**Introduction**

I work on describing the impact of different types of irrigation regimes on streamflow dynamics. The motivation for our work was predictions in ungauged basins, or PUB. Most of these PUB efforts focus on natural basins, and there’s a gap in our knowledge about PUB in heavily managed basins. One of the most influential examples of water management in the world is irrigation, so we’re hoping to eventually create a method to estimate the irrigation regimes occurring in a sparsely gauged, but heavily agricultural basin. Our first step was to look at how streamflow dynamics change with a variety of irrigation and catchment types. We also took a look at the environmental impacts of irrigation in each catchment type.

**Model**

We used a lumped soil moisture model to describe a catchment. The core of the model is the soil. When soil moisture exceeds field capacity, leakage travels down to a shallow aquifer, which in turn supports baseflow to the river. Finally, we have a deep groundwater component, which is recharged by the shallow aquifer when it reaches a certain threshold of storage.

To this core model, we have added four irrigation sources, which we model individually. These are shown in the colored dashed lines. Our sources types are import from outside the catchment, withdrawal from the channel, from the shallow aquifer, and from the deep aquifer. We’ve set irrigation requirements to follow a common deficit irrigation strategy, where irrigation is triggered when soil moisture reaches 60% of field capacity. One important thing to note is that if the source of irrigation would run dry if this irrigation was applied on a given day, we don’t provide irrigation on that day.

We solve with model with a Monte Carlo method, and describe our streamflow output using three parameters: Qbar (average streamflow magnitude), alpha (average peak height), and lambda (average peak frequency). Because each of these streamflow parameters can change once irrigation begins, we combined these three parameters into a Euclidean distance metric between natural and irrigated conditions to describe streamflow change that’s attributable to irrigation.

**Irrigation and Streamflow Dynamics**

Here’s an example of what streamflow looks like under four irrigation scenarios, representing the four sources. These hydrographs can be compared directly to the natural streamflow hydrograph. You can see that importing water increases streamflow. One important thing to note is the saw tooth pattern in Source 1 and Source 4, which arises from periodic irrigation. Sources 2 and 3 don’t have such a distinct saw-tooth pattern because they are able to provide irrigation less often; they dry a lot more easily than deep groundwater, and of course more easily than the import, which is assumed to be an infinite supply.

We repeated this analysis for 400 types of catchments, and describe changes in streamflow due to irrigation using the Euclidean distance metric. Each catchment was described using two dimensionless groups, D1 and D2. 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 soil moisture dynamics. 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. 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. Second, in humid catchments, irrigation wasn’t needed, so it is irrelevant to our study.

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.

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. 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. Finally, withdrawals from the deep aquifer are able to provide irrigation for all catchment types that need irrigation. So in the sense of ability to provide 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 within the catchment is vastly different. The groundwater may be depleted by 100 years if the shallow aquifer is unable to recharge it quickly enough.

**Environmental Implications**

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 created 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).

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 large 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.

**Summary, Future Work**

In sum, we looked at how irrigation affects different streamflow metrics and an environmental impact metric. This work was the first step towards expanding PUB efforts to make predictions about irrigation in heavily managed basins. We have a lot more work to do; we’ll expand our models of irrigation by modeling other realistic irrigation strategies, such as fixed schedules and the crop coefficient method. Then 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.