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0:00:00 Speaker 1: So, without further ado, kicking off our speaker series, we have the incomparable Graham Fogg, to give you an overview of California groundwater. So, take it away, Graham.

[applause]

0:00:13 Graham Fogg: Thank you very much, Jay and I would like to thank the troika of [0:00:20] ____ for inviting me to give a sweeping lecture on the first day of classes, actually, this was... This took a little while to put together. It was a little daunting in fact. But, what I'm gonna do, I'm gonna cover a lot of ground with a lot of equations. No, no equations.

[laughter]

0:00:39 GF: Actually, I don't think there's a single equation. A lot of pictures and I want to convey some of the things that I see as key to understanding groundwater, in general, and California groundwater, in that, it's not what you think it is, I think in a lot of cases. The systems don't look the way you think they look. And I think there's things you need to know about that, and I want you to look at examples of overdrafts since the thread of the seminar is a lot of it about the new legislation and overdraft and dealing with it. I want to look at what does overdraft look like? How is it seen or detected or measured? And then I hope that that will feed into your discussions on the future of California groundwater management and the legislation as it continues to unfold.

0:01:37 GF: So, I have an outline and I'm not going to go through this bit by bit now, but there'll be fundamentals on a current and general background. Then I'm gonna look at the different types of overdraft. This is a longer list than, I think, what people have seen, because about three of these are lumped into this category of water quality. But the water quality effects of overdraft are very different depending on which mechanisms we look at and then sustainable yield to be woven into this thread, I hope.

0:02:10 GF: I'd like to talk about groundwater myths; some of these might not come out till the very end and some will come out as we go along. This idea that pumping of fossil water is non-sustainable and the groundwater storage depletion, all of this takes a long time to recover, another myth.

0:02:26 GF: Groundwater levels tells us how much groundwater storage is changing and so on. Quality of most groundwater is degraded and then the counter, good quality groundwater today is likely to stay that way. And then a potential myth, that climate change will decrease groundwater recharge, so, the counter thought there.

0:02:45 GF: And then I would like to show some examples from Coachella Valley, Yolo County, Davis area; you're looking at the Yolo County data, specifically Davis, and campus wells. That's kind of interesting what's going on there. I was surprised. And Orange County... So, a little bit of background on California water use and supply. This is from the 2014 California Water Plan, and there's too much here for me to go through, but, basically, you have applied water use on the left and dedicated and developed water supply on the right, and I just wanna point out the groundwater portion which is the crimson here. If you take out the in-stream environmental here basically, the groundwater portion accounts for, anywhere between 20 and 50 to 60% depending on the year. These are different years of the stage developed water supply.

0:03:47 GF: And, of course, this groundwater cut varies with area. It's a very high percentage in the Colorado Lake Basin, for example, while we're in the Sacramento Valley, San Joaquin Valley a bit lower as well. Up north, north coast, is almost, except to those communities, people who depend on it locally. Groundwater use and thousand of acre feet, California is the champion of the states. It uses more than any other state. How can it use so much groundwater?

0:04:23 GF: Because groundwater... California is watery compared to other states? No. How come we use so much groundwater in California compared to Texas? Texas is a bigger place, it's got bigger aquifers, the permeability of those aquifers is not nearly as high as in California. But how come California pumps so much groundwater? The overdraft is worse in some states than California. The answer is, a lot of that water that we pump from groundwater ultimately comes from snow. We have a snow pack, and we use that snow pack; we store it and we irrigate. We irrigate like crazy in California, especially, compared to these other places. So, it's our surface water management and irrigation and groundwater management, that results in such a huge groundwater productivity in the state for better or for worse.

0:05:24 GF: And that also, I could have added another myth which is that more efficient irrigation will always result in more water. More efficient irrigation results in less groundwater recharge and less ability to pump groundwater. It's a zero sum game. So this is another subtlety about groundwater/surface water management.

0:05:46 GF: I don't know which side to face here. When you go to like a tennis match where people are looking back and forth, and every other slide I... But everyone's head has to turn. I'm naturally going left here. No, political reason.

[laughter]

0:06:04 GF: A lot of public wells in California, this is the easiest math I could find of public wells in California, they tend to trace out where the major aquifers are, it's hard to know exactly how many, public water supply wells. These are wells that serve 25 connections... So, these serve multiple connections, multiple households. So, the City of Davis wells are all public supply wells. There's 20,000 to 35,000 public supply wells.

0:06:35 GF: There's many more private wells, but they're not mapped. They're not managed; they're not monitored; they're not regulated, but there's... According to the 1990 census data, they estimated about 450,000 private wells. I've seen other estimates that estimate over a million private wells. These are mainly household wells; they're shallower wells. They'd be like a well drilled for a home to supply water. And again, there's parts of the state where it shows zero density, which would not be the case. There would be some private wells out there, but not good control on how many. But, the best estimate that I would go with at this point is on the order of a million private wells in California.

0:07:21 GF: Groundwater currents, it's dictated by the geology. This is a geological map of California, and you see the Central Valley here, this yellow... That's alluvial materials as indicated by this color over here. The Sierra Nevada mountains, cascades up North. Basically, you can't see this very well.

0:07:46 GF: And I think I have it in a little bit more visible format right here... [background conversation]

0:08:08 GF: Well... That's enough of that. Basically, I can do it from here. But basically, the materials... The yellow and pink are the major aquifer materials in California. You see them in Central Valley, Salinas Valley, Coastal Basins, Orange County, and the basin and range, alluvial valleys, they're all these yellow regions out here; and up north, the pink are volcanics. These are rocks, hard rocks, but they're relatively permeable. There are some coastal basins in the the North Coast, but to my knowledge do not constitute major aquifers. And you can go into the national atlas and look up major aquifers and bring up the map of major aquifers, this is what you'll find. Now the Central Valley and Salinas Valley and so on, the basin and range and the volcanics up north. Not much is known about the volcanics up north. But a fair amount of groundwater is there.

