Chapter 5

The Water Cycle, Supply and Demand

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I. THE USES OF WATER

During the energy crisis of 1973, prudent householders caulked their windows, closed their chimney dampers, and turned down their thermostats in order to impede the flow of energy through their houses and thus to get more out of each BTU as it passed through. Some analysts predicted that the energy shortage that induced this behavior would soon be followed by a water shortage, which, in an analogous fashion, would induce householders to impede the flow of water through their houses by such measures as fixing leaky faucets, shortening shower baths, and putting bricks in toilet tanks. But in contrast to the energy saving measures, the seemingly analogous water saving measures would, under some circumstances, be ineffective.

On the surface, the analogy between energy and water is almost perfect, since both may be thought of as fluids. Indeed, early physical theories asserted that at least one form of energy—heat—was literally a fluid. Both energy and water flow more or less continuously through the household, performing useful functions on the way. One would suppose, therefore, that the cause of conservation would be served in both cases by reducing the flow. This is true in the case of energy, but, as we shall see, not necessarily in the case of water. When we view the world as a whole and not just the household imbedded in it, we find that the analogy between energy and water is no longer so exact.

Consider, for example, two identical toilets, one in New York and one in Philadelphia, each with a brick in its tank placed there by the owner with the aim of reducing the tank's volume, hence the amount of water used for each flush. What, in fact, does each brick accomplish? New York takes its water by pipeline from the upper reaches of the Delaware Valley and discharges its waste water into the lower Hudson River. The New York toilet brick, by reducing the drain on the upper Delaware reservoirs, allows more water to flow down the Delaware River. On its way to the sea, this water performs many useful functions whose value can be credited to the New York toilet brick.

The Philadelphia toilet brick is different. Philadelphia takes its water out of the lower Delaware and puts its waste water back into the same lower Delaware a little further downstream. The effect of the Philadelphia toilet brick is simply to reduce the rate of circulation of water through the system. In no way does the brick increase the quantity of water in the river. Nor does it improve the quality of the river's water either, since the amount of pollution added to the river is the same with or without the brick. Thus the toilet brick in Philadelphia, unlike that in New York, accomplishes no effective water conservation (although it may save some pumping energy).

The difference here is that in one case the water use is cyclic and in the other case it is not. Water conservation cannot be understood without taking account of the cycles in which the various uses are imbedded. In this respect water is more complex than many other resources, such as energy, which can reasonably be treated by one-way, source-sink models. Since practically every use of energy irreversibly increases entropy, recycling is impossible. The best we can do is to place certain uses in tandem—for example, we can keep houses warm with the low temperature heat discharged by power plants—so as to get as much good as possible out of the one-way energy flow. This one-way character of energy makes for a relatively straightforward conception of conservation that is not applicable to water.

By the same token, the economics of water is less straightforward than that of other commodities. This is true both in theory and in the market place. Economics is permeated with the one-way model implied by word pairs such as resources-consumption and supply-demand. Although we often break out linear pieces of the water cycle and talk about "water resources" and "water consumption" or "water supply" and "water demand," our actual use of water is much too cyclic and interactive to be adequately described in an aggregate way by such terms. The example of the toilet bricks should suffice to illustrate the point.

Another related problem with the economics of water is ownership. Conventionally, ownership attaches to physical objects or to batches of a commodity. In the one-way flow of iron from mine to junkyard, for example, ownership passes from hand to hand, with price reflecting at each stage the value added (or subtracted) by whatever physical or chemical modifications may have occurred since the last sale. Even such an intangible commodity as energy lends itself readily to clear-cut ownership: as coal, the energy is locked in a physical commodity; as electricity it can be metered to a consumer, who is free to dissipate it to the environment in whatever manner suits him. Ownership of specific masses of water, on the other hand, is in many cases infeasible. The riparian law, for example, has long recognized the impossibility of attaching absolute ownership to the water flowing in a stream.

How, then, are we to deal with water as a commodity? A thing cannot be bought and sold unless it can be owned. To deal with water it is necessary to go to a more abstract concept of ownership, namely the ownership of *rights*. The riparian law recognizes the right of a streamside landowner to divert and use the stream's water in various ways, provided the net deleterious effect on downstream owners is held within specified bounds. The water is not owned, only rights with respect to its use are owned.

Of course, all ownership is ultimately a matter of rights; nothing is owned absolutely. Though a man may have a deed to his home and even regard his home as his castle, he is still constrained in most places from using it for certain kinds of otherwise legitimate business. His rights of ownership are not absolute. Nevertheless, for most things and most purposes, the inexact but concrete and convenient conception of physical ownership is adequate. Water is one of the exceptional commodities (land is another) for which the more abstract conception of rights ownership must be taken explicitly into account.

What then is the economic value of a water use? How much should be paid for it and to whom? In principle, competition between uses should establish prices for water rights so that these can be bought and sold like physical commodities. And to some extent markets for water rights do exist and, for better or worse, do determine for society which uses shall take precedence. But the device of attaching ownership to rights, even though it has often been applied with considerable ingenuity, has not been able to draw all water decisions into the market place. In many cases, including those involving the most urgent environmental issues, water rights are too ill-defined or broadly held to be marketable. In these cases, choices about what uses are to take precedence inevitably devolve upon planners and political leaders. It seems to be in the nature of things that the economics of water must give way to the politics of water.

To appreciate in a vivid way the bewildering variety and subtlety of the interferences and interactions between water uses that must be taken into account if planning is to be rational, it is good to consider some examples. Although the following examples are couched in hypothetical terms, several of them illustrate real problems on the Delaware River.

1. Evaporation

A power plant with an evaporative cooling tower and an irrigated farm withdraw water from the same stream. Both operations intervene in the water cycle in the same way: they short-circuit to the atmosphere water that would otherwise flow to the ocean. The two operations are also in direct competition: if one depletes the stream, then the other is precluded from operating. The conflict is simple and direct. One can imagine a market mechanism, perhaps an auction, for allocating the water between the two uses on the basis of economic value. On each side the additional productivity made possible by the availability of the water would determine the bid.

2. Pollution

Two cities are located some miles apart on the same river. Both take water out of the river for municipal use and both release their waste water back into the river. In the stretch between the cities the river purifies itself to some extent, but tap water in the downstream city smells more of chlorine and costs more than in the upstream city because of the more elaborate treatment made necessary by the residual pollution. In this case there is an economic and esthetic conflict between the two uses but neither one precludes the other. The conflict here is more oblique and subtle than in the first case. Where should the treatment be done? At the outlet of the first city or the inlet of the second? Which city should pay? Before heaping the entire burden on the upstream city, note that if *either* city were absent (ignoring any other considerations) the other city would be free of any cleanup burden.[1]

3. Quality versus Quantity

As in the previous example, two cities take their water from the same river. One city, as before, releases its waste water into the river, but the other city is located some distance away and releases its waste water into the estuary of another river. The first city diminishes the *quality* of the river's water, the second its *quantity*. Although both interventions are for "municipal use" and thus are often lumped together in statistical compendiums, they impose very different burdens on the river, and conflict therefore in very different ways with alternative uses. For many purposes, "municipal use" is not a very helpful category; neither is "industrial use," for similar reasons. In fact the prevalence of such categories makes meaningful estimates of water "supply" and "demand" very difficult to construct.

4. The Weather and Uncertainty

A town is supplied by a reservoir. The system is of the once-through type with no recycling. The probability of a drought severe enough to cause a shortfall is small but not zero. Various insurance measures can be taken: a supplementary reservoir can be built, standby wells can be drilled, a pipeline to a neighboring system can be laid. Or, the risk can be ignored. How much should the town be willing to pay (including environmental costs) to reduce the risk of shortfall? In principle it should be willing to pay no more than the discounted expected loss from shortfalls. In practice this quantity is virtually impossible to calculate because both the probabilities and the losses are so imperfectly known, especially the latter. Difficult trade-offs involving risk are inherent in the economics of water.

5. Aquatic Life and Ignorance

A reservoir catches the high spring runoff for later use by a municipality. In the estuary, the boundary between fresh and salt water, which used to move downstream in the spring, is now stabilized by the reservoir's action. Certain organisms which had adapted to the seasonal salinity changes are affected. In particular, oysters, which can stand the salinity change, are now attacked by oyster drills, which cannot. Previously, the oyster drills were held in check by the springtime rush of fresh water.

The estuarine life is highly complex, and we do not know all of the consequences of changing the fluctuations of flow. We do know that the estuaries are a vital link in the whole oceanic web of life, and we know that in at least one instance a dam (Aswan) has caused a massive ecological disaster in an estuary. Should we worry? The difficulty here is that the conflicts between uses (where "uses" is taken in a broad sense) fade out into the dark fringes of our ignorance, so that we are not even sure what the conflicts are.

6. Ground Water and the Unknowable

A town in an arid region "mines" water from a large aquifer. It releases its waste water to a stream, which runs into the ocean. In fifty years the aquifer will be dry. This water use precludes whatever opportunities the full aquifer might have offered to unborn generations. The conflict is difficult to adjudicate fairly because the unborn generations have no representative in court.

This example illustrates a subtle point. Not only must existing uses be taken account of, but also potential uses. But potential uses exist only in the imagination, and the imagination (or potential imagination) is virtually infinite. The unborn generations could conceivably invent a use for the ground water that we would admit is better than our present use. For example, they might find a way to use the water conservatively (i.e., with recycling) so that the aquifer would not run out. Or, conceivably, living arrangements might so change that the ground water would be of no interest to the unborn generations.

Though subtle, the question of potential use is by no means academic. The water planners in New Jersey are saving the potential sustained yield of the Pine Barrens (whatever that may be) for imagined future development in the southern part of the state, and they therefore resist suggestions that the water be shipped north where it could be used now. But the future of southern New Jersey can be imagined in many ways, not all of which involve development. What image of the future should guide us?

7. Esthetics

A city has a choice between a dirty lowland source and a clean upland source. Although the lowland water can be treated for less than it costs to develop the upland source, the city chooses the latter for "esthetic" reasons.

