be applied to rivers with similar issues. After identifying sites that are interesting to zoom into for restoration, for which I will discuss parameters for in a later section, I could potentially use a LiDAR data acquisition device to more thoroughly map the landscape of sites for restoration plans developed to a further extent. However, this will not be in the scope of this class.

**History Review:**

Before the construction of large dams, the Colorado River ragged through its canyons, often on an erratic path that varied through seasons and years. In the Lower Colorado, the floodplain region of the river, this led to diverse wetland systems with abundant waterfowl, native fish, and a variety of fauna. This turbulent river and vigorous ecosystem have since been compromised as humans have gradually tamed the river through a variety of structures over the last 170 years². Today, the river is unlikely to reach the Sea of Cortéz, aside from a recent agreement between the U.S. and Mexico, Minute 319, discussed at a later point. Alternatively, the Colorado’s primary uses are for hydroelectric power and to provide a reliable supply of water for farmers and urban users, which are accomplished by large dams and reservoirs such as the Hoover Dam
and its reservoir Lake Mead. Today, roughly 70% of all the river’s water used goes to agriculture

As a result of these blockages, the water is now colder, clearer, and more sediment starved than the original river. Without seasonal floods to introduce nutrients and seeds to the area, as well as laterally change the landscape by creating features such as backwaters that acted as healthy habitat, the flora and fauna have changed drastically. The native vegetation has been outcompeted by ubiquitous Salt Cedar (Tamarix) and Giant Reed (Arundo donax). This decrease in diversity and reduction of riparian habitat influenced the fauna of the area, such as the Southwestern Willow Flycatcher, to decline in abundance and ultimately be placed on the endangered species list.

Many competing interests make it difficult to design a restoration strategy that is process-based. The primary restoration plan, the Multi-Species Conservation Plan (MSCP), was created and is managed largely by entities that have higher stakes in hydropower and water allocation rather than restoration. Additionally, the law of the river allocates very specific amounts of water to entities and states throughout the entire lower Colorado River, making it necessary to design restoration plans without infringing on an important resource. Changing temperatures and precipitation patterns are likely to amplify bureaucratic difficulties in distributing water along the entire stretch of the Lower Colorado River for restoration purposes. Fortunately, the law of the river is not infallible in allocating every drop to agriculture, power, or for urban use. It is possible to reuse water that farmers use to flood alfalfa fields, in addition to argue that ensuing native vegetation will be less water intensive than existing invasives and ultimately more beneficial for flora, fauna, and recreational and historical enjoyment.

Mimic pulse flows in some stretches of the Lower Colorado River have been shown to increase ecosystem health. The flooding of riparian areas results in the flushing of salts and creation of new habitat by supplying nutrients and genetic material. It is important to note, however, that in some cases an addition of nutrients and seeds might be necessary since an abundant amount of organic material is trapped behind the dams. On the other hand, sediment releases from the dams are not widely discussed in the literature and would be worthwhile to look more into. More frequently manual sediment removal is discussed, as well as dam decommission. Minute 319 is a concrete example of a pulse flow carried out in 2014 as the result of an agreement between the
United States and Mexico. The goal of the treaty was to find cooperative mechanisms in order to address water shortage in the Colorado River delta and ultimately led to the river reaching all the way to the Gulf of California\textsuperscript{7}. Minute 319 turned out to be a huge success, which provides us with a relevant precedent that periodic pulse flows can not only be beneficial for the entire Lower Colorado River, but received positively. The question now is one of reducing risk to adjacent development and finding the optimum range of water to be released at the appropriate times.