0:09:10 GF: The occurrence of water in these systems in the Central Valley, it's in pores of sedimentary materials: Sand, silts, gravels, clays. In these harder rock terrains, the granites of the Sierra Nevada, the volcanics, the water occurs in fractures and other kinds of openings in the rocks. Examples of these, beneath Davis, right here our groundwater occurs in cores in sedimentary deposits. In the volcanics up north, it's lava flow. I'll show you a picture of one in a moment, these are much more permeable. In many cases, there's a lava tube, which it can form a cave and quite extensive porosity and permeability. In the granites in the Sierra Nevada, there's something more like... Like this, or this, where you get hard rock cracks. So here's an example of fractured granite the Sierra Nevada.

0:10:08 GF: So, there's groundwater everywhere, but the groundwater in the mountains where the granites dominate, that's the central and southern Sierra is much, much less permeable than the materials in the Central Valley by a factor of 100 to probably 100,000, something like this. Nevertheless, there is groundwater there. The volcanics can look like this; this is actually up in Oregon, north of California, Newberry Crater. This is a recent lava flow, and you could possibly tell from the crinkly texture that there's a fair amount of porosity, or ability for water to move through something like this. These volcanic deposits could be quite prolific in terms of the permeability such as up here on the Modoc Plateau in Shasta and Lassen and so forth. These may play an important role in mitigation of loss of snow storage under climate change. Just the groundwater in the mountains can serve as an interim storage mechanism for water.

0:11:10 GF: Now, the key thing in terms of California's water use is the Central Valley. Central Valley is not the only thing going on in terms of water, groundwater management in California, but it's the key aquifer; it's one of the biggest aquifer systems in the world. So, I'm going to spend a fair amount of time talking about what this is, what it looks like, how deep is it, what's the freshwater distribution in it and so forth and so on. You'll see a lot of depictions of the Central Valley that are very generalized, just looking north, gone through on this cross-sections for the Central Valley. You've got recent sedimentary deposits in brown and then older sedimentary deposits and then harder and ravine rocks. The thickness of this stuff is, right here, is probably about 3,000 feet, maybe 4,000.

0:12:06 GF: In the Tulare Lake Basin, the thickness of these materials is up to 9,000 feet. Quite thick materials. And here's a depiction of the Sacramento Valley cross-section and the San Joaquin Valley depicting the thicker sediments in the San Joaquin Valley. So, a lot of what you see are generalized pictures like this. It's all brown, or it's all white or yellow. Of course, it's much more complicated than that. These materials in the Central Valley, got here by erosion from the mountains and deposition by alluvial fans. Here's a nice depiction of an alluvial fan in Montana but our fans here in the Central Valley are not spectacular. So, they're not photogenic. So, here you have a river coming out the mountains depositing sediments in the shape of a fan. That's how our aquifer system, here much of it in the Central Valley was built. Here's a picture of... Or a depiction of the King's River alluvial fan, coming out of the Sierra Nevada right here, and it is a low relief alluvial fan. Again, if you look at a photograph of it, you'd hardly know it, but this river has fanned across this flood plain, this alluvial plain, for some 1.5 million years and [0:13:30] ____ before it depositing materials and basically making the aquifer as rhe basin geologically subsides and accepts these sediments as time goes on. Again, on a million-year time scale.

0:13:47 GF: There are nice depictions of the San Joaquin Valley and Sacramento Valley groundwater system like this. And this, we're gonna return to this later, but right now, I'd like to give you a feel for what are these materials really like? Again, you see a lot of pictures like this, where it's all blue and there's these little lenses. Those are to indicate clays, and people look at these enough, and they get the idea that the system here in the Central Valley is really like that. It's actually nothing like that. Sometimes, it doesn't matter. In a lot of cases, it does matter and as we get deeper into groundwater management, it matters in a big way.

0:14:32 GF: Now, I'm not saying Claudia Faunt, who is my friend and colleague is wrong, but this is a generalized depiction, and it behooves us to look in more detail at it. Here's another depiction from the California Water Plan of an aquifer and again, if you look at these enough, you think, "Well, that's the way the world is." Again, it's not like that, at all. It's more like that. It's almost precisely more like that without the lignite and the peat, but you've got rivers that deposited materials and deposited sand bodies, and these materials are not aquifer materials at all. If you look at this, you say, "Well, where's the aquifer? There's all these little lenses, that are staying through here. That's exactly the kind of thing that our water comes from in Davis and much of the Central Valley; it's a network of these sand bodies.

0:15:24 GF: There's another flavour. How do I this? Well, we spent the last 25 years, my students and I, looking at actual data from California and other places, well data, of the materials that are there in the subsurface. Here's a model of the materials beneath the Kings River alluvial fan. It's an aquifer system. Aquifers are the gravel on the sand. So, those materials there are aquifer materials. Everything else, the green, the blue, the lipstick pink, whatever that is, are non-aquifer materials. That is, they store water, these other materials, store water, but they don't transmit the water readily to wells, except over a long, long time frame.

0:16:16 S1: Another piece of work that was done made the COSUNA System using actual well log data and the technology that was used to do this was developed here at UC Davis in the '90s. It's... It melds geologic theory and data and geo-statistical spatial... Statistical theory and data to built realistic geologically and hydrologically realistic models of the subsurface. Here again, the aquifers beneath the COSUNA System, south of the American are the red and the yellow. The rest are non-aquifer materials. Lawrence Livermore, Livermore Valley, here's another model that was done. The aquifers are in yellow here. Here's a closer look at these things. This is the Woodland area. In my geo-statistics class, Steven Maples, sitting right over here, I think, took well log data from the Woodland area and built a model similar to what you've seen of the aquifer materials and the non-aquifer materials. Actually, these are not clays, but they're mixtures of clays, silts, and sands that are much lower in permeability in the Woodland area. A lot of gravel in Woodland, hence all the red. That's the influence of Cache Creek, and Katie Markavich who was also in the class, took well log data recently from Davis and did the same kind of the model for beneath where we're sitting right now.

