**Re-operate Lake Powell and Lake Mead for Ecosystem and Water Supply Benefits**

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## Abstract

The endemic fish population has been resurgent within the Grand Canyon reach of the Colorado River. While this population boom has been attributed to prolonged drought within the Colorado River basin, there are additional challenges those require further attention to sustain the native fish population, e.g., **ensuring temperature for spawning**, **sustaining bug population**, which is the primary food source, **hindering the encroachment of predatory fish** within the Grand Canyon region, etc. The purpose of this study is to create a hypothetical dam operation scenario to address these three issues mentioned above while ensuring that the Lower Basin states (California, Arizona, and Nevada) and Mexico get their yearly allotted water of 8.23 million acre-feet (MAF) fixed by the Colorado River Compact, 1922.

**Introduction**

The portion of Colorado river between Lake Powell and Lake Mead, known as the Grand Canyon (Figure 1), has a unique ecosystem, which has been home to number of endemic species for ages. For example, humpback chub (HBC), razorback sucker, bluehead sucker, flannel mouth sucker, and speckled dace are native fish species to Grand Canyon (National Park Service, 2014). The construction of Glen Canyon Dam (GCD) in 1963 has disturbed the natural physical and environmental processes of the Grand Canyon (Wright et. al., 2009, Schmidt et. al., 1998), which in turn has drastically affected the growth of native species. Some of the major impacts are the change in temperature which used to fluctuate greatly during pre-dam period to a relatively cold steady temperature, increased water clarity, reduced nutrient, changed flow pattern, reduced sediment load (Gloss et. al., 2005), hydropeaking, etc. But there has been a recent resurgence since the elevation at GCD has dropped during early 2000 due to drought condition; especially the Humpback chub (HBC) population has increased within the Grand Canyon reach, which was usually confined within the Little Colorado River, a tributary of the Colorado River (Rogowski et. al., 2018). The drought that started in early 2000, is somewhat responsible for this population boom, as the elevation of the Lake Powell decreased, the release temperature of the water increased which eventually has risen the river temperature within the Grand Canyon section of the river, and decrease in elevation of Lake Mead created the Pearce Ferry rapid at RM 281.5 which prevented non-native predatory species to swim upstream. While Colorado River Compact of 1922 and Water Treaty of 1944 ensures the Lower basin water requirement which are 7.5 and 1.5 maf/year (USBR) for Lower basin states and Mexico, the reduced river flow has proved to be of great importance for native fauna. The present study will try to create a hypothetical scenario to ensure,

* the water temperature is adequate (14-20oc) in summer months within the Grand Canyon Reach of the Colorado River which is a requirement for the spawning of native fish population.
* the elevation gap at Pearce Ferry Rapid is maintained to block the predatory fishes coming from Lake Mead.
* the lower basin states and Mexico will get the required amount of 8.23 MAF per year.

**Literature Review**

Most of the native fishes are acclimatized to temperature fluctuation (from 0°C to 27°C during pre-dam period), but spawning occurs during summer months when temperature exceeds a certain threshold (Gloss et. al., 2005). For instance, humpback chub, an endangered fish species, requires summer water temperatures in between 14 to 25 °C to spawn (Valdez et. al., 2013). Also, its greatest egg hatching success occurs at 20°C (U.S. Fish and Wildlife Service). Before the construction of Glen Canyon Dam, the water temperature within the Grand Canyon was highly variable; with icy spring run-off to the warm 29.4°C summer flows (Glen Canyon Dam Wiki, 2020). However, after the operation of Glen Canyon Dam, the river turned in to cold monotonous stream (Figure 2). As a result, the late-twentieth century studies found that the population of HBC was restricted to the Litter Colorado River and nearby areas in the mainstem Colorado River only (Glen Canyon Dam Wiki, 2020 and Rogowski et. al., 2018). However, recent surveys indicate a resurgence of the HBC population near the western region of the Grand Canyon. Researchers has determined that the western Grand Canyon HBC is relatively young and hypothesized that the resurgence happened after 2000 (Rogowski et. al., 2018). Specifically, there are speculations that Powell was at its lowest in 2005 and it was releasing warm water (15 °C) comparatively that would have helped the growth of the humpback Chub (Voichick et. al., 2007). Likewise, there are evidence showing the growth of other native fish populations such as Bluehead Sucker, Flannel mouth Sucker, and Speckled Dace in recent years (Kegerries et. al., 2020).

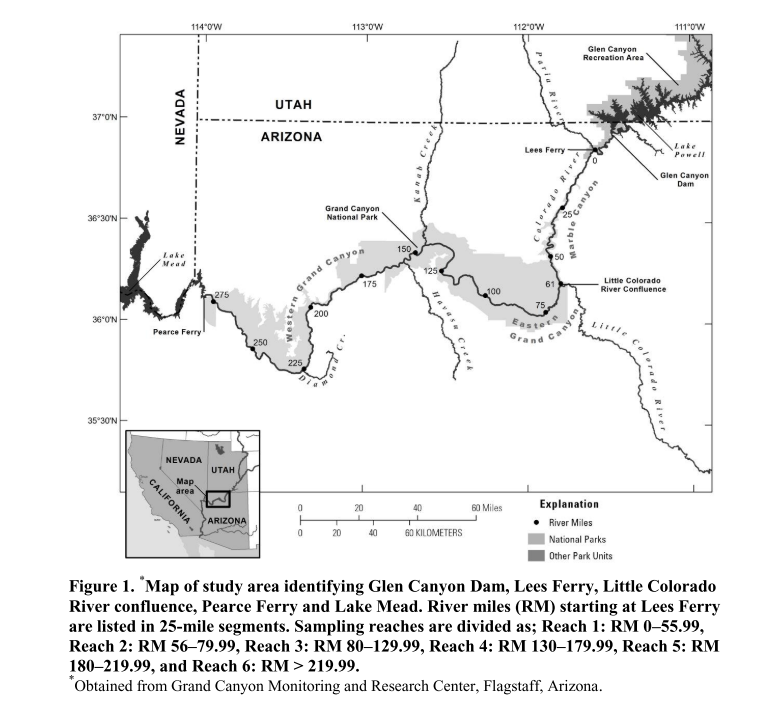


Figure 1: Different reaches of the Colorado River at Grand Canyon (Bunch et. al., 2012)

Besides stream temperature, there can be number of possible reasons attributed to this revival of native fish population in the Grand Canyon. For instance, creation of natural barrier called Pearce Ferry Rapid that obstruct the upstream movement of non-native fishes from Lake Mead, Trout management flows between 2003-05 that controlled the non-native trout fish population by destroying trout eggs (USGS 2011), and High Flow experiments (HFEs) which helped: rate of sediments transport, development of sand bars, removal of non-native vegetation, and growth rate of native flora and funa (Rice 2012). At present, to increase river food web in the Grand Canyon, bug flow experiments are in practice since summer 2018. The idea behind bug flow experiment is to provide steady low flows on weekend for invertebrates to lay and hatch eggs (Kennedy et. al., 2016). Since it is an on-going experiment, therefore, the eco-system benefits from the experiment are inconclusive, but hydropower benefits from the experiment are encouraging.