C. H. J. Hull, an engineer with the Delaware River Basin Commission, believes that this was a major factor in New York's decision to take Delaware rather than Hudson water.[2] He believes, moreover, that the esthetics of drinking water relate not to its chemical composition, but to its history. He was brought to this view, he says, by the fastidiousness of his family:

> They simply could not—and have not to this day—overcome their repugnancy toward second-hand water, no matter how well renovated. Don't bother to point out that second-hand water may be used in making some soft drinks. I've tried this argument too; it doesn't work. There is just no rationalizing an intangible thing like esthetic sensitivity.
>
> Although I haven't yet admitted it to my family, living with such fastidi-

> ous creatures has had its effect on me. I seldom drink a glass of water without experiencing an involuntary thought about its history. The result is that my intake of water, at least in its undisguised state, has diminished.[3]

The attitude of Hull and his family seems at first sight to be similar to that of the organic gardeners: only nature's product, untouched by technology, will do. This view seems rather out of keeping with the usual image of the engineer as a no-nonsense type devoted to technological miracles. But perhaps Hull is merely expressing a preference for one technology over another, since the purveyance of nature's untouched product usually requires engineering works of at least as great magnitude as the processing of man's mess. The organic gardeners, on the other hand, tend to eschew technological miracles of any kind. They are the sort who take pleasure in drinking rainwater collected from their own rooftops according to instructions found in the *Mother Earth News.* The thought that the water might have trickled over bird droppings on its way down the roof probably only increases their sense of contact with nature. Esthetics has many facets.

The Tocks Island controversy has generated a great deal of talk about esthetics, though mostly of a more visual kind—the beauty of clear water running over stones, of the teardrop shape of an island, of a drooping tree along the riverbank, of other such images associated with a free-flowing river. Some have even tried to focus the issue by presenting it as a simple choice between abundant drinking water and the beauty of the natural river. While this has hardly any real validity, it does rightly recognize the central role esthetic considerations have played in the controversy. But it wrongly implies that these considerations are all on one side.

Engineering is an extremely esthetic pursuit. In fact, the element of esthetics in engineering is just about as great as in architecture, though its nature is a little different. In engineering, beauty is not only visual, but also abstract. It is a matter of clarity, simplicity and subtlety—what in mathematics is called elegance. The mechanism of the combination lock (the kind you turn alternately right and left) is beautiful, not because its metallic embodiment is especially pleasant to gaze at, but because the *idea* it is based on is so incredibly simple. (If you don't know how it works, try to figure it out. It is an amusing puzzle.) The clavichord mechanism, the crystal radio, the automobile differential are further examples of devices with abstract elegance. Early steam locomotives and modern racing catamarans are appealing in both an abstract way and in a sensory way. So are dams.

Elegant devices embody clear and simple solutions to clearly perceived problems. But clearly perceived problems are necessarily based on an idealization of some segment of reality. And although it is the ability of science to idealize that gives it its power, it is nevertheless often true that when an elegant solution to an idealized problem is embedded in the real world, the effect is less than elegant. Thus, although steam locomotives are very beautiful to look at, to listen to, to ride on, and to contemplate, they are an environmental abomination. The first ones ran on wood and denuded entire mountainsides. During their later, coal burning heyday, they spread a thick blanket of grime over practically every city of the industrialized world. The best of them wasted most of the energy stuffed into their fire boxes.

As a solution to the clearly perceived problem of bringing a steady supply of pristine water to the people, the dam is elegant for its conceptual simplicity. Indeed, for sheer simplicity it rivals the wheel. When the realization of the simple concept is placed in the unidealized real world, however, it, like the steam locomotive, fails to fit in a number of ways. It is, for example, incompatible with the habits of anadromous fish, disruptive of the estuarine shellfish balance, and excessively hospitable to bluegreen algae. And its useful life is limited by siltation. Such awkward aspects of reality are not included in the idealization which lends the dam its elegance. Moreover, any special measures taken to cope with the difficulties detract from the simple elegance of the original concept.

In their failure to fit perfectly into the real world, dams are no different from any other device ever invented by man. None has ever fitted perfectly. On the other hand, dams are very large scale devices, so that the inelegances stemming from their lack of fit are also large scale.

In the Tocks controversy, as in other environmental controversies, esthetics is much more than a matter of natural beauty. It pervades our processes of thought.

8. Growth

A region can dam its river at some economic and environmental cost in order to provide water for continued conventional growth, or it can leave its river alone, conserve water, and limit conventional growth.

In the minds of the participants this is surely Issue One in the Tocks controversy. It nevertheless hardly ever surfaces in any sustained, coherent way, but only in passing remarks. Probably it seems too fraught with values, prejudices, and political pitfalls to be much good for legalistic case making. But since it is really Issue One, it deserves some discussion here.

In the 1930s, the Tennessee Valley Authority (TVA) was seen by its creators as a shining humanitarian enterprise that would bring order and prosperity to an impoverished people and set an example for the whole country. The image was neat new farms on a fertile, protected flood plain, lighted by electricity from humming water turbines. All this to replace moonshiners' shacks.

The spirit of TVA progressivism is well captured in a film made by Pare Lorenz in 1937 entitled "The River." The film shows how the earlier clearing of midwestern forests had led to soil erosion and disastrous flooding and how people suffered as a result. The need was clear: the natural flood control previously provided by the forests had to be replaced by the works of man. Elegant concrete structures with water gushing over their faces in controlled torrents appear on the screen. Then the power lines, then the newly prosperous farmer plowing his field against a scenic backdrop. The film is low key but stirring. There is not the slightest trace of cynicism and not the slightest trace of doubt about what is the right course of action. Our ancestors may have been imprudent when they cut the trees, but the dams will atone for their error and will repay their debt to nature. The progressive spirit of TVA has continued to motivate the government dam builders to this day.

Odd, then, that it is just those who imagine themselves to be most progressive who are now berating the Corps of Engineers for building too many dams. The images have changed. The term "progress" has gone somewhat out of style and has been more or less replaced by the more technical-sounding term "economic growth." And this concept in recent years has lost so much of its luster that it no longer raises eyebrows to say that economic growth is a mixed blessing. The governor of Oregon has even made the braking of growth an official state policy.

The images which have brought about this change have been negative. "Progress" was to bring gradually more wealth to each individual, but "economic growth" is now perceived by some as gradually diminishing each person's wealth, or at least certain components of it such as his share of open space, clean water, clean air, natural beauty, quiet, and health. Hardly anyone who has lived more than two decades can have escaped seeing a beloved hilltop invaded by houses, a familiar country road transformed by commerce, a swimming place ruined by scum, a peaceful town split by a highway and suffocated by its traffic, or a favorite valley flooded. Such perceived retrogression conflicts with the deep feeling, especially characteristic of Americans, that life should get gradually better. This sense of inexorably creeping loss is surely the real engine driving the opposition to the Tocks Island Dam.

Opponents of conventional development believe that under present circumstances real wealth can be increased only by improving the *efficiency* with which environmental resources are used—for example, by using less water for each ton of steel, less steel for each passenger-mile of transportation, and less transportation to conduct our business. Or less land for each ton of coal, less coal for each kilowatt-hour of energy, and less energy for each square foot of office space. And so forth.

Achieving such gains is not necessarily a matter of frugality: redirected technology can do a great deal. Nevertheless, a renewed sense of frugality does seem to be accompanying the current environmental awareness. Will the old Puritan slogans be revived? ("Use it up, wear it out, make do, or do without.") Will people be perverse enough to see frugality as improving the quality of life in some moral sense, as the Shakers and others once did?

Frugality brings us full circle—back to the problems of water conservation with which we began. As we saw, the conservation of water is not quite so obvious a matter as it may seem. The trouble is that water is already conserved by nature. With negligible exceptions, water is neither created nor destroyed; it just moves endlessly around a grand hydrological cycle. Although we say we do, we never really consume water; we merely intervene in the natural cycle by short-circuiting, delaying, or polluting parts of it. Unfortunately our various interventions conflict with one another in a bewildering variety of ways. Conserving water merely means modifying one intervention so that another, conflicting one may be larger.

II. WATER'S PATHWAYS

Figure 5–1 shows the main water cycle in a stylized way. Rain water striking the earth is driven by gravity to the sea. A typical path passes first through the ground, then out into a stream, and finally into the saline ocean.

1. Diversions for Human Use

For a variety of reasons, man diverts water from its natural pathways into others of his own making. These diversions can be classified as forward, local, or backward according to the relative locations within the cycle of the points of withdrawal and discharge. A

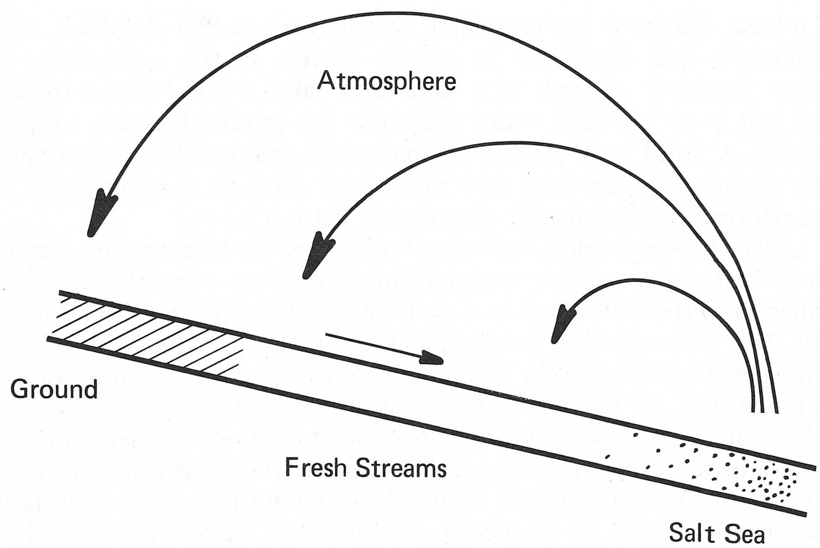

Figure 5-1. The Main Water Cycle

forward diversion is one whose discharge point is further along in the cycle than its withdrawal point (assuming the path tracing starts and ends with the atmosphere). A local diversion is one whose withdrawal and discharge points are close enough together to be regarded as identical, and a backward diversion is the opposite of a forward diversion.

Forward diversions are the most conventional kind. A typical example is a municipal supply system, such as Newark's, that takes water by aqueduct from an upstream point on a river and discharges it after use at a downstream point. From the point of withdrawal to the point of discharge, the river's flow is diminished by the amount of the diversion. A cooling tower that short-circuits river water directly to the atmosphere is another example. From the site of the tower to the sea, the river is diminished by the amount of the tower's diversion. In general, a forward diversion has the effect of diminishing flow along some segment of a natural path. It is usually this effect that limits the volume of water that can be allowed to flow through a forward diversion.

