

Lecture 10

How much water do people use?

So having come this far with supply, I want to turn to the demand side, and the first thing I want to do is divide water use into its main categories. There are three main uses to which fresh water is put—for domestic uses—drinking, washing, cooking, cleaning; for agriculture—most obviously, for crops but also for animal husbandry, and for industry.

Domestic use. Most obviously, people use water for personal use—drinking water, washing, cleaning, and cooking. Of these drinking water amounts to an average of 2 liters per person per day or about 730 liters a year, or 0.73 cubic meters, though this can go up to as much as 2 cubic meters in very hot countries. But this very obvious use of water is the least of it. Other uses are increasingly matters of choice and lifestyle—more or less can be and is used for cleaning, cooking and bathing. Total use for cooking and washing ranges from 2 to 15 cubic meters per year, and total household use ranges from less than 30 to about 75 cubic meters. As we'll see in a few minutes, the amount used changes with changes in water pricing.

Use in agriculture. The amount of water used in agriculture depends, first, on how much water is available from rainfall, and how it can be supplemented, and second, what sort of crops are grown. Crops require air, mineral nutrients which are usually but not always derived from soil, water and a growing or frost-free season, each crop of course having different requirements. The water requirement can be expressed as the ratio between the mass of water transpired by a plant in growing a given quantity of crop and the mass of the crop. In the case of wheat, the ratio is 500 to 1, corn, 350, cucumbers, 717, and so forth. Since the kernels of wheat have to be milled before they can be made into bread, Cohen calculates that one kilogram of bread requires two kilograms of wheat, so that the production of one kilogram of bread requires the consumption of 2×500 kilograms or one cubic meter of water. Since one kilogram of bread yields 3500 kilocalories, getting each person 1,000 kilocalories of bread per day, or about 40 percent of the total diet, would require a yearly consumption of $365/3500 \times 1,000$ or about 104 cu.m. for this purpose alone. In other words, you use about 140 times as much water growing bread per person as you do for drinking water per person, some indication of the relative importance of water for agriculture.

Since a complete diet is about 2500 kc per day, a diet of bread alone would require $104 \text{ cu.m} \times 104$ or 260 cubic meters of water a year. But of course man does not live by bread alone. Other foods have much higher requirements. For example, meat is produced by grain-eating animals, and the production of a kilogram of animal protein requires both enough water to sustain the livestock and also the water to grow its feed. Needless to say, it takes more than one kilogram of feed to produce a kilogram of meat; Cohen estimates that it takes 10 times as much water to produce a kilo of meat as it does to produce a kilo of grain, a ratio which I feel is high for reasons we'll get into but which we can accept for the sake of argument. Vegans take the position that, because eating meat uses more water than using feed, meat-eating constitutes an unsustainable use of resources, which is true to the extent that water is in short supply, as we'll go into later today. Both meat and vegetables have higher water requirements—sometimes much higher—per amount of kilocalories than bread, and as the proportion of the diet that consists in meat or vegetables increases, the amount of water

required also increases. If these foods average five times the water requirement of the grain staple, then a diet consisting half of the staple would require 130 cu m to grow the staple and 650 m to grow the other foods, for a total of 780 cu.m. Once again, consider the relative importance of water for drinking and water for agriculture. If we accept the 780 cu.m. figure, we use 1000 times as much water to raise our food as we do for drinking.

Cohen offers two other estimates which neatly bracket the 780 cubic meter estimate, one of 560 cu.m per year and the other of 1,000. My own feeling is that these estimates are high. If the feed conversion ratio for chicken is 2:1, as we discussed last week, and it takes 100 cu.m of water to grow one kg of feed, and half the chicken is edible, it takes 400 cu. m. to grow enough feed for one kg of chicken meat plus the amount the chicken itself drinks, so I=d be inclined to go with the lower estimate.

Note, though, although quantities of water estimated at between 560 cu m and 1000 cu m per person per year are required to grow food, yet, because of international trade in food, those cubic meters are not necessarily found in the countries where the food is consumed. For example, Singapore produces no food at all, but instead produces secondary and tertiary productsBmanufactured goods and servicesBand exchanges them for food, in effect importing the water required to produce the food as well. (By the way, Singapore actually imports all its drinking water as well, from Malaysia).

Irrigated agriculture

There are three main demands for irrigated agriculture. First, where precipitation is highly seasonal and it is desired to extend the growing season, precipitation has to be supplemented by irrigation.

Second, irrigation can be used to make arid countries productive. Desert countries are in some ways ideal for agriculture, since they feature long growing seasons and lots of clear days, so that solar energy can be used in photosynthesis. The one thing they are missing is water. If irrigation water can be pumped in from elsewhere, these formerly almost completely unproductive countries can become incredibly productive; one perfect example is the Imperial Valley east of San Diego, which naturally receives 5 to 8 inches a year of rainwater but which produces all kinds of high-end vegetables. It is able to do so because it receives a huge amount water from the Colorado and uses it to irrigate crops.

Third, irrigation is used when it is important to regularize the supply of water. As we saw when we discussed the Green Revolution, high-yielding crop varieties require precise water control, or to put it another way require generous water supplies at precise points in their growing cycle. Obviously, hoping that rainfall will cooperate precisely with these requirements is asking a lot; it=s much safer to supply the water in a controlled way by human agency. So the spread of the Green Revolution meant increased demand for irrigation water.