0:17:51 GF: And here, it's a little bit hard to see, but this is a three-dimensional model. The aquifers are the red, the red zones right here. So, that's the Davis aquifer system. So, what does this look like in 3D? It's not a sand pile. It's not a pile of gravel. It's something more like this. So these systems, they are not layers of layer-cake materials. They're not piles of sand and gravel. It would be easier if they were, but also our whole system would be much more contaminated with contaminants if it were like that. But it's more like an interconnected network, and this is also... This, how do I know it's interconnected? This also comes from years of research done here at UC Davis by myself and Thomas Harter on how these sand bodies interconnect, how we know, and what are the consequences of it?

0:18:53 GF: One consequence of it is you get an integrated network of aquifer materials that behave in a very specific way. It also makes them hard to recharge. It makes them somewhat protected from contamination but not totally protected from contamination, and it leads to a lot of other interesting and important side effects. So, if you want a conceptual feel for what these aquifer systems are like, a lot of people think of the layer cake. That's what you'll see in the newspaper and magazines. A better analogy would be the human body. In the human body, you have fluids coursing relatively rapidly through veins and arteries. And then outside the veins and arteries, it's tissues. The tissues are mostly water also, and there's lots of mass exchange between the tissues and the veins and the arteries.

0:19:49 GF: These aquifer systems in places like the Central Valley, or Orange County, Salinas, the Basin Range, are more like the human body, in terms of how the fluid moves and exchanges, than the layer cake model would suggest. So, let's look at some other fundamentals of ground water, and talk about, a little bit more about the consequences of these networks. And this, by the way, this is also why I usually don't refer to it as an aquifer. It would be kinda like, each of these is an aquifer. We don't refer to the human body, or the system that makes up the human body as the vein or the artery. It's a system of veins and arteries and organs and tissues. So I refer to these systems as aquifer systems. It's a system of aquifers. It's not one box or entity that can be managed specifically in that way, necessarily.

0:20:56 GF: So here we go back to a cartoon, so, when we draw cartoons explaining groundwater, we go from the complex back to the simple. Just to make a point, yes, ground water does move beneath our feet. Here is a water table; that's the upper portion of the zone of saturation, and this would be called an 'unconfined groundwater system'. And there's also something called a 'confined ground water system'. And that's what we're dealing with here. These systems are confined. Who cares? What does that means? Well, this, here's an aquifer. This might be, could be 100 miles, could be 100 meters. The scales doesn't matter. But these kind of systems do occur on a hundreds of miles spatial scale. There's in this case, this example, it's just a schematic, an unjointed limestone above it, that might leak water, but it's lower permeability of the material in this aquifer. So water moves through this material relatively easily.

0:22:02 GF: And in a system like this, if you drill a well, and screen it there, and the aquifer, the water level will rise to a level that's higher than the top of the aquifer. In this case, I drew it such that the pressure surface, the potential energy surface, is up here. So this does happen quite routinely, where the potential energy surface, or the pressure in the aquifer is high enough to push the water in the ground water system. If you put a well there, above land surface. And that's how we get flowing wells. There's not as many of these as there used to be, because we've developed a lot of our ground water systems and those pressures are lower than that.

0:22:44 GF: So that's a confined system. It's kinda like the, in terms of the pressure in the system, it's kind of like the plumbing in your house. The plumbing in your house, if there's a pressure drop in one part of your plumbing, like if it's an old house. And you're taking a shower, and your room-mate flushes the toilet, the hot water decreases, perhaps, if the pressure is not handled too well in an old plumbing. But that pressure response is quick. So, that's a pressure response. So, if pressure or water levels up here dropped, in this confined aquifer, it might take only a matter of hours, days or weeks for that effect to go 20, 30 miles down into the system. Depends on the system. When these confined aquifers affects far away, it can have a big spatial footprint. The systems respond very, very quickly. That's the concept of flow. In this same system, it may take 5,000 years for a molecule of water to get from there to there.

0:24:03 GF: So, that's the difference between transport, moving an actual molecule of water from there to there, and flow. The first analogy I used with the pressure response is the principle of groundwater flow and pressure changes in the system. Those happen very quickly. And that also, as I'll explain in a minute, is why the myth of fossil water not being sustainable is a myth. I'll come back to that. So, after development of that groundwater system, the head surface or the potential metric surface might be down here. The water table, this looks like this is labelled as a water table, but the water table is this right here. That's the water table. So, what we think of as a water table, "Oh so-and-so measured... UC Davis Well measured the water table." That's not the water table. You're measuring the pressure surface in a confined aquifer well, and changes in that surface don't lead us directly to information on changes in groundwater storage.

0:25:12 GF: So, let's say that we develop that system and the water levels come down. Then we might get a surface like this. If we pump this well, the counter depression, we get a draw down cone. Water levels decrease. It extends far and wide. When we run a short term pumping test on wells in the Davis area for my 146 class, in just four hours, the effects of that pumping test goes out a half a mile to a mile. If you pump for a week, it'll go out miles. So these confined aquifer wells have a big effect. The aquifer stays full of water but the de-pressurization happens over a big area. By the same token, if I add recharge in this system far away, I can benefit downstream resources because of that pressure response in the system. In contrast, if I put a well in the water table system over here where there's no confining done. It's not like the plumbing in your house anymore. It's more like the water in a potted plant up here. Then pump that well, the water levels decline in a very local area around the well.

0:26:28 GF: So, the way these systems work here, we pump the water from beneath a place like Davis, the confined aquifer system that looks more like that than what these depictions suggest, the confined aquifer system de-pressurizes over a big area. Water slowly drains and leaks from the recharge area and across the confining beds in the City of Davis and campus cases it's through the silt and clays that form these confined structures and the water table slowly, slowly declines. But the water table changes very little. During the drought, the water table in this area probably went down a couple of meters. The water levels in the wells on campus and in the city went down on the order of 20 or 30 meters. That's pressure response consistent. People started looking at the water levels in the wells more carefully and they saw, "Oh my God! This summer, the water levels went down 50 feet." Well, they do that every summer. A lot of the wells, the water levels go down 100 feet and recover in the ground next year. And I'll show you an exception to that.