Local diversions are not limited in this way. Since the points of withdrawal and discharge are the same (by definition), such a diversion is in effect an independent circulation whose rate of flow does not affect any other flow rates. In principle, then, the rate of flow through a local diversion can be arbitrarily high. A typical example of a local diversion is a municipal system, such as Philadelphia's, that withdraws and discharges at nearby points on the same body of water. Another example is a farm that takes ground water from a well and puts its waste water back into the ground through a septic system. A third example is a seacoast town that desalts seawater and puts its waste water back into the ocean. All these systems could be run arbitrarily fast without diminishing natural flows.

Local diversions are, however, limited by contamination. Almost every water use except evaporation introduces some foreign substance into the water, and in a cycle such substances tend to accumulate. The accumulation is mitigated somewhat if one link in the cycle is dispersive (the river, in Philadelphia's case) or if one link is a filter (the ground, in the case of the farm). But the capacity of such helpful links is usually limited, so that the allowable magnitude of the contaminating water use is also limited. This magnitude has been exceeded, for example, on Long Island, where the well–septic tank system, multiplied by hundreds of thousands, has resulted in a slow accumulation of soluble nitrates in the ground water, until now hazardous levels have been reached.

Expanding the capacity of a local diversion, then, is usually a matter of pollution control. Thus pollution control has a direct bearing on the magnitude of potential water supplies. It also has an indirect bearing in that forward diversions are often undertaken, despite their great cost, in order to avoid pollution (see the comments of C.H.J. Hull in Section I-7). Thus it is not possible to estimate the water supply potential of a region by means of volumetric calculations alone; cleanup possibilities must also be taken into account.

Backward diversions are the least common kind. A hypothetical example would be the pumping of water from a lake to the top of a mountain, with waste water discharged at the top into a natural stream. Another example would be the shipment inland of desalted water from a seaside plant, with the waste water discharged into a river. In all cases, the flow along some segment of a natural path is *increased* by the diversion. Despite this dividend, backward diversions are uncommon because they necessarily require energy: they must do the work the sun would otherwise do. In driving the water cycle the sun does two kinds of work: it lifts the water against gravity and it separates the water from salt. Backward diversions must also do one or both.

A transfer of water from one stream to another is neither a forward nor a backward diversion, since it diminishes the flow in one stream and augments it in the other. Such a transfer can, however, be regarded as the sum or simultaneous occurrence of a purely forward and a purely backward diversion.

2. Conservation—Limiting the Diversions

Traditionally, water engineers have devoted their efforts to diverting ever more water for human use. But as the diversions have grown and their environmental effects have become more evident, people have begun to ask if so much diversion is really necessary, and have suggested various measures for reducing the demand for it. Such measures can reasonably be called conservation measures.

Conservation measures, in contrast to projects for increasing diversions, tend to avoid the destructive chain reaction effect, so common in our technological society, wherein the solution of one problem creates another. Increased diversions, for example, tend to increase the burden on the sewer system, whose expansion creates further problems, and so forth. Conservation measures, on the other hand, tend to relieve such problems.

Within our framework, conservation measures fall into three main types: (1) those that reduce the *volume* of a forward diversion, (2) those that reduce the *length* of a forward diversion, and (3) those that reduce contamination. There appear to be significant opportunities for measures of all three types. This section discusses some examples.

Cooling of many kinds constitutes one of the largest components of water use. Any serious effort to conserve water must consider cooling. Water is especially useful for cooling because of its high heat of vaporization. In evaporating, a single gram of water absorbs about 580 calories of heat, or enough to cool 58 grams of water or 542 grams of steel by 10°C. Thus, from an engineer's point of view, the evaporation of water provides a very attractive way to transfer heat to the atmosphere.

In a study of three Massachusetts towns during the drought of the 1960s (the most severe of record) Russell, Arey, and Kates[4] estimate the annual per capita loss due to a 15 percent water shortage to be only about $10. One important reason for this startlingly low value was that in many cases measures undertaken by industries to save cooling water were found to be profitable, so that over the long run they generated net gains, which offset some of the drought losses. The savings were achieved, according to the authors, by "recycling" cooling water. Though no explanation of this is given, it may mean that water flowing in a forward diversion (e.g., municipal water from an upland source) was being used for cooling in such a way that only a small fraction was actually being evaporated, with the rest simply passing through. This would be characteristic, for example, of the simple and common "once-through" method. By rearranging their systems to evaporate a larger fraction of the input water, so that less total input water was needed, the industrialists reduced their demands on the forward diversion. This would be an example of a Type 1 conservation measure, since it reduced the *volume* of the diversion.

The diversion it relieved, however, was that associated with the municipal water supply; it did nothing to relieve the diversion of water to the atmosphere by evaporation. Indeed, the rate of evaporation is determined by the cooling load, so that as long as evaporative cooling is to be used, the volume of this diversion cannot be reduced. Nevertheless, a Type 2 conservation measure might be applicable in a case such as this: if the cooling tower could be moved closer to the sea, then the *length* of the evaporative diversion could be reduced.

This possibility has become important in the Tocks Island Dam controversy. A Delaware River power plant originally planned for an upstream site has been moved to the estuary, where its forward diversion, being shorter, has less impact on the river's flow. Though the move was made primarily for reasons other than water conservation, the conservation effect has pleased some environmentalists, who are urging that other plants be moved as well.

Going one step further, evaporation can be abandoned altogether and heat can be transferred to the atmosphere through conductive metal surfaces, usually of copper or aluminum. While this is feasible, the dry surfaces, operating without the benefit of those 580 calories per gram, must be very large. Lots of metal and lots of space are needed.

Ideally, of course, "waste" heat should not be dissipated by cooling, but should be put to good use. Schemes to do this go by the name of "total energy systems." These usually use the waste heat for direct space heating, for indirect cooling by means of an absorptive cycle, or for chemical processes. Their more widespread adoption is inhibited by the fragmentation of planning: power plants that make the heat, and houses or factories that could use it, are planned by different people.

A spectacular piece of evidence that conservation has large potential in industry is provided by the Kaiser steel plant in Fontana, California, which uses only 4 percent of the water used by conventional plants.[5] In spite of the cost of special equipment required to achieve this, Kaiser is able to compete in the market for steel.

Sunday supplement articles on water conservation tend to concentrate on the universally familiar household segment of use. (Such articles generally assume tacitly that the household is imbedded in a forward diversion so that reductions in volume are effective.) It may seem startling that the average American uses 75 gallons per day. Thus a family of four uses 300 gallons per day, or two brimming bathtubs full.[6] Households in other industrial countries use less. According to one text:[7] ". . . some water authorities in Britain maintain that 25 [30 U.S.] gallons per head per day is an adequate supply for domestic needs, while many American engineers do not blink at supplying up to 70 [84 U.S.] gallons per head per day for exactly the same purpose." Part of the explanation, no doubt, is that machines for washing clothes and dishes, especially abundant in the United States, use more water than hand methods, though other aspects of life style are probably also important.

How much water does a comfortable standard of living really demand? No one knows for sure, but there are some inventive people who think we could get along with much less water than we now use. One proposal is to use the waste water from washing for flushing toilets. Since each of these uses accounts for about half the indoor total, this measure in principle could cut indoor consumption by 50 percent. A similar saving would be achieved by the Swedish composting toilets, which use no water at all. Another proposal, for which a variety of small savings totalling 25 percent is claimed, is centralized, electrically operated valves.[8] Further proposals concern various means for improving the efficiency of washing.

A more immediately effective Type 1 conservation measure, however, would be the repair of leaks in municipal distribution systems supplied by forward diversions. A 1960 analysis of New York City's decision to build the Cannonsville reservoir in the upper Delaware Basin concluded that more than Cannonsville's yield could have been obtained by fixing the leaks in New York's pipes.[9] About one-third of the saving would have come from fixing street mains and two-thirds from fixing pipes on customers' premises. The per gallon cost of the former would have been less than one-hundredth, and of the latter less than one-third, the cost of Cannonsville water. The Cannonsville reservoir was nevertheless built, and the leaks were never fixed.

This odd decision was consistent with a venerable tradition in New York City politics. At least since 1900 the City has been more or less continuously criticized for failing to fix the leaks in its mains and for failing to install meters so that customers, who now pay a flat rate, would have an incentive to fix their own leaks and maybe even moderate their notoriously profligate water using habits. Other cities, after installing meters, have experienced reductions in consumption of as much as 40 percent.[10] To date, New York City officials have successfully resisted all such criticism, even though at times of crisis it has sometimes been intense. Their reasons for doing so are apparently rooted in the Catch-22 logic of bureaucratic politics. They are certainly not economic.

Whatever its cause, New York City's negligence has a direct bearing on the Tocks Island project, even though it is seldom mentioned in debate. New York takes much of its water from the upper Delaware. Water not taken by New York could be released down the Delaware River and could serve precisely the same functions as water released from the proposed Tocks reservoir. For the sole purpose of feeding its leaks, New York City is taking at least enough water to cover the 300 million gallons per day (mgd) New Jersey would like to export out of the Delaware Basin into its northeast region.[11] The provision of this 300 mgd (which we will discuss in more detail later) is seen by the Tocks proponents as a major justification for the dam.

Although the physical sense in which the Tocks Island Dam is to service New York's leaks is clear, the connection is hardly ever pointed out by the dam's opponents, for a decidedly nonphysical reason. The reason is that a U.S. Supreme Court decision of 1954 allocating 800 mgd of Delaware water to New York City is seen as an insuperable barrier. It is as if the Himalayas had sprung out of the earth under the river, cutting off a piece of the upper Basin from the rest and permanently diverting its water to the Hudson. No one has yet observed that no such mountain range exists. If New Jersey had to pay for the Tocks Island Dam, and if all parties pursued their own economic interests, then New Jersey and New York might well find it advantageous to strike a bargain under which New Jersey would pay for fixing New York's leaks and installing meters there, in return for additional water releases down the Delaware from New York's reservoirs. But since New Jersey does not have to pay for the Tocks Island Dam, it has no incentive to consider such a bargain and it may as well believe in the Himalayas.

III. FLUCTUATIONS

The previous section on the routing of water—its natural pathways and manmade detours—allowed, for simplicity, the tacit assumption that flows are uniform in time. This, of course, is not the case. Natural flows fluctuate widely in response to fluctuations in the weather.