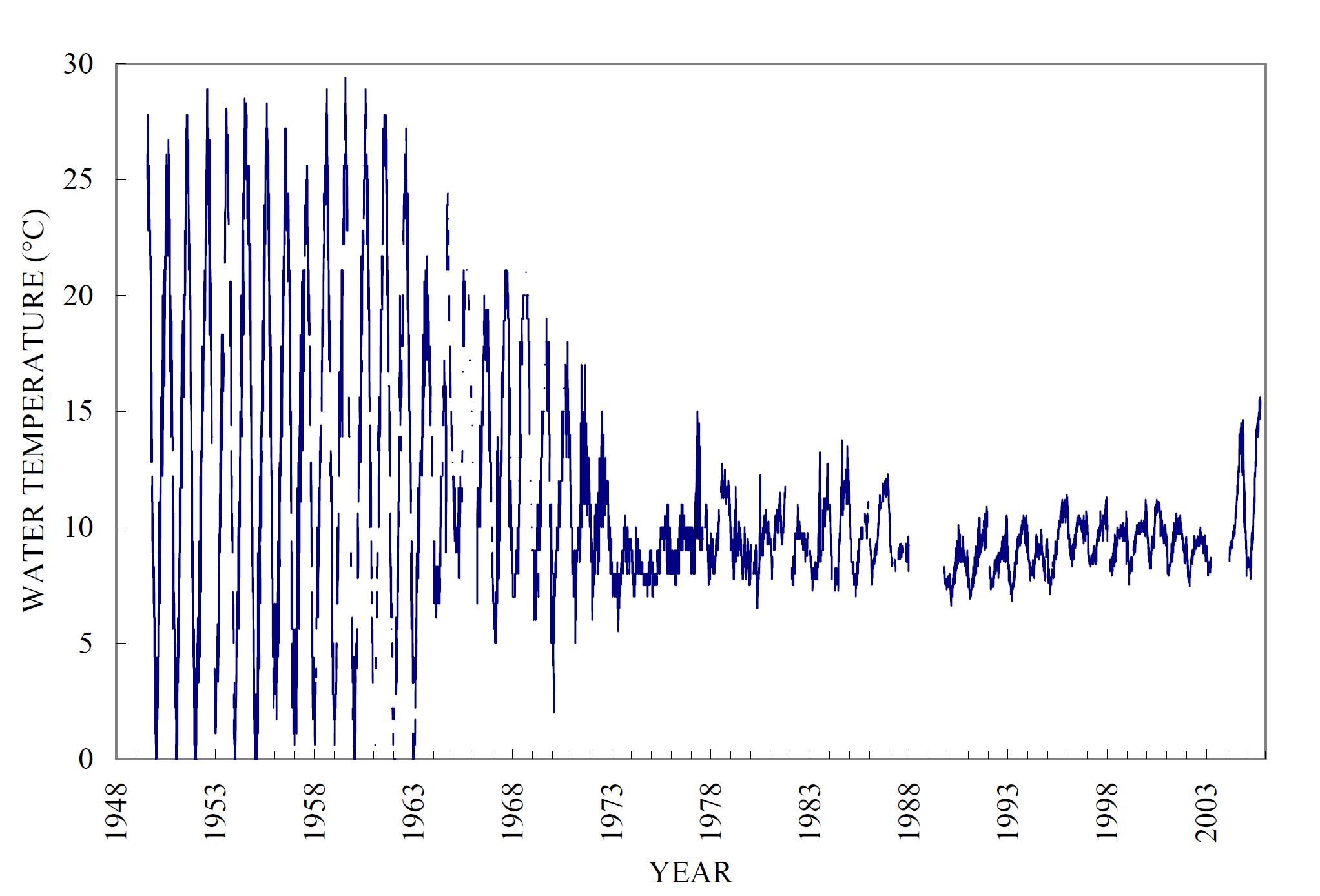


Figure 2 Daily water temperature measured or calculated at Lees Ferry gauge (station id 09380000) (Voichick et. al., 2007)

Geographically, the Colorado River passes through seven western states (i.e. Arizona, California, Colorado, Nevada, New Mexico, Utah, and Wyoming) of U.S and drains into the ocean in Mexico. The equitable allocation and distribution of Colorado River water among the stakeholders is ensured through Colorado River compact of 1922 (USBRa). The compact divided the states into two basins: Upper basin which consists of Colorado, Utah, Wyoming and New Mexico and Lower basin that includes Nevada, Arizona, and California. Although Mexico was recognized as shareholder of the Colorado River in the 1922 compact, but its share was not decided until Mexican water treaty of 1944 (USBRb). Article III of Colorado River compact,1922 allocates equal amount of share to both the basins i.e.7,500,000 acre-feet of water per annum. It also enforces that the upper basin states will not cause the flow of the river at Lee Ferry to be depleted below an aggregate of 75,000,000 acre-feet for any period of ten consecutive years. In addition, the Colorado River compact in various of its articles allows the development of storages facilities, water supply network, and hydropower generation plants to get maximum benefit from the apportioned water. For instance, Hoover Dam was built in lower basin in 1936 to control floods, ensure continuous water supply and produce hydropower. Likewise, Glen Canyon Dam was completed in 1966 and its main reason was to safeguard lower basin water share and produce hydropower. In 1922 compact, the share to Mexico will be upheld by any of basin in surplus or both basins will contribute equally.

