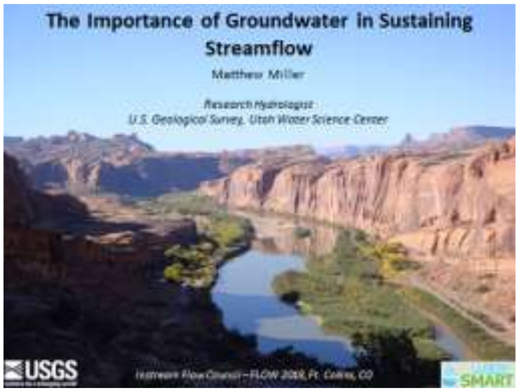
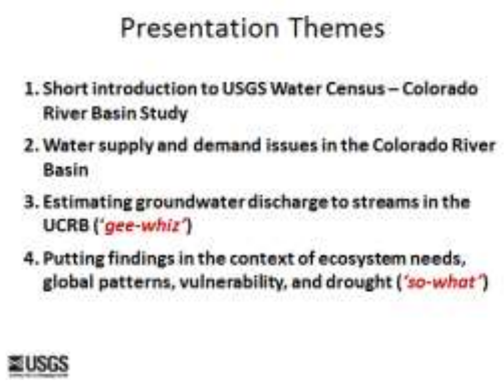
LeRoy: Our next speaker is Matt Miller, and Matt is a research hydrologist with the USGS in Denver and has worked on a variety of topics relating to water quantity and water quality and today he's going to talk to us about the importance of ground water and sustaining stream flow, an obviously important topic when it comes to thinking about drought. So, Matt . . .



Matt Miller: Okay, thanks LeRoy! I'd like to thank Tom and the Instream Flow Council for inviting me to talk today. It's a real honor to be here. So as LeRoy mentioned, I'm going to talk about the importance of groundwater in sustaining stream flow. This is some work that I've been doing with a number of collaborators at the US Geological Survey over the last three to five years. And kind of as a brief overview of what we'll talk about today, I'll start with a short introduction to the USGS water census with a focus on the Colorado River Basin study. Mindy Dalton covered this in great detail yesterday and gave a great presentation so I'll just touch on this briefly.

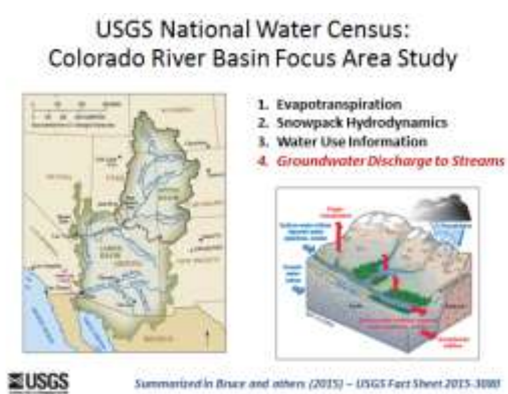
We'll talk a little bit about water supply and demand issues in the Colorado River Basin to give some context for why we're addressing this question of the role of groundwater in sustaining stream flow. And then we'll get into what you might call the "gee whiz" part of the presentation, this is kind of the technical aspects. We'll get into some of the science. And I think it's important to spend some time on this so that we understand where the estimates and the numbers are coming from such that when we then think about implications, you know the data we're working with are and where they came from. And then lastly, we'll get into the "so what" part of the presentation. That is, we'll put the findings and results into the context of ecosystem needs, patterns that have been observed globally and then we'll also talk a little bit about vulnerability of stream flow to changes in say, anthropogenic activities or climate change and specifically drought.



This work was done as part of the USGS National Water Census and specifically, the Colorado River Basin Focus area study that Mindy mentioned yesterday. This was one of three of the first focus area studies that took place. It happened between 2012 and 2015. In the map here we're looking at the Colorado River Basin, it's a very large basin and traditionally it's split into two basins: the Upper Basin and the Lower Basin. That split occurs at Lee's Ferry which is just downstream of Glen Canyon Dam and just upstream of the Grand Canyon.