0:27:45 GF: So, this is kinda how it works. Deep confined systems, slow leakage from a water table feed, that's the stuff on top of the system. But in our system here, the entire system is these inter-bedded, interconnected sand bodies and gravel bodies that behave like this confined aquifer system. So coming back to that myth, the myth is and you see it all over the press, it's a colossal flaw, mistake. And people think, "Okay, if the water I pump here is 3,000 years old then the water coming out of the tap here is 1,000 to 3,000 years old on average." It is. So, the logical thinking is, "If that water is 3,000 years old, it must take 3,000 years for it to be replaced." And the answer to that is no. That's incorrect. Do we say that because the average age of the water in the oceans is 3,000 years... It's 2,000 or 3,000. I think it's 3,000 years to be... But if we remove some ocean water from the oceans, is it gonna take 3,000 years for that water to be replaced? Well, no. It'll come into the ocean somewhere else. If we take water here that's 3,000 years old, it will be replenished in terms of its potential energy or it pressure or water level while water is coming in here or leaking through the confining beds.

0:29:20 GF: So hence, don't let anyone tell you that if you're pumping old water, fossil water, that that is a non-sustainable practice. Marc Reisner made the mistake in Cadillac Desert. A lot of people take this lay person's approach to groundwater, take things like the old age of much of the groundwater, and take it in a direction that is not appropriate. Any questions about this fossil water thing before I move on?

0:29:53 Speaker 3: What about places in the Middle East where it is really old water, and there isn't any recharge?

0:29:57 GF: So the Nubian sandstone in Egypt, where it's a huge, it's like a subcontinental scale confined aquifer, [0:30:06] ____ the USGS thinks that that's probably an exception where the water there is so old that it's not likely to be replaced. It's also possible to pump more groundwater out of a system than it can sustain, such as the older lava. In the older lava, yeah, they're pumping old water, but the problem is they're pumping at a rate that's much higher than the recharge rate, and for the ability of the system to replenish itself. Okay, again I showed a flowing well, the depiction here is an actual picture of a real live flowing well, and I think it's in California. At least, it's on the California Water Education Foundation poster, it must be. Yes?

0:30:50 Speaker 4: Are there ever situations where you have such a high recharge level where the pressure causes a crack in the subsurface?

0:30:57 GF: I'm not aware of that problem, but there is the case where over-pumping a system can cause a subsidence, and I'll show examples of that which also can induce cracks that go all the way to the surface. I have some pictures, but I didn't include them in this slide. Okay, looking more at the Central Valley, here's a map of the thickness of the sediments in the Central Valley. Earlier, I said the thickness in our area, in the Davis area is I think I said on the order of 3000. Actually this says it's more like on the order of 2000 feet. It gets thicker in the southern part of the valley, the Tulare Lake Basin, up to 9000 feet there and further south. Now, about half of this, actually I think the sedimentary thickness here is a bit more and below this are mostly marine rocks. Marine rock were deposited with salt water in them so, inherently, they tend to have a poorer water quality, but typically a third to a half of these materials have fresh water in them. Here's the thickness of aquifer with fresh groundwater in feet, in the system, and again, in our area, this is a bit north of us; this shows about 2000, 2500 feet of fresh water in the system down toward Modesto. I believe, that's 1000, Tulare Lake Basin, and quite a thick deposit of or thickness of freshwater down there.

0:32:56 GF: So, below the fresh water is the saltwater. This is one of the... Mostly unrecognised potential problems with over production of ground water. If you pump too much of the fresh water, guess what? You start pulling up salt water. That's something that, as far as I know, is not happening appreciably yet. It's something you don't wanna mess with because, when it does happen, it's hard to reverse the effects of that. So, when you see in these pictures of the San Joaquin Valley, like Claudia has made, in the bottom, there's this depiction of old saline water. This is schematic. In reality, about half the system in the bottom part of it is salty water. The rocks may not be as permeable down here, but still it's a thick sedimentary system. So, again over production of the fresh water can pull up this saltwater. So let's start looking at overdraft and what is over draft? Overdraft is pumping more groundwater than the system can sustain. It is not pumping more groundwater than the recharge. Sustainable yield of groundwater does not equal recharge. It's a more complex base in response to that. So that's why the wording here is kinda precise. It's more groundwater than the system can sustain. So, what constitutes nonsustenance? It's this list of problems, and these are subjective. There's nonsustainable storage depletion. In theory, you could empty out a basin if you pump too much over time.

0:34:44 GF: There's some places in the world where that appears to be happening. You can get land subsidence. Surface water or ecosystem effects increase energy cost because the pumping lift is greater. Bad water intrusion from aquitards and from depth. We'll look at both of these by alluding to the latter. Basin salt imbalance. This is the only groundwater problem that scares the hell out of me. All these other ones, I'm really concerned about, but they don't scare me like this one does, and then there's sea water intrusion. So, let's look at examples. So here's the groundwater overdraft trends in the Central Valley. This one is obviously the nonsustainable storage depletion. This is a fine example in the Tulare Lake Basin showing groundwater loss. This is from groundwater level measurements and models showing the groundwater loss. In the Sacramento Valley, this is 2004, I believe, we've been happily not so much in overdraft except locally. Except perhaps here in Davis, and I'll show you an example. Delta and east side streams may be the opposite, that's kinda interesting. So, the entire state is not in a crisis.

0:36:00 GF: There are crisis locations and the Tulare Lake Basin is certainly one of them in terms of groundwater overdraft. And here's another depiction of that cumulative groundwater depletion in the Central Valley. And this is from the USGS data, these data and the grey satellite data, which is this last portion to piece together a more recent trend, and this... You may not really see an effect of the drought because they were pumping like crazy in the Tulare Lake Basin well before the drought. The amount of depletion here amounts to something on the order of one to 1.5 million acre-feet per year, which is DWR's listed amount of annual statewide groundwater overdraft, or maybe it's 1.2 million acre-feet per year.