This study is aimed to build a systems model for the Grand Canyon Reach of the Colorado River considering water supply, and eco-system objectives. The presented work will explore possible operational schemes for both reservoirs under different volumetric and ecological scenarios. The developed model will be helpful to quantify trade-off between ecosystem and Lower Basin water requirement objectives. Which means the model will give us a hydrograph for Glen Canyon Dam which will favor ecosystem objective (i.e. number of steady low flow days) which is required for the growth of the bug population, the primary food source of native fishes within the Grand Canyon Reach.

Kennedy et al., (2016) in their study found that dams with high intensity of hydropeaking -sub daily fluctuation in releases to meet energy demand—has low invertebrates’ diversity. Hence, providing large number of steady low flow days will help increase bugs population. Which in other words means more food available for fishes. Another recent study which is under review, attributed the rise in river temperature to GCD releases, especially within the first 141 kilometer from the GCD, for the rest of the region, the increase in temperature is attributed to a combination of discharge, short water radiation and local air temperature (Mihalevich et. al., 2020). So, the model will also try to incorporate the developed reservoir elevation and downstream temperature relationships for Lake Powell (e.g. Figure 3) in order to provide favorable conditions for native fishes. Finally, the hydrograph for Hoover Dam help us meet the lower basin demands and keep the Lake Mead Elevation lower than 1135 ft. While increased temperature is a requirement for the native fishes during the summer months, it will also favor the non-native fishes such as channel catfish, common carp, fathead minnows [National Park Service, 2018]. It is uncertain how raising the temperature will affect the native and non-native ecosystem, but to reduce further complexity, this study will to delve into the ecology part of the Grand Canyon reach, and consider that a temperature range between 14-20oc will only benefit the endemic fish population.

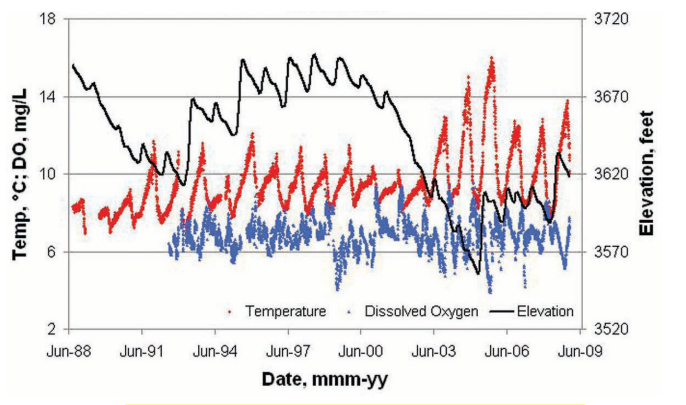


Figure 3 Daily water temperature and dissolved oxygen concentration below Glen Canyon Dam with Lake Powell water- surface elevations, 1988–2008 (Williams, 2009)

**Model Description**

This is a monthly timestep model which run for a period of three years. For initial results, we are considering three years from WY 2017-2020. The required data were collected from USBR website and CRSS software. The model will use the inflow values for the Lake Powell, the Paria River, the Kanab Creek, The Havasu Creek, The Little Colorado River and Diamond Creek to achieve following objectives,

**Objective 1: Environmental flow**

Water should be released from an elevation within the following range for the summer months mentioned below. The values were received from an on-going research related to temperature model within the Grand Canyon Reach.

Table 1: The required Elevation and Storage Range of Lake Powell

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Month (Month number in the model) | Minimum Elevation[ft] | Storage at that Minimum elevation[acf] | Maximum Elevation[ft] | Storage at that Maximum elevation[acf] |
| May (M8,20,32) | 3530 | 6238450 | 3700 | 24322365 |
| June (M9,21,33) | 3560 | 8323055 | 3700 | 24322365 |
| July (M10,22,34) | 3610 | 12730300 | 3700 | 24322365 |
| August (M11,23,35) | 3655 | 17846128 | 3700 | 24322365 |

The flow for fishes is considered adequate (temperature wise) if the release is between the above mentioned range of elevation. So, the objective will be maximize the number of months in three consecutive years when the end of the month storage (12 months in total for three years) are with in the range mentioned above.

Requirement 1 =

We can use a reliability metric to quantify the efficiency of the modeled system.

Max Obj\_ 1 = Requirement 1 / 12 (M8:M11, M20:M23, M32:35)

**Objective 2: Upper Basin Delivery**

The upper basin will deliver 8.23 million acre-ft on an average to the lower basin states. So, for three years, the total amount will be 24.69 MAF on an average which should be delivered to the lower basins. If the total delivery in the consecutive three years is,

Total Delivery in three years =

Then our objective will be to minimize the difference between the total amount delivered and the required amount delivered for the three years period.

Min Obj\_2 = |24.69 MAF - Total Delivery in three years |

**Objective 3: Months when Mead elevation is less than 1135 ft**

The third objective is to keep the elevation at lake mead below 1135 ft above MSL. At 1135 ft, storage capacity of Lake Mead is 15.12 MAF.

Obj\_Fraction\_3 =

We will use Multi objective constraint method to solve the problem

**Model Formulation**

The model formulation part is provided in Appendi-2. The codes are still in the preliminary state. The codes can be found in Aveek, M.R., 2020. The required data and copy of this report is also uploaded in the GitHub repository.

**Results**

We are still at the stage of model development, hence, there are no results available at the moment. During last few weeks, we have refined our initial thoughts about the system and has successfully coded 50% of our understanding about the system in GAMS. Currently, we are working on the development of objective function equations. As discussed earlier, this is a multi-objective problem and three of its objectives need sigmoid (tangent) or arc-tangent functions for their representation. The tangent or arctangent functions, primarily, can be considered as step function where the function switch the satisfaction value around the threshold (refer Figure 4 for illustration).