Industrial use. After agriculture, there is the question of industrial use. In Europe, 34 percent of freshwater is used for agriculture and 54 percent for industry, with the balance for drinking, domestic use and recreation. In North American, industrial and agricultural uses are each a bit over 40 percent, while in Africa and Asia over 80 percent of water withdrawals are for

the purpose of agriculture. Industry uses water for cooling purposes as in thermoelectric power plants as well as in mining and manufacturing operations.

The single use that consumes the greatest amount of water is as the cooling agent in thermoelectric plants, that is, plants that burn oil, coal or natural gas to generate electricity. As we'll see next week, thermoelectric technology has been changing over the past 15 or so years in the direction of more power output per amount of fuel burned, and as it does so the amount of water needed per unit of electricity produced also decreases. On the other hand, as we'll also see, the demand for power is increasing, and faster than the bonus from more efficient power plants. Efficiency increases on the order of 15 percent are expected, but expected demand for power is expected to rise by a bit more than 50 percent, as we'll see on Thursday. Remember, though, that the population is growing more slowly than original estimates indicated, and if this is so these estimates of future growth may well be too high. Just as the FAO study of food production erred on the high side because slower than expected population growth meant less demand for food, so slower than expected population growth will mean less demand for water, in every way: less domestic consumption, less agriculture, less industrial use. Keep this point in mind for the balance of this discussion.

Beyond hydroelectric cooling, the uses of water in industry are indescribably various. The only general point I want to make is that use reflects cost. During the nineteenth century in California, one of the major techniques for gold mining was hydraulic mining, in which the hillsides would be sprayed by high-pressure hoses in order to dislodge and separate the ore-bearing rock; again, the water was free and was used just as freely; as water prices increase, these intense-use techniques tend to be replaced by other, lower-use technologies.

Water use trends

Demand in the world. At first glance, it looks as if the demand for freshwater may be reaching the outer limits. As I say, the main uses for water are domestic, industrial and irrigation for agriculture, and of course each use has been increasing. Of the three main uses of water, domestic use constituted under ten percent of the total in the US at least, while industrial and agricultural uses are each between 40 and 50 percent; in less industrialized countries, domestic use stays under 10 percent but agriculture takes the lion's share of the balance.

Domestic use involves both quantity and quality of life issues. As the population grows, the amount of water needed simply to keep it alive increases as well, and more or less in direct proportion to the sheer increase in numbers. Water use can also increase as standards of living increase, in such ways as more washing or cleaning.

As for irrigation, a growing population needs increasing amounts of food. The ways in which food production can be increased more or less all involve increased water use, whether arid land is put in production through irrigation, or in countries with seasonal rainfall when the growing season is extended through irrigation, or in areas using high-yielding varieties where irrigation is used to supply water at critical times in the plant's life cycle. There are also food quality issues as people upgrade from staples to staples plus proteins and vegetables. Vegetables are thirstier than grains, and cattle are much thirstier than either. Both phenomena increased food production to feed the much increased population of the twentieth

century, and increasing amounts of higher-end food such as meat and vegetables as wealth increases even faster than population, enabling people to trade up. Both were much in evidence in the twentieth century. Both contributed to increases in water use, more people mean more calories need to be raised to be consumed, and trading up from a staples-based diet to a protein and vegetable based diet involves using more water per calorie. Finally, economic development implies both vastly increased amounts of power use, as we'll see next week and vastly increasing industrialization in all its forms. Again, both imply more water use, both absolutely and per capita.

Given the fact that more people and higher standards of living each imply more water use, and we have both going on at once, you might think that the pressure on world freshwater supplies is increasing, and that a possible ceiling may come into play. We can increase agricultural production and yield, but it's not easy to see how we could increase precipitation, or runoff or infiltration for that matter. Precipitation feeds some crops directly, and a small percentage of rainwater is captured in rural districts for drinking water, but for most domestic use, all industrial use and all irrigated agriculture, you have to use one of the two forms of stored freshwater: runoff or underground infiltration.

Demand in the United States. But when we turn from the world to the United States, we may see a different dynamic at work. During most of the twentieth century, and peaking in the 1980s, demand for fresh water increased dramatically in the United States, both absolutely and per capita (3). In absolute terms, the total quantity of water withdrawn was 56 cu km in 1900 and 600 cu km in 1980, a more than tenfold increase. Meanwhile, population increased by less than four times, so that water use per person must have about tripled. Beginning in the 1980s, however, the trend reversed, with sharp drops in water use per capita and in total withdrawals as well. Of the three main categories of water use, the smallest, domestic use, showed an increase, but the two largest uses, agricultural and industrial, both decreased, sharply. In percentage terms, irrigation water withdrawals fell by ten percent, as did withdrawals for thermoelectric cooling, while other industrial uses fell by forty percent. Yet these decreases in water use did not coincide with shortfalls in production. Quite the contrary, both industry and agriculture became more productive than ever before in the 1980s and 1990s. What was basically happening was that more efficient agricultural techniques were coming on line in both agriculture and industry.

Water for agriculture. Consider the case of irrigation in agriculture. Water use on the farm varies, and can shift dramatically with shifts in water prices, as we'll discuss later. Irrigation water has to be brought from the water source to the crop, and there are different ways of doing this, some more or less expensive in water use and cost of construction. The simplest and cheapest way is to dig a ditch from the source to the farm, and run the water down a series of sub-ditches or sons of ditches between furrows. This has the disadvantage of losing a lot of the water to infiltration. The simplest cure for this, and the next step up in terms of expense from the unlined ditch, is to line the ditches with concrete. This costs more initially, but you save all down the line because your losses to infiltration disappear, so it's a tradeoff between the cost of concrete and labor and the cost of water. Even if you line the ditches and cut down on infiltration, though, there's still the problem of evaporation from them, which of course can be very severe in hot climates. The solution is pipes rather than ditches, which are

still more expensive and so is another, higher tradeoff of initial cost and cost of water.