It was observed that forward diversions borrow water from natural pathways, and that such diversions are usually limited by the need to avoid excessive reduction of the natural flow. A variety of physical, biological, and economic circumstances impose constraints on natural flows that cannot be violated without environmental or dollar cost. In planning diversions, therefore, water engineers must find means for raising the minima—that is, for filling in the troughs of the graph of flow versus time. With the troughs filled in, greater diversion is considered allowable up to the point where the borrowing it entails brings the minima back down to a specified limit. The traditional source of water for filling in a trough is a preceding peak, or set of peaks, and the traditional device for accomplishing the transfer of water from peaks to troughs is the dam. Dams, then, are devices for raising minimum flows and thus permitting expansions of forward diversions. The "safe yield" of a dam is the magnitude of the forward diversion the dam permits under some constraint on minimum flow and some criterion of safety.

This, in brief, is the traditional way of dealing with one kind of fluctuation in one context. It is not the only way or kind or context. From noise to business cycles, man is beset by unwanted fluctuations on every hand, and he has invented dozens of ways of dealing with them. But one often finds in widely different contexts methods that are similar or analogous in some way. Certain time series taken from the stock market are indistinguishable from certain others taken from nature; insurance and electric grids use similar kinds of averaging; a mathematical "theory of storage" applies with minor modifications to dams, inventories, and queues. And so forth. But even taking account of such analogies, there remain a number of fundamentally different ways of dealing with fluctuation. This section briefly examines some of these in the context of water.

1. Getting at the Source

It is fashionable these days to list weather modification (cloud seeding) among the means for increasing water supplies. This gets right to the ultimate source of irksome hydrological fluctuation. To level out the weather into one monotonous drizzle is a delightful science fiction possibility that the rain makers have not failed to achieve through lack of enthusiasm. Edith Weiss, who has looked seriously at the possible consequences of a really effective weather modification technology, has discerned a hair-raising tangle of legal, political, and international problems.[12] Although bringing rain in times and places of genuine drought would have undoubted humanitarian benefit, it is difficult to imagine mankind stopping with that.

In our present state of civilization it is perhaps just as well that weather modification is still a nonresource.

2. Filling in the Troughs

Dams are the traditional trough filling devices, but there are others too, for which a convenient generic term is "standby sources." Standby sources are common in utilities such as electric power that face a fluctuating difference between demand and supply.

Electric power engineers distinguish between base load generators, which run continuously, and peak load generators, which run intermittently. Typically, different types of plants with different economic characteristics are used for the two functions. Base load is provided by plants (e.g., nuclear reactors) that have relatively low operating (e.g., fuel) costs and relatively high capital costs; peak load is provided by plants (e.g., gas turbines) with the opposite characteristics. The reason for the trade-off is clear: since standby sources such as peak load generators produce relatively little yearly output for their capacity, the burden of their capital cost falls relatively heavily on each unit of output. Hence, the relative premium on low capital cost.

Some water supply systems are seemingly analogous. New York City's water is supplied by reservoirs, supplemented by a standby pumping station on the Hudson River at Chelsea, which is used only if the reservoir supply runs low. Like the peak load generator, the standby station at Chelsea has relatively low capital cost and relatively high operating cost (energy).

But the analogy is far less accurate than it might seem, for the reservoirs are, in fact, not continuously operating base load plants, but rather are standby devices, like the Chelsea pumps. If the river flows were uniform and unfluctuating, the aqueduct alone could purvey the water to New York City and no reservoirs would be needed. In the same sense that a pump is idle unless its blades are turning, a reservoir is idle unless its level is declining, for only then is it providing any water that is not otherwise available. Since its level declines only at times of low flow, a reservoir operates as a standby device. Its economic characteristics, however, are those of a base load plant. This can make a reservoir relatively uneconomic compared to other standby devices.

The output of a reservoir is conventionally stated as an addition to "safe yield." The cost of the reservoir is often divided by this quantity to give a normalized cost—so many dollars per mgd of additional safe yield. The cost is thus spread out over a constant, uninterrupted flow, most of which, typically, could have been obtained without the reservoir. Although this procedure is conceptually more appropriate for a base load rather than a standby plant, it is not really wrong, provided the same procedure is applied to all alternatives.

Consider, for example, a comparison between a reservoir and aqueduct on the one hand, and a standby well and aqueduct on the other hand. We will assume that the aqueduct is the same in both cases so that its cost cancels out of the comparison. In the second case the aqueduct brings water from the (undammed) river whenever it is available; the well is brought into action only on the relatively rare occasions when the river flow is inadequate. Even though the well actually produces little water on the average, it *makes possible* an uninterrupted supply, just as the reservoir does. To make a consistent comparison, then, we must spread the cost of the well over the whole flow, including the flow when the well is idle. The result, as before, is so many dollars per mgd of additional safe yield.

It is equally correct, and perhaps conceptually better, to allocate the cost in both cases to just that portion of the water actually supplied by the standby source. This merely sets a new baseline: the natural flow in the undammed river is taken as given, so that only the water needed to fill the gaps is counted. This water can reasonably be called "insurance water." When the cost of a reservoir is allocated only to the insurance water it actually supplies, the per gallon cost can be startlingly high. In a report prepared by the Institute of Public Administration for the Corps of Engineers as part of the NEWS study,[13] the cost of providing insurance water by means of reservoirs in the New York metropolitan region is estimated at $22 per thousand gallons (1970 dollars)—or about 100 times the normal price! While this number can hardly be taken literally (it is based on a very simple aggregate model of runoff variation), its magnitude does not appear implausible. The implication, of course, is that even expensive means for supplying insurance water could compete with reservoirs. At $22 a thousand gallons, water could almost be brought in by truck.

Such a high number should spur every inventor to seek better ways of obtaining insurance water. Two general sources are the sea and the ground. Though much inventive effort has gone into the desalting of sea water, costs remain high and environmental problems persist. Ground water, whose technology (so far) is simpler, appears more promising.

A. Desalting. During the 1960s the federal government, through its Office of Saline Water, mounted a major effort to make desalting economically competitive. The reports of this agency fill a bookcase six feet high and six feet wide. In recent years, however, the effort has greatly diminished and in 1972 the Office of Saline Water was dissolved.

A fundamental difficulty with desalting is that it requires a great deal of energy. On the basis of fundamental physical principles it can be shown that at least 2.6 kwh must be expended to extract 1000 gallons of fresh water from sea water by any method whatever. Ingenuity cannot reduce this limit any more than it can create perpetual motion. Moreover, no practical method has even approached the limit; an efficient existing plant requires 145 kwh per 1,000 gallons.[14] The reason for this is also fundamental: to approach the theoretical limit it would be necessary to perform the extraction very slowly, and the slower the extraction, the greater the capital cost of the plant per gallon per day of output.

Apparently, an important stimulus to the efforts of the Office of Saline Water in the 1960s was the seeming imminence of abundant nuclear power. It was hoped that by using the waste heat from the nuclear plants to desalt water, both electricity and water could be produced at competitive costs. Unfortunately, a variety of technical, environmental, and political problems that have gradually come to light in recent years have diminished the promise of both technologies, although the combination may still find uses in special situations (islands) where fresh water is especially scarce and costly.

Aside from the land use problems associated with any large industrial installation, desalting plants have their own special environmental problem, namely the disposal of prodigious quantities of concentrated brine. This is especially acute inland (where the source of salt water might be the ground), but even along the seacoast the effects on aquatic life might be troublesome.

In 1966 a group of investigators called the "Northeast Desalting Team,"[15] who looked into the potentialities of desalting for New York City and northern New Jersey, estimated that desalted sea water could be produced at about twice the cost of standby pumping from the Hudson. Their estimate assumed a 300 mgd standby plant using heat from a power plant. This leaves a factor of two to go on the economic side and a substantial problem to overcome on the environmental side—not a hopeless gap to close, but still a discouraging one.

A more immediate prospect is the use of dilute salt water; if the salt concentration is low, then the energy required for desalting is correspondingly low. Thus, mildly brackish water from estuaries, or waste water containing small amounts of dissolved solids, are both promising candidates for desalting. In fact, desalting of dilute solu-

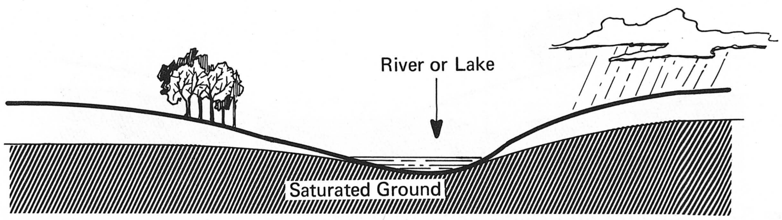

Figure 5-2. Ground Water Under Virgin Conditions

tions is a necessary step in many recycling procedures. The membrane method, which is applicable especially to dilute solutions, shows considerable promise. The development of a really good, inexpensive membrane could have a major impact on water technology.

Although every method of desalting requires a substantial plant, capital costs are low enough (and operating costs high enough) to make desalting usually look better as a standby source.[16] Relative to reservoirs it has the capital cost advantage that its plants can be built in stages as needed, while reservoirs must be built all at once.

B. Ground Water. The second commonly mentioned standby source is ground water. More fresh water is stored in the ground than anywhere else except the polar ice caps—more than in all the lakes and rivers and more than in the atmosphere. But it has many peculiar properties that make its role in water supply complex.

Physically, surface and ground water form a single system. The water table is continuous with the surfaces of rivers and lakes, as shown in Figure 5-2. Water is readily transferred between surface bodies and the ground. Under virgin conditions, the system fluctuates about an equilibrium state with fluctuating rainfall. Rain raises the water table, thereby creating a pressure head that drives the water out of the ground into the lakes and streams. After the rain, the water table slowly subsides as the streams drain away the excess water. It is the ground water, not direct surface runoff, that keeps the rivers going between rains.

The soil above the water table may be periodically moist, but it is not saturated. Only the water in the saturated zone is normally counted as ground water. Most plants take their water from the upper zone, intercepting it on its way down. But a few, called phreatophytes, reach right down to the water table and drink ground water. That portion of precipitation that reaches the water table is called recharge. In virgin equilibrium, the recharge equals the sum of

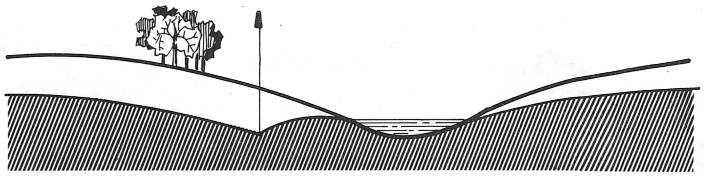

Figure 5-3. Equilibrium Water Table with Well

streamflow and the evapotranspiration of phreatophytes. Removal of ground water through a well causes the volume of stored ground water to decline until a new equilibrium is established. The lowering of the water table eventually reduces the flow in nearby streams, and, if there are phreatophytes, it may reduce their evapotranspiration. After a new equilibrium is established, the well discharge is just equal to the reduction in stream flow and evapotranspiration.