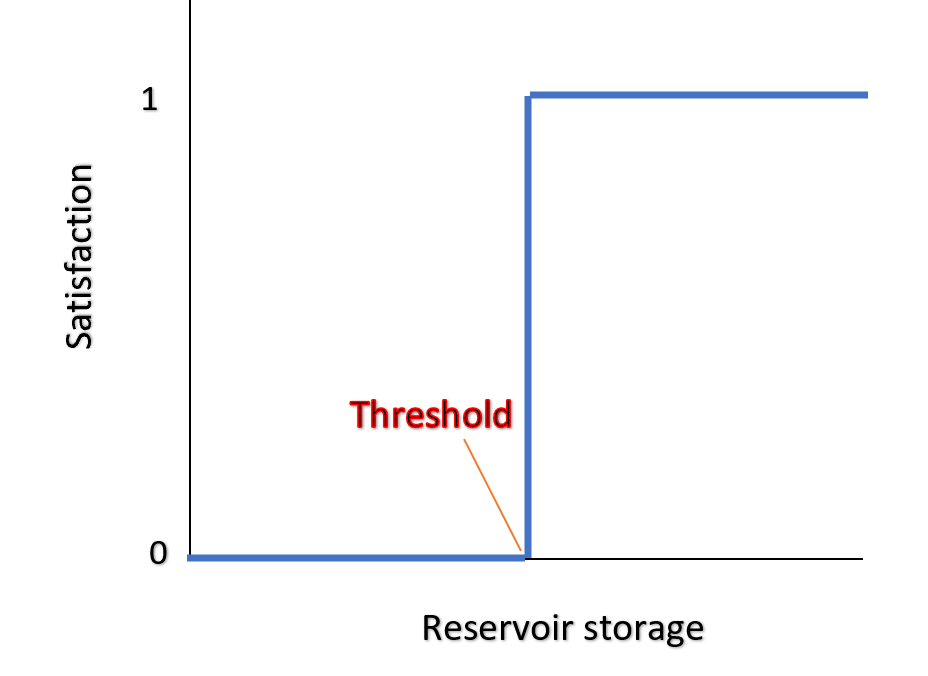


Figure 4: Example sigmoid function

**Current challenges and considered approaches**

We are currently exploring the functions (e.g. tangent and arctangent) that can represent our objectives. We are training the available functions so they can produce desirable satisfaction values under identified conditions. Lastly, we will decide about plotting the results of the model. With 4 objectives, plotting all the results will be the next challenge in itself.

**Conclusion**

This document is an intermediate progress report that illustrates the problem, past works, and shares the future goals to achieve the objective. We were not able to generate results as we are still modifying the GAMS code, but we intend to develop a running model within November 25. The updated code and the results will be uploaded in Aveek, M. R., 2020 repository.**References:**

Bunch, A. J., Osterhoudt, R. J., Anderson, M. C., & Stewart, W. T. (2012). *Colorado River Fish Monitoring in Grand Canyon , Arizona — 2012 Annual Report*. (December), 1–41. <https://doi.org/10.13140/RG.2.2.31954.61124>

Glen Canyon Dam Wikia, (2020), <https://gcdamp.com/index.php?title=TEMPERATURE>

Glen Canyon Dam Wikib, (2020), <http://gcdamp.com/index.php?title=File:LTEMP_monthly_volumes.png>

Gloss, S., Lovich, J., & Melis, T. (2005). *The State of the Colorado River Ecosystem in Grand Canyon: USGS Circular 1282*.

Kegerries, R. B., Albrecht, B., McKinstry, M. C., Rogers, R. J., Valdez, R. A., Barkalow, A. L., … Smith, E. O. (2020). Small-Bodied Fish Surveys Demonstrate Native Fish Dominance Over 300 Kilometers of the Colorado River Through Grand Canyon, Arizona. Western North American Naturalist, 80(2), 146. <https://doi.org/10.3398/064.080.0202>

Kennedy, T. A., Muehlbauer, J. D., Yackulic, C. B., Lytle, D. A., Miller, S. W., Dibble, K. L., & Baxter, C. V. (2016). Flow management for hydropower extirpates aquatic insects, undermining river food webs. BioScience, 66(7), 561-575.

Mihalevich, B. A., Neilson, B. T., Buahin, C. A., Yackulic, C., & John, C. (n.d.). *Water temperature controls for regulated rivers in complex topographic regions*.

National Park Service (July 24, 2018), (<https://www.nps.gov/grca/learn/nature/fish-native.htm>)

Rice, J. Controlled Flooding in the Grand Canyon: Drifting Between Instrumental and Ecological Rationality in Water Management. Organization & Environment, 26(4), 412–430. https://doi.org/10.1177/1086026613509250 (2013).

Rogowski, D. L., Osterhoudt, R. J., Mohn, H. E., & Boyer, J. K. (2018). Humpback Chub (Gila cypha) Range Expansion in the Western Grand Canyon. Western North American Naturalist, 78(1), 26–38. <https://doi.org/10.3398/064.078.0105>

Schmidt JC, Webb RH, Valdez RA, Marzolf GR, Stevens LE. 1998. Science and values in river restoration in the Grand Canyon. BioScience 48:735–747.

United States Bureau of Reclamation <https://www.usbr.gov/lc/region/pao/pdfiles/crcompct.pdf>

United States Bureau of Reclamation <https://www.usbr.gov/lc/phoenix/AZ100/1940/mexican_water_treaty.html#:~:text=The%20Mexican%20Water%20Treaty%20of,Colorado%20River%20Compact%20of%201922>

U.S. Department of the Interior. (2016). *Record of decision for the Glen Canyon Dam long-term experimental and management plan final environmental impact statement*. 196.

U.S. Fish and Wildlife Service (<https://www.fws.gov/fisheries/freshwater-fish-of-america/humpback_chub.html#:~:text=The%20humpback%20chub%20reaches%20sexual,57.2%20%E2%80%90%2075.2%20degrees%20Fahrenheit>.)

U.S. Geological survey. <https://pubs.usgs.gov/fs/2011/3002/fs2011-3002.pdf>

Valdez, R. A., Speas, D. W., & Kubly, D. M. (2013). Benefits and risks of temperature modification at Glen Canyon Dam to aquatic resources of the Colorado River in the Grand Canyon. U.S. Bureau of Reclamation, Upper Colorado Region, Salt Lake City, UT, (September).

Voichick, N., & Wright, S. A. (2007). Water-temperature data for the Colorado River and tributaries between Glen Canyon Dam and Spencer Canyon, northern Arizona, 1988-2005 (p. 24). Washington, DC: US Geological Survey.