I'll be talking today, exclusively about the Upper Basin which is the portion upstream of Lee's Ferry. The focus area study was broader than just the work on groundwater discharge to streams. There were a number of topics that were covered that are listed here. They include digging deeper into evapotranspiration and making improved estimates; thinking about snow pack hydrodynamics; acquiring better and more information on water use; and then again what I'll focus on today, the question of groundwater discharge to streams.

At the bottom of the slide, I've referenced a USGS fact sheet that was led by Brett Bruce and published in 2015. This provides a really nice summary overview of all the different components of this focus area study, so if you're interested in the other components I would point you towards that fact sheet as a starting place.



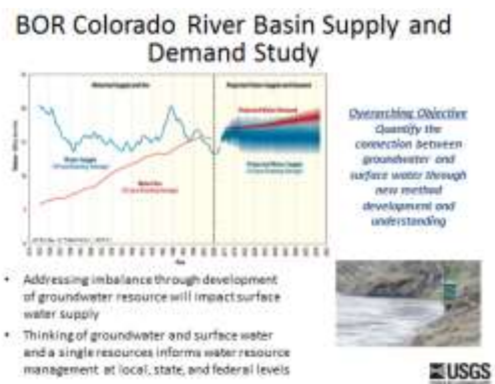
Before we even got the project off the ground there was lot of work that went into figuring out what the important issues in the Colorado River Basin are, such that we were providing information that was useful to decision makers and stakeholders in the Basin. We started this off by having a number of different meetings with stakeholders and decision makers across the Basin, importantly this included the Bureau of Reclamation, who we've interacted with a lot throughout the course of this study. The strategy for figuring out what questions we were going to address focused largely on filling information gaps and one of the gaps that really stood out was the lack of groundwater information in the Upper Colorado River Basin.

That's not to say that we don't know or didn't know anything about groundwater, there's a lot of information about things like depth to groundwater. There are a lot of groundwater flow models, but really what we were lacking was information about the role of groundwater in sustaining surface water flow in the Basin.

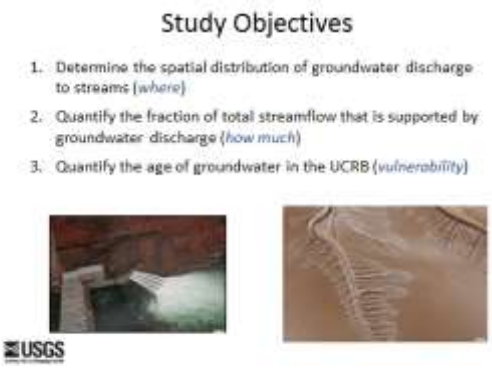
As hydrologists, we've known for a really long time that groundwater and surface water are an inter-connected resource, but except for some small watershed scale studies, this has really been a qualitative understanding. What we've lacked is detailed estimates of how much of a role groundwater plays in sustaining stream flow and how that varies across large regions like the upper Colorado River Basin. Lastly, I'll just point out that we wanted to build this work off of the historical wealth of the US Geological Survey data that are available across the Basin. There are a lot of data out there so we didn't collect any new data for this study. It was more of a data-mining effort and trying to see what we could learn from existing data that are publicly available.

This is a graph that was published a part of the Bureau of Reclamation Colorado River Basin's Supply and Demand Study. This graph is specific to the entire Basin, both the Upper Basin and the Lower Basin. What it's showing on the X-axis is time from about 1920 then projecting the future out to about to 2060. On the Y-axis we're looking at the volume of water in million-acre feet. The blue line shows historical water supply and the red line is water use or water demand. The vertical dashed line that you see there on the plot is the year 2008. What we see is that historically, water supply has been greater than demand. That is, we've had enough water to meet the needs of water users in the Basin. But in the recent past and then moving into the future, and looking at projections, what we see is that demand is going to outpace supply. So there's this imbalance between the amount of water available and the amount of water that is needed to sustain conditions as they currently are.