It is important to realize the significance of this simple fact. In equilibrium all water taken from wells is, in effect, stolen from streams and plants. Thus the capacity of an aquifer to yield water depends less on the rate of recharge than on one's willingness to reduce stream flows and the welfare of phreatophytes, if there are any. Of course there are other constraints on groundwater use also. Among them are salt water intrusion (esp. along seacoasts), land subsidence over mined-out aquifers, manmade pollutants, and interference between neighboring wells.

If water is sucked at a moderate rate from the center of a pond, the surface, so far as the eye can see, remains flat as it recedes. But there must in fact be a slight depression toward the middle—otherwise there would be no pressure gradient to drive the water in from the edges. Since the resistance to the inward flow is slight, only a slight distortion of the surface develops. In the ground, where the resistance to the flow of water is high, a very deep depression of the water surface (or of the potential head in the case of a confined aquifer) called the "cone of depression" develops around a withdrawing well. As time passes the cone slowly expands until it reaches a lake or stream. The surface ultimately comes to rest in a new equilibrium in which the flow through the lake or stream is reduced by the amount of the well withdrawal. Figure 5-3 shows the equilibrium shape of the water table after a well has been introduced into Figure 5-2.

The time from a disturbance to a new equilibrium may be very long. A well in permeable ground right next to a river may stabilize in days or weeks, but in other places only after decades or even centuries. Thus almost everywhere where the water table has been disturbed by man, it is in a state of disequilibrium. In some places, particularly in the West, aquifers are being "mined." These aquifers will go dry before a new equilibrium is established.

In the East the prospect is for ultimate equilibrium with surface flows. In this state, as we have seen, water taken from wells is merely subtracted from rivers (assuming phreatophytes are not a factor), and thus does not add to available supplies. But this does not mean that aquifers are useless. They can serve any or all of three functions: they can act as filters, as conduits, or as reservoirs. In the last role they are smoothers of fluctuation.

In nature, aquifers provide a great deal of smoothing of surface flows. Indeed, without them streams would be torrential during rains and dry in between. But the storage capacity of the ground is very large and it could provide even more smoothing than it does under natural conditions. In order to realize this extra smoothing, however, it is necessary to operate wells intermittently, just as it is necessary to operate the gates of an off-stream surface reservoir intermittently if it is to equalize the flows in a stream. Constant withdrawal from a well accomplishes only a diversion of water, but no smoothing of surface flows.

To set up an effective schedule of well withdrawals, one needs to know the effect of each well on surface flows. Figure 5-4 shows in a hypothetical case the surface flow deficit resulting from the short term pumping of a well. The effect can be spread out over weeks, months, or even years, depending on the permeability of the ground and the distance of the well from the nearest streams and lakes. If these parameters are right, then the well water can be taken during a period of low surface flow and the flow deficit can occur largely during the following high flow season. A nice application of this principle is proposed by Young and Bredehoeft for a stretch of the Platte River:

> One can design a pumping system to take advantage of the delay between groundwater pumping and its effect on the stream and thus use the aquifer as a storage reservoir. The aquifer underlying the South Platte Valley represents the largest available reservoir remaining on the river. A properly designed conjunctive use system will store water during the nongrowing season for pumping during the growing seasons. By using the delay time of the aquifer, the groundwater reservoir can be operated so that it will have only a small effect on the stream during the growing season.[17]

Even without precise location of wells and timing of withdrawals, however, some smoothing of surface flows can be achieved. If a well is far away from the streams it affects, the intermittent use of the

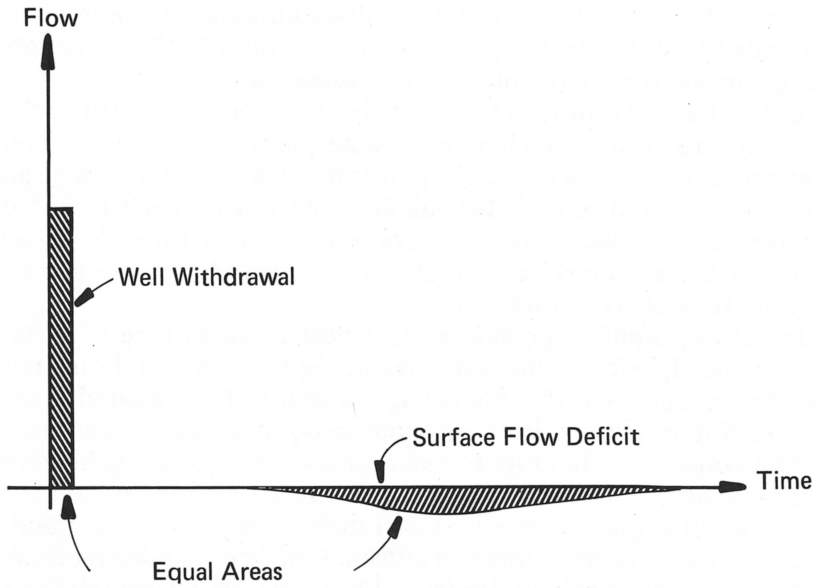

Figure 5-4. Effect of Well on Surface Flow

well may produce a nearly uniform reduction in surface flows. Using such a well during low flow periods in conjunction with a pipe that takes surface water during high flow periods can produce a steady supply of water that depletes high flows more than low flows. The net smoothing effect is similar to that of a surface reservoir.

The region that would be served by the Tocks reservoir contains a great deal of ground water, much of it now withdrawn in a continuous way that uses the aquifers only as pipelines but not as reservoirs. To assess the real potential of the region to produce a continuous flow of water, it would be necessary to postulate an extensive system of conjunctive use of ground and surface water. This apparently has not been done. The NAR Study[18] does give estimates of total potential ground water yield by region, but these are based on annual recharge rates. As we have seen, recharge rates do not contain the information we would really like to have. Bredehoeft and Young comment on the recharge approach as follows:

> Commonly, hydrologists make a water budget in which estimates of the virgin rate of recharge and discharge are made. Some think that the magnitude of the virgin rate of recharge and/or discharge indicates the size development that can be made in the system. Theis (1940) pointed out the difficulties of such an approach. A water budget is usually of little or no

value in assessing the capability of wells in the system to yield water, the water levels at any point in the system, and changes in the rates of discharge and/or recharge.[19]

3. Putting the Eggs in Many Baskets

Insurance companies and portfolio managers count on averaging fluctuations from many sources. If the sources are sufficiently independent, then, on the average, the peaks and troughs from different sources will tend to cancel out so that the aggregate is smoother than any typical component. In a similar way, electric power companies attempt to average fluctuating demands in different places by means of large interconnection grids.

Unfortunately, dry spells tend to be widespread, so that the analogous interconnection of neighboring water systems, unless done on a very large scale, would accomplish relatively little smoothing. However, there is some local variation in the difference between demand and capacity that could be leveled by better interconnection. In particular, northern New Jersey, which is served by dozens of small independent companies, could increase its effective margin of safety by better interconnection arrangements.

4. Shifting the Burden

Unwanted fluctuations tend to propagate through whatever system they infect. This is true whether the system is an electronic circuit subjected to noise, or a production process subjected to fluctuating demand or supply. Fluctuating rainfall leads to fluctuating grain yields, which leads to fluctuating income to the farmer. In such systems the unwanted fluctuations are often attacked at various points by various means. Reservoirs level out the water supply, grain storage levels out the grain supply, and insurance, or its equivalent, levels out the farmer's income. Ultimately, these disparate undertakings are all aimed at the same fluctuation, and they therefore tend to trade off against one another: Do you store the water or do you store the grain? Or some of both?

One way of dealing with fluctuation, then, is to transfer it from one part of a system to another where it will do less harm. In some manufacturing industries it is common practice to match output to a randomly fluctuating demand by means of frequent layoffs and rehiring. To counteract the untoward effects of this on their members, some labor unions have demanded a guaranteed annual wage, whose effect is to transfer the burden of the fluctuation from the employees to the stockholders, who, they argue, are better equipped to absorb it.

A case involving water occurs in the Northwest, where electricity generated by water is used, among other things, to make aluminum. When water is short, aluminum production is interrupted, and demand is met from aluminum stockpiles. This effectively substitutes aluminum storage for water storage. At the economic optimum the marginal cost of enlarging the power reservoirs would be equal to the marginal cost of equivalently increasing the aluminum stockpile. Fluctuations within systems, then, can be suppressed at various points or can be transferred to other points. To recognize all the options this implies, it is necessary to look at whole systems at once and not just pieces.

In water supply planning, institutional, political, and conceptual constraints have often restricted the view to something less than the whole system. Attention has been focussed primarily on physical hydrology and the engineering of dams and conduits, and much less on the economics of demand and the technology of water use. Demand is usually estimated by simple extrapolation of aggregate quantities, while supply systems are designed and optimized with elaborate sophistication to insure that they will meet the estimated demand "safely." The reliability of the supply—which, in spite of the language, is not perfect—tends to be measured primarily by the probability of its failure and not by the sizes of the deficits, or their costs to water users. Demand for water tends to be seen as rigid and inviolable so that any deficit is a disaster. Water, it is said, is essential to life.

A consequence of this view is that fluctuation is suppressed as close to the source as possible by means of storage. As little fluctuation as possible is allowed to propagate out into the rest of the system. But it may be that the rest of the system is less intolerant of fluctuation than we might have thought. Some water is indeed essential to life and its supply cannot be interrupted, but this is only a small fraction of what we use. For most purposes water is no more than a valuable commodity, among many others. In a well ordered economy the cost of handling fluctuation at various points in the system would be traded off against the cost of eliminating the fluctuation at the source.

5. Living with It

The idea of tolerating fluctuation is directly contrary to the concept behind the phrase "safe yield." Under the safe yield concept a sharp distinction is drawn between continuous and intermittent supplies, and in principle only the former are regarded as having any economic value. Since absolute continuity cannot be achieved in

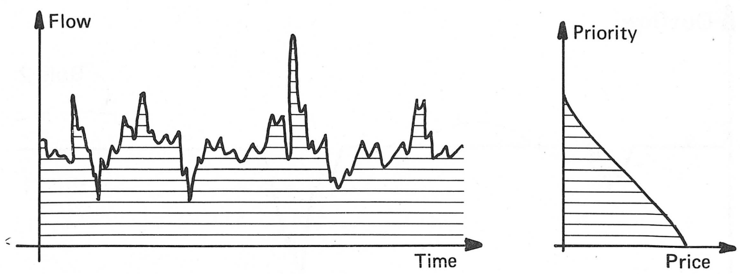

Figure 5-5. Subdivision of Flow

practice, an arbitrary risk level is set to distinguish the valuable from the worthless supply streams.