0:36:53 GF: That's an example of that. Here's some other data from the recent water plan on... This is for different years, 2005-'06, '06-'07, '07-'08 and so on, of changes in water storage based on two different estimates of two different assumed set of parameters. There's still a fair amount of uncertainty in the exact numbers, but you see the trends during this time period.

0:37:20 S1: Subsidence. Subsidence, one other myth I could've put up there is the subsidence does not destroy aquifers. You will read that in the newspaper from time to time. Subsidence is like a patch of those clays and silts that I showed in those figures. We have plenty of them here. So in most places in the Central Valley, there is some potential, or in some cases a lot of potential, for land subsidence. Basically, you squeeze the water by de-pressurizing the aquifer out of the clays and silts and that causes the land surface to subside. In Davis, we've subsided since the '50s probably at least a meter or two. Up in Knights Landing, there was 10 feet of subsidence that was measured into the 1980s. It's probably a bit more since. Sometimes, some of the subsidence is from gas production, or oil and gas production.

0:38:20 GF: So let's look at some examples of subsidence. This is the classic one... That's cut off there. This is the classic one in the San Joaquin Valley showing... And this is 1977 there. It's cut off. The photo was taken in 1977 from the Mendota area in the valley. Back in 1925, the land surface was up there. So this is an extreme case. This is 10 meters, the subsidence in Central Valley. This is one of the things of course that prompted importation of surface water through the State Water plan and to some extent through the Federal water projects, the Central Valley project. That's a classic case.

0:39:10 GF: More recent data showing depth to water. So these are groundwater levels below the [0:39:15] ____ in Mendota. This other line over here that's charted on the right-hand side here, is vertical displacement up to 2010. And these are in feet, so we're talking tens of feet. Nevertheless, measurable displacement where as the groundwater level drops down, in this case, they re-induce subsidence. And there's been quite a bit of subsidence measured in the Southern San Joaquin Valley or the Tulare Lake Basin, especially during this recent spate of increase in groundwater pumping. Here's a map of... This is also from the State Water Plan, 1926 to 1970 subsidence in the San Joaquin Valley and Tulare Lake Basin. This is in feet, so the dark purple is 24 feet.

0:40:09 GF: This is the problem. Why is it a problem? Maybe in some places it's not a problem, but it can destroy railroads, pipelines, canals. Some of the canals that distribute water for the various water projects don't any longer incline in the direction that would allow the water to drain in the direction it should, so drainage is a problem. It can affect roadways, buildings. In the Houston-Galveston area of Texas, it's reactivated faults. These faults have destroyed portions of neighbourhoods and buildings. So it's like a surface water and ecosystem effects.

0:40:55 GF: So when you pump groundwater, and here we're pumping groundwater that formerly was just flowing to a stream. We pump the groundwater, and if you do it enough, you eventually start taking water out of the stream. Any amount of ground water pumping ultimately has some effect on some surface water thing. In many cases you might be pumping enough groundwater or a small enough amount of groundwater, that the effects are minimal. That's what we often see. But it's very hard to have any groundwater production that does not have some effect on surface water here, and we're taking water from the streams. Southern Sacramento County is taking water from the Sacramento River, not called out as such, but it is.

0:41:42 GF: South Lake Tahoe is taking water via wells from the lake. It's kind of under-the-table water. No one is really saying much about it, but nevertheless, this happens. It doesn't get called into question until these sorts of things get brought into a place like this, court. Well, this is not a court of law, but one day, you'll all be there, right? So this is the effect of groundwater pumping on surface water as an example. The prime example in California is the development of groundwater that happened in the early part of last century, at the beginning of the early part of last century. Here's a visualization of California's soggy past, on this website, where this guy created what a Landsat image might have looked like of California say 100 years ago. And there's Tulare Lake; there's Owens Lake, it's gone too pretty much. And you've got wetlands, riparian zones along the Central Valley that the [0:42:44] ____ you can see it really well. Of course, there's no Tulare Lake, and people say, "Well, it was drained for irrigation." Well, yeah, that was part of it, but another big part of the reason the lake disappeared was, we pumped enough groundwater that the lake never... No longer got fed by groundwater, and that's true of many of our surface water bodies, and wetlands up and down the Central Valley.

0:43:10 GF: And that's an example of ecosystem effect, and here's a nice image from Claudia's USGS publication, that shows former locations of riparian wetlands and water bodies in the Central Valley that have since been transformed just by land use, but also by groundwater management. I'm skipping over increased energy costs, because it's obvious, right? We pump deeper groundwater, it costs more in energy to bring it to the surface. I heard that people are experimenting with solar power for groundwater pumping. I haven't heard as to whether you can pump at a high enough rate. A lot of these irrigation wells are pumped one to 2000 gallons or 3000 gallons a minute. I don't know if solar power would handle that. If it would, that would be great.

0:44:02 GF: This one. This is one of the ones where it's not well-characterized, but it's scary. So it's one of those things where I would really rather avoid this happening. So let's look at what that is. Bad water intrusion from aquitards and from depth. So I showed you this earlier. The fresh water is not all fresh water in this big bathtub. It's not a bathtub; it's something much more nuanced than that. And what's below this fresh water is non-potable saline water. Fresh water by this definition for this kind of mapping is anything less than 1000 parts per million total dissolved solids. Even above 800, a lot of that water will be marginal use, and it might have trace elements, arsenic, selenium, so forth thrown, would make it of questionable usability. But nevertheless, again, if you exploit too much of this freshwater, even though we're not on a coast, we don't have to worry about ocean water intrusion in Fresno, there could be in essence ocean water intrusion from below if you over-produce the system. At what point that happens? We haven't done the analysis. It requires data and a type of modeling analysis that has not been done.