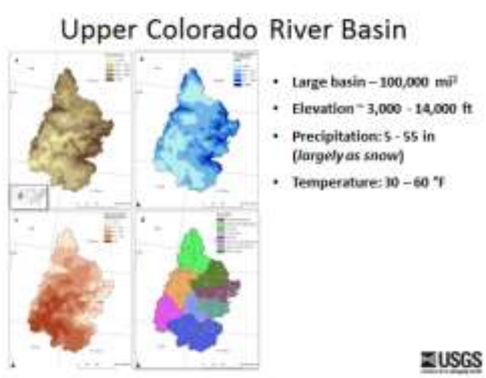
One question for decision makers and managers in the basin moving forward is how do we deal with and address this imbalance? One possible solution is to go out and continue to develop groundwater resources, and this idea fed into the objective of this study which was to quantify the connection between groundwater and surface water, which we did through new method development with the hope of developing new understanding. Simply put, the objective is to put numbers on this connection to allow folks to better think of groundwater and surface water as a single resource, and in turn use that understanding to inform how we make decisions about how we manage our water resources.



We have three specific study objectives as part of this work. One was to determine the spatial distribution of ground water discharge to streams. That is, where in the basin is most of the groundwater moving from the groundwater system into the surface water system? The second was to quantify how much of stream flow is supported by groundwater. For example, given the amount of water in the stream, is twenty percent of that coming from groundwater or is eighty percent of it coming from groundwater, and how does that vary across the basin? Third, we wanted to, to the extent that we could, quantify the age of the groundwater that's discharged into streams in the Upper Colorado River basin. The reason that we wanted to do this is that age information provides insight into the question of vulnerability. For example, if the groundwater that's discharging to the streams falls as precipitation years to decades ago, your stream flow may be more vulnerable to immediate changes in the landscape, either anthropogenic or climatic. On the other hand, if the groundwater that's discharging to streams is say hundreds to thousands of years old, perhaps there's a bit of a buffer between when any changes that take place across the landscape and when the effects of those changes would be expected to show up in the stream.



The Colorado River Basis is a very large basin that covers five different states in the Western United States, about 100 thousand square miles in area. There is a huge elevation range from about 3000 feet above sea level in the Colorado Plateau, so if you've ever been to places like arches or Canyonlands National Parks, these sort of low elevation desert areas, all the way up to about 13,000 feet in the Colorado Rocky Mountains. With this elevation gradient we also see large gradients in both precipitation and temperature. At lower elevations you can get as little as five inches of precipitation a year, whereas the higher elevations get above fifty inches of precipitation. Most of this high elevation precipitation falls in the winter as snow. You can see there is a broad range in average annual temperatures again that correspond with this elevation gradient.

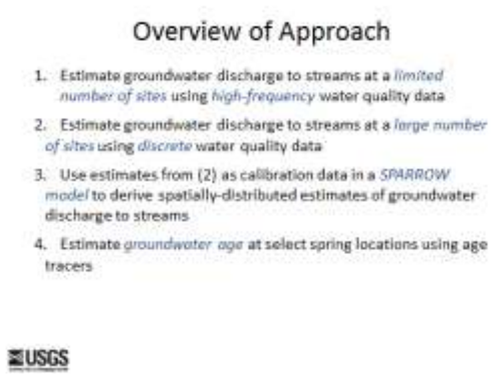


Okay, so I'm going to provide a sort of step-by-step overview of the approach and then I'll go through each of these steps in a bit more detail. The first thing that we did was to survey existing data across the basin, and identify a handful of sites where we had high frequency stream flow and water quality data. Those are sites with a stream gage that's making stream flow measurements at say fifteen minute intervals and also have a water quality sonde in the stream that's making water quality measurements at the same interval. As you'll see in a minute we used these water quality data as an indicator of where the water is coming from, that is, is it coming over the surface as snow melt or is it coming from the groundwater?

That was a good start but with a limited number of sites across the basin it's hard to say something broadly about what's happening in a large region. So we wanted to come up with a method to gain information about groundwater discharge to streams at a larger number of sites, and we recognized tjat there's a lot of stream sites across the basin where we have continuous stream flow but we only have discreet water quality measurements. That is, somebody's gone out to the stream at a weekly or a monthly or every two month interval, dipped a bottle in the water, taken it back to the lab and done an analysis. So we wanted to make use of those data to come up with estimates of groundwater discharge to streams at a larger number of sites.