At any rate, the water arrives at the farmgate. From there, it can be distributed by ditches of water running between the rows of crops, by sprinkler, or by drip irrigation, which brings the water in plastic tubing to the roots of the individual plant. Ditches are the cheapest to build but the least efficient way of delivering the water, sprinklers are more expensive to install but more efficient at delivery, and drip irrigation is the most expensive but most efficient method. In hot and dry Arizona, water efficiencies in excess of 90 percent are regularly achieved. In other words, if 100 cu.m are delivered to the farmgate, 90 cu.m or better arrive at the crops. As you can see from this Indian data set, the use of drip irrigation can dramatically raise yield while using less water. I guess if I had to sum up this chart I would say yields increased by 30 percent of average while water use dropped by 50 percent.

Now, whether to line the ditch with concrete or not, or to substitute pipes, or to use sprinklers or drip irrigation instead of ditches to bring water from the farmgate to the individual plant, is basically an economic tradeoff between the cost of construction, which occurs once at the beginning of the project, and the cost of the water, an expense which recurs every year. As you can see, as the price of water increases, the incentive to undertake the economic cost of lining the ditches or substituting pipes for ditches and save the cost of the water also increases. If the water is free, there's no motive to undertake any water saving measures at all. So the pricing of water and the efficiency of water use are intimately connected with each other. According to Cohen, introducing water pricing for domestic or for farm use has the effect of decreasing water use by a lot--25 or 30 percent. We'll get back to all these issues when we discuss the Aral Sea.

The point for the world supply of freshwater is that increasing population, food supply, area under irrigation and industrial output are not necessarily accompanied by increases in freshwater use. As time has gone on, the projections of water use in the future have become progressively more conservative, though never conservative enough. In other words, the further back in time you go, the more water was thought necessary to feed the increased populations of today. As you move toward the present, the estimates declined, but didn't decline fast or far enough to accurately predict what actually happened. Actual water use regularly came in lower than the downwardly-revised estimates. My guess is that this trend will continue as greater water efficiencies continue to be introduced and population increases more slowly than had been anticipated.

Water pricing. The key way to induce greater efficiency of water use is to make it cost-effective to do so. Free goods are always abused. If you don't pay for water, you can have the most thirsty crops, or house gardens for that matter, at no additional cost to you, but if you have to pay for the water you start to substitute other, less thirsty plants, and the higher the price the greater the degree of substitution. In the US, water is sold by the public sector, and prices reflect political forces rather than economic or technical factors. Farmers pay five cents a cubic meter for water, while domestic and industrial users pay five times as much. This does not encourage farmers to be as water-efficient as possible, except in very hot and dry regions, like the Southwest, where water use can get expensive even at these very low rates. According to Cohen, the amount of water use is quite sensitive to price, at least once you get past a certain

minimum, and certainly with respect to completely optional uses like carwashes and fountains in ornamental gardens.

Use and consumption. Water that is withdrawn by human beings from the hydrologic cycle undergoes one of two fates: consumption or discharge. For example, water withdrawn for agriculture is either consumed (through evaporation or transpiration) or not, and if not returns to the hydrologic cycle as runoff or infiltration. Similarly, water withdrawn to cool an electric power plant is usually returned to the system, less losses due to evaporation.

Note that use is not the same as consumption. Consumption means used up, can't be put to further use. Human drinking water can return to the system after being cycled through the human being and used as fertilizer, a widespread practice in China and Korea. Similarly, farm runoff (again, the part that isn't evaporated or evapotranspired) returns to the system as runoff, and so does water after being put to an industrial use.

The bottom line of demand. The bottom line is that we may be following a sigmoid curve on the demand side. The rate of population increase is slowing down, and will probably add another fifty or so percent to the earth's population before steady state is reached. Use per person is increasing, but there too the rate of increase will slow down as more efficient water use technologies are used, and more such techniques will be used if water is turned from a free good into a good with a price. Use per capita in the United States leveled off in the 1980s, and since more efficient water delivery systems were employed, the amount of water withdrawn from the system to meet that level of use declined quite steeply, more steeply than the US population increased. The combined effect of these three variables—continued but slowing population growth, moderating or even slightly shrinking demand per person and more efficient water delivery techniques resulting in smaller withdrawals to meet demand—was that water use in the US has been falling for the past 20 or so years even though the population has been rising.

We can't assume that this trend will immediately take hold worldwide. For one thing, as India, China and other Asian or Latin American countries industrialize, use per capita may increase, not remain flat as in the United States, as the need for industrial coolant increases. Nonetheless, as more efficient techniques diffuse worldwide, it is absurd to believe that these presently-industrializing countries will use the more wasteful techniques of yesteryear in preference to the more efficient techniques now being developed. So on a worldwide level we have increased populations but with the rate of increase decelerating, more industrialization, which tends to raise levels of water use, but more efficient agricultural and industrial techniques, which makes for declining rates of use.

How do these variables balance out? As we can see, per capita water withdrawals have been slowing to a stop, or even slightly declining, on a worldwide basis since the 1980s. If the population may be expected to increase by another fifty percent or so, we may estimate that demand will top out at somewhere around 140 percent of today's demand; so if we're now using about 3,900 cubic kilometers per year, use may flatten out at 5,500 cubic kilometers or so.