Williams, N. T. (2009). Projecting Temperature in Lake Powell and the Glen Canyon Dam Tailrace. 2008, 1–9. Retrieved from <https://www.researchgate.net/profile/Theodore_Melis/publication/258998603_Proceedings_of_the_Colorado_River_Basin_Science_and_Resource_Management_Symposium_November_1820_2008_Scottsdale_Arizona/links/00b7d529a09f5a86cb000000.pdf#page=165>

Wright, S. A., Anderson, C. R., & Voichick, N. (2009). A simplified water temperature model for the Colorado River below Glen Canyon Dam. *River Research and Applications*, *25*(6), 675–686. [https://doi.org/10.1002/rra.1179](https://doi.org/10.1002/rra.1179\)

Appendix 1

Figures

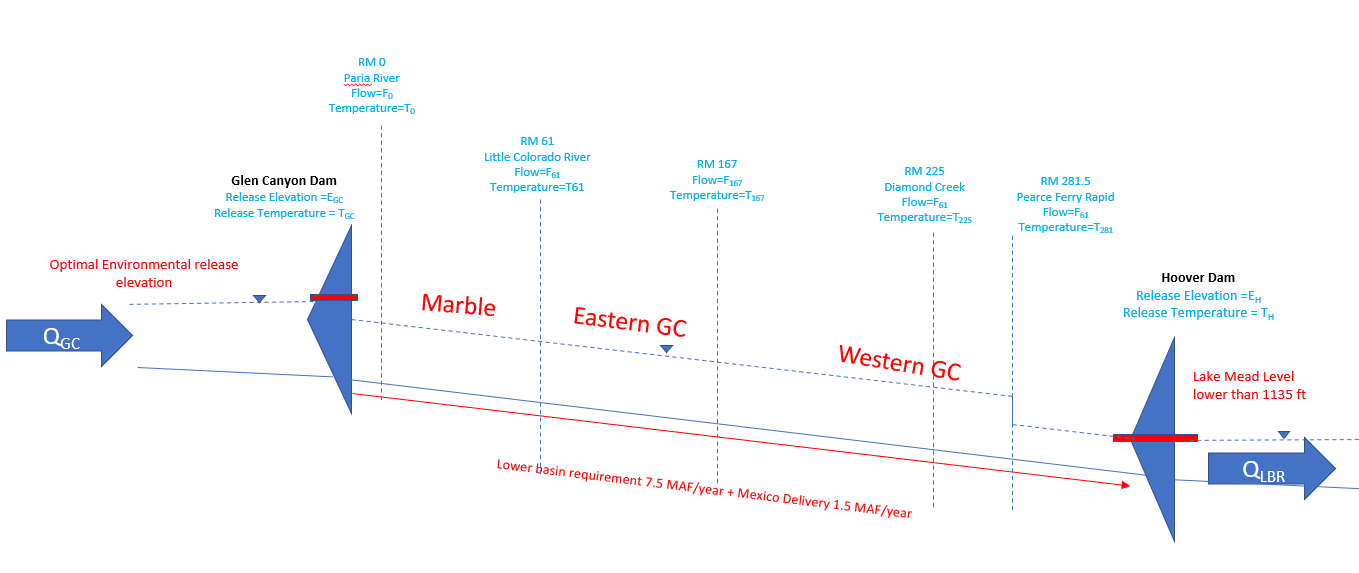


Figure A1: Schematic of the problem

Appendix 2

**Model Formulation**

|  |  |
| --- | --- |
| **Sets** | |
| yr | water years y1:y3 |
| M | Months in a year M1:M12 |
| modpar | Saving model parameter: ModStat and SolStat [Model and Solve Statistics respectively] |
| **Data** | |
| Inflow\_Powell | Inflow coming to Powell for UB states per month [maf] for WY2017-2020 |
| Inflow\_Paria | Inflows from Paria River to the Colorado River near Glen Canyon per month [maf] for WY2017-2020 |
| Inflow\_LitColorado | Inflows from Little Colorado River to the Colorado River near Glen Canyon per month [maf] for WY2017-2020 |
| Inflow\_KanabCreek | Inflows from Kanab Creek to the Colorado River near Glen Canyon per month [maf] for WY2017-2020 |
| Inflow\_Havasu | Inflows from Havasu Creek to the Colorado River near Glen Canyon per month [maf] for WY2017-2020 |
| Inflow\_Diamond | Inflows from Diamond Creek to the Colorado River near Glen Canyon per month [maf] for WY2017-2020 |
| evap\_Mead | Lake Mead monthly Evaporation [maf] for WY2017-2020 |
| evap\_Powell | Lake Powell monthly Evaporation [maf] for WY2017-2020 |
| Init\_Powell | 14664000 acf |
| Init\_Mead | 10182000 acf |
| **Decision Variables** | |
| **Mass balance at different locations** | |
| Storage\_Powell(M) | Storage in Lake Powell at each time step (acf) |
| Flow\_atParia(M) | Inflows at the confluence point of Paria River (acf) |
| Flow\_atlitColorado(M) | Inflows at the confluence point of Little colorado River (acf) |
| Flow\_atDiamond(M) | Inflows at the confluence point of Dimaond creek (acf) |
| Storage\_Mead(M) | Storage in Lake Mead at each time step (acf) |
| Rel\_Powell (M) | Release from Lake Powell afte |
| EOM\_Powell(M) | End of the month storage at Lake Powell (acf) |
| EOM\_Mead(M) | End of the month storage at Lake Mead (acf) |
| **Volumes** | |
| Vol\_Powell | Total volume of water released from lake powell during study period (ac-ft) |
| Vol\_Mead | Total volume of water released from lake Mead during study period (ac-ft) |
| **Release** |  |
| Rel\_Powell(yr,M) | Release from lake powell (cfs) |
| Rel\_Mead(yr,M) | Release from Lake Mead (cfs) |
| **Constraints** | |
| **Mass Balance** | |
| EQ1\_Powell\_1styr(yr,M) | **Mass balance at Lake powell during year 1 (ac-ft),** we need to convert the release for every month.  Storage\_Powell(yr,M) =e= Init\_Powell$(ord(M)eq 1)+ Storage\_Powell(yr,M-1)$(ord(M)gt 1)+ Inflow\_Powell(yr,M)- Rel\_Powell(yr,"M1")\*Convert\*31 - Rel\_Powell(yr,"M2")\*Convert\*30 - Rel\_Powell(yr,"M3")\*Convert\*31 - Rel\_Powell(yr,"M4")\*Convert\*31 - Rel\_Powell(yr,"M5")\*Convert\*28 - Rel\_Powell(yr,"M6")\*Convert\*31 - Rel\_Powell(yr,"M7")\*Convert\*30 - Rel\_Powell(yr,"M8")\*Convert\*31 - Rel\_Powell(yr,"M9")\*Convert\*30 - Rel\_Powell(yr,"M10")\*Convert\*31 - Rel\_Powell(yr,"M11")\*Convert\*31 - Rel\_Powell(yr,"M12")\*Convert\*30 - evap\_Powell(M)\*Storage\_Powell(yr,M) |