Third, we took the estimates from these sites where we had discreet data and used them to develop a watershed model called SPARROW to come up with spatially distributed estimates of groundwater discharge to streams at locations all across the basin, including places where we don't have measurements of stream flow and water quality.

Then lastly, to get at the question of groundwater age and vulnerability, we identified a handful of very large springs across the basin where we used age tracers to quantify groundwater age.



For the sites with the high frequency water quality data we combined measures of stream flow with the water quality constituent of interest, which in this case is specific conductance. That's simply a measure of the electrical conductivity of the water. You can think of it as all of the ions in the water, and it is commonly used as a surrogate for salinity. In the top graph here, you can see four years of data at a site on the Colorado River. The black line is stream flow and the red line is the specific conductance measured from the sensor. What we see when we look at the stream flow data is this consistent repeatable pattern over time at a given site and across space in the basin. In late spring or early summer every year the snow melts and there is an increase in stream flow due to the snow melt runoff, and then as the summer proceeds, that snow melt decreases and there is a decline in flows which are then low and steady throughout the remainder of the season.

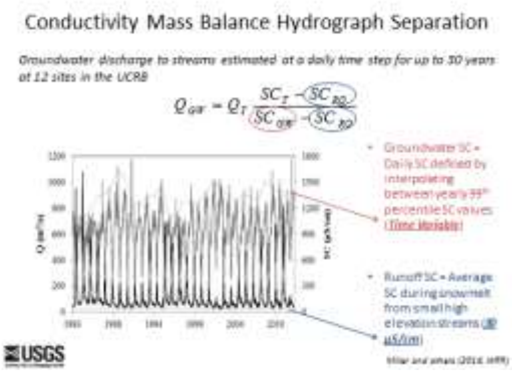
If we look at the specific conductance data, it follows the opposite pattern. That is, when there are peak stream flows during snow melt conductance is very low because the melting snow doesn't have a lot of ions in it. Then during the low flow part of the year there tends to be a peak and a relatively steady and stable specific conductance in the stream because the snow that's fallen previously infiltrates into the subsurface, and as it interacts with soils and rocks in the subsurface, it picks up solutes and makes its way to the stream as groundwater, resulting in higher conductance. So we used these data to develop the conceptual model that's shown on the bottom part of the slide. On the left you can see the snow melt time period when there is high flow and low conductance in the stream. During this time there is a lot of low conductivity, snow melt runoff and overland flow discharging to the streams, but there is also intermediate and higher conductivity groundwater flow that's discharging to the streams.

We can contrast that then with the low flow time period when the snow is no longer on the landscape and the low conductivity overland flow discharging to the stream during snowmelt is gone, so you're left with the intermediate and higher conductivity groundwater sustaining stream flow.

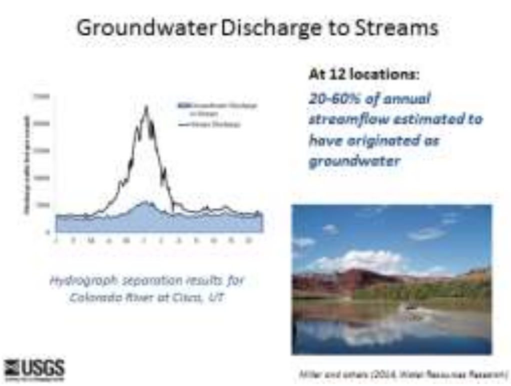
This is a site on the Colorado River with about thirty years of data. Stream flow is in black, conductance is in gray, and while it's kind of hard to see the patterns they follow the same pattern that I showed on the last slide. The equation on the top shows how we used the streamflow and water quality data to estimate groundwater discharge to streams. It's a simple two-component mass balance, and basically what it says is that groundwater discharge to streams is a function of the measured stream flow which we have from the gage, measured specific conductance in the stream which we have from the sensor, and estimates of specific conductance of the two end-members. In this case the snow melt runoff end-member, which has a low conductance value, and the groundwater end-member, which has a higher conductance value.

