**Introduction**

Our research is a step towards making predictions in heavily managed and ungauged basins, with a focus on irrigated catchments. We were interested in finding out how irrigation affects streamflow dynamics, and how it affects environmental sustainability factors such as groundwater storage.

We were guided by two research questions: first, how does a given irrigation strategy affect streamflow for a variety of catchment types? And next, how heavily does irrigation impact water supply and sustainability in each catchment type?

**Method**

To answer our questions, we used a modified soil moisture and transfer model based on Botter’s 2007 paper. It’s a lumped model that describes a catchment using four soil properties (porosity, wilting point, field capacity, root depth) and three climate properties (maximum ET, inverse mean of rainfall, and frequency of rainfall) and a recession constant used to describe baseflow.

The black arrows in the figure describe the core of model. The soil column receives input in the form of precipitation, and output in the form of evapotranspiration and leakage, which occurs when soil moisture exceeds field capacity s1. The leakage feeds into the shallow aquifer, which provides baseflow to the river through a recession constant. Finally, there’s a deep aquifer that experiences a constant rate of recharge when it is depleted below a certain threshold.

We model four sources, or cases, of irrigation, one by one. Our first source is import from an infinite water supply outside of the catchment. The second, third and fourth sources originate from inside the catchment. The second source comes directly from the river, the third source originates from the shallow aquifer, and the fourth source originates from the deep aquifer.

We solved this model for each individual irrigation sourcing type using a Monte Carlo method for a period of twenty years. We chose a runtime of twenty years so the system can reach a steady state, and our steady state was chosen so that all our streamflow statistics – frequency of peaks, height of peaks, and average streamflow – change by less than 5% in 5 years. We also investigated a range of aridity indeces for each irrigation sourcing type.

This is an example of the output of the model, for an arid catchment with aridity of 2.5 (where the Budyko aridity index is ET/lambdap/gamp) under natural, or no irrigation, conditions. Here we’ve taken about five hundred days of a Monte Carlo run of the model. The streamflow lines up closely with precipitation.

We’ve chosen to represent natural streamflow with three parameters: alpha, the average peak height; lambda, the average peak frequency; and barQ, the average magnitude of streamflow. These three parameters averaged over a period of twenty years and are combined into a “Euclidean distance metric” that describes the difference in streamflow dynamics between natural and irrigation cases.

**Results and Discussion – panel 1**

Streamflow with the four types of irrigation sourcing for the same catchment are shown next. You can see that the sourcing from outside the catchment increases streamflow magnitude, while the other source types decrease streamflow magnitude. Average alpha (or peak height) also decreases, indicating lower shallow aquifer storage. For Source 4 (groundwater), lambda actually increases, indicating more “choppy” streamflow because the shallow aquifer depletes very frequently in the form of groundwater recharge, but irrigation to the soil still causes leakage, which periodically fills the shallow aquifer. The presence of regular irrigation in Sources 1 and 4 is seen in the “sawtooth” pattern of streamflow, indicating regular increases in shallow aquifer storage from leakage due to irrigation. The sawtooth pattern isn’t as pronounced in Sources 2 and 3, which indicates that the river and the shallow aquifer, in this arid catchment, aren’t able to provide the required irrigation as often. There are more “saws” on the higher streamflow times in Source 3, indicating that the shallow aquifer is better able to provide irrigation than Source 2.

We repeated these Monte Carlo runs for twenty years over four hundred types of catchments with varying aridity indeces, and compared the effect of irrigation on streamflow as measured by the distance metric for each catchment type. Each of these contour plots shows the distance metric across catchment types for a given irrigation source.

The x and y axes of these contour plots are dimensionless numbers containing seven catchment (soil and climate) parameters, developed by Porporato et al., 2004. D1 is the ratio between the soil storage capacity and the mean rainfall input per event, and D2 is the ratio between the rate of occurrence of rainfall events and the maximum evapotranspiration rate. These two dimensionless groups define the interaction of the most important climate, soil, and vegetation parameters in controlling soil moisture dynamics. We have kept constant soil properties and ET max, while varying rainfall parameters of lambda and gamp. Our constant parameters are: s1 = 0.8, sw = 0.45, n = 0.35, Zr = 30cm, and ET = 0.5 cm/day. We have assumed that 10% of the catchment area is irrigated, and 100% irrigation efficiency. The bottom right corresponds to arid catchments, with low average rainfall intensity and low frequency of rainfall. The top left corresponds to humid catchments with frequent and intense rainfall.

Some of the catchment types should not be considered in our analysis. There are three exception cases where irrigation should not be considered. First, in arid catchments irrigation is needed, but less than 50% of that need is provided by the given source. This is an unrealistic irrigation scenario and won’t be considered. Second, in humid catchments, irrigation wasn’t needed, so it is irrelevant to our study. Finally, for rare and very arid catchments, streamflow never experiences a peak during our run time and it was impossible to calculate a distance metric in these cases. These areas are also ignored.