0:45:21 GF: But the idea of water coming from aquitards, and these systems... What do I mean by aquitards? The aquitards are the non-aquifer material, like these clay-ey or silty materials that we have beneath Davis and Woodland. As you go deeper in these materials there's water in there. We don't know the fall here. In many cases, in other basins, we find as you go deeper, the total dissolved solids or the quality of the water in these fine-grain non-aquifer materials gets worse. But we can't sample water from these to figure out what the water quality is. It is reasonable to assume that the quality of water of these non-aquifer materials gets worse with depth, because the water turns over much more slowly the deeper you go.

0:46:16 GF: So again, maybe there's fresh water in this deep gravel, or down here, or one beneath it. Could be a 1000 feet beneath it where there could be fresh water. If you over-produce it and start pulling in too much water from a non-aquifer materials, that can also degrade the water quality. Really hard to know, but again, it's something you don't want to explore through over-pumping of the system and then find out what's happened when it's too late.

0:46:45 GF: This last one, and this is the one that scares the hell out of me, is the basin salt imbalance. And this is not a very good figure, but what it shows is, it's water levels in the Central Valley, and focus on the arrows. So we've got Southern San Joaquin Valley and Tulare Lake Basin down here. See these arrows? They're pointed in. They're pointed inward towards a pumping center. So essentially, all the groundwater in that area is exiting through wells there. There's no water exiting through natural outlets in the basin. Down here in the Tulare Lake Basin, there's no natural outlet for the groundwater. In the past, it's questionable whether there ever was, but it appears that there was some groundwater exiting into the Southern San Joaquin Valley, like so. So, so what? Well, when this happens, when the basin, the hydrologic basin loses its outlet, you risk salinating the basin. Why is Mono Lake salty? Why is the salt in the sea salty? There's no outlet except for evaporation.

0:47:56 GF: If you over-exploit a groundwater basin, like this one here, this is before exploitation; this is after exploitation of the wells. You can't see it very well, but the water levels are down and basically the only exit for the water is the wells. A lot of irrigation there so the water's applied for the land. What happens when that water evaporates? The salts are left behind. So you set up a closed basin by overdrafting it to, in which there's no longer an exit for the salts. So this is one of those things where it's insidious and so bloody slow that we're not paying attention to it. There are people working on the salinity problem, but the long-term salinization for a groundwater basin, that's something that we haven't really started to calculate and model carefully. I have a student working on it, but it's gonna take a lot of work to figure this out. But the problem is the consequences unfold on a time scale of decades to centuries. It's not one of these things where you can look at it and monitor for 10 years and say, "Oh yeah, I've got cause and effect. I need to do X to fix it".

0:49:15 GF: This is a thing where over long time periods you could essentially destroy the water resource. And it's irrigation water and what are you gonna do? Desalinate the irrigation water and pass the cost of desalinization onto people buying food? Well, maybe in 20 years we'll have an infinitely cheap source of energy and desalinization won't be a problem, but that's kind of a gamble to hold out for that. And then sea water intrusion, and this is kind of obvious, but on the coast, we have sea water in the sediments along the coast line, and there's a fresh salt water barrier if we over pump, and we bring in that salt water wedge to intrude. This is happening, has been happening in Salinas Valley, Orange County, San Diego area. The San Diego area and Orange County, they've been treating waste water, injecting it along the coast to keep the salt water out fairly effectively.

0:50:25 GF: One more comment about groundwater quality, and I'll try and wrap up within about 10 or 15 minutes, is that gonna be okay for timing? The groundwater quality is degrading in many systems, yes, but most of the groundwater quality is still good. There's a little bit of a dichotomy there. And the quickest way for me to summarize this, in much of my research at UC Davis has been on this topic. And I ran around the world in 2002 lecturing on it and basically the summary of a lot of the work is that if you take a glass of water. Is this Davis water?

0:51:11 S?: Mm-hmm.

0:51:11 GF: If you take Davis water, you think, "Well, you just told me that the age of this water is about two or 3,000 years on average", actually it depends on what well it comes from. Actually, the molecules of water are a mix of ages. Some of the ages are gonna be on the order of decades, some will be hundreds of years old in terms of how long they've been in the system; some are thousands of years old. So if you take most any groundwater sample, the recharge date of the water molecules could be 1893, 1974, 1814, it's a mixture of ages. This is a general research result, and it's widely accepted now in groundwater. So what does that mean? That means if you look at the distribution of ages from that water sample, and let's say the water is a little bit contaminated with nitrate, Davis has been having trouble with nitrate contamination. The portion that's contaminated with nitrate is only the portion that's young enough to have been affected by anthropogenic nitrate contamination. Our sources of nitrate contamination have only been around about 60 years so only the young fraction is contaminated.

0:52:33 GF: That's good in that that contaminated groundwater is mixing with clean groundwater in aquifer system and in the well resulting in something that's overall less contaminated. But it also means that over time the fraction of water that's contaminated is going to increase for this potentially to contaminate it. So if we see contamination in the groundwater today, and that contamination's from a persistent, non-point source, we can expect decades to centuries of worsening water quality. This is why some have called me Dr. Doom of groundwater quality. So if Mal can be Dr. Doom of the delta, this is my Dr. Doom thing. But I'm really an optimistic person. So basically, this is a big ongoing problem that is... That we have to keep in the back of our minds when we talk about managing groundwater and the groundwater legislation. Fortunately, the legislation does have a groundwater quality hook in it that I think is very important. But the basic thing to remember is most of the fresh groundwater resources are hundreds to thousands of years old, yet most of the contaminant sources are 50 to 60 years old. Here's some exceptions. The groundwater ages even for short screens are highly mixed.

0:54:01 GF: And, there was a stream of papers on this. So in many systems, there's significant potential for water quality to get worse over a very long timeframe. This is like one of those Jared Diamond examples of creeping normalcy. It's a problem that changes so slowly, it's really hard to keep track of it. And we wrote about in a WRR article in 2006. This set the stage and helped reinforce the USGS's National Water Quality Assessment programs, and it also set the stage for the UC Davis nitrate work that was led by Jay Lund and Thomas Harter. And some of that work also compiled data on numbers of wells exceeding the nitrate maximum contaminant limit, and their increase in time. Again, this is consistent with what I was saying earlier about the mixture of ages of groundwater from our samples and this very long-term insidious incursion of shallow contaminated water into the deeper system.