**Solution:**

To answer the problem of how to implicate pulse flows, as well as decide on restoration sites to zoom into, I used a combination of hydraulic modeling (HEC-RAS, and its pre-processing add-on to ArcMap, HEC-GeoRAS) and suitability analysis. The hydraulic modeling software HEC-RAS has been widely used to model different types of flow, sediment transport, and flood inundation all over the country, including in the Grand Canyon and International Boundary regions of the Colorado river\textsuperscript{8}. HEC-RAS requires two types of data: geometric data and flow data. The geometric data includes a Digital Elevation Model (DEM) of the area that informs necessary cross sections, distance until next cross section, Manning’s values, and any important structures such as bridges or weirs. The geometric data can be processed in ArcMap using HEC-GeoRAS after creating contours and then a TIN from the DEM. HEC-GeoRAS enables the creation of river centerline, bank lines, and flow path lines, and then creates cross section lines based on the criteria set. In this case the cross sections are 500m apart and 1000m long. Hydraulic structures can also be added in HEC-GeoRAS. The flow data describes the amount of flow, which I can add a number of times depending on the amount of pulse flows being tested\textsuperscript{9}, and will be added in HEC-RAS after the pre-processing stage. Lower Colorado River discharge data, the law of the river, and prior work on optimum amounts of water for mimic pulse flows were used to decided on the quantity of discharge per dam for mimic pulse flows that will be most useful to test\textsuperscript{10}. The 1/3 arc second DEM is sourced from USGS National Map Viewer. Given that USGS does not provide data for Mexico, I have not yet been able to find international DEMs. The projection used for pre-processing, HEC-RAS, and the suitability analysis is NAD 1983 Zone 11N. Manning’s values are calculated using 2014 Lower Colorado River flow rate data using the following equation:
\[ v = \frac{R^{2/3} S^{1/2}}{n} \]

Where, \( v \) = average velocity, \( R \) = hydraulic radius, \( S \) = slope of water surface, and \( n \) = Manning’s roughness coefficient. However, for the natural portions of the stream, we can assume that the Manning’s value is 0.035.

After running the hydraulic model for all mimic pulse flow amounts, the inundation information is loaded back into ArcGIS along with the DEM, and shapefiles of adjacent cities/developments, roads, MSCP sites, and critical species habitat. The first criteria in the suitability analysis, inundated development, will be prepared by clipping the development layer to the results from HEC-RAS. I gave inundated development a higher weight because these are the areas at highest risk and will be given priority in decision-making when pulse flows are proposed to constituencies. The second criteria in the suitability analysis, areas of critical species habitat (as outlined by the Endangered Species Act), are periodic along the Lower Colorado and should be focused on to ensure the best habitat restoration occurs. Finally, MSCP sites were chosen as criteria because of any existing recreational or cultural infrastructure that might exist and can be expanded upon. The conceptual model of the solution is graphically represented below for the above-described solution (Figure 2).

![Conceptual Model of Solution](image-url)
Results:

The following results are from a small portion of the Lower Colorado River, just below Parker Dam and Lake Havasu, for this paper we will refer to this area as Reach 1. The modeling software performed much better and was less arduous with a smaller area. These results are therefore, the results of hydraulic modeling exploration and will lend to a conclusion about how it can potentially be improved.

Pre-Process

In the pre-process stage, Reach 1 was used to delineate the river, banks, flow paths, and cross sections (Figure 3). A TIN is commonly used for this portion of analysis; however, it is unknown whether the original DEM could be used. The process was straightforward and primarily made use of editor to create features. In HEC-GeoRAS it is optional that you draw bridges or other lateral structures, none were drawn. Directly from this step in ArcMap, the river corridor data was exported into HEC-RAS format.

Figure 3. Pre-process results using HEC-GeoRAS in ArcMap
Process

After opening the data in HEC-RAS, it was visualized using Geometric Data window (Figure 4). The steady flow data using the average daily discharge value from the Parker gauge in 2014 was input (7800 cfs) and the Manning’s value was input as well. Subsequently, I ran a steady flow analysis. This process was representative of trial and error in that once the analysis would run the errors would need to be fixed. For example, both the downstream and upstream ends of the reach were created as “junctions” that did not join any other feature. This meant that they were invalid and were blocking the completion of the analysis. Since no other rivers were actually joining this portion of the Colorado River, I was able to just delete them. A few of the cross sections also had to be lengthened. Since the input data included the elevation data, this was not a problem. The successful steady flow analysis was visualized in the X-Y-Z Perspective Plot as shown in Figure 5. The results were then exported to GIS data, which was in an .SDF file format. Since, this is not a supported format in ArcGIS, the conversion software FDO2FDO was downloaded to convert the .SDF files to .SHP files. Unfortunately, the software was unable to process my request because the .SDF file was
evidently an “unsupported version.” At this point in time, I have not been able to fix this problem but am in the process of getting in contact with someone from the Army Corps of Engineers that might be able to help.