It may well be, however, that the distinction is not sharp, and that the real economic value of supply streams falls off gradually with increasing intermittency, i.e., with increasing frequency and length of gaps. Consider, for example, a fluctuating source as depicted in Figure 5-5. If the flow is divided into layers as in the figure, the lowest layers are least intermittent and the highest layers are most intermittent. If the layers were sold separately (in the form of priority rights) the price would diminish monotonically from the lower to the higher layers. A reservoir, or other smoothing device, would create more of the high value layers at the expense of the low value ones, thereby increasing the value of the whole supply. This formulation presents us with a classic economic optimization problem. At the optimum, the cost of a further increment of smoothing exactly equals the increase in value the smoothing generates. In general the optimal smoothing will be less than total.

The economic value of the smoothing achieved by a reservoir depends not only on the size of the reservoir but also on the way in which it is operated. This can be illustrated by contrasting two operating rules: (1) Water is released at a constant rate r, so long as the reservoir is not empty; (2) water is released at a rate $r(Q)$ that varies with the quantity Q of water stored in the reservoir. The output under the two rules is shown qualitatively in Figure 5-6. Thus, Rule 1 produces infrequent severe shortfalls; Rule 2 produces more frequent but milder shortfalls. Which one is economically preferable depends on the character of the market for intermittent supply. If a surface reservoir is operated conjunctively with a well field, Rule 2 might be advantageous for the following reason: the capital cost of the well and pump depends on its yield. A small well operated for long periods is cheaper than a big well operated for

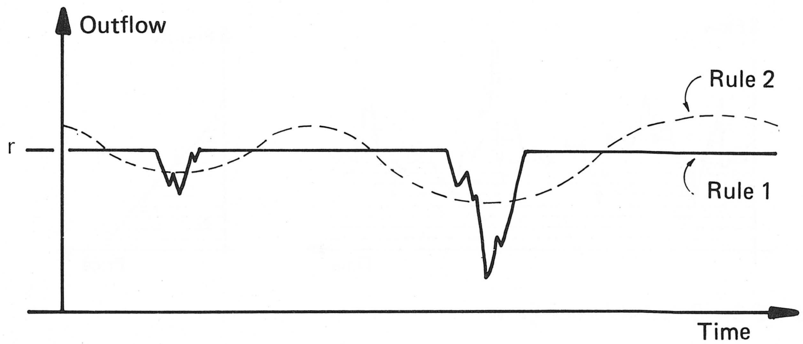

Figure 5-6. Effects of Different Reservoir Operation Rules

short periods. Thus the conversion of short severe shortages to long mild ones reduces the cost of the well.

Instead of slicing the flow graph horizontally, as in Figure 5-5, one can slice it vertically and attach prices to the vertical slices according to their height. In times of shortage (short slices) the price would be high and in times of plenty (tall slices) the price would be low. This is similar in principle to the "peak load pricing" telephone and power companies use to encourage their customers to level their demand over time. If the economist's device of exponential discounting for comparing values at different times is accepted, then horizontal and vertical slicing of the flow graph are nearly equivalent.

With an appropriate pricing scheme in effect, what might the market for water of graduated intermittency look like? If the cost of reservoir supplied insurance water is really $22 per thousand gallons as the Institute of Public Administration report maintains, then the incentive to buy relatively low priority water for some uses would seem to be substantial. Would a car washing establishment improve its profit by buying low priority water along with insurance against business lost during rare dry spells? Could a water using manufacturer of a storable product (soft drinks) profitably use low priority water and sell from inventory during gaps? A great deal of summer demand is for lawn watering in some places. How much is it worth not to tolerate a brown lawn every few years? How uniform must our habitat be?

Making our habitat uniform is a primary human occupation. As Socolow observes in Essay 1 (p. 19), "The thrust of most of industrial society has been . . . to reduce man's vulnerability to nature's excesses, and, by extension, to reduce man's subordination to nature's variability." The devices we have invented to reduce our subordination to nature's (and man's) variability are legion. Air conditioning levels out the varying temperature, electric lights level out the varying illumination, and Muzak levels out the mood. Mutual funds smooth out the financial bumps of the market place and accident insurance, however lamely, attempts to smooth over some of life's pain. The drive for uniformity and regularity is very general: it extends to spatial as well as temporal fluctuations. The irregular cave is replaced with planar floors, walls, and ceilings; the superhighway cuts straight and level through the undulating landscape. Corners are square, lines are straight, circles are round; the works of Euclid are visible on every hand.

Science fiction writers, extrapolating the human striving for regularity to its limit, have created visions of totally uniform environments, usually underground. In E.M. Forster's story, "The Machine Stops," each person lives alone in an underground cell, which he seldom leaves:

> Imagine, if you can, a small room hexagonal in shape, like the cell of a bee. It is lighted neither by window nor by lamp, yet it is filled with a soft radiance. There are no apertures for ventilation, yet the air is fresh. There are no musical instruments, and yet, at the moment my meditation opens, this room is throbbing with melodious sounds. An arm-chair is in the centre, by its side a reading-desk—that is all the furniture. And in the arm-chair there sits a swaddled lump of flesh—a woman about five feet high, with a face as white as a fungus. It is to her that the little room belongs. . .
>
> Night and day, wind and storm, tide and earthquake, impeded man no longer. He had harnessed Leviathan. All the old literature, with its praise of Nature, and its fear of Nature, rang false as the prattle of a child.
>
> Few travelled in these days, for thanks to the advance of science, the earth was exactly alike all over. Rapid intercourse, from which the previous civilization had hoped so much, had ended by defeating itself. What was the good of going to Pekin when it was just like Shrewsbury? Why return to Shrewsbury when it would be just like Pekin? Men seldom moved their bodies; all unrest was concentrated in the soul.[a]

IV. WATER SUPPLY IN THE DELAWARE BASIN

1. Original Tocks Planning

Although it was the sense of urgency created by the 1955 flood that stimulated the planning for Tocks Island Dam and its sister projects, three other purposes—water supply, recreation, and power—were pursued simultaneously. This was in accord with the pre-

[a]E.M. Forster, *The Eternal Moment and other Stories* (London: Sidgewick and Jackson, 1928).

vailing view that water projects should be as "multipurpose" as possible. Moreover, the accelerating and seemingly endless growth visible on every hand could easily be seen as demanding water development of all kinds. Before long, each of the purposes acquired its own sense of urgency in the minds of the planners quite apart from the urgency of flood control.

The drought of the 1960s, which came just a few years after the eleven-volume House Document 522 was published, lent further urgency to the water supply purpose, which soon overshadowed flood control as the main concern of the politicians and planners. Even today, with the memories of both the flood and the drought considerably faded, water supply remains the dominant theme of the dam's supporters.

Two quite different analyses of water demand in support of the dam were undertaken. The first, done before the drought by the Corps of Engineers, is contained in House Document (H D) 522, Appendix P, published in 1960.[20] The second analysis was done eleven years later (1971) by the DRBC. In the intervening decade, changes in technology, changes in public attitudes, new political pressures, and changes in the DRBC's own perceptions produced a new water use picture. Thus the sources of demand included in the DRBC analysis were almost entirely different from those included in the earlier one done by the Corps. In spite of this difference the demands projected by the DRBC neatly absorbed just the amount of water that was to be provided by the Corps' reservoir system over the 50-year planning period.

Although finding demand to fit supply, rather than the other way around, may seem backwards in this context, it is not, in a larger sense, necessarily the wrong way to look at things. As the finite size of the earth makes itself felt, our perception of progress is beginning to change. We are beginning to see progress in the adaptation of demands (hence of life style) to the finite supplies offered by the earth rather than in endless growth of supplies to meet arbitrarily given demands. In a curious and certainly inadvertent way, the DRBC adopted the viewpoint of the conservationists.

Among the motives of the DRBC in reanalyzing demand may have been a desire to correct the errors in the Corps' original analysis. As we shall see, certain conceptual faults in this analysis rendered its results virtually meaningless. The DRBC largely corrected these faults. Very briefly, the procedure in HD 522 is the following: The basin is subdivided into "problem areas," in which water "requirements" are estimated separately. Then the yields of the various reservoirs are assigned to the different areas so that the requirements of the latter will be covered. All the yield of the Tocks Island reservoir is assigned to the problem area labeled "Trenton-Philadelphia."[21]

Within each problem area, requirements are broken down into four categories: (1) domestic and municipal, (2) self-supplied industrial, (3) agricultural, and (4) upstream surface losses. Requirements in the four categories are added together and the sum is compared to the minimum flow in the stream. The excess of the requirements over the minimum flow is called "required augmentation." Reservoir yields are assigned until their sum at least equals the "required augmentation."[22] It is not clear what conception of river flows inspired this calculation. The calculation can conceivably make sense only if "requirements" are somehow reduced to the flow *in the river* necessary to accommodate all the various contemplated uses. Because of the great variety of these uses and the complexity of their interactions, such a reduction to river flow is not simple and, in fact, was not done by the Corps.

The point is sufficiently illustrated by the Corps' treatment of the first category, "domestic and municipal" requirements. Except for a numerically minor adjustment, domestic and municipal requirements are set equal to the sum of all domestic and municipal withdrawals from the river. But the riverside communities put almost all the water they withdraw back into the river as waste water. Moreover, the points of withdrawal and discharge are distributed along a considerable stretch. The city of Trenton, for example, withdraws and discharges several miles above Philadelphia. The quantitative effects of the various withdrawals and discharges on the river's flow are at once complex and slight. They have no relationship whatever to the "required augmentation" calculated by the Corps.

In any case, the details of the Corps' calculation, which concerned only water quantity, are largely beside the point, because the real problem for Trenton and Philadelphia is not water quantity, but pollution. To be sure, augmentation of flow may have an effect on pollution control, but the effect is not simple. It depends, among other things, on the local patterns of mixing and diffusion, which in the Trenton-Philadelphia area are complicated by tidal oscillations. By pushing pollutants downstream, it is even possible for low-flow augmentation to worsen pollution at some places and times.