So where do we stand with fresh water supplies? So the question is whether we could

support that level of use. The answer to this question is not that easy to come by. It may be that, absent widespread desalinization, the supplies of freshwater will not increase much further. Absent the putative growth due to climate change, there won't be more rainfall. Use of groundwater is limited, either in quantity or in time. In other words, if you limit the use of groundwater to the recharge rate, you're limited in the amount you can use, and if you use water at a rate faster than the recharge rate, you deplete the supply and so are limited in time. Use of runoff depends on building dams, which depends on the availability of good-I mean politically acceptable sites for dams. Meanwhile, it would seem that the human demand for water is increasing in all three dimensions, domestically as population increases, agriculturally as those same people have to be fed, and industrially as the transition from an agricultural to an industrial economy proceeds. Population is increasing, industrialization is increasing and the demand for irrigation is increasing. So it's facially plausible that demand may outrun supply for this crucial resource.

But a closer look seems to negate such fears. I said we were using 3,900 cubic kilometers of water, and might have to be prepared to use 5,500 cubic kilometers. According to one projection, that of Gleick, we will be using about 4,500 cubic kilometers around 20 years from now, or 600 cubic kilometers more than today. Most of the 4,500 cubic kilometers—About two-thirds of it, to be more exact—will be used for agriculture. According to another estimate, however, agricultural use of water can be brought down by at least a quarter by using more efficient irrigation techniques, saving around 800 cubic kilometers, a savings rather larger than projected increases of 600 cubic kilometers due to population growth. If this is so, water usage may already be peaking, and may start falling in the next couple of decades. In this case, which, given the track record we've established over the past couple of decades, I do not consider at all unlikely, we will not have to increase water supplies at all.

Increasing the supply of water

But let's take the more pessimistic view that demand for water will continue to increase, pushing our use of existing sources closer to the limit. What then? I mentioned last week that desalinization is possible, and the issue with desalinization is not whether it's technically possible but whether it's economically feasible, whether the cost of the energy input is greater or less than the water output. If the cost of desalinization technology fell so as to make saline water available in a large scale way, of course water supply problems would be over, certainly in the foreseeable future and probably forever.

As I was saying earlier, the price of water in the US is generally 25 cents a cubic meter, although farmers get a very favorable price break. This gives us a benchmark for fresh water supply. If water could be provided by desalinization for that price, then the supply of fresh water would be virtually unlimited. As it is, it costs about 80 cents per cubic meter to desalinate water. I put an article into the reader on this, and this **Chart** is taken from that article. When I first glanced at the chart, I was quite excited, because it looks as if there are three areas, namely Singapore, around Ashkelon in Israel and in Tampa Bay, Florida, where water is being desalinated at around 45 to 55 cents per cubic meter, which I was hoping implied a technical breakthrough that would be bringing the price of desalinated water to something close to existing fresh-water prices. If that were happening, the potential supply of water would be metaphorically speaking infinite. As it turns out, these places are flukes, with special

circumstances, not technical breakthroughs, accounting for the low prices. In the Israeli case, Ashkelon is quite close to the Gaza Strip, and the result is that land costs are next to nothing – the price of land there has hit the floor. In the Tampa Bay case, the city extended credit to the plant operators at concessional rates, and the low price of water reflects the low price of credit, not technical breakthroughs.

Desalinating countries

So far at least, then, the price of desalinated water is at least three times that of fresh water, except in countries that are both arid and energy-rich, like the oil-rich states around the Persian Gulf. Western Australia, where there is a lot of coal, is in something of the same position.

In general, water desalinization takes place in two kinds of countries – arid and energy-rich countries, as just mentioned, water-short and rich small countries, like Singapore and Israel, and arid coastal regions of large countries, like southern California. Arid and poor countries don't desalinate because it costs too much. I'll get back to this when we discuss climate change.

Desalination on a world scale

Desalination capacity on a world scale is increasing in a reasonably healthy way, but so far it's not a major factor in world water supply. Forty million cubic meters a day, the world's existing capacity, is about 13 billion cubic meters a year, or enough to supply the needs of about 13,000,000 people, or 0.2 percent of total world population – one-five hundredth of the total. Those 13 billion cubic meters cost, on average, about 6.5 billion dollars more than the comparable amount of fresh water.

So let's imagine that we needed 100 times as much desalinated water as at present – enough for 1.3 billion people, in other words. Putting aside economies of scale and further technical developments on the one hand, and the fact that diverting that much energy to desalination would put an upward pressure on energy prices and so on the price of desalination itself, that would cost 100 times 6.5 billion dollars or 650 billion dollars. The total size of the world economy is now 50 trillion dollars. Having to divert that many resources to desalination would mean a diversion of 1.3 percent of gross world product – by no means an impossible amount. The price of food would also increase with more expensive water, but food prices are at their lowest point in history and going lower. None of this sounds impossible at all. It is true that energy resources would have to be diverted, but we'll discuss energy problems that this week.

In practical terms, desalinization remains a deep reserve, something we can do if we have to, but something we don't yet have to use on a large scale. If fresh water starts running short, its price will rise, say from 25 to 40 or 50 cents or so. As supplies tighten, less thirsty crops and varieties would be used, there would be faster utilization of more efficient irrigation techniques like drip and sprinkler irrigation, and supplies would be stretched out. Finally, if there are technical improvements in desalination techniques, the point may be reached when the price of energy meets the price of water, so that it would be economically feasible to rely on desalinated water on a large scale. If and that is a big if that happens, the supply of fresh

water would in effect no longer be limited.