The approach that we took to define those end-members was to use the data in the stream. So for the runoff end-member we used a very low value that was an average of conditions during peak snow melt in high elevation streams. We went to streams where we thought or knew that the majority of the flow in that stream was coming directly from surface runoff of snow melt. In contrast, then, at each site we picked the highest conductance during the lowest flow time period of each year and interpolated between those values to get an estimate of the groundwater end-member conductance.

The end-member conductance values can then be plugged into the equation at a fifteen minute or daily time step or however frequently you have data, to estimate groundwater discharge to streams.

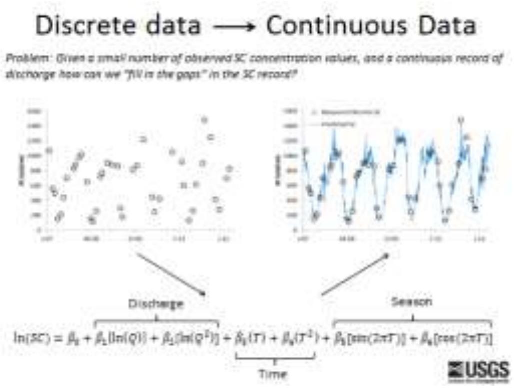


This plot shows an example of what the results of this looked like. This is a mean daily hydrograph for the Colorado River at Cisco. You can think of this as a long-term average annual hydrograph. The black line is discharge, and the shaded blue area is the estimated fraction of that discharge that originated as groundwater. There were twelve sites across the basin with high frequency specific conductance data where we could apply this approach, and looking at these mean daily hydro graphs, we estimated that among these twelve sites, anywhere between twenty and sixty percent of the annual stream flow originated as groundwater.



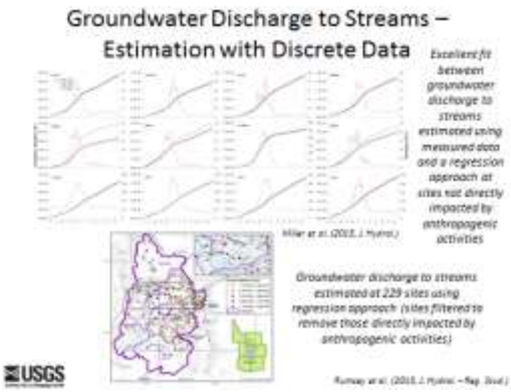
That was a great start, but it's only twelve sites so we've got these point locations across a large basin and we wanted to be able to say something more broadly and have estimates in a larger number of sites. So we were left with this problem where we had discreet data where you've got samples at say a monthly increment as shown here. In the plot, time is on the X-axis and specific conductance is on the Y-axis, and the question is how can we fill in the gaps between the discreet data points so that we can apply the method I just described to estimated groundwater discharge to streams continuously?

I won't get into the mathematics behind this, but basically we used a regression approach that relates conductance to continuous discharge, time, and season to fill in the gaps between sample dates and come up with a regression-derived estimate of conductance. Because conductance behaves conservatively this is a relatively easy thing to model and you can see that the blue line on the plot, which is the regression-derived estimate of conductance, follows the expected seasonal pattern and matches the measured values quite well.