In Appendix C, prepared by the Public Health Service, House Document 522 does discuss water quality in some detail. With respect to low-flow augmentation the Health Service concludes the following:

> It was indicated above that an increase in fresh water flow to the estuary from the present minimum monthly of 2,610 cfs to a regulated minimum

> of 4,060 cfs in 1980 will result in a relatively small increase in dissolved oxygen above the [Delaware] State line and an even smaller decrease in dissolved oxygen below the State line. Although it is anticipated that the quality of the estuary in 2010 will be somewhat less than at present, it is believed that the further increase in regulated flow from 4060 to 4720 will not result in a further significant increase in dissolved oxygen. Nor is it believed that the additional increase in fresh water inflow will significantly decrease further the dissolved oxygen levels below the State line. Further, it is not anticipated, then, that the increase in fresh water flow augmentation will change the dissolved oxygen levels in the estuary to such an extent that additional sewage treatment facilities can be deferred. As was pointed out in Part B, the quality of the estuary can be maintained at least at present levels only by substantial increases in waste treatment measures. Undoubtedly, the addition of low flow regulation will supplement the waste treatment programs, but it is estimated that the quality of the estuary will not be altered materially by the augmentation of low flows. A tangible monetary benefit can not therefore be ascribed to the increase in flow, although an intangible supplemental benefit should be recognized.[23]

It appears, then, that H D 522 did not provide any really clear and convincing uses for the prodigious quantities of water to be stored behind the Tocks Island Dam. In addition to the Trenton-Philadelphia water supply, H D 522 does mention briefly three other possible uses of Tocks water, but for various reasons it dismisses them as unimportant. It is precisely these three uses that dominate the DRBC's 1971 report.

A. **Electric power plants.** Power plants use enormous amounts of water for cooling. In the late 1950s, at the time H D 522 was being prepared, the standard cooling technique (called "once-through") was to withdraw water from a river, run it through the power plant's condensers, then discharge it back into the river. The Corps dismissed this water use "as imposing no specific demands on developments for augmenting stream flows since the return to the stream is equivalent in quantity and quality to the withdrawals in each instance of such use."[24] On close scrutiny, this seemingly obvious proposition turned out to be false. In passing through a typical condenser, the river's water is heated by about 20°. After discharge to the river, the water dissipates this heat in part by evaporating some of itself. Until the late 1960s, it was apparently not widely recognized that the water thus lost is appreciable.

In the meantime, another more serious side effect of once-through cooling came to light. Very large power plants created such large masses of heated water in the downstream stretch that fish could not escape, and some susceptible species were killed in large numbers. This effect, among others, forced the power companies to look for alternate methods of cooling. One commonly considered method evaporates water in huge hyperbolic towers. No hot effluent is discharged into the river, but evaporative losses are about twice as high as with the once-through method. Another technological change—the coming of nuclear power—threatened to drive the evaporative losses even higher. Because of their lower thermal efficiency, nuclear power plants generate in the condensers almost twice as much waste heat per useful kilowatt-hour as fossil plants; hence they must evaporate almost twice as much water (see Essay 7).

These two technical developments, each contributing almost a factor of two to water losses associated with power plants, occurred, or became prominent, during the decade following the publication of H D 522. Together with the apparently burgeoning demand for electricity, they created the raw material for truly horrendous projections of evaporative water consumption. Thus it came about that an element of water demand that was dismissed in one sentence by the Corps in 1960 played a major role in the analysis of the DRBC in 1971.

B. Salinity Control. Downstream from Philadelphia, the estuary becomes gradually saline. Water is considered unsuitable for drinking (i.e., salt can be tasted by some people) when the concentration of chloride ions exceeds 250 parts per million (ppm).[b] Therefore, one is especially interested in knowing the location of the boundary between water that is more and less saline than the 250 ppm standard. This boundary is often called the "critical isochlor" or "salt front," though the latter term is misleading since the salinity change is gradual. Tidal motion causes the critical isochlor (along with all its noncritical companions) to make daily excursions up and down the estuary. In addition, the volume of fresh water coming down the river influences the position of the isochlors. Spring floods drive them down the estuary; droughts allow them to creep upstream.

During the drought of the middle 1960s the critical isochlor reached the most upstream point of record and caused the authorities some concern that it might reach the Torresdale intake of the Philadelphia water system, or that saline water might seep into certain riverside wells used by the city of Camden. Emergency

[b] It is common practice to measure salinity by the chloride ion concentration. In seawater, the chloride ion concentration is 15,000 ppm. Most sea salt is sodium chloride.

releases of fresh water from upstream reservoirs were made in an effort to hold the salt back, and contingency plans for running Philadelphia's intake pipes upstream were drawn up. Although the 250 ppm isochlor was still ten miles downstream from Torresdale at its highest point, and the maximum salinity observed at Torresdale was about 50 ppm of chloride, the experience was felt by the DRBC and other water authorities as traumatic, and it strongly influenced their subsequent thinking.

Back in the days of H D 522, the dramatic image of salty water coursing through the Philadelphia mains seems to have been absent. H D 522 treats salinity control almost casually as a mere convenience for estuarine industry:

> Of particular interest to the water users in the tidal section of the Delaware River is the contribution that may be secured through the control of salinity. The salinity front, while not affecting sources of water currently being utilized for domestic supplies, continually poses treatment problems for water-using industries downstream from Eddystone in the Chester-Marcus Hook area.[25]

As we saw, salinity control was not an element in the Corps' 1960 calculation of "required augmentation." In the DRBC's 1971 analysis it constituted the largest single element.

C. Out-of-Basin Exports Within New Jersey. Of all the "golden numbers" associated with Tocks Island, perhaps the most golden of all is 300 mgd. The meaning attached to this number varies somewhat, but usually it is taken to be the amount of water northeastern New Jersey will some day have to import from the Delaware Basin. Most people profess ignorance of its origins, but some water resources officials claim that it goes back to the mid 1920s, which means that the famous number will soon be celebrating its fiftieth (or golden) anniversary.

Its true origins are somewhat obscure. The 300 mgd per se seems to go back only to about 1955, though its ancestry may well extend all the way back to the 1920s. One researcher, examining the question for the DRBC, found that reports from 1922 to 1955 consistently projected a diversion from the Delaware to northeastern New Jersey of about 400 mgd.[26] Apparently it became customary in water supply planning to supplement various reservoir schemes in northern New Jersey with a diversion from the Delaware of this amount, despite the varying projections of demand and advancing time horizons. How the 400 mgd got translated into 300 mgd is not clear, but it may have resulted from subtracting off the diversion through the Delaware and Raritan Canal, whose capacity is generally taken to be about 100 mgd.

In the 1955 TAMS report,[27] the Delaware and Raritan Canal diversion was indeed separated from a 300 mgd, which figured prominently in the conclusions. This latter figure, however, was not the amount of water northeastern New Jersey would have to import from the Delaware Basin, but was rather the amount northeastern New Jersey would need by the year 2000 from *all* new sources beyond what it could obtain by expansion of its existing sources. The report believed that the entire 300 mgd could be obtained from the interior of the state if necessary, though the plan preferred by TAMS provided for 100 mgd to be obtained from the Delaware and 200 mgd from the interior of New Jersey. According to the summary of the report given in H D 522:

> The final report on the [TAMS] survey stated that specific studies of surface and ground water resources show that there are sufficient potential water resources available to the State of New Jersey to provide for predictable needs. All of the State's water requirements to the year 2000 can be met entirely from resources within the boundaries of the State. These can be developed without interstate agreements, or approval of the Supreme Court of the United States. There are, however, economic advantages in using water from the interstate Delaware River to provide the additional supplies which will be needed in the State's Northeastern Region after 1966.[28]

In spite of the "economic advantages," the Corps did not include any exports to New Jersey in its demand projections, as we have seen. In fact, it regarded exports to New Jersey as outside the limits of its responsibility:

> Since diversions from the basin are authorized by the U.S. Supreme Court, it would be presumptive to project, for purposes of this investigation, diversions to satisfy, wholly or in part, the water needs in adjacent areas at designated dates in the future. Therefore, except for current diversions, the water uses of primary interest are those within the basin's boundaries. Furthermore, this approach was supported by the fact that local water resources and their capabilities to satisfy the water needs in the areas adjacent to the basin were beyond the scope of this investigation.[29]

Putting New Jersey beyond the scope of the investigation is particularly striking in light of the dominant role New York's diversions had played in the history of the Delaware Basin starting as far back as the court battle of 1930. The possibility of a New Jersey diversion was not entirely forgotten, however. After the comprehensive plan was set, the Corps simulated its operation on paper, applying water input data from the 1930–31 drought, and found the safe yield for the year 2010 to be 367 mgd higher than they had expected. This excess, they remark, could be drawn upon for diversions to Wilmington and northern New Jersey.[30] Though not entirely forgotten, northern New Jersey clearly had low priority in H D 522.

At the time of the preparation of H D 522, there was no controversy and the 300 mgd had not yet become a golden weapon. This role came later as the number was passed about among the adversaries in the ensuing controversy. In hearings it was repeatedly quoted by proponents of the project with authority and urgency, and was often associated with this or that deadline. So formidable did it become that opponents of the dam chose not to challenge it but instead expended great effort in devising schemes for diverting the golden 300 mgd from the Delaware without the Tocks Island Dam.[31] The State of New Jersey lent it official status by formally requesting permission of the DRBC to make the 300 mgd diversion some time in the future. To date, permission has been neither granted nor refused. By 1971, when the DRBC staff undertook its reanalysis of demand, the 300 mgd diversion had become so well established that the DRBC could confidently include it as a major element in demand without detailed justification, although privately emphasizing that its willingness to grant New Jersey's request could not be considered a foregone conclusion.

During 1975, as New Jersey officials prepared for the DRBC decision on Tocks that was to be made in August, water supply in the northeastern part of the state was uppermost in their minds. The main question was whether imported Delaware River water would really be needed.[c] Comparing the cost of transporting Delaware water to northeastern New Jersey with the cost of developing a series of local sources, the officials found, somewhat to their own surprise, that the former was higher. This discovery played a role in New Jersey's negative decision on Tocks in 1975 and, for the time being at least, it put the golden number on the shelf.