To reach the end of this topic for now, the bottom line is that we will not run out of fresh water on a world scale. It may become scarcer; the price may go up and cause the price of food to go up. At the very worst, we'll be using all available fresh water before steady state population is reached, and the last ten or so percent of fresh water will have to be supplied by desalinization. If so, we would have to throw energy in to get water out, which would increase the burden on energy supplies; but as for actually running out of water on a worldwide scale, I can hardly conceive of that happening.

P x A x T and R/U analyses

To help sum up on water supplies, let's think about them in terms of our P x A x T and R/U analyses. In P x A x T terms, Population is increasing, and Affluence, or standard of living is increasing as well; as people have more disposable income, they tend to trade up in food quality, eating more meat and vegetables and relatively less of the grain staple. As we've seen, meats and vegetables require more water than grain per mass of food, so as people trade up they need more water devoted to agriculture. Moreover, as people develop economically they need more water for industrial purposes, and particularly for coolant in power generating stations. So both the P and A factors make for more water use. Yet, as we've seen, per capita water use is declining in the United States and flat in the world as a whole, despite the upward pressures of more people living better. The only explanation is that the T factor is bringing water use down, both the use of tailwater (better recycling) and the substitution of more efficient modes of use, chiefly sprinkler and especially drip irrigation for ditch irrigation, producing more yield for less water use (analogous to more messages for less copper as we move from landlines to fiberoptics), as fast as P and A are bringing it up. Moreover, as population pressures ease, we can expect the P pressure to slow down, while the T factor continues to help the situation.

Now think about it in R/U terms. So far, we've been discussing the U side of the equation: more people wanting better food tend to use more water, but more efficient water use and better recycling tend to slow use down. What about the R side? There are limits about how much more of the resource can be found. Possibly we can find deep-down aquifers, but the deeper they are the more it costs to pump the water out. The most prominent potential R factor is desalination, which as we've seen is there if we need it.

As far as I can see, the basics of the situation are as follows: I would expect that a combination of three factors will not make it necessary to desalinate water or move onto the R side at all, at least on a world scale. Those three factors are the slowing of population growth, the increase in yield and the more efficient use of irrigation water through drip instead of ditch and tailwater use. If, against expectation, water availability is not adequate despite these three factors, we can then turn to the R side and desalinate to the extent necessary. This would be an economic burden but not an impossible one to bear.

Distributional issues

Things are different, though, when we turn from the world scale to regional scales: while there may not be a worldwide water shortage, some regions and localities are not nearly

as generously supplied as others.

As you can see, Brazil alone has about enough water to meet all the world's needs, if all of it could be utilized, while Australia, about the same size as Brazil, has about one-fifteenth as much. Distribution is also uneven within countries. China is about the same size as the US and has a bit less water, but it also has four times the population. Again, the US, a bit larger than Brazil, has about 45 percent as much water, with no shortage expected in the more populated East. However, lack of fresh water is apparently placing a ceiling on population growth in the southwest. Russia is also fairly generously supplied with water, but more than half its water is found in Siberia, where only three percent of its population lives; water in the European part of the country is not found in such generous supply.

If per capita availability is starting to be in short supply at around 1000 cubic meters a year, we may expect the most hard-pressed countries to be those in arid climates with dense populations, and if the dense populations are quickly growing, serious problems could be developing. The countries with dense populations in arid climates are mostly those in the Middle East and Africa. Among these countries, those with lots of cheap energy, like Saudi Arabia, Libya, Kuwait and Qatar, and those with developed economies that can afford the energy costs involved, like Israel, are already using desalinization to increase their naturally meager supplies, or are importing water from neighboring countries, like Singapore. The problems with water are likely to be found where populations continue to rise rapidly, because lack of modernization is preventing the demographic transition from being brought to a conclusion, and where nature has not generously provided water, countries like Kenya, Rwanda and Somalia. The picture many of us have of Africa is wet and jungly. This is true only of a small area, between the Congo river basin and the west African coast. Much of the rest of the continent is a high and rather dry plateau, something like what New Mexico would be like if it were moved twenty degrees closer to the Equator. It is here, in east and central Africa, that severe water supply problems will most probably develop, if they develop anywhere. Another likely candidate is Central Asia, for reasons I'll go into after the break.

To finish this section off, let's draw a profile of a country in which severe water shortages are likely to occur. They will be **arid countries with rapidly growing populations, high fertility rates, slow transition, poor infrastructure, and lack of effective governments – the governments will either be weak and unable to deliver services or corrupt.**

Case studies in water management and mismanagement

1. The Aral Sea

This is a lecture about anthropogenic changes to the environment. If you recall the Ehrlich-Simon business at the beginning of the course, it really went beyond a debate on whether the price of copper is going up or down. The question is whether the development of the industrial economy and the economic development of Asia, Africa and Latin America pull in one direction and the environment pulls in the opposite direction, whether the more industrialism and economic development you have the worse the environment, or whether economic development and environmental preservation can coexist. Now, when we began with the demographic transition, you'll recall that, given the fall in the death rates that

triggered the population boom, it became absolutely necessary to go on with urbanization and industrialization and all the things that tend to bring the birth rate down; failure to do that would have meant bigger population increases and bigger problems. So that makes it look as if economic development is needed. But there's plenty of anecdotal evidence that solving the population problem through development is causing other and maybe bigger problems, from global warming to water pollution. So I want to look at a case study in this case related to water use and water pollution, both because it's one of the biggest environmental disasters on the planet possibly the biggest and because it may shed some light on this bigger question of the economy versus the environment.

It's about the Aral Sea, located in Uzbekistan and Kazakhstan, two of the successor states to the Soviet Union. The Aral Sea was once the fifth-largest inland body of water in the world, covering an area about the size of all of Northern California and now it's in the process of completely disappearing. As it does so, the health and welfare effects on the people living nearby and there are millions of them are severe. What is happening to the Aral Sea and why?