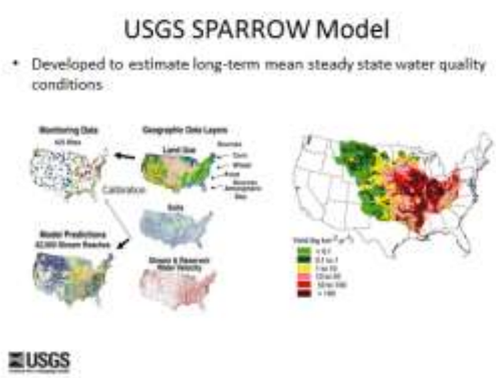


To convince ourselves that we could use the regression-derived estimates of conductance from the discreet data to estimate groundwater discharge to streams, we went back to the twelve sites where we had the continuous water quality data and estimated groundwater discharge to streams using both approaches. It may be difficult to see on this side, but we've got the twelve sites plotted with the mean daily hydrograph in the background. The solid black line is the cumulative estimate of groundwater discharge to streams obtained using the sensor data and the red line is the cumulative estimate obtained using the discreet data with the regression approach. So we can see that at nine of these twelve sites we get a near perfect fit in groundwater discharge to streams estimated using the two approaches. The three sites where there is a mismatch are all on the Dolores River, and if you're familiar with that basin, the Dolores River runs through a valley that's a collapsed salt anticline. Because of that, there's a lot of very saline groundwater discharging to the River, and for a number of decades now there's been a project in place to pump that saline groundwater out of the system before it reaches the stream. What that results in is highly variable conductance within the stream itself so it makes it a hard thing to model.

We took these results and we reasoned that well, what this suggests then is that if we can identify sites where we have discreet water quality data that are not directly impacted by some anthropogenic activity like groundwater pumping, or being right downstream of say, a major reservoir, that we can take the discreet data and use them as we would the continuous data to estimate groundwater discharge to streams. We surveyed data across the basin and filtered out sites with known anthropogenic impacts and identified about 230 sites where we could come up with these estimates of groundwater discharge to streams.



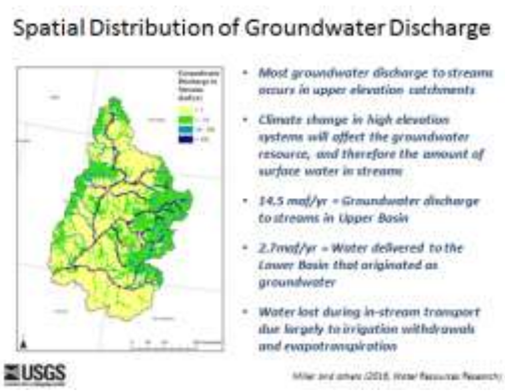
We then used the estimates of groundwater discharge to streams at those 230 sites as calibration data in a watershed model. The model we used was the USGS SPARROW Model. This is a model that was developed and has been used extensively to estimate long-term mean stead-state water quality conditions. We simply adapted and applied it to estimate long-term mean steady-state groundwater discharge to streams. Briefly, the way that this works is that the 230 estimates of groundwater discharge to streams distributed across the basin are statistically related to physical water shed characteristics like land use, soil type, climatic variables, and so on. There is also a stream routing network built into the model such that if you estimate some amount of groundwater discharge to streams at a headwater site, that water can be routed downstream to the next reach and accumulated and so on throughout the entire stream network.



This model allows you to make estimates of groundwater discharge to streams for all stream reaches across the basin even when there aren’t measurements in those areas. This map shows the results of the modeling effort. Darker colors indicate more groundwater discharge to streams, lighter colors indicate less. There are a couple things that stand out from this map. One is that you can see that groundwater that's being discharged to streams is being routed through the major rivers. You can see the Colorado, the Green, the San Juan, and so on. The other thing is that if we look at the estimated groundwater discharge to streams in a low elevation watershed, where the yellow areas are, in say the Colorado Plateau, and compare that with the estimated groundwater discharge to streams in some of the more high elevation areas, what we see is that in general, the higher elevations watersheds tend to generate more groundwater discharge to streams. If you think about it that makes sense, right? That's where most of the precipitation falls, snow melt infiltrates the subsurface and discharges to the streams as groundwater.

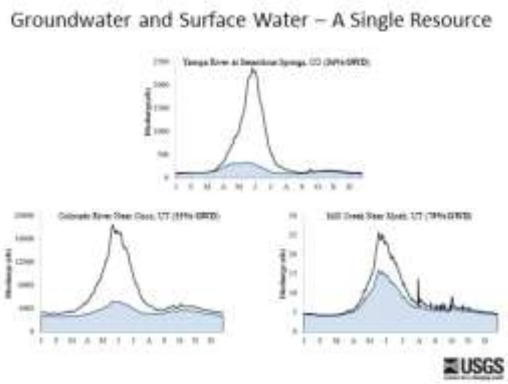
There have been a lot of studies recently that have suggested that high elevation alpine systems are likely to be the most sensitive systems to environmental change. Again, be that climatic or anthropogenic change. So, any change that takes place in these high elevation systems that affects the groundwater resource is also going to affect the surface water resource because the stream flow in these high elevation systems is being sustained by groundwater.