0:55:15 GF: So, looking at Davis too, from a water quality perspective, here's nitrate with time in Davis, the number of wells. And if you fit lines to these, you generally get a significant positive slope. This is why the City of Davis has been drilling deeper wells. So here is a picture of wells at UC Davis. This is UC Davis' drinking water wells. These are down 12,000, 14... 1,200, 1,400 feet. This is what's known as the the deep aquifer beneath us. The campus has reserved that for its drinking water. The campus uses shallower wells in the shallow and intermediate aquifer for utility water; landscape and lab water, things like that.

0:56:06 GF: The city's deep wells that they've been drilling mainly in the last ten years are shown here. These are where the screens are in those wells, as a function of depth. And most of these wells were just drilled within the last ten years. And here's the interesting thing. Here's water levels in a typical city well, but the shallower city wells. More comparable to this stone here. Through time, each of these cycles is a year, the water levels go down in the summer, recover in the winter, or spring, go down the next summer. So it's this ongoing cycle. As long as it's not a drought, around here, for the most part, our groundwater levels have declined a lot in the summer but recovered. And here you see the drought. This is the last three years of drought. That's the effect of the droughts, the change of these high standards.

0:57:03 GF: So we would normally say, Davis is not in overdraft, except for the drought. The water levels have been recovering. It's in a sustainable state. Unless we want the water levels to be higher, to get more water to Putah creek or something like that, that could be another criteria. Here is the City of Davis' deep aquifer. Wells are a typical flat from the deep wells. This is showing not just a decline during the drought, but a decline going back to... For some reason, I can't see it on here.

0:57:43 GF: I believe that's back to 2008. This is about six years. And the other wells in Davis, most of them with a deep well show a similar trend. Here's the campus drinking water wells. And one of them, a typical one, that most of them look about like this, from the deep aquifer. This is going back to... That's 2000. This is in the 1990s. And back then, it was... There weren't non-sustainable trends of great worry. I think they've had some trouble with their instrumentation. And we're still working for that, but over the last ten years, and this is about when the city started pumping the deep aquifer, and look at what's happened. See the campus water levels.

0:58:31 GF: So, basically, the question was, when the city started poking into the deeper aquifer, they came to me and others at the campus came to me and said, "Can the deep aquifer handle it?" And I said, "I don't know." No one's done a model of Yolo County yet that reliable enough for us to even test that. The monitoring data are ambiguous. You might not know until you start doing it, and I think we're getting the answer in that. And one of the troubling things here is the city's water-levels in their wells are low enough, that's minus 80 below sea-level. That's minus 100 that indicates to me that there's something in the wells is pretty hard, I mean really hard. That's affecting the campus wells, and it's probably responsible for this.

0:59:34 GF: And here's a trend in the UC Davis utility wells. Again, not a lot to speak of, but you certainly see the drought effects in those shallower intervals. So, is the system in overdraft? Sometimes data like this is all it takes, if it's just a yes or no question. Another case-study, I started working in California with Harvey Banks before I came to California in the late 1880s. Sounds like...

1:00:07 S?: 1980s.

1:00:08 GF: A long time ago, but.

[laughter]

1:00:11 GF: Back in the 18...

[laughter]

1:00:15 GF: Yeah, anyway, Coachella Valley, I worked with Harvey who was wonderful to work with, for about eight or 10 years, and he hired me to do a model of Coachella Valley, which had a fabulous dataset. Coachella Valley is down here by the Salton Sea. It's an alluvial valley, and I just want to point out to the monitoring data, what it told them.

1:00:39 GF: Here's well data. This is elevation of the water level and the well going back to 1925, fabulous data set. And it took care to collect this data and curate it. And they had groundwater levels going down; obviously, they were in overdraft, and they knew it. They imported Colorado River surface water and started recharging it and using it for irrigation in lieu of groundwater. Water levels came back up. It took about 10 years, 10 to 15 years to recover most of that; that had happened in the last, previous 30 or 40 years.

1:01:16 GF: And then as often happens, they started to exceed their sustainable yield again and conditions went in this direction. But this clearly tells them, what are the conditions that create overdraft or arrested or reverse, that's the kind of information it takes. They had a lot of other data on drain flows and others, here's a well and an unconfined part of the system. Again, the trends through time tell a story of what the basins experience, what the sustainable yield is, and the model which shows... Which is these solid lines on the model simulated ebbs going back 60 years in a system from different parts of the basin shows you that these models can be built and calibrated to become actually quite reliable as predictors, not mimickers, but predictors of changes in groundwater conditions.

1:02:16 GF: So, this kind of modeling aspect... You'll hear more about modeling later in the course, is one way to try to figure out what portfolio of groundwater and surface water management actions would bring the basin into balance or cause it to go out of balance. And just a quick overview of the Orange County system and its managed off of a recharge system. This is one of the best examples in the world of managed aquifer recharge, and this is going to have to go very quickly, but Orange County, I think most of you know where it is, and Santa Ana River, and they've managed the Santa Ana River with an off-basin storage, its spreading basins, to recharge the groundwater system and over the years, they've recharged more and more. This just shows the progression of the facilities they built to store groundwater. Done a lot of work on characterizing, modeling the groundwater system, and one of my students, Steve Carl, got involved in some intensive modeling in that system.

1:03:25 GF: And you may think, "Oh, it's a simple system unlike Central Valley," but it's just like the kind of stuff I was showing you in Central Valley in terms of complexity, and there's a picture of a recharge in action. But basically, they've averaged 274 million cubic meters per year from a variety of sources. That's about 220,000 acre feet.

1:03:50 GF: That's a lot of water to very successfully recharge the system. Just to get some of these high points, I think I covered the fossil water part, the groundwater storage completion, always takes a long time to recover; people say this because they think, "Oh, water takes a long time to replace." "3,000 year old water takes 3,000 years to replace." No. I think giving you the background to refute that. Groundwater levels tell us how much ground water storage is changing, but most of the ground water levels certainly is confined to aquifers.