In geographic terms, the Aral Sea is the result of something called the water budget of its drainage area. Let us say the area within this range of mountains all drains toward this central lake (top view). Over this defined area, there is a certain amount of rainfall in the course of the year; call it P for precipitation. As we remember, $P = E + T + R + I$: Some of this rain evaporates back to the atmosphere, some is used by plants, and some enters the ground as groundwater, some runs off into streams and rivers and finally the central lake. So over the course of the year a certain amount flows into the lake, and a certain part of that evaporates. So the size of the lake at any one time is a function of how much is flowing in and how much is evaporating. The amount of evaporation is a function of two basic variables, the temperature and the surface area not the volume. If you have two lakes containing the same volume of water, one broad and shallow and the other deep and narrow, there will be much more evaporation from the broad, shallow one, as you can imagine. Because the Aral Sea is very broad and shallow, the rate of evaporation relative to the volume of water in it is fairly high, and relatively minor changes in the amount of inflow will cause large swings in its surface area.

Now, as we discussed, the climate is subject to change, and so the size of the Aral Sea is also subject to change, probably in the big cycles of the Ice Ages and in the smaller, thousand-year cycles. But the current shrinking and near-disappearance of the Aral Sea is not part of the usual climate cycle. It's caused by human beings, and, again as in the case of climate change, what is unprecedented about anthropogenic effects is not the fact that the lake is changing in size, which has been happening since forever, but the rate of change that's occurring now: in this case, the lake has lost well over half its surface area in the past thirty years and will probably disappear entirely in the next thirty. The much smaller water volume of the current lake goes hand in hand with greatly increased salinity, so the lake is already dead, with almost 200 species of aquatic animals and many more plant species going extinct.

What has changed the water budget so drastically that the entire lake will disappear is the use of the river water that formerly replenished the Aral Sea for irrigating crops, specifically cotton. Now, the choice of cotton as the main crop for a region like this is an idiotic thing to do,

geographically speaking. To see why this is so, you need to know something about the geography of the region that drains into the Aral Sea and about the agronomy of cotton. The Aral sea basin is sort of egg-shaped, with the sea as a very small yolk all the way over to the western side of this oval-shaped area. So the Aral Sea is way over on the west side of the basin. The east side is framed by very high mountain ranges. Most of the basin is quite arid, due to its inland location, gets under eight inches of rain a year; what moisture there is tends to get hung up as snow on the mountains on the east, the Hindu Kush and Pamirs. In the spring, the snow melts and starts to flow toward the far western side of the basin, almost 700 miles away. There are two main rivers, the Amu Darya and Syr Darya, that flow from the mountains to the east, the one emptying into the south side of the Aral Sea and the other into the north side.

These two snowmelt rivers are fresh, but as they come down from the hills they pick up low concentrations of mineral salts from the soil, and eventually these salts are deposited in the Aral Sea. Since the Aral Sea has no outlet, the salt concentration has increased over the centuries and as a result the Aral Sea is quite salty. If you want a familiar geographical analogy for all of this, think of the Great Salt Lake in Utah. Once again, we have a lake draining a fairly arid inland basin, but with snow that builds up on the eastern side, the Wasatch Mountains in this case. The snowmelt from the mountains drains toward the lake at the bottom of the basin in three rivers, the Jordan, Bear and Weber, and again, dissolved salts in the soil are carried by the rivers to the inland lake, making it quite salty over time. And, as we can tell by the salt flats west of the Great Salt Lake, the size of the lake is subject to fluctuations with the fluctuating climate. But this is where the analogy stops, because the Salt Lake is not disappearing.

So back to the Aral Sea. These river valleys—the Amu Darya and the Syr Darya—have been inhabited for thousands of years. Alexander the Great knew of them as the Oxus and Jaxartes rivers. They were real gardens, thanks to these long, slow-flowing rivers, known for their melons and fruit, the result of bright sunshine and warm temperatures combined with ample river water. And things continued that way until the middle of the twentieth century.

The far reaches of Central Asia were independent emirates that were taken over by Czarist Russia only in the last part of the nineteenth century, just in time for the Bolshevik Revolution, which led to the establishment of Soviet governments in what became Uzbekistan and the other Central Asian republics in the early 1920s. The resources of the Amu Darya and Syr Darya valleys were then developed as part of Soviet central planning.

There were two fundamental problems related to this. The first had to do with the priorities of Soviet planning. These priorities were made on the basis of what was good for the Soviet Union as a whole, as this was judged by the planners, not in terms of what was good for Uzbekistan. The central authorities thought it would be desirable if the Soviet Union was not dependent on outside countries for its cotton supply. The idea was to be independent of the world market, not part of it.

But cotton as a crop has two peculiarities. The first is that it has to have a growing season of at least 200 days a year guaranteed frost-free. Since most of the Soviet Union was located fairly far to the north, the only place in the entire Soviet Union where it was possible to find growing seasons over 200 days long was here in Uzbekistan, in the Amu Darya and Syr

Darla river valleys. So, in order to make the Soviet Union independent of the world cotton market, it was decided to devote the resources of Uzbekistan to the production of cotton.

But this brings us up against the other peculiarity of cotton. It's quite a thirsty crop. Cotton requires over a meter of rainfall per growing season on every meter of surface area growing the crop. This is why most of the world's great cotton regions are found in quite warm and wet climates—places like Mississippi or South China. There is a very high grade cotton grown in Egypt using irrigation from the Nile, but all I can say is, the Amu Darya is one thing and the Nile is the second biggest river in the world.