At the basin scale as a whole we estimated that about thirteen and a half million acre feet per year of groundwater was discharged to the streams in the basin. However, at the outlet at Lee's Ferry, we estimated that only about two and a half million acre feet per year of the water that's being discharged to the Lower basin originated as groundwater somewhere in the Upper basin. So, about eighty percent of the groundwater that discharged to streams across the basin was lost during transport somewhere in the basin. While I don't have time to show it today, we did some statistical analyses to identify the major factors contributing to that loss, and it turns out somewhat unsurprisingly that diversions for irrigation and evapotranspiration are the two dominant processes driving those losses.



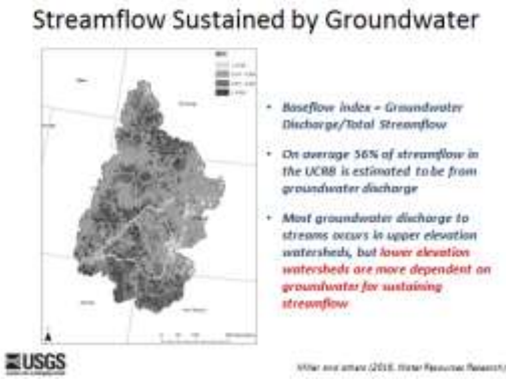
I think these results provide us with a unique opportunity to think about and understand groundwater and surface water as a single resource. What we're showing in these plots are the mean daily hydrographs for three sites across the basin. The upper plot is the Yampa River at Steamboat Springs, Colorado. This is a high elevation, snow melt dominated river. Again, discharge is in black, and the shaded blue area is the estimated fraction of discharge that originated as groundwater. At this site, we estimated that just over thirty percent of the annual flow originated as groundwater discharge to streams.

In the bottom left, we're looking at the Colorado River near Cisco, Utah, so this is a low elevation large river. At this site we estimated that just over half of the stream flow originated as groundwater. And then on the bottom right we see Mill Creek near Moab, which is a small desert stream in the Colorado Plateau where we estimated that about eighty percent of the total stream flow originated as groundwater.



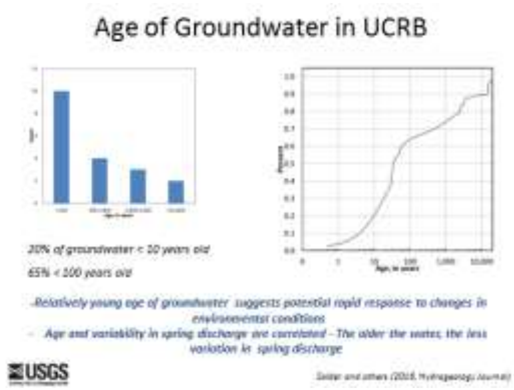
So to take that concept and extend it across the basin we developed another SPARROW Model for total stream flow such that then we could take the model estimates of groundwater discharge to streams and divide them by the model estimates of total flow to get what we call a base flow index. That's simply the fraction of total streamflow that originated as groundwater. This value ranges from zero to one.   A value of one means that all of the stream flow originated as groundwater, and a value of zero means that all of the stream flow originated as snow melt runoff.

At the basin scale, we estimated that over half, on average about fifty-six percent of the stream flow in the basin originated as groundwater discharge to streams, and we also see some interesting spatial patterns. In the lower elevation watersheds, if you recall, there tends to be less groundwater discharging to streams, but what limited water is there is more dependent upon groundwater discharge to streams for sustaining stream flow. Whereas the higher elevation sites have more groundwater discharging to streams, but they also have a lot of snow melt runoff coming into those systems, so the high elevation streams are less dependent on groundwater for maintaining stream flow.

