**Introduction**

The premise of my work is that there should be a way to estimate the kinds of water supply and management practices that’s happening in a catchment by looking at streamflow and some remotely sensed data. We want to be able to apply these kinds of method to PUB efforts.

So existing PUB efforts usually focus on predicting streamflow in undisturbed natural basins. It’s based on the assumption that basins with similar natural characteristics will have similar streamflow patterns. But, given the high level of disruption of many basins from natural conditions, we think that incorporation of human activity prediction in PUB is an important next step in the field.

**Expand PUB methods to irrigation basins**

Specifically, I’ve decided to focus on developing a method for estimating irrigation practices based on streamflow. Irrigation is one of the most common human disruptions in basins around the world, and is a great place to start developing a method.

My first step is to look at how streamflow changes with a variety of irrigation sources in a given catchment. Then, I’ll come up with a “fingerprinting” method that relates streamflow back to the irrigation happening. This type of fingerprinting will help us make predictions on irrigation based on streamflow data.

If you look at this graph, you’ll see streamflow timeseries of a relatively arid catchment that requires irrigation. The black line is the natural, non-irrigated condition. The colored lines each represent irrigation using a particular source. Blue is import from outside the basin; red is direct channel withdrawal, and purple and green are shallow and deep aquifer pumping.

There are a few things to note here. You can see that importing water increases streamflow, and the other sources decrease streamflow. There is also saw tooth pattern in some of these lines, particularly the import and deep aquifer sources, which arises from periodic irrigation.

The change in streamflow magnitude and these sawtooth patterns can be summed up in three streamflow parameters: Qbar (average streamflow magnitude), alpha (average peak height), and lambda (average peak frequency). We use percent changes in these metrics to develop a fingerprint.

**Irrigation can be tracked in streamflow fingerprints**

Let’s take a look at three different catchments, all of which are arid and need irrigation, and see if we can discern a difference among streamflow fingerprints for each of the four sources.

It’s clear that it’s possible to differentiate among the sources for each catchment using this fingerprint, but it’s also clear that the fingerprint of irrigation may change slightly for each catchment.

Next, we can look at how these fingerprints change across catchment types? We can take a broad look at different climates and soils using contour plots. These plots show percent change in each streamflow metric for each source, for a variety of catchment types (described here using two dimensionless numbers). If we know the climate and soil characteristics of an irrigated catchment, we can locate that catchment in these plots. If we can then model a “natural streamflow” for the catchment, we can compare that to actual streamflow data calculate percent changes in each of the three parameters, and create a fingerprint for that catchment. Then, we can go back to these contour plots and locate our catchment within plots for each source type, and construct what the fingerprint would look like for each source, and estimate, by comparing the actual fingerprint to the four hypothetical fingerprints, where the irrigation water is coming from.

We might also be able to eliminate some irrigation sources in certain cases. First, if the catchment falls in the bottom right, hashed region, the given source can provide less than 50% of required irrigation. This is an unrealistic irrigation scenario, and we can eliminate the corresponding source as a possibility. Second, in humid catchments, irrigation wasn’t needed, so we can conclude that no irrigation is being done.

**Environmental Implications**

We can also go a step further and predict water crisis syndromes like unsustainability (in depletion of groundwater or shallow aquifer), ecological destruction (in large perturbation of streamflow volume) and social impact (the ability or inability of the given irrigation source to provide a basin’s irrigation needs).

These contour plots have the same layout as the previous set – catchment characteristics are collapsed into two dimensionless numbers, and they show environmental impact of each of the four irrigation sources.

A rating of bright green, indicates that irrigation is provided without negative impact on sustainability or ecology. This happens for all catchment types if irrigation is imported, some catchments for deep aquifers, and a very small fraction of catchments for shallow aquifer pumping.

This is just an extension of the fingerprinting. If we see symptoms like river drying or land subsidence in an arid catchment, then it might help us confirm our estimation of the irrigation source.

**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.

**Extras**

First, it’s easy to differentiate an import from the other three sources because average streamflow increases compared to the natural case. Because this is an arid catchment, the river is not able to provide any irrigation, so its lambda (or peak frequency) is unchanged from the natural case; no irrigation is abstracted or provided. The difference between pumping from the shallow versus deep aquifer is subtle, but lambda increases more for the deep aquifer than the shallow aquifer. This is because the deep aquifer is able to provide the required irrigation more often than the shallow aquifer, causing the streamflow to experience peaks more often.

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.

Direct river withdrawals have the most detrimental impact on the catchment, particularly by not meeting irrigation needs and destroying the river’s ecology. Direct channel withdrawals will almost never be able to provide above 50% of irrigation requirements, even for humid catchments. 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.

**Future Work**

In sum, we looked at how irrigation affects different streamflow metrics and predicted how each irrigation strategy would impact water crisis syndromes. This work was the first step towards expanding PUB efforts to make predictions about irrigation in heavily managed basins. We’ll expand our models of irrigation by modeling other realistic irrigation strategies, such as fixed schedules and the crop coefficient method.

We’ll validate our predictions through comparison with basins for which irrigation and streamflow details are already known. Finally, we’ll use statistical techniques like Bayesian analysis 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.