1:04:23 GF: It's a pressure response, so, we have to carefully translate that data into change and storage, it's doable, but not that simple. So, that's one of the reasons we don't have good cause and effect feedback between groundwater pumping and the effects of that pumping. The water levels in most of our wells are kind of these false pressure surfaces in a confined aquifer...

1:04:47 GF: Quality of most groundwater is degraded. We've talked about that; good quality groundwater today is likely to stay that way, debatable. And a potential myth, climate change will decrease groundwater recharge, here what I'm talking about, let's get through this... In the Central Valley, the situation beneath the rivers is mostly like this: The water levels have been drawn down below the rivers. Previously, the groundwater sustained a lot of rivers. For much in the Central Valley it's like this. So, a major source of recharge to the aquifer is the rivers.

1:05:25 GF: So, if we have earlier snow melt, higher winter stream flow, it's possible that we'll get more winter recharge to the groundwater from the streams. That's one of these little hydrologic subtleties, a chain reaction of the hydrology, in response to climate change, that just hasn't been followed through on, yet. So, it's too simplistic to just say climate change means warmer temperature, more evaporation, less recharge. Yes, in some areas, the coast ranges, especially. But in the context of something like this, there are counter-examples where it could go differently. So, I better stop there; thank you very much.

[applause]

1:06:14 GF: Time for some questions. Any questions?

1:06:27 Speaker 5: So, the discussion of bad water coming from the specific strata as opposed to coming out from depth. I think we probably have seen some of that, in some cases already with respect to arsenic. I don't know if you've looked at much of the arsenic data. When I look at the way water supply levels put in now, they put a well in; they stream across the more permeable zones, but they're sandwiched between the tighter zones. And then, they pump it for a relatively short period of time. This is what water quality looks like. But then when they bring it into production, they start just with arsenic that they didn't think there were gonna get and it's probably coming out of those clays; at least that's what I thought. So I was wondering if you have any comments?

1:07:05 GF: No, that's an excellent point. There's a lot of new data that's actually maybe coming onto campus shortly from the this firm BESST, B-E-S-S-T where they have point sampling of both the flow of water coming in the well stream, and the water quality of that water, where they can detail specific intervals where you have bad water flowing. And those are... When you have that sort of thing, that water is avoidable. But my concern is, even if you don't screen an interval, if you overdraft the system too much, eventually more [1:07:47] ____ water will come from the confining beds and you risk a larger scale water quality degradation.

1:07:58 S5: I think that's exactly what we've seen in some of these data where they do try to in effect zone test the sand zones, but because they don't pump for that long, they don't allow for the interaction of the place that longer term flow. It takes longer for it to actually come in and mix with the sand waves.

1:08:18 GF: No. That's an excellent point.

1:08:19 Speaker 6: Some of the data you looked at it seems it increases the nitrate with time. Do you also see increases in solute concentrations as well from from say, some of this more ion-rich, older water in the clay units finally dissolve or diffusing out and actually getting into the aquifer?

1:08:37 GF: I haven't had good enough data stats to explore that, but I think one could go and get data perhaps, from places like the city. I wish the campus had been monitoring the quality of the water longer term, more than they have. But some places do that, and I think you're likely to see some trends like that or not. A lot of people, they will monitor water quality and not see a change for four years and say, "Well then, why bother?" The problem is the changes that they should anticipate seeing might not be evident for 10 or 20 or 30 years. It's something you just have to do forever...

1:09:26 Speaker 7: Can you imagine a future scenario where in the Southern San Joaquin a combination of subsidence and groundwater overdraft might adversely affect the flow of the river itself? Perhaps even reversing flow?

1:09:40 GF: The San Joaquin River?

1:09:41 S7: Yeah.

1:09:43 GF: I suppose it's not impossible. I haven't looked at the gradient on the river enough to make a supposition about that. But the San Jo Valley is not a high-relief place. It's flat as a bath tub almost. That'd be an interesting thing to look into. You could look at the amount of subsidence, look at the gradient on the river and make that calculation.

1:10:18 Speaker 8: When you were talking about the poor water quality intrusion from aquitards and from depth, you said that the analysis of where that might start to happen hasn't been done in California. Have they done it elsewhere? Or have those methods just not been invented yet?

1:10:39 GF: Well, Mr. Kaley just pointed out that it has been done in a way based on the screen sampling of input of things like arsenic and I think also uranium from certain intervals. But in terms of... The problem is, on a bigger scale, we don't know much about the quality of the water in those materials with that. So, if we suck real hard on an aquifer system for 20 years, and it may take that long to get an appreciable amount of water out of the fine grain materials, we don't know enough about the water in those materials to project what the consequences will be. Most of the water that's in a canteen spent some time in clays and silts. So, if the ratio, if the amount of water being pressed out of clays and silts increases too much, there may be these unfavourable trends, but it's really hard to predict. I don't know that we'll ever have the data to predict that so it's one of those things. For me, it's a reason to not over-exploit the basin. It's one of those things you want to avoid.

1:11:58 S1: We have time for one, last, quick question.

1:12:00 Speaker 9: Just on a technical side, I'm curious how you generate those maps of aquifers. Do you use some sort of like sounding equipment or it's just based on pumping tests?

1:12:08 GF: We take well log data where the driller logs the different materials, which are incidentally proprietary in California, so we can only get the data if we have state or federal funding. It's one of the ironies of working in California. Very open place, right? And sometimes you have physical log data, and in other cases, we've used surface geophysics to complement those, and those are the hard data. And then we build an interpretation of the origin of the deposit, the geologic processes are laid down, which help us sort of connect the dots. And the rest of it is stochastic, spatial, statistical method based on transition probability and mark off changes. So the mark off change represents the probability of transitioning from one material to the next, vertically or horizontally. And that builds into the system a very compact three-dimensional model of the spatial distribution. The software was generated here and we're working on a book on it. Well, thank you very much.

[applause]

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