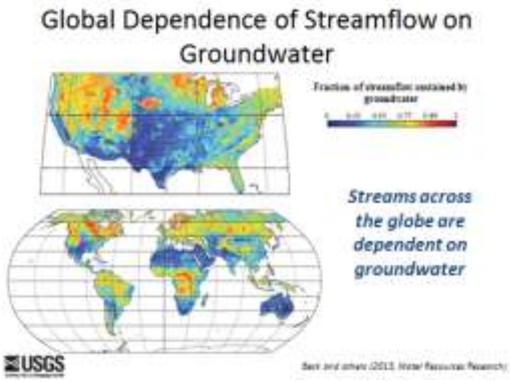


What are some of the implications of this at an ecosystem scale? if you've ever been to the low elevation desert ecosystems in the Colorado Plateau, you've probably recognized that they are very dry, desolate environments. The exception to this is riparian zones. This book published by Robert Webb and others called The Ribbon of Green highlights the importance of these riparian zones. What our results are suggesting is that stream flow in low elevation streams is sustained by groundwater discharge to streams. In turn, the streamflow sustained by groundwater supports riparian zones. There have been a number of studies that have come up with statistics such as less than two percent of the land area in the West is covered by a riparian ecosystems but up to or above seventy percent of the endangered species in this area depend on those ecosystems for survival. This is an example of broader ecosystem impacts of groundwater discharge to streams.

Briefly I want to touch on groundwater age. While I won't get into the details, we identified twenty large springs and used age tracers to quantify groundwater age and the results of that are shown here. On the left you can see the number of springs that have ages in a given range. A lot of the springs were discharing groundwater with estimated ages of less than ten years. On the right, we're looking at a frequency distribution of groundwater ages. To highlight some of the main results from this, we found that about twenty percent of the groundwater in these springs was less than ten years old and about sixty-five percent was less than a hundred years old. While one hundred years might sound like a long time, from a groundwater/geologic perspective, it's a relatively short time. What these results suggest is that there may be a rapid response between when anthropogenic or climatic changes take place on the landscape and when the effects of these changes will show up in the response of groundwater discharge to streams.

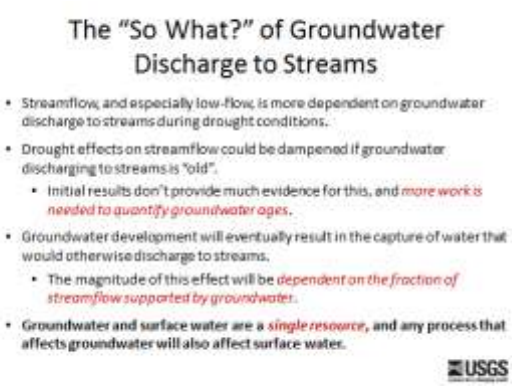


Stepping outside of the Colorado River Basin, there have been a number of studies that have used different techniques that have made estimates of groundwater discharge to streams at national and global scales. I just put this up here to highlight that this isn't just an issue in the Colorado River Basin. Groundwater is an important contributor to stream flow nationally and globally. Looking at the global map you can see that stream flow at high latitude sites and tropical sites in particular are estimated to be largely dependent on groundwater discharge to streams.



To wrap up and summarize the "so what" of this presentation, I’ve shown that during low flow conditions, especially in dry systems, stream flow is more dependent on groundwater discharge to streams. It's for that reasons that if and when we move into more drought-like conditions we can expect to have less snow melt runoff, and what stream flow we do have may be more dependent on groundwater discharge to streams. It is possible that the effects of a drought could be dampened if the groundwater discharging to streams is old, but we don't really have a good understanding of the spatial distribution of ages yet, and our initial results don't provide a whole lot of evidence for this dampening effect. I would highlight this as an area where more work is needed to better quantify groundwater ages across large regions.

Finally, if groundwater development is a tool that is used to deal with projected imbalances between water supply and demand, I think our results suggest that any removal of groundwater from the system is eventually going to be reflected in the stream flow. So just something to keep in mind. The magnitude of this effect is going to be dependent on the fraction of stream flow supported by groundwater. Lastly, if there is one message that I think is an important take home, it's that groundwater and surface water are indeed a single resource. Any processes that affect the groundwater resource are also going to affect the surface water resource. So I will stop there and I look forward to the discussion. Thank you.




Thank you
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