| EQ2\_Powell\_2ndyr(yr,M) | **Mass balance at Lake powell during year 2 (ac-ft)**  Storage\_Powell(yr,M) =e= Powell\_yr1$(ord(M)eq 1)+ Storage\_Powell(yr,M-1)$(ord(M)gt 1)+ Inflow\_Powell(yr,M)- Rel\_Powell(yr,"M1")\*Convert\*31 - Rel\_Powell(yr,"M2")\*Convert\*30 - Rel\_Powell(yr,"M3")\*Convert\*31 - Rel\_Powell(yr,"M4")\*Convert\*31 - Rel\_Powell(yr,"M5")\*Convert\*28 - Rel\_Powell(yr,"M6")\*Convert\*31 - Rel\_Powell(yr,"M7")\*Convert\*30 - Rel\_Powell(yr,"M8")\*Convert\*31 - Rel\_Powell(yr,"M9")\*Convert\*30 - Rel\_Powell(yr,"M10")\*Convert\*31 - Rel\_Powell(yr,"M11")\*Convert\*31 - Rel\_Powell(yr,"M12")\*Convert\*30 - evap\_Powell(M)\*Storage\_Powell(yr,M) |
| EQ3\_Powell\_3rdyr(yr,M) | **Mass balance at Lake powell during year 3 (ac-ft)**  Storage\_Powell(yr,M) =e= Powell\_yr2$(ord(M)eq 1)+ Storage\_Powell(yr,M-1)$(ord(M)gt 1)+ Inflow\_Powell(yr,M)- Rel\_Powell(yr,"M1")\*Convert\*31 - Rel\_Powell(yr,"M2")\*Convert\*30 - Rel\_Powell(yr,"M3")\*Convert\*31 - Rel\_Powell(yr,"M4")\*Convert\*31 - Rel\_Powell(yr,"M5")\*Convert\*28 - Rel\_Powell(yr,"M6")\*Convert\*31 - Rel\_Powell(yr,"M7")\*Convert\*30 - Rel\_Powell(yr,"M8")\*Convert\*31 - Rel\_Powell(yr,"M9")\*Convert\*30 - Rel\_Powell(yr,"M10")\*Convert\*31 - Rel\_Powell(yr,"M11")\*Convert\*31 - Rel\_Powell(yr,"M12")\*Convert\*30 - evap\_Powell(M)\*Storage\_Powell(yr,M) |
| EQ4\_Mead\_1styr(yr,M) | **Mass balance at Lake Mead during year 1 (ac-ft)**  Storage\_Mead(yr,M) =e= Init\_Mead$(ord(M)eq 1) + Storage\_Powell(yr,M-1)$(ord(M)gt 1)+ Rel\_Powell(yr,"M1")\*Convert\*31 + Rel\_Powell(yr,"M2")\*Convert\*30 + Rel\_Powell(yr,"M3")\*Convert\*31 + Rel\_Powell(yr,"M4")\*Convert\*31 + Rel\_Powell(yr,"M5")\*Convert\*28 + Rel\_Powell(yr,"M6")\*Convert\*31 + Rel\_Powell(yr,"M7")\*Convert\*30 + Rel\_Powell(yr,"M8")\*Convert\*31 + Rel\_Powell(yr,"M9")\*Convert\*30 + Rel\_Powell(yr,"M10")\*Convert\*31 + Rel\_Powell(yr,"M11")\*Convert\*31 + Rel\_Powell(yr,"M12")\*Convert\*30+ Inflow\_Paria(yr,M)+ Inflow\_KanabCreek(yr,M)+ Inflow\_Havasu(yr,M)+Inflow\_Diamond(yr,M)+ Inflow\_LitColorado(yr,M)-Rel\_Mead(yr,"M1")\*Convert\*31 - Rel\_Mead(yr,"M2")\*Convert\*30 - Rel\_Mead(yr,"M3")\*Convert\*31 - Rel\_Mead(yr,"M4")\*Convert\*31 - Rel\_Mead(yr,"M5")\*Convert\*28 - Rel\_Mead(yr,"M6")\*Convert\*31 - Rel\_Mead(yr,"M7")\*Convert\*30 - Rel\_Mead(yr,"M8")\*Convert\*31 - Rel\_Mead(yr,"M9")\*Convert\*30 - Rel\_Mead(yr,"M10")\*Convert\*31 - Rel\_Mead(yr,"M11")\*Convert\*31 - Rel\_Mead(yr,"M12")\*Convert\*30 - evap\_Mead(M)\*Storage\_Mead(yr,M) |
| EQ5\_Mead\_2ndyr(yr,M) | **Mass balance at Lake Mead during year 2 (ac-ft)**  Storage\_Mead(yr,M) =e= Mead\_yr1$(ord(M)eq 1) + Storage\_Mead(yr,M-1)$(ord(M)gt 1)+ Rel\_Powell(yr,"M1")\*Convert\*31 + Rel\_Powell(yr,"M2")\*Convert\*30 + Rel\_Powell(yr,"M3")\*Convert\*31 + Rel\_Powell(yr,"M4")\*Convert\*31 + Rel\_Powell(yr,"M5")\*Convert\*28 + Rel\_Powell(yr,"M6")\*Convert\*31 + Rel\_Powell(yr,"M7")\*Convert\*30 + Rel\_Powell(yr,"M8")\*Convert\*31 + Rel\_Powell(yr,"M9")\*Convert\*30 + Rel\_Powell(yr,"M10")\*Convert\*31 + Rel\_Powell(yr,"M11")\*Convert\*31 + Rel\_Powell(yr,"M12")\*Convert\*30+ Inflow\_Paria(yr,M)+ Inflow\_KanabCreek(yr,M)+ Inflow\_Havasu(yr,M)+Inflow\_Diamond(yr,M)+ Inflow\_LitColorado(yr,M)-Rel\_Mead(yr,"M1")\*Convert\*31 - Rel\_Mead(yr,"M2")\*Convert\*30 - Rel\_Mead(yr,"M3")\*Convert\*31 - Rel\_Mead(yr,"M4")\*Convert\*31 - Rel\_Mead(yr,"M5")\*Convert\*28 - Rel\_Mead(yr,"M6")\*Convert\*31 - Rel\_Mead(yr,"M7")\*Convert\*30 - Rel\_Mead(yr,"M8")\*Convert\*31 - Rel\_Mead(yr,"M9")\*Convert\*30 - Rel\_Mead(yr,"M10")\*Convert\*31 - Rel\_Mead(yr,"M11")\*Convert\*31 - Rel\_Mead(yr,"M12")\*Convert\*30 - evap\_Mead(M)\*Storage\_Mead(yr,M) |