**Final**

Since the hydraulic modeling results were unavailable to include in the suitability analysis, I made a tool that buffered 5 distances (10m, 50m, 100m, 250m, and 500m) from the river and then clipped development to these areas to act in the place of the hydraulic output. Development included various forms of land use, specifically, transportation, communication & services, residential, commercial & services, other urban & mixed urban/built-up land, and industrial areas. There are no MSCP sites in Reach 1, and in fact, only a small percentage of them along the entire Lower Colorado River. The critical species habitat includes all areas that are either aquatic or riparian. The resultant map, and preliminary suitability analysis, shows the areas of development closest to the Colorado River, as well as critical species habitat, and can be seen in Figure 6.

Uncertainties that likely occurred include a potential lack of precision due to the coarse elevation data. This could easily be remedied once better data is available. There is also a certain amount of uncertainty in the HEC-RAS model dependent on the amount of information provided. For example, bathymetry data would be beneficial in developing a more holistic surface to be flooded but is largely unavailable. Manning’s values could have been more specific based on the substrate of the river in any particular reach, however were likely not far off from the true value.
It is also possible that additional development is being presently built and was therefore overlooked.

**Conclusion:**

The conclusion for this paper more pertinently discusses the utilization of HEC-RAS in determining areas of inundation using a Digital Elevation Model with ArcGIS. HEC-RAS itself is a very powerful tool that has progressed since its first iteration but is slightly incompatible with ArcGIS. Although there exists a pre-processing tool for HEC-RAS, HEC-GeoRAS, there is not an available post-processing tool that allows us to visualize the results in ArcMap. This is not ideal as it interferes with the overall analysis, as flood or pulse flow inundation is likely only a small portion of which. Using what I have learned from this modeling assignment, I plan to develop software or a workflow that allows for quicker, straightforward, and precise analysis of digital elevation models for inundation of banks during pulse flows. This is important, as pulse flows are a primary process-based restoration tool for areas that have been heavily dammed and damaged, such as the Colorado River. HEC-RAS could be a very useful tool for restoration ecologists and environmental planners, as an alternative to the primary engineering user base it currently has, if we were able to incorporate the data into ArcGIS more seamlessly. It would be especially powerful if the entire HEC-RAS process were able to take place within ArcMap or other ArcGIS software. This would enable easier visualization of pulse flows and quicker determination of the appropriate range.

Pulse flow visualization is one of the first steps in determining their implication. The overall process must include frequency and timing since the implication of pulse flows should be different on wet and dry years to not only coincide them with the seasons but climate change and releases from agriculture. For flows that are meant to restore habitat the amount of sediment and available nutrients as well as vegetation would be ideal to include as well. This sort of analysis is out of range of HEC-RAS and something that would be important to include in a new piece of software that can be used within ArcGIS.

Given the adjacencies of development to the river, as seen in the preliminary suitability analysis, any induced amount of flooding could potentially affect these areas. In order to ensure that more development is not built within a certain distance of the river (to be determined by more
extensive modeling) policies need to be created that not only take into account mimic pulse flows as a means to restore habitat, but also include buffers that protect development from potential larger floods in wetter years. Based on the stringent over-allocations of the river water by the law of the river, a re-estimation of practical water use should occur based on climate prediction models. Some percentage of the water, also based on climate prediction models, should be set aside for mimic base and pulse flows that can restore groundwater and not only benefit habitat but increase the quality of water without having to build more expensive desalination plants. With that in mind, policies should be more interconnected in what they mandate. For example, we would like to introduce more frequent mimic pulse flows to decrease the salty sediment, but if agriculture were managed in a responsible way, there would be less need to desalinate the water before it arrives in Mexico. This could be accomplished through agro-ecological principals that do not require as intensive of irrigation, produce food that is socially available to the people that are closest to it, and make use of practices that have proven to work in these areas in the past without extensive water use such as dry farming. By incorporating innovative systems that can benefit habitat and water quality, such as buffer riparian areas in between the river and its adjacent agricultural operations to filter and use excess salts and nutrients, we would be benefiting many people and organisms. And finally, connecting back to a previous point, through sectoral allocations and policies between municipal, power, and agricultural economies that are more representative of their synergistic and interconnected nature, restoration is more likely to be holistic and last for future generations to enjoy.

The first step in important policy changes, however, is creating a cohesive pulse flow model, development risk map, and restoration strategies for mitigation. HEC-RAS could be an important tool in this process as I continue to iron out the kinks and potentially develop new software and/or tools that could assist environmental planners in complex problems such as the one of the Colorado River.
References:


