David L. Sedlak

Nobel Conference 45

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Thanks for the introduction. I'm just waiting for this to switch over to my talk. I'm actually pretty impressed there's a lot of you here. I thought that the Twins game was starting. [laughter] Oh, it starts at 4:00? Oh, that's why you're still here. OK. [laughter] OK. I have the computer here so if I'm running a little late, I can update you on the scores. [laughter] I also realized that, you know, after 3:00, it's sudden death for high school students, right? You know, classes end at 3:00 and this is like overtime and so it better be good is what I'm thinking.

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So the organizing committee put together an exciting two-day program here to explore the significance of water to important topics, like economics, public policy, conflict, sustainability. They invited the world's leading experts to share their thoughts and experiences about the challenges associated with this and what we're going to face in the coming years with our water resources as climate change becomes more important. And I'm really looking forward to hearing tomorrow's talks. I heard some great talks today. And I'm really happy about that. But there was a problem when I got invited here and that is, when I was invited to join the group, I struggled to understand exactly how I fit here.

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I'm an expert. I'm not an expert on those big, weighty issues related to, I don't know, economics or public policy. I talk about them at the dinner table. But I study molecules. I study a very small scale. And as an environmental engineer who's interested in removing chemicals from water, I didn't at first have an idea what I was going to say to you that would be relevant about these very large-scale issues related to water sources. So I have a big challenge ahead of me to show you how removing trace concentrations of organic chemicals from water can play an important role in solving some of our most pressing water quantity problems, not water quality problems. And to illustrate this connection between water quality and water quantity, I want to tell you a story. And it's a story about an unquenchable demand for water that our cities exert. They want potable water.

And I want to tell you about the way in which we're going to satisfy this demand by having them drink sewage. [laughter]

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All right, some of you this sounds like a far-fetched idea. Think about it, the space station is recycling its own sewage. We have the technology. We have the technology to take sewage and make it into drinking water. In fact, cities like Los Angeles and Singapore are doing this now. They're talking wastewater and they're putting it back into the potable water supply.

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But that's not really what I want to talk to you about, because from a sustainability point, the advanced treatment plans that are used in places like Los Angeles and Singapore aren't going to be good enough. We have to figure out a way to use natural systems, to use the bacteria, the sunlight, the soil in our natural systems to purify water to provide a solution of this pressing problem of urban water need. And that's what I hope to tell you about today.

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Now if that student, if that fourth-grade class that Nancy talked about is going to learn about the hydrologic cycle, they'll probably see a cartoon like this one. At least in California where we have mountains, the water evaporates from the ocean. It goes up to the mountains. It falls on the mountains and it runs off back to the city. I don't know how this happens in Minnesota, but it does. [laughter] But in that fourth-grade class, it's quite likely that they're going to forget something in this figure. They're going to forget to put the people in. The people are an important part of the hydrologic cycle, because they're interested in taking this water and using this water. And when they're done with the water, they put it back into the river and it goes back into the sea and nature re-purifies that water and recycles it.

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But we're not in a situation where there's only a few people on the landscape. There are many, many people on the landscape. And the people in the upstream areas that get the water first are going to use that water and put it back into the stream. And the second city just further down the stream is going to take that water and reuse it. And the question that we have is can we rely upon the natural processes that occur between an upstream city and a downstream city to purify that water or can we intervene somehow, either with an engineered solution, a technological solution, or a natural solution to purify this water.

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Now before we pursue this question, I want to think about this issue of water use and I want to tell you why I'm focused on urban water use and not some of the other uses of water. This figure shows you water use in the United States on a national level. And it's a deceptive figure. Because when you look at a figure like this, you would think that the potable water supply, that is the portion of the supply that cities use is a very small fraction of the total. And about half of the water that we use is for thermoelectric power, mainly cooling as part of power generation. And a lot of it is used for irrigated agriculture. So you would say to yourself, if we want to solve the water problems, let's not pay much attention to this potable water supply piece of the pie, let's focus on the other ones. But if you're a city, you don't have a choice.

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So a rapidly growing city really only has one thing that it does. It supplies potable water. And thermoelectric power generation usually happens where there's adequate supplies of water, it happens on rivers. And irrigated agriculture happens where there's lot of water. So cities have this problem that they face where they have to bring water into the city and they can't just steal it from agriculture all the time or they can't take it away from thermoelectric cooling plant. They have to find new water supplies. And so to illustrate the conundrum that cities face with water supply, I want to talk about the two largest cities in the United States. I want to talk about New York and Los Angeles and let's take a look at where they get their water from and when you see it, you'll understand why there's so much pressure on them to find new water supplies and why water reuse or water recycling is such a reasonable approach for them.

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So this figure here shows you New York City. And what you can see when you look at New York City is that New York City's down here but New York City's water supply comes from two watersheds here in green, the Croton Watershed, and the Catskills

Watershed. And this water is shipped by way of these red lines here down in a series of pipelines and tunnels until it comes into New York City. So New York maintains a very large infrastructure to bring water into the city. It brings about 4 billion liters per day of water down and it does this by managing an area that has an area or a footprint that's probably about four or five times the size of the city itself. And as a result, New York City is a big landlord. New York controls development in the Catskills area. It acquires land in sensitive areas that might contaminate its water supply. And it also sets up agriculture restrictions on how land can be used. New York City is involved in retrofitting sewage treatment plans, fixing septic tanks when they break in these watersheds. So New York City almost acts like a landlord in the watershed that is its water supply. So it's a major endeavor. It takes a lot of money, a lot of effort, and a lot of political will.

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Los Angeles is no less complicated. So this figure shows you California and the red lines show you the three main sources of water coming into Los Angeles. So in Los Angeles, we have water coming in from the Colorado River down here. And I should probably extend this red line all the way out to Colorado because that water's coming from the Colorado basin and it's being shared with the Western states by treaty and shipped into Los Angeles.

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We have water coming from the Eastern Sierras here, starting up here at Mono Lake, see there's a little picture of Mono Lake so you can see what it looks like, that Eastern Sierra water supply comes down to Los Angeles here through the Owen's Valley and then finally we have water coming from the Sacramento/San Juaquin Delta. And you can see those are all three major infrastructure projects where water is transported very long distances and there are a lot of environmental issues associated with that. For example, the delta is an area where is a lot of endangered species disputes or a lot of disputes about who owns the water.

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The Colorado River water is also subject to a lot of litigation and a lot of fights. California water wars feature the Colorado River very prominently. And the Eastern Sierra is a place where there's also been a lot of fights over who owns the water and who has rights to it. Oh, and I should probably mention here that according to some of the climate change models, the Colorado River is probably going to start drying up and places like Lake Meade will disappear and the Sacramento/San Juaquin Delta is likely to collapse from the result of sea level rise. So Los Angeles has this tenuous, unsustainable situation. But they have a very large water infrastructure required to maintain its city.

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So here are the two cities we looked at, Los Angeles and New York. You can think about them as little ticks on the map, sticking out their little water supply tendrils, grabbing water from everywhere around them. Now let's think about the other cities in the United States that are rapidly growing, like Denver and Dallas and Atlanta. These are three cities that are rapidly growing and their growth has happened in the second half of the 20th century. And as a result of being latecomers to water rights, they don't have the rights to as much water as New York or Los Angeles. So building a large water supply infrastructure really isn't an option for them. They have to find other sources of water and all three cities are finding that their development and growth is being limited by the availability of water. So when you say that this issue is a Southeastern United, Southwestern United States issue, it's not. It's a national issue and it's especially acute in the southern part of the country, probably because population is growing very quickly, not so much because it's dry and arid there.

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So Minnesota, this could happen to you if you had more people who wanted to live here. [laughter] I'm sorry, I was just trying to see if you were all awake still. It's kind of dark out there. OK.

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When we look at this globally, this issue of urban water supply becomes even more important. I've plotted here the size of the population of the ten largest cities in the world in 1900, 1950, and 2000. And what you can see when you look at this slide, first of all, you can see that the center of population is shifting from Europe to North America to Asia and South America. But what's more interesting to me here is not where these cities are located but how big they are. So at the turn of the century, the biggest cities in the world were only a few million people. And then in the 1950s the largest cities were between 5 and 10 million people. And today the largest cities are between about 15 and 25 million people. And so big cities keep getting bigger and the footprint of these cities, or the density of people living in an area, means that those cities have an unquenchable thirst for water and they have to import water from longer and longer distances if they want to bring it in.

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This morning Dr. Pachauri talked about water street. And this is a figure from a U.N. Water Development Report showing the band of water stress. And so what you can see is the dark orange are the most water-stressed areas in the world and the light orange are less water stressed. And what's plotted here are some of the largest cities in the world. And so what you can see is many of these, the majority, in fact, of these large megacities are located in areas with water stress, and according to climate change models, many of these areas are only going to become more water stressed in the future. So there's a real need for water.

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So where can a rapidly growing city find access to more water? They can drink out of the toilet. [laughter] Now, there are many reasons why recycling sewage is attractive. Cities [laughter] No, I'm serious about this. This is very attractive to cities because cities own this water. Right now they're paying to get rid of it. Here's some water that they actually own and they say, well, if we own the water, if we can just clean this enough so we can use it, we've solved our problems and we don't have to grab water from other people.

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Now you might be familiar with non-potable reuse. You maybe drive along the highway and it says, being watered with non-potable reuse, danger, toilet water, don't drink or something like that. This idea of using this water for other applications, that is taking this wastewater effluent and using it for golf courses or using it for highway irrigation, it's very common. But it's not economically very attractive. That is, there's a real economic traction associated with taking this sewage and treating it to the point that you can put it back into the water supply because then you don't have to build a second distribution system to distribute this water around the city. And this is the force that's driving cities into potable water reuse.

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Now to understand potable water reuse, to help you get over your aversion to sewage because you seem to have one [[laughter] I want to go back in history and I want to go back to the time of the Romans. This right here, A, this is the cloaca maxima and the cloaca maxima was the sewer that the Romans put in that went through the middle of downtown Rome and took their sewage out to the Tiber River. And the Romans were so happy about the cloaca maxima, they made a goddess. And the goddess was named Cloacina and they'd say prayers to her, 'Clacina, goddess of the tide, whose sable streams beneath the city glide.' [laughter] It was a very good thing. Because they were getting this nasty water out of the city and into the river and it wasn't their problem anymore. And throughout history, the idea of building sewers was essentially to get wastewater out of your city and make it someone else's problem and whose problem it was you didn't care about.

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Here's Mexico City. Very much what they do there. So what I've done here is I've drawn for you the water movement through Mexico City. So the arrows are scaled to be about the approximate side of the different sources of water. So you've got most of the water coming into Mexico City is coming from extraction of ground water from the Mexico City aquifer, and when they're done, and then some of that water is being recharged back after they're done. And you can see that this arrow here is fatter than this arrow here, which means that they're taking more water out of the Mexico City aquifer than they're recharging into it, and that's causing a problem of subsidence. So if you've ever gone to Mexico City and you've gone to the Cathedral in downtown, you'll see it's leaning over on one side and you have to walk down about ten steps to get down into it because it's sinking as the water gets taken out of the Mexico City aquifer and the city starts sinking.

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So Mexico City doesn't have a very sustainable situation. They have some water coming in imported from a nearby valley. Some of this water is recycled, but the vast majority of it goes out as sewage. And this water that goes out as sewage is the Mexico City's contribution to the next valley downstream.

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Here's some photographs of what it looks like as you drive out of Mexico City. The one on the top left-hand corner you can see the amin sewage discharge coming into the river. And then you can see kind of this river of sewage working its way down with the foam on the surface, going all the way down until it gets to this reservoir on the bottom left hand corner, or what formally used to be a reservoir.

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So this is raw sewage from all the people in Mexico City working its way downstream and going to a place called the Mezquital Valley. So this figure here shows you in a little bit more detail Mexico City. The sewage goes into a thing called the Grand Canal and then the Western Interceptor. These are those big canals I showed you pictures of. And they go out to a couple of dams here and eventually they come out to a valley where it's used for irrigation. So they flood irrigate corn with sewage. So this is the raw sewage here and they just empty out a board and they let it flood irrigate.

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So the people of the Mezquital Valley have found a very creative solution for this wastewater that's sent to them from Mexico City because without it they wouldn't have any water for irrigation. So it seems like a happy solution to a problem. Except it's not. It's a huge public health problem. So children in the Mezquital Valley tend to have a very high incidence of a disease called Ascaris, which is a parasitic worm that they get from being exposed to the sewage. So it's not a perfect system but you can see how the sewage goes out of the city, is untreated, and is reused happily by people downstream because they really need the water, and then causes a public health problem.

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Now this is a problem, a kind of problem that we used to face here in the United States. This is a figure of a sewage farm near Salt Lake City in about 1900. And it was very common in the United States when we first started building sewers to build sewage farms at the outlet of the pipe. So what they're doing here in this figure is the same thing that they're doing now in Mexico City except they're wearing hats. [laughter] And what they're doing is, they're taking the sewage and they're using it to irrigate these fields. And it wasn't just in Salt Lake City. California had a number of places where sewage farms produce prize produce, so you can go on the internet and read about the Pasadena orang-, the oranges that were grown in Pasadena at the famous sewage farm before they had Cal Tech. [laughter] There's no relationship there. [laughter]

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And so this practice, though, of sewage farming was abandoned in the period between 1900 and 1920 because people realized that it was causing a public health problem. So as people learned more and more about disease transmission, public health officers started saying, you know, this probably isn't a good idea. We should do something about it.

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And here's what we did. So you can see in this figure, I'm plotting the population of the United States at different periods and years and here's the total population of the U.S., growing from about 60 million at the turn of the century to about 280 million today. And here's the urban population of the U.S. in blue so you can see that we've become an urbanized country. Most people live in the city now. But what's more interesting to me is that starting in about 1880, almost everyone in the urban area had sewers and almost everyone living in the urban environment has always been served by sewers.

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Around 1900, when people became aware of disease coming from sewage, we started putting in drinking water treatment plants, namely chlorination and water filtration. And by about 1940 everyone in the urban areas had drinking water treatment. And it was only after that that we started putting in sewage treatment plants. So sewage treatment plants, really only about half the country were served by sewage treatment plants at the time of the Second World War. And in the post-war period up through the Clean Water Act, we built sewage treatment plants and now we treat essentially all of the sewage, all of the water that goes in the sewers.

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So in the United States, we no longer have any raw sewage to build sewage farms around. We have treated sewage. We have wastewater effluent. I might call it effluent today. And really to understand the idea of reusing wastewater, we first have to understand the sewage treatment process. So let’s take a very quick look at a sewage treatment plant. And by the way, thanks to the people, the AV people in the back, they threatened to put a picture of a sewage treatment plant behind me for my entire talk and I [laughter] I complained. I thought Nancy got like bayou behind her. And Charlie got like mountains and I . . . well. [laughter] So thank you. Thank you. So this is what we teach our, one of the things that we teach out students when they start learning about environmental engineering is that sewage treatment plants use physical, chemical and biological treatment to remove particles, and the particles are where the pathogens tend to reside, and dissolved chemicals and nutrients and organic matter. And this figure just shows you the reductions in concentrations of things like suspended solids, oxygen demand. Remember Nancy just told you about dissolved oxygen disappearing? This is a way of measuring that organic matter that exerts an oxygen demand in the bottom waters, ammonia and organic carbon. And you can see sewage treatment plants do a great job at removing these things. And so whether you have secondary treatment, which I’m calling biological treatment here, where you put in extra nitrogen and phosphorus removal or you build a super duper treatment plant with biological treatment, nitrogen and phosphorus removal and filtration, you can get rid of 80, 90, 95 percent of the things that were obvious in the sewage.

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And as a result you end up with an effluent from the sewage treatment plant that looks pretty good. It doesn’t look that brown sewage that came in. It looks like almost clear water. So it’s very hard to tell from tap water. Maybe if you’ve ever been to Philadelphia, there’s a, oh, no, I'm going to get e-mails now. [[laughter] Never mind. It looks like surface water that you take out of a river. And that result of that water looking so clean has caused a sense of complacency and when we look at a lot of our surface waters, because we live with effluent-dominated waters and we often don't know it. So many places that you go around the world, you’ll find a surface water that's fed completely with wastewater effluent and you'd be none the wiser.

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Here's an example. Here's a watershed near Cambridge. So here's Cambridge in England. And this figure is showing you the watershed, so you can see the little tiny rivers here. And the black dots show you the locations of all the sewage treatment plants. And the colored reaches of the river show you what fraction of the total flow of the river consists of wastewater effluent. So you see these red reaches of the river here, this section of the river, the river is between 50 and 100 percent wastewater effluent. And this section of the river is between 25 and 50 percent. And if you go to this river, which is a sizeable river in the U.K. and you walk along the banks, you wouldn't know it was sewage effluent in that river. It would just seem like an urban stream to you.

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Closer to home, the Trinity River's a great case study of this. This is the Trinity River here. It goes from Dallas down near Houston and discharges here in the Gulf and the water flows for a period of about 2 weeks from Dallas down through the Gulf and it's essentially 90 percent wastewater effluent during normal flow conditions. So when there's storms, maybe it's less effluent. But most of the time that river, and the fish living in that river, and everything going on in that river is happening in wastewater effluent.

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Well, is there a reason to worry about that? That's a situation that's been going on for a long time in the U.K. and in the Trinity River and many other places. And really, I don't know if we would've been able to answer that question 20 years ago, but it was about that time that we started getting some hints that there were problems in these effluent-dominated rivers.

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So this is some research that was done by John Sumpter in the U.K. looking at feminized fish in rivers, those effluent-dominant rivers like the one I showed you before. And so this is a complicated figure. Let me explain it to you. So what is here shown on this axis in a logarithmic scale is the concentration of the vitellogenin. This is a blood protein that you normally find in female fish that are about to lay eggs. But this is being measured in male fish that really aren’t going to be laying any eggs anytime soon. And the concentrations here compare the white bars and the black bars. The white bars is before the fish are exposed. And the black bars are after the fish are caged in the river and exposed to river water for a couple of weeks.

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And what you can see here, for example, here’s a clear example. E is where a sewage treatment plant discharges into the river, and you can see above E, you see no difference before and after you expose the fish, but below E you can see about a hundred thousand times increase in the level of the vitellogenin in these male fish. And if you take these fish back to the laboratory and you look at their gonads under a microscope, you’ll see testes here, testicular tissue, and you’ll see ovarian tissues here. So this fish is what we call an intersex fish, it’s both male and female at the same time, even though it was born male. And I got very interested in this research when it first started coming out because it was really intriguing and I said, well, what could be responsible for feminizing these fish? And I went back and read the literature and read all the studies that they were doing, trying to figure out what could be responsible.

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And I noticed whenever they did an exposure to a man-made chemical, they would always run a control where they would expose the fish to one of the estrogens, like 17 beta-estradiol, the human estrogen. They’d use that as a control. And I did some back-of-the envelope calculations quickly and came up with this idea that maybe it was the small amounts of steroid hormones left in sewage after the sewage treatment process that could be responsible. And it was kind of a very surprising result to me because the levels I predicted were so low. And I was expecting to see nanogram per liter levels of these steroid hormones in the wastewater. And nanogram per liter, part per trillion, is incredibly low. Like when Nancy was giving you her talk, she was talking about nutrients in milligrams per liter. When you think about, I don't know, chlorine disinfection byproducts in drinking water, you usually talk in terms of micrograms per liter. Here was something that at nanograms per liter was capable of feminizing a fish. And it was a really hard thing to do but we set out to measure these compounds in the wastewater effluent and that's what we did.

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These are some of our first data measuring concentrations of steroid hormones in wastewater effluent. And what you can see is that a typical activated sludge treatment plant, which for our purposes is your garden-variety sewage treatment plant, was producing, I don't know, about 3 or 4 nanograms per liter of these steroid hormones, and it only takes about 1 nanogram per liter to feminize a fish in the laboratory. So the cause of the feminization of the fish that Sumpter's group was observing in the U.K. were these steroid hormones coming out of the sewage treatment plants.

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For many years after that, whenever you'd talk to someone about this, they'd say, well, why are there still fish living in the river? If they're being feminized, why are they able to reproduce? Why do I still catch fish when I go fishing? And it wasn't until about 2 years ago that a study was done that convincingly showed people that feminization of fish from steroid hormones could have important impacts at the population level. So you notice I managed to stick Minnesota into the talk somehow, but unfortunately the research happened here in Ontario. [laughter] So I tried, I really tried.

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But this is a study that was done by Karen Kidd and her group at the Experimental Lakes area in Ontario where they actually took a lake and for a period of about 3 years, they added about 5 nanograms per liter of ethinyl estradiol, the birth control pill active ingredient, to the lake. And what they plot here is the population of fathead minnows. So the number of fathead minnows in either the young age class or the older age class, and here's when they, here's 2 years before they started the experiment. Here's when they started adding the estradiol, and when they got done with adding the estradiol, no more fathead minnows.

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And so there were still other species of fish in the lake but the fathead minnows were sensitive to this chemical and they couldn't compete with the other fish when the stress of the ethinyl estradiol was there. So there really was something that could occur at the population level.

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Now I got asked here and, you know, there was a lot of interest in hearing about pharmaceuticals and personal care products and drugs and all these things that sound really interesting. Like, wow, I can't believe that all this stuff is in my drinking water. And before we talk about that, I just want to think in terms of concentration a little, I want to think about also when things have effects and what's interesting to us because it's novel and what's interesting to us because it's actually a human health risk or an ecological risk.

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So I plotted here again on a logarithmic scale, concentrations in wastewater effluent of some contaminants. Sodium chloride, side, nitrate, chloroform. You get this when you disinfect drinking water with chlorine. And estradiol down here. And you can see that there's about 10 orders of magnitude here differences in concentration but that doesn't say anything about the toxicity. For example, nitrate's a good example. Nitrate is probably the number one drinking water contaminant in California. We have agriculture that's contaminating drinking water wells with nitrate. The levels of nitrate in wastewater effluent are about the drinking water maximum contaminant level. So drinking wastewater effluent, if you ask me, should I drink wastewater effluent, I can tell you, no, there's a health risk from drinking the nitrate in there.

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So there are lots of things in there that we know about. Or chloroform. We know that this chemical is related to health risks and this is present in wastewater. So it's not just whether something occurs that determines whether it's interesting to us. It's really whether it occurs at concentrations that cause health effects.

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So I thought I at least had to show some of these things. So let me show you three examples of some of the other chemicals that you can find in wastewater effluent. So in wastewater effluent, you can find things like artificial sweeteners, antimicrobials, or antibiotics, betablockers, these drugs that slow down your heart for heart therapy. And these are the structures, just so that the organic chemistry class can put them on the exam, I thought I had to put them up here. [laughter] And what you can see here the structures look like the pesticides maybe that we're interesting, that we're used to studying. And the other thing about them is they occur in this concentration range below 10 to the minus 6 grams per liter, or sub microgram per liter. So they occur in the tens of nanogram per liter concentration range.

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I think of these things for tracers for wastewater. They tell me that there's wastewater effluent in the river. They don't necessarily tell me whether there's going to be a health effect. Some of these compounds have been tied to ecological effects. So I'm definitely c-, I'm concerned about them and their potential to affect aquatic ecosystems. But I already know that wastewater has something in it that can cause ecological effects. So the fact that metoprolol can also call reproductive problems in fish or Triclosan can cause problems with algae doesn't really change the story much. I already know that there's a threat of putting wastewater effluent into a river when I'm worried about the aquatic ecosystem.

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But what about the people? I'm really here to talk to you today about indirect potable water reuse and water recycling and I'm interesting in human health concerns. So for most chemicals, the wastewater effluent concentrations are negligible in comparison to what we're exposed to in foods and beverages and household products. So it's a little bit silly to think about exposure to a surfactant from shampoo in our drinking water when we're putting grams of it on our head, those of us who have hair, and we're worried about nanograms of it going into our mouth in the drinking water. Because probably when you shampoo with it, you're probably getting a little bit in your mouth as you're doing it.

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So really the question to ask when we think about this practice of potable water reuse is are there chemicals in the wastewater effluent that due pose serious health concerns? This is an example in wastewater effluent that we've worried about for a number of years because of the possible health concerns. The chemical is called NDMA. It's not Ecstasy. That's MDMA. [laughter] This is Nitrosodimethylamine. Here's the nitroso bond. Here's the dimethyl group here. And this compound we can find in wastewater effluent at concentrations upwards of 500 nanograms per liter. And if we look at the potential human health threats associated with drinking this stuff in our tap water, if we want to set a level that's protected at the one a million lifetime cancer risk level, we would be down at 0.7 nanograms per liter. If we want to choose a level that's a compromise based upon other sources of exposure and the ability to measure it and the ability to satisfy the governor, we set 10 nanograms per liter.

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And so in California, there's a notification level for NDMA of 10 nanograms per liter because that's what we believe is unsafe to be in a water supply. And you can see that wastewater effluent often contains concentrations that are almost two orders of magnitude higher.

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Where is this stuff coming from? Well, we're able to see it in the raw sewage, these black bars here. So it means that it's in the sewage before any treatment occurs. It's also formed when we disinfect the sewage. So this is an interesting case where people, or we chlorinate wastewater effluent to kill any pathogenic microorganisms that might be present, and in the process of chlorinating the wastewater, we actually make NDMA. So the blue line here shows you the concentrations of NDMA in nanograms per liter before chlorine disinfection at a wastewater treatment plant. And the red line shows you what was present after chlorine was added. So this is the last step in sewage treatment, we normally add some chlorine to kill any pathogenic microbes that survived the treatment process, and in the process we're making more NDMA.

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So that’s an example of a chemical in wastewater that I would worry about a lot more than I would worry about an artificial sweetener because this is a potable, sorry, a potent human carcinogen that you don't really want people to be drinking.

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Is there anything else that we should worry about in wastewater effluent? Well, you know, there, I guess I left my crystal ball at home, but if I were going to speculate about what could cause problems, I’d think about some of the other disinfection byproducts. So a lot of research has occurred recently to show that when we chlorinate or chloraminate water, we make a whole suite of products and sometimes those products are toxic. I’d also worry about industrial chemicals that get dumped down the sewer. So we’ve had some experiences in California where we’ve seen things like 1,4-Dioxane, which is a solvent, showing up in the wastewater at high concentrations as a result of an industrial application. So there are ways to control that but I think we need to start thinking about the sewer the same way that someone who has a house with a septic system thinks about it. So you really want to think about what goes into that septic tank the same way you want to think about what goes into your sewage treatment plant because you care about what happens to this water afterwards.

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So if there’s a take-home message for the fourth-grade class, it’s don’t dump 1,4-Dioxane down your tank. [laughter] Or any other toxic chemical. But there’s another issue that I’ve started getting interested in recently related to this question of chemicals in water that could affect human health. And it’s not really health as much as aesthetics and perception. So if we have water and it doesn’t smell good or it doesn’t taste good, we don't want to drink it. And a lot of the projects that are moving forward now, considering this possibility of recycling sewage or reusing sewage don't consider the aesthetics of the water that we’re going to produce.

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So it’s probably no surprise if I tell you that sewage smells funny and it doesn’t taste good. [laughter] But when you take a student and ask your student to tell you why it doesn’t smell good and why it doesn’t taste good, you have to send her in the lab. So this is a picture of Ava Agoose [sounds like], one of my students, working with a GC olfactometer. Where the detector for the instrument is her nose and she records on a little speaker and a little like Gameboy controller what's coming through at different times and then we try to figure out what molecules are responsible for that smell. And then we take that try to figure out ways to treat it, to remove that smell. Because to go through all this effort to purify wastewater effluent to reuse as a potable application and then have people refuse to drink it because it tastes funny seems like a bad idea to us.

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OK. So I told you, people drink sewage. But they don't drink sewage, they drink wastewater effluent, and they don't drink wastewater effluent, what they drink is highly-treated wastewater effluent. And so this is the same sort of process that the astronauts use on the space station, you take wastewater effluent and you put it through reverse osmosis membranes. And that reverse osmosis membrane has a cutoff that's smeller than molecular size. All it does is it lets water molecules through. So the salts and the pathogens and the colloids stay behind and the water that comes through that reverse osmosis process, just in case anything made it through, goes into an ultraviolet reactor. So this is an ultraviolent reactor with hydrogen peroxide as another barrier, and then this gets put into a drinking water supply. So this is the process of multiple barriers for advanced wastewater treatment. And it's the approach that people are using to purify sewage and put back into the water supply. And it's being done around the world now and it'll continue to be done to a greater degree in the future.

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Here's an example of the best-known project United States. It's the groundwater replenishment system in Orange County near Los Angeles. And the Groundwater Replenishment Project, which opened about 2 years ago, takes wastewater effluent down here, it's no longer proposed, they actually built the plant. They treat it with this reverse osmosis, UB Peroside process. They pipe it up the watershed and they put it into some sand pits that used to be used for, you know, dug out for construction. And then it infiltrates in the aquifer and the people down here in the Magic Kingdom, when they turn on their tap and they get the groundwater out, they're drinking that highly-purified wastewater effluent. It's about 10 percent of the water supply of Orange County if I recall correctly.

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This is another important project. This is the Newater Project in Singapore. It's the Singapore Public Utility Board built a similar treatment plant in Singapore a few years ago where they use this reverse osmosis treatment process, so this is a picture of the reverse osmosis membranes. Right now it's supplying about 2 percent of Singapore's water supply and not a lot of it is going directly to the reservoir. And the reason it's not going to the reservoir is that the semiconductor manufacturers are so happy to have this water because it's so pure that they can use it in the processes a lot easier than they can use local tap water. And the situation in Singapore is very interesting because it's illustrative of how water we use is tied to water security and some of these issues about urban water supply come to play when we think about globalization and the potential for conflict, like we heard this morning in Dr. Pachauri's talk. So Singapore, if you're never been there, is an island nation state. So this is it for the whole country. And it's all just one big city on an island. And their water historically has come from Malaysia as a fresh water supply. And so Singapore, worrying about the possibility that that Malaysian water supply might not be there forever, has tried to diversify their water portfolio with something that they call the four taps. And the four taps are the imported water coming from Malaysia, the Newater, which I just told you about, desalination, so they have a small desalination plant, and rainwater capture and collection and putting the rainwater into the reservoirs. And you think, well, that's nothing novel about that. But imagine a city with the density of downtown Minneapolis capturing every drop of water that fell in the gutters and on the buildings on the streets and putting it into the reservoir.

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So they have a number of challenges and I'll submit that the Newater process, the advance treatment process, is probably the easiest one from an engineering standpoint. Now this experience in Singapore and the experience in Orange County has convinced a lot of people in the water industry that water reuse is really the way to go. And a few years ago when Brisbane in Australia was suffering a history drought, so I can say this now, you think you've got drought problems. OK, here's Southeast Queensland in Brisbane and what I'm showing you here in this plot is the percentage full that their reservoir is.

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So in normal times, their reservoirs run about 50 percent full. But in a period starting in about 2005 to 2007, they had a very long, extended drought and they got to a point where they had only about 15 percent capacity in their reservoirs and they were using the water up at a few percent per month, so you could see where this is going. It’s going to zero. And when it gets to zero in Brisbane, that’s real bad news because there’s no other source of water. So you would've turned on the tap and nothing would've come out. And so Brisbane’s response to this water crisis was to build advanced treatment plants. And so this is the Western Corridor Project that was built in Brisbane very, very, very quickly because of the concerns that they were going to run out of water. And you can see here, the advanced treatment plant down here, the AWTP, here next to the wastewater treatment plant, was going to pipe water up here and release it into the Wivenhoe Rservoir. And it would’ve looked a lot like the Newater Project in Singapore or like the project in Orange County, except instead of putting it into the groundwater, they were putting it into the reservoir.

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But it never happened. And there are two reasons why it never happened. Well, one reason you can see here is that it started to rain and they didn't need it anymore. But we know with climate change that that’s only a short-term respite. But the other thing that happened is that the Australian, one of the national newspapers, started writing editorials critical of the project and telling the public that they ought to be squeamish about this, they ought to start worrying about the sewage going into their water supply. And so it became kind of a political hot potato and the project went on hold.

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And, you know, reading about this and learning about it and seeing it, I was a little puzzled because I thought about the Trinity River and I compared it to the Southeast Queensland Project. So as the speaker on a talk, you’re allowed to withhold key information from your audience. And I withheld a piece of key information from you. I withheld the fact that this is Lake Livingston, it’s the drinking water reservoir for the city of Houston. And so the city of Houston has been using water from the Trinity River. And that Trinity River water has flowed from Dallas and Forth Worth, from the sewage treatment plants, down to Lake Livingston with very little dilution from other sources and only conventional treatment, not this advanced treatment like they used in Australia.

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So in Australia, it was reverse osmosis and UB Peroxide before going in the reservoir. And at the Trinity River, it was conventional wastewater treatment and that's it, down to the reservoir. And so I started thinking about the two reasons I could come up with why people in Houston are comfortable with this. One is they probably don't know about it. This is a, a process that is [laughter] oh, the cat's out of the bag. Oh, no. One is that it's happened gradually over time. Dallas and Fort Worth used to be a lot smaller and so it's not, it hasn't always been an effluent dominated river. And there are plenty of people drinking out of rivers that are primarily wastewater effluent so whether it's the Schuylkill River in Philadelphia, the Chattahoochee River in Atlanta, they're not alone here. So out of sight out of mind.

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But the other reason is that I think people are very comfortable because there's this natural barrier here where the water travels 2 weeks to get to Lake Livingston and then it spends about half a year in Lake Livingston before it comes out in people's taps. And this ideal of the hydrologic cycle that I started out with is really in our minds, it's in our consciousness that nature purifies water and makes it safe again. And so really I think we have a perception, I think we're hard wired to believe that as water moves in the environment, it gets purified.

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But I'm not into belief-based science, I'm into science-based science, or hypothesis-based science. And so we've done some research in the Trinity River. And one of the things we've seen in our research in the Trinity River is that the river is actually quite good at removing these contaminants. And so this figure here shows you concentrations in nanograms per liter of three different pharmaceuticals. Maybe you're familiar with ibuprofen. And you can see that as the water flows from Dallas and Forth Worth up here, for about 2 weeks on its way to Lake Livingston down here, you get pretty good removal of these compounds, 80 or 90 percent removal.

And that removal is a natural process. It's not a function of dilution because we know by measuring other chemicals and other water quality parameters that there's no dilution going on during this sampling period.

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Well, when we were doing research on this, it wasn't just enough to figure out that the compounds were being removed, we wanted to know how they were being removed. And one of the tools that we used to discriminate between biological transformation reactions by microbes and photochemical reactions or abiotic reactions in the sediments, was to use the fact that some of these pharmaceuticals have chiral centers, or chiral carbon. So, again, for the chemistry exam, you can put this molecule on and ask where the chiral carbon is. This is a molecule where there are two forms based on its chirality, or its optical, its properties, I guess, in how it's put together. And what we see is that for chiral compounds, when they undergo biodegradation, we sometimes see the preferential degradation of one of the forms or another. Kind of the same way aspartame tastes sweet to your tongue but has no calories. It's slowly degraded in the body. And so in the case of metoprolol, we were looking at the two different enantiomers of metoprolol to discriminate between bio transformation and chemical reactions and to make a long story short, we saw that there was an enantiomer selective degradation. So we just measured the EF , the ratio of the two different enantiomers as this chemical went downstream.

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So you can see the metoprolol degraded or the concentrations decreased as the water flowed downstream. But more importantly to me, this ratio, this enantiomer fraction also changed, which indicated to me that for metoprolol, the compound was disappearing by biotransformation.

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We've also seen that photodegradation is an important process for removing these compounds in rivers. In the Trinity River, we found that for some compounds, in this case this is Diclofenac, a pain reliever, there was about 50 percent of the loss, that's this dotted line here, was from biotransformation reactions and about 50 percent was from photochemical reactions. And the reason that photochemical reactions were more important is that the Trinity River is relatively dark and turbid. And if you go to the river like the Santa Ana River in Southern California, which is shallow, it's only about a half a meter deep and very clear, the rates of photochemical reactions become a lot faster. And the reason they become a lot faster is that the light can penetrate deeply into the water and you get lots of opportunities for photochemical reactions.

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And so for us it's been very interesting, this idea that you can exploit these biotransformation reactions by microbes and these photochemical reactions that occur with sunlight. And we've thought, well, if only we could build a Trinity River next to every one of our sewage treatment plants we'd be OK. Except the Trinity River is about 200 kilometers long and that's a lot of space, right? You can't really do that. And so we had this idea that maybe we could be a Trinity River in a box.

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And that's this idea of ecological engineering is getting away from advanced wastewater treatment systems where we rely on reverse osmosis and energy-intensive processes like ultraviolet light to remove contaminants, to use nature to remove the compounds. And so we've thought about either exploiting biological reactions where we build communities of microbes that can degrade contaminants. And microbes that are different than the ones that do biological treatment in the sewage treatment plant. And photochemical reactions where we take advantage of sunlight to break down contaminants. And that's been really one of our focuses in our research the last few years.

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I'll just give you a quick example of how the biology in a wetland is different than the biology in a sewage treatment plant. This is an experiment where we looked at a variety of different trace organic chemicals that you might find in wastewater, and we put these in a liter of water at a very low concentration, about a microgram per liter, and at a microgram per liter, the bacteria that we add to the sample can't stay alive. There's not enough food for them to live. So we give them another source of carbon. And the other source of carbon we give them is either carbon from the effluent of a sewage treatment plant or carbon from a decaying wetland plant. And what we find is when we give these experiments the exact same amount of carbon, the bacteria that grow on the wetland plant carbon do a much better job degrading these contaminants than the bacteria that grow on the wastewater effluent. So we think that there’s something special about the plants growing in wetlands and the microbial community that facilitate the breakdown.

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So that was one way to study it in a laboratory but not being content to study this in the laboratory, we’re actually studying this in the field. So I co-opted a bunch of graduate students a few years ago to help build a treatment wetland. And so what we did is we went to a local sewage treatment plant and we popped a bunch of wetland plants into some submerged cells that had clay bottoms on them and we put these wooden berms here to make sure the flow went through these in a serpentine pattern so it spent a lot of time in there.

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And now we’re studying wetlands. So now I’m a wetland engineer. And what we’re doing is, this is what our wetlands look like now, see all the plants grew in nicely? But we left a couple of the wetlands here, like the wetland photocell here, open for photochemical reactions. So we’ve built a new kind of treatment process where we use wetland plants to, so the water flows through these different cells here and the bacteria that live on the wetland plants break down the chemicals and then when they’ve gone through there, they go into one of these photocells and the sunlight shines on them and helps break down the ones that didn't biodegrade.

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So that’s kind of a work in progress that we’ve been working on and we’re just getting preliminary data and it’s pretty encouraging about the ability of these wetlands to remove the contaminants. So kind of that’s more or less my talk and that’s where I was last week on Thursday. And I gave my talk to my graduate students and they said to me, ‘You know, we’re a little disappointed that you never came back and answered the question, are we ready to take the plunge, or are you ready to take the plunge? So are you ready to drink this stuff. And I said to them, hmm, I’ve given that actually a lot more thought that you might imagine, you know, because it’s something that comes up over and over and I said, like all answers, I’m going to have to back off and not give you a clear answer to it. And I, then I thought again, I said, no, the answer to that is yes. And the reason that the answer to that is yes it that I would rather drink that highly-treated wastewater effluent that's been through an advanced treatment process or perhaps through a treatment wetland or through the environment or through a groundwater system. I'd rather drink that than drink the atrazine-contaminated water that many people in the Midwest find themselves drinking. [applause] And I'd even rather drink that than a lot of the Colorado River water that people drink in Los Angeles because that's stuff's salty, it doesn't taste good to me. This stuff, I've had the Newater water that comes out of the Newater treatment plant and it's fine. It's probably as good as Dasani, better. [laughter] So I don't think there's a big problem here. It's really one of perception and understanding the hydrologic cycle and understanding what happens to your water.

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So some concluding thoughts. Water reuse is attractive. It's attractive to urban water supplies because it makes sense economically, logistically and in terms of water rights. I don't know if it's attractive to you. Advanced treatment, the kind of treatment that we use on the space station, the kind of treatment that we use in semiconductor manufacturing to remove things, that can remove contaminants. There's very little that makes it through those advanced treatment plants. In fact, we can't really measure what comes through those advanced treatment plants other than H_2O. But in terms of potable water reuse, public acceptance is really a critical issue. And that public acceptance seems to be predicated on having a natural barrier. So as a culture, we've become accustomed to having the hydrologic cycle protecting us and purifying our water.

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So these natural barriers are critical. I didn't talk about groundwater. Groundwater is a wonderful, natural barrier. It attenuates a lot of contaminants. I talked to you a little about treatment wetlands. I'd be happy to talk about groundwater storage and groundwater treatment long enough for you to miss the first four innings of the game. [laughter] I also didn't talk today about protection and restoration of aquatic ecosystems. I think wetlands also can play a role in purifying sewage effluent before we release it to the environment because I'm also very concerned about some of the effects on aquatic organisms that sewage effluent can cause. And then I also just wanted to remind you that this advanced treatment process that is very common now isn't good enough. It's not sustainable. It's energy consuming. It produces waste that we have to dispose of. And really this idea of natural treatment systems is the future. And with that, I'll just put up some acknowledgements of people who have helped in this research and also funding agencies and thank you for your attention. [applause]