| EQ6\_Mead\_3rdyr(yr,M) | **Mass balance at Lake Mead during year 3 (ac-ft)**  Storage\_Mead(yr,M) =e= Mead\_yr2$(ord(M)eq 1) + Storage\_Mead(yr,M-1)$(ord(M)gt 1)+ Rel\_Powell(yr,"M1")\*Convert\*31 + Rel\_Powell(yr,"M2")\*Convert\*30 + Rel\_Powell(yr,"M3")\*Convert\*31 + Rel\_Powell(yr,"M4")\*Convert\*31 + Rel\_Powell(yr,"M5")\*Convert\*28 + Rel\_Powell(yr,"M6")\*Convert\*31 + Rel\_Powell(yr,"M7")\*Convert\*30 + Rel\_Powell(yr,"M8")\*Convert\*31 + Rel\_Powell(yr,"M9")\*Convert\*30 + Rel\_Powell(yr,"M10")\*Convert\*31 + Rel\_Powell(yr,"M11")\*Convert\*31 + Rel\_Powell(yr,"M12")\*Convert\*30+ Inflow\_Paria(yr,M)+ Inflow\_KanabCreek(yr,M)+ Inflow\_Havasu(yr,M)+Inflow\_Diamond(yr,M)+ Inflow\_LitColorado(yr,M)-Rel\_Mead(yr,"M1")\*Convert\*31 - Rel\_Mead(yr,"M2")\*Convert\*30 - Rel\_Mead(yr,"M3")\*Convert\*31 - Rel\_Mead(yr,"M4")\*Convert\*31 - Rel\_Mead(yr,"M5")\*Convert\*28 - Rel\_Mead(yr,"M6")\*Convert\*31 - Rel\_Mead(yr,"M7")\*Convert\*30 - Rel\_Mead(yr,"M8")\*Convert\*31 - Rel\_Mead(yr,"M9")\*Convert\*30 - Rel\_Mead(yr,"M10")\*Convert\*31 - Rel\_Mead(yr,"M11")\*Convert\*31 - Rel\_Mead(yr,"M12")\*Convert\*30 - evap\_Mead(M)\*Storage\_Mead(yr,M) |
| **Release Equations** |  |
| EQ7\_maxstor\_Powell(yr,M) | **Powell storage max (ac-ft)**  Storage\_Powell(yr,M)=l= Maxstorage\_Powell |
| EQ8\_maxstor\_Mead(yr,M) | **Mead storage max (ac-ft)**  **Storage\_Mead(yr,M)=l= Maxstorage\_Mead** |
| EQ9\_minstor\_Powell(yr,M) | **The minimum storage equivalent to reservoir deadpool level (ac-ft)**  Storage\_Powell(yr,M)=g= Minstorage\_Powell |
| EQ10\_minstor\_Mead(yr,M) | **The minimum storage equivalent to reservoir deadpool level (ac-ft)**  Storage\_Mead(yr,M)=g= Minstorage\_Mead |
| EQ11\_MaxR\_Powell(yr,M) | **Max Release for Powell(cfs)**  Rel\_Powell(yr,M)=L= Max\_RelPowell |
| EQ12\_MaxR\_Mead(yr,M) | **Max Release for Mead(cfs)**  Rel\_Mead(yr,M)=L= Max\_RelMead |
| EQ13\_MinR\_Powell(yr,M) | **Minimum Release for Powell(cfs)**  Rel\_Powell(yr,M)=g= Min\_RelPowell |
| EQ14\_MinR\_Mead(yr,M) | **Minimum Release for Mead(cfs)**  Rel\_Mead(yr,M)=g= Min\_RelMead |
| EQ15\_TotVolPowell(yr) | **Total volume of water released from Lake powell during water year (ac-ft)**  Vol\_Powell(yr)=e= Rel\_Powell(yr,"M1")\*Convert\*31 + Rel\_Powell(yr,"M2")\*Convert\*30 + Rel\_Powell(yr,"M3")\*Convert\*31 + Rel\_Powell(yr,"M4")\*Convert\*31 + Rel\_Powell(yr,"M5")\*Convert\*28 + Rel\_Powell(yr,"M6")\*Convert\*31 + Rel\_Powell(yr,"M7")\*Convert\*30 + Rel\_Powell(yr,"M8")\*Convert\*31 + Rel\_Powell(yr,"M9")\*Convert\*30 + Rel\_Powell(yr,"M10")\*Convert\*31 + Rel\_Powell(yr,"M11")\*Convert\*31 + Rel\_Powell(yr,"M12")\*Convert\*30 |
| EQ16\_TotVolMead(yr) | **Total volume of water released from Lake Mead during water year (ac-ft)**  Vol\_Mead(yr) =e= Rel\_Mead(yr,"M1")\*Convert\*31 + Rel\_Mead(yr,"M2")\*Convert\*30 + Rel\_Mead(yr,"M3")\*Convert\*31 + Rel\_Mead(yr,"M4")\*Convert\*31 + Rel\_Mead(yr,"M5")\*Convert\*28 + Rel\_Mead(yr,"M6")\*Convert\*31 + Rel\_Mead(yr,"M7")\*Convert\*30 + Rel\_Mead(yr,"M8")\*Convert\*31 + Rel\_Mead(yr,"M9")\*Convert\*30 + Rel\_Mead(yr,"M10")\*Convert\*31 + Rel\_Mead(yr,"M11")\*Convert\*31 + Rel\_Mead(yr,"M12")\*Convert\*30 |
| **Upper and lower bound of Releases [cfs]**  For the time being, we are only considering water releases from through the turbines  We intend to analyze different scenarios where water will be spilled or released from the river outlets | |
| Max\_RelMead | 49000 cfs |
| Min\_RelMead | 0000 cfs |
| Max\_RelPowell | 31500 cfs |
| Min\_RelPowell | 0000 cfs |
| **Upper and lower bound of Storage [acf]** | |
| Maxstorage\_Mead | 27767000 [acf] |
| Minstorage\_Mead | 30172 [acf] |
| Maxstorage\_Powell | 27865918 [acf] |
| Minstorage\_Powell | 20303 [acf] |
|  |  |