Now you can begin to see why it was geographically stupid to devote this region to cotton. It's just too dry. Cotton requires over 40 inches of rain a year, and Uzbekistan gets a fifth of that or less. Planting a thirsty, low-value crop like cotton where water is scarce is a fundamentally wasteful and uneconomic thing to do. Where water is scarce, agriculture should concentrate on plants that don't use a lot of water, like wheat or barley, so that what water there is gets a lot of bang for the buck, or on plants that are high-end, like grapes and melons, so you get a lot of bang for buck in that sense; and in fact grapes and melons were the traditional crop of this region, before the Russian takeover. Putting in cotton was a terrible choice for Uzbekistan, because it spent the scarce resource on a low value crop and so assured that the region would be impoverished. There would also be chronic water shortages for other crops or domestic and industrial use, thus stunting the area in that sense and creating the hardship of constant water shortages and water rationing. The right thing for Uzbekistan would have been continuing grapes and melons, selling them abroad and buying cotton from areas good at producing it, like the US or China. But the Soviet planners weren't thinking of a prosperous Uzbekistan but of keeping the Soviet Union out of the capitalist world market.

So that was one problem with Soviet central planning in Uzbekistan. It was oriented not toward Uzbekistan but toward the Soviet Union. The second thing wrong was that it was central planning. Under Soviet-style central planning, cost effectiveness was not an economic issue, as it is in a market economy. The idea instead was to orient production to filling quantity quotas, with a disregard for how many inputs were used up in the process. This led to incredible waste and shoddiness. There wasn't enough water to begin with, but the water that was used for cotton production had no price, so what water there was was just thrown at the cotton crop, even though there was really no margin for waste in terms of the water budget. In Uzbekistan, the idea was to take the water in the Amu Darya and Syr Darya and run it through irrigation canals to feed the cotton. So there was a need to build the canals. So the state construction company was required to build hundreds of kilometers of canals. And this was done. And if the canals leaked water like sieves nobody was counting so what difference did it make? The canals of the Amu Darya were not lined with concrete over these hundreds of kilometers, since it was cheaper and quicker to build them without lining them, and literally half the water was lost to infiltration before it was delivered to the crop. By way of contrast, irrigation systems in Arizona, where water does have a price, lose ten percent of the water en route to delivery. The effect of the absence of water pricing was that twice as much water was needed to grow cotton in Uzbekistan as in the American south, even though water is scarce in Uzbekistan and plentiful in Mississippi.

The bottom line is that, beginning in the 1960s, an increasing percentage of the water from the Amu Darya and Syr Darya was diverted for irrigation. Of course, as less water reached the lake, the sum of in and out turned negative: the inflow could no longer make up for the water lost to evaporation and the lake started to shrink, and as ever-higher percentages of water were diverted the shrinkage accelerated.

The current rate of diversion is 110 percent. Almost none of the water of the Syr Darya or Amu Darya is reaching the Aral Sea, which will therefore evaporate to nothing. This had been foreseen but accepted by the Soviets as the cost of their cotton policy; they called Uzbekistan a national sacrifice area. They claimed to be looking into a plan to divert water from the Lena and Ob, Siberian rivers that flow north into the Arctic Ocean, into the Syr Darya, but it's quite expensive to pump large volumes of water from one watershed to another. The reason these rivers are in different watersheds, after all, is that there's higher ground between them, so to get the water from one watershed to another means you have to pump it uphill, which costs a lot. The Siberian water diversion idea would have been so expensive that nothing ever came of it. After the Soviet Union fell apart all thought of this has come to an end.

What were the other effects of the diversion of the water? The former Aral Sea fishing industry is completely gone, and so you can see pictures of fishing boats forty or fifty kilometers from the present water line; remember the broad, shallow shape of the Aral Sea. Still more serious is the fact that dozens of miles of former lakebed are exposed as the sea shrinks. The Aral Sea is a salt lake, so exposing the lakebed means exposing huge salt deposits and other kinds of deposits as well. What other kinds of deposits? As long as river water was still reaching the Aral Sea, it was dosed with very high concentrations of fertilizer and pesticides. It works like this: the irrigation water is taken from the river and sent in ditches to the farmgate. There it divides into sub-

ditches. Call them sons of ditches if you like. And these flow past the individual rows of cotton plants. Meanwhile fertilizer and pesticide was liberally applied from above; remember that under the Soviet system inputs didn't count. All that mattered, from the farm manager's point of view, was meeting the production quota. So as many chemicals as he could get hold of were applied to force a big crop. The soil became saturated with these pesticides and fertilizers and they were picked up by the irrigation water as it ran past. Not all this water is transpired by the cotton plants. Some infiltrates in the soil and by underground paths, as you know, makes its way into rivulets and back into the river, and when it does it's loaded with chemicals.

Remember that I said the rate of diversion from the Amu Darya is 110 percent. How is this possible? As I just said, some of the water abstracted for irrigation finds its way back to the river, and as it continues downstream it's taken out again, cycled through another cotton field and finds its way back to the river again. So by the time the water gets way downstream it's really loaded with all sorts of agricultural chemicals. These flowed into the sea and settled on the seabed, and as the seabed is exposed through evaporation these chemicals, along with the salt, are exposed as well.