In the remaining, non-exception cases, redder areas on the plots represent irrigation heavily affecting natural streamflow, which is undesirable. Most of the catchments don’t experience very extreme changes in streamflow. The remaining areas on the map in blue represent areas where irrigation is both needed and received without significant impact to the streamflow indicators of lambda, alpha and barQ.

In Source 1, the red area in the bottom right corner (or arid catchments) represents an increase in streamflow magnitude since the irrigation is being imported from outside the catchment. In Source 4, the red area in the bottom right represents a decrease in streamflow since groundwater depletion triggers recharge from the shallow aquifer. Clearly, there should be a way to distinguish between these two extreme changes in streamflow (and thus environmental) conditions. We address this later.

The feasibility of irrigation in arid catchments is highly dependent on the source of irrigation. Imports from outside the catchment are able to provide irrigation whenever needed, and will change streamflow significantly in the arid catchments, as indicated by the high distance metric. Direct channel withdrawals will almost never be able to provide above 50% of irrigation requirements, even for humid catchments. However, when there is no synchronization in irrigation, some of the more humid catchments will be able to receive most of their irrigation requirements through the river because less synchronization of irrigation means that smaller amounts are withdrawn from the river each day, instead of a large amount withdrawn all at once, and the river is more likely be able to provide irrigation. For withdrawals from the shallow aquifer, there is a ribbon of catchment types with intermediate aridity where the shallow aquifer is able to provide most of the irrigation requirement. The bottom right half triangle of catchment is too arid for the shallow aquifer to provide irrigation, and the top left triangle is humid enough that no irrigation is required. Finally, withdrawals from the deep aquifer are able to provide irrigation for all catchment types that need irrigation. In the sense of providing irrigation, sourcing from deep groundwater in the short run is about the same as sourcing from outside the catchment. However, the environmental impact of Source 4 and Source 1 are vastly different. The groundwater may be depleted by 100 years if the shallow aquifer is unable to recharge it quickly enough.

**Results and Discussion – panel 2**

To differentiate between Source 4 and Source 1, and to quantify the effect of irrigation on environmental and social indicators, we used an environmental and social impact metric. We were guided by Srinivasan et al’s 2011 paper in creating a weighted metric to describe irrigation’s impact on groundwater and shallow aquifer storage (representing environmental sustainability), average streamflow (representing ecological stability), and feasibility of agriculture/irrigation in that catchment (representing economic stability).

To describe sustainability, we used metrics for groundwater and shallow aquifer storage. If the storage in these aquifers after 20 years was below 50% of initial storage, we gave it a weight of negative one. If more was stored at the end of 20 years than at the beginning, we gave it a weight of positive one (though this is unlikely; GW recharge is only triggered at a threshold). Finally, if total irrigation is 1.5 times greater than deep aquifer recharge or leakage into the shallow aquifer over the course of 20 years, we gave it a weight of negative 0.5.

To describe social and economic vulnerability, we compared actual irrigation provided to irrigation needed. If less than 50% of needed irrigation was provided, the weight is negative one; and if more than 90% of needed irrigation was provided, the weight is positive one.

Finally, to describe ecological impact, we compared the average streamflow magnitude with and without irrigation. If this ratio is less than 70%, it was weighted negative one; if it is greater than one, it is weighted positive one.

Red areas on these contour plots show detrimental impact of irrigation, and blue areas describe small or positive impact of irrigation. As expected, Source 1 gives a positive impact on the catchment because irrigation needs are met without affecting groundwater sustainability or river ecology. In contrast, direct river withdrawals have the most detrimental impact on the catchment, particularly by not meeting irrigation needs and destroying the river’s ecology. Sourcing from the shallow aquifer is detrimental to a good portion of the catchment types because irrigation needs aren’t met and the shallow aquifer is depleted. However, there is a ribbon of catchment types for which sourcing from the shallow aquifer is fine. Finally, groundwater irrigation is the next best thing to irrigation imports, with the vast majority of the catchment types not detrimentally affected by irrigation. However, it is important to note that in arid catchments, deep aquifers continue to be depleted for up to 100 years before drying. This isn’t captured in the environmental impact contour plot.

**Conclusion**

We have used a simple lumped model to produce reasonable estimations of streamflow behavior in response to irrigation. Our streamflow metrics, alpha, lambda, and barQ help us describe the changes in streamflow due to irrigation, and the environmental impact metric helps us describe the sustainability of each irrigation source. Our results will help us expand PUB efforts to make predictions about irrigation in heavily managed basins using clues from streamflow.

**Next Steps**

We will expand our models of irrigation by modeling other realistic irrigation strategies, such as fixed schedules and the crop coefficient method. We’ll look for unique fingerprints of each irrigation strategy on streamflow metrics to help us tease out the types of irrigation happening in each catchment. We’ll validate our predictions through comparison with basins for which irrigation and streamflow details are already known. Finally, we’ll use statistical techniques to compute the likelihood of an irrigation practice in a set of potential irrigation scenarios using streamflow data alone, based on our knowledge of how streamflow dynamics change for certain irrigation sources, synchronicities, and catchment types. Our work will inform PUB methodologies in heavily irrigated basins in a variety of catchment types.