**Objective Function**

**Objective 1: Environmental flow**

Water should be released from an elevation within the following range for the summer months mentioned below. The values were received from a on-going research related to temperature model within the Grand Canyon Reach.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Month (Month number in the model) | Minimum Elevation[ft] | Storage at that Minimum elevation[acf] | Maximum Elevation[ft] | Storage at that Maximum elevation[acf] |
| May (M8,20,32) | 3530 | 6238450 | 3700 | 24322365 |
| June (M9,21,33) | 3560 | 8323055 | 3700 | 24322365 |
| July (M10,22,34) | 3610 | 12730300 | 3700 | 24322365 |
| August (M11,23,35) | 3655 | 17846128 | 3700 | 24322365 |

The flow for fishes is considered adequate (temperature wise) if the release is between the above mentioned range of elevation. So, the objective will be maximize the number of months in three consecutive years when the end of the month storage (12 months in total for three years) are with in the range mentioned above.

Requirement 1 =

We can use a reliability metric to quantify the efficiency of the modeled system.

Max Obj\_ 1 = Requirement 1 / 12 (M8:M11, M20:M23, M32:35)

**Objective 2: Upper Basin Delivery**

The upper basin will deliver 8.23 million acre-ft on an average to the lower basin states. So, for three years, the total amount will be 24.69 MAF on an average which should be delivered to the lower basins. If the total delivery in the consecutive three years is,

Total Delivery in three years =

Then our objective will be to minimize the difference between the total amount delivered and the required amount delivered for the three years period.

Min Obj\_2 = |24.69 MAF - Total Delivery in three years |

**Objective 3: Months when Mead elevation is less than 1135 ft**

The third objective is to keep the elevation at lake mead below 1135 ft above MSL. At 1135 ft, storage capacity of Lake Mead is 15.12 MAF.

Obj\_Fraction\_3 =

We will use Multi objective constraint method to solve the problem

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| **Category (Possible Score)** | **No Evidence** | **Does not Meet Standard** | **Nearly Meets Standard** | **Meets Standard** | **Exceeds Standard** | **Self- Score** | **Instructor Score** |
| **Title**  **(2)** | Absent  0 | Evidence of one.  0 | Evidence of two.  1 | Evidence of three.  1 | Title, author name and contact info. Neatly finished with no errors. 2 | 2 |  |
| **Introduction**  **(10)** | Absent, no evidence  0 | There is no clear introduction, main topic, or outline of content.  1 - 5 | The introduction is either:   1. Too sketchy. Gives an inadequate overview, Or: 2. Too detailed, info later repeated   6 – 7 | The introduction overviews the project and previews the wiki page(s) structure  8 | The introduction overviews the project, work done, and organization of the wiki page(s). An effective summary. Gives enough detail to motivate the reader to continue reading.  9 - 10 | 8 |  |
| **Technical Content**  **(43)** | No content provided or analysis evident.  0 - 10 | Little content provided. The reader has no idea about the problem, solution method, results, or what was done for the project.  11 – 20 | Sketchy: may have left out 2 or more content areas; flimsy or incomplete methods; results have errors; and/or recommendations do not derive from the results. No tables, figures, or pictures presented.  21 – 33 | Wiki lacks adequate detail, but content for 4 of the 5 areas is provided and includes one or more tables, figures, or pictures. Most prior work referenced and hyperlinked.  34 – 38 | Defines problem, provides background information, describes solution method(s) used, and presents the results and recommendations that derive from the results. Uses tables, figures, and pictures to illustrate the above. Prior work referred to through references and hyperlinks.  39 - 43 | 33 |  |
| **Organization and Development**  **(15)** | No evidence of structure. | Little evidence of structure or organization.  1 – 8 | Organization of ideas not fully developed. Two or more pages, sections, or sub-sections missing or out of order. 9 – 11 | Sub-pages, sections, sub-sections, and/or lists present, but their use not perfected. 12-13 | Logical sequencing of ideas. Uses sub-pages, sections, sub-sections, and/or lists to order, present, and develop ideas. In each section, one or more paragraphs develop each idea. 14 - 15 | 11 |  |

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| --- | --- | --- | --- | --- | --- | --- | --- |
| **Category (Possible Score)** | **No Evidence** | **Does not Meet Standard** | **Nearly Meets Standard** | **Meets Standard** | **Exceeds Standard** | **Self- Score** | **Instructor Score** |
| **Word Usage and Format**  **(15)** | Not applicable | Many, distracting errors in grammar, spelling, sentence structure, word usage, significant figures, tables, and figures. Unacceptable at the graduate level. 1 – 8 | With some grammatical errors. Figures are too small and/or under-labeled, although they are usually of acceptable quality and focus. Incoherent tables. Inconsistent fonts and headings. Could be improved by being more meticulous.  9 – 11 | Almost no errors in punctuation, capitalization, spelling, sentence structure, word usage, significant figures, and presentation of figures and tables. No broken hyperlinks.  12 – 13 | Punctuation, capitalization, spelling, sentence structure, word usage, and significant figures all correct. Clear, consistent fonts and headings. Good wiki processing skills. Figures and tables presented in correct format. No broken or empty hyperlinks. 14 - 15 | 11 |  |
| **Conclusions**  **(10)** | Absent  0 | Incomplete and/or not focused. 4 - 6 | The conclusion does not adequately restate the main findings. 7 | The conclusion restates the main findings. 8 | Effectively restates the main findings and recommendations to solve the problem. 9 - 10 | 7 |  |
| **Hyperlinks and References**  **(5)** | Absent  0 | With many errors or only 1 hyperlink provided.  1 – 2 | With some errors and only 2 hyperlinks provided.  3 | With few errors, at least 3 hyperlinks to content outside the USU domain  4 | All citations and references listed in ASCE format with no errors. Include at least 4 hyperlinks to content or work outside the USU domain. 5 | 5 |  |
| **TOTAL** (100) |  | | | | | 77 |  |