The Amu Darya has a delta, and as you might expect this rich bottomland, located right next to the former lakefront, is densely populated. When the lakebed is exposed, the salt, liberally mixed with pesticide and fertilizer residues, blows off the lakebed and on to the populated areas. The health results are catastrophic. Infant mortality is higher in Uzbekistan than in the Sudan. The incidence of kidney disease, esophageal cancer and a host of other diseases is the highest ever recorded. There's little water for domestic use, so simple things like drinking and cleaning are a problem.

What are they doing since independence? The Soviet Union died in 1991, and Uzbekistan regained control of its own destiny. What have they been doing since then about freeing themselves from this insane dependency on cotton?

Sad to say, nothing. In fact, for the first few years the Uzbeks were actually extending cotton production. Why were they doing this?

They're stuck. The Uzbek demographic transition is incomplete. When the Soviets took over, the population was around five million. Now it's around 24 million, because the transition from traditional high to modern low birthrates was incomplete, partly because the Uzbeks were kept on the cotton farm instead of urbanizing and developing their own industries, and partly because birth control is not very widespread in this Islamic culture. Remember the way the Demographic Transition works: the longer it takes to accomplish, the bigger the population boom. In the case of Uzbekistan, keeping them down on the farm growing cotton meant that the population explosion went right on booming. No other crops were grown, no other techniques were known, no other markets were developed. There were no other skills and no money available to develop other industries in any case. Meanwhile these 24 or 25 million people have to be fed.

In this situation, it was thought that the best thing to do was continue on with cotton production. The fact that the old-line Communist government remained in

power under a new name, filled with dinosaurs who also don't know anything except how to grow cotton, probably doesn't help either.

It really looks like Uzbekistan is at a dead end. The scarce resource, water, is thrown away trying to produce a crop in which Uzbekistan is really not competitive. The much richer and wetter countries—China, the US and Egypt—can easily outperform Uzbekistan on the world market, and add to that the fact that Uzbekistan is in the middle of Central Asia, with few foreign connections, either of business networks or of transportation lines.

As for the Aral Sea, it's a goner. The latest idea is to dike off a bit of the northern end and preserve that, while giving up on the rest of it. This means a bit of Syr Darya water is entering the former sea from the north, but the entire Amu Darya is committed to irrigation. Uzbekistan is on a treadmill and can't get off. The population keeps rising, the only export industry doesn't work, and the water resource is completely committed.

What could they do? Remember the Utah analogy. There are plenty of geographic similarities between Utah and Uzbekistan, as we saw, though there are points of difference too. Asia is much bigger than North America, and by the same token the inland basin of Asia is much bigger physically than the North American basin. The population in Uzbekistan is also much bigger: Utah has only 3 million people instead of 24 or so million to worry about. In addition to that, Utah is not as dry as Uzbekistan; it gets 20 or so inches of rain a year rather than six or eight. Still, for what it's worth, let's think about what Utah agriculture is like. They don't grow cotton or rice in Utah. Agriculture is based on much less thirsty crops like wheat, or much more remunerative crops like fruit, or is used for sheep pasture.

So let's suppose Uzbekistan did find a way to switch from cotton to fruits, melons and sheep. Would there be a market for these products? Not yet, but one could be developed. In China, wealth is increasing much faster than population, so average wealth is going up and people tend to trade up, as we were saying last week, to more meat- and fruit-based diets and fewer staples. The China market is huge, of course, and while the road connection is pretty bad now, it could get better.

What else can they do? Get more efficient water delivery systems, for one thing. Losing half the water en route in a country where water is so precious is ridiculous. Those ditches should be lined with concrete or better still replaced by pipe. The plants should be fed by drip irrigation rather than by open furrows.

So why don't they do it? As I say, they're really stuck. It's such a poor country that the resources to put in top of the line equipment just aren't there. The single thing they could do that would probably help the most is line the irrigation canals with cement so they don't lose all this water to seepage, but even this seems to be beyond them. Retraining people from cotton to horticulture or viticulture would be good, but there's nobody available to do the retraining.

What's the basic lesson? This is a case in which development has totally ruined

the environment, led to an impoverished economy and ruined the health and prospects of the people. Is the basic lesson that economic development is bad? Not exactly. Remember that it's not as if you have a choice. The demographic transition and the population increase that accompanied it meant that the traditional way of life had to be transformed. The lesson is that stupid development is stupid and leads to bad consequences. The scarce resource, water, was wasted and abused in Uzbekistan and for no decent return. The Soviet government felt it didn't have to pay attention to these basic facts because it was opting out of the world economy. This was its most fundamental mistake. Uzbekistan simply isn't cut out for cotton production, and there's no way to change that; if you try, the people who live there are going to pay the price. There are countries much better suited to cotton, so let them do it; stick to the things you really are best at, and trade with them to get your cotton. This is why international trade is good. No one country is good at everything. Trade lets it concentrate on what it's good at, make money at that and use the money to buy what else it needs. When everybody concentrates on what they do best, the wealth of the whole world increases.

The Aral Sea is not alone. The Aral Sea is not the only inland water body that's in the process of disappearing. Other inland lakes and seas, fed by rivers in arid regions, are also disappearing for the same reason: the water from the rivers that feed them is abstracted for irrigation. Other examples include Lake Chad, fed by rivers from northern Nigeria and the Central African Republic, and the Dead Sea, fed by rivers in two water-scarce countries, Israel and Jordan.

The same thing is happening to rivers that formerly reached the sea. One example is the Yellow River in China, and another is the Colorado river of the Southwestern United States; by the time it reaches the Mexican border it consists of agricultural runoff and industrial sludge.

The Colorado and Chad cases also bring up another issue, that of international rivers. Both arise in one country but have their mouths in another. Next time we'll discuss how international rivers are governed.