2. The DRBC Projections of 1971

It is not clear to what extent the DRBC's reanalysis was motivated by a desire to correct the faults in H D 522. Certainly these faults had been criticized many times, but there is little evidence that the

[c]For the political context of this story, see Essay 3.

criticism was of much concern to the dam's proponents. As late as 1971, in testimony submitted to a committee of the Pennsylvania legislature, the Corps included a verbatim copy of the key Table P-10 from H D 522, which summarizes the faulty calculation outlined above.[32]

Whatever the DRBC's motivation, its reanalysis did in fact correct the conceptual errors in HD 522. Instead of vaguely equating water withdrawals with water "use," it clearly specified depletive uses so that inputs and outputs could be treated in a consistent fashion.

The DRBC analysis is implicitly based on what might be called the "bathtub model:" The river from Montague to Trenton is seen simply as a tub with the sum of the inputs balanced against the sum of the outputs. Only water not returned is counted in the outputs. This of course, drastically reduces the amounts attributed to municipal use by Trenton and Philadelphia. The DRBC somewhat arbitrarily takes municipal losses (i.e., net consumptive use) to be 10 percent of withdrawals.

Although the bathtub model is adequate for many purposes, complications arise when the water is taken from the fresh-salt transition region. For some time the DRBC staff treated water evaporated from any location as a simple withdrawal from the bathtub:

> It is worth noting that the consumptive use of brackish water from the Tidal Delaware River and Bay, *no less than* consumptive use of fresh water, unless compensated by regulation of fresh water inflow during critical low flow periods, will result in greater concentration of sea salts in the estuary and upstream advance of any isochlor. [Emphasis added.][33]

This statement is not correct. Water evaporated from the saline part of the estuary has less effect on the upstream salt distribution than the evaporation of an equal amount of water from the fresh part of the river. The effect diminishes gradually with position downstream. There is, in fact, substantial conservation gained by moving power plants to the estuary. In 1974 the DRBC staff modified their excessively conservative position as a result of a consultant's study.[34]

The DRBC demand and supply projections are summarized in Figure 5–7. The figure brings out clearly the importance of the three depletive uses discussed above: electric power, exports, and salinity control. Without these, present capacity (no Tocks) is more than adequate well beyond the year 2000. Even including electric power and exports, present capacity serves until 2010. The really critical item, dwarfing all the rest, is salinity control. The salinity control

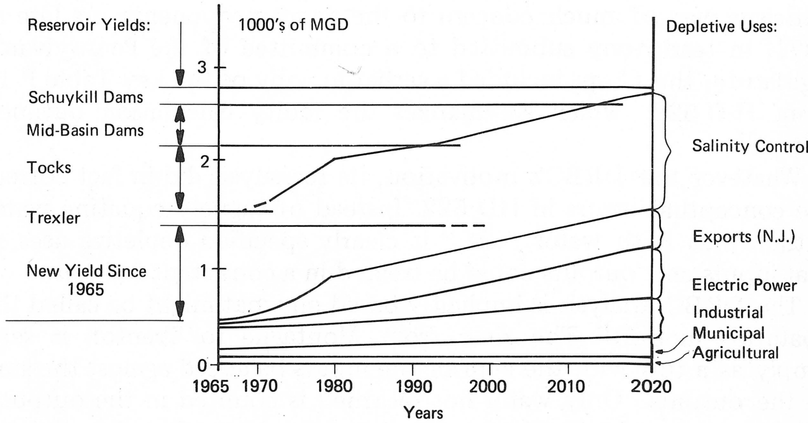

Figure 5-7. Water Demand and Supply as Given by the DRBC Staff Report of 1971.

This figure does not appear in the DRBC report but is derived from the data in the report. By "reservoir yield" the DRBC apparently means the amount by which the minimum flow at Trenton could have been increased during the worst drought year if the reservoir had existed. Unfortunately, this amount depends on how much other storage capacity is already there: the first increment of storage increases the minimum flow more than the second and so forth. Thus the first interval on the chart, "new yield since 1965," seems disproportionately large. Most of this interval represents the difference between the minimum flow at Montague now required by the Supreme Court decision and the actual minimum flow at Montague that occurred during the drought. The DRBC study assumes that the present minimum flow requirement would be met in a future drought.

layer in Figure 5–7, of more than 1,000 mgd, represents the *additional* margin of low flow, above that which occurred at the depth of the 1960s drought, that the DRBC wanted to have. The DRBC's water supply justification for the Tocks Island Dam rested heavily on the validity of this margin.

The DRBC's projection of water use for salinity control shown in Figure 5–7 was based on their minimum flow standard of 3,000 cfs at Trenton. This number had become firmly imbedded in the Tocks controversy and had assumed the typical golden hue. Skeptics of the dam tended to dismiss it out of hand with comments such as: "It was pulled out of a hat; they might as well have chosen 2,000 or 4,000," or: "They used 3,000 because they thought they were going to get the dam, and that's how much the dam could provide," or: "During the drought the flow was way below that and the salt never got anywhere near Philadelphia," or simply: "It's just a golden number." The DRBC defended the number as essential to both pollution and salinity control in the estuary, giving three specific reasons: (1) to protect Philadelphia's water supply from excessive salinity; (2) to protect the aquifers, particularly in Camden, that are recharged by the river, from excessive salinity; and (3) to maintain the waste assimilative capacity of the upper estuary.

The last reason is somewhat different from the other two. The DRBC's pollution control plan was based on mathematical modelling of the estuary done by the Delaware Estuary Comprehensive Study (DECS). The particular calculations supporting the DRBC's dissolved oxygen objectives assumed the 3,000 cfs minimum inflow at Trenton. The figure therefore became embedded in the pollution abatement program.

In principle, the purpose of maintaining a minimum flow is to provide a minimum degree of dilution of the river's pollution load. But dilution tends to be unsatisfactory for two reasons: first, because large amounts of clean water are usually needed to have much effect, and second, because the extent of the polluted water is increased in the same ratio that the concentration of pollutants is decreased. Congress, in its Water Resources Act of 1972, specifically forbade government agencies to substitute dilution for control of sources:

> In the survey or planning of any reservoir by the Corps of Engineers, Bureau of Reclamation, or other Federal agency, consideration shall be given to inclusion of storage for regulation of stream-flow, except that any such storage and water releases shall not be provided as a substitute for adequate treatment or other methods of controlling waste at the source.[35]

On the Delaware, the beneficial effects of dilution appeared to be small in any case. According to a 1966 report based on DECS work there is no improvement in the minimum level of dissolved oxygen when a steady inflow of 6,000 cfs is compared to the DRBC's 3,000 cfs. The effect of the increased flow is merely to move the oxygen sag downstream. At points downstream of the Philadelphia Navy Yard, the dissolved oxygen is actually reduced by the higher inflow (see Fig. 5–8).[d] Dilution was not, in fact, a large part of the DRBC's abatement program. This program depended primarily on reduction of effluents. In the minds of most people, and indeed in most DRBC documents, the dominant reason for the 3,000 cfs minimum was control of salinity.

In the context of salinity control, the 3,000 cfs had tended to assume an absoluteness that belied its true probabilistic nature. Since salinity is strongly related to fresh inflow, it can be stated more or less absolutely that maintenance of flow at Trenton above 3,000 cfs will keep the chloride concentration at the mouth of the Schuylkill

[d]This agrees essentially with the earlier HD 522 (see above, p. 193).

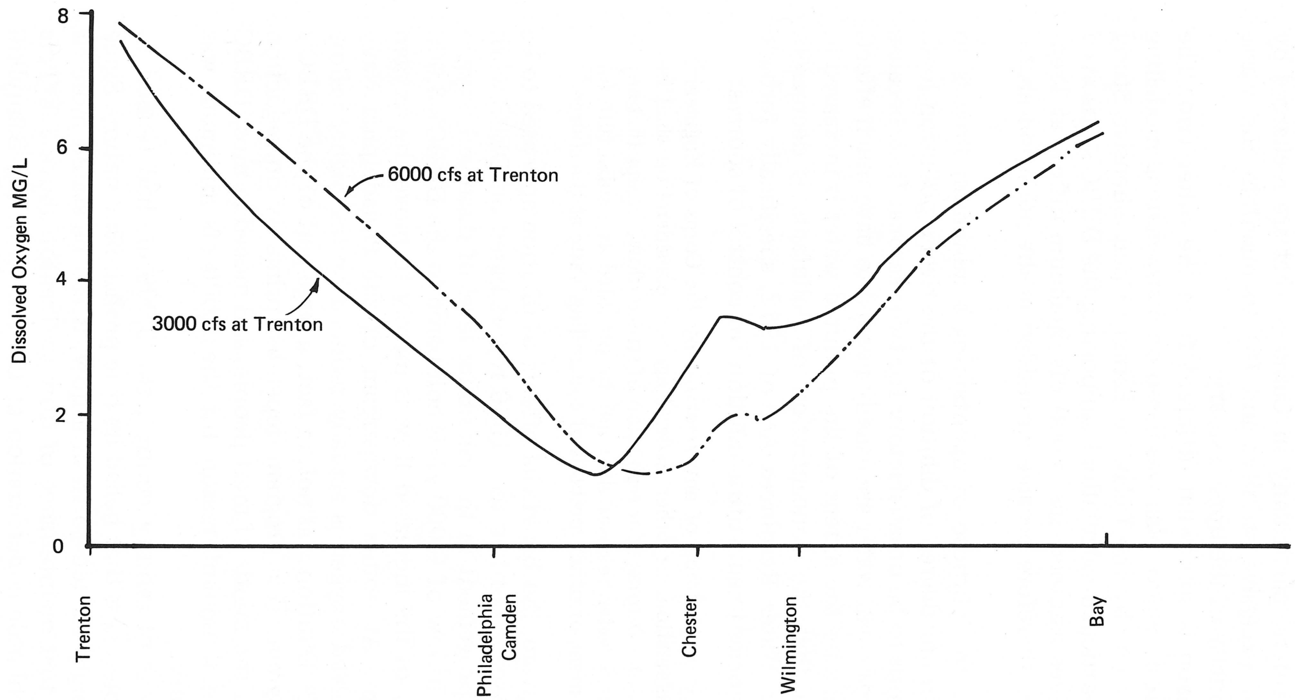

Figure 5–8. Dissolved Oxygen for Different River Flows[36]

Oxygen is depleted by pollution. The oxygen "sag" below Philadelphia inhibits the migration of fish and thus affects aquatic life in the whole river. Adjustment of river flow affects mainly the position of the sag rather than its severity. To raise the minimum oxygen level significantly requires not more flow, but abatement of pollution sources.

River below the 250 ppm drinking water standard.[e] The absoluteness was reinforced by statements such as that made by a member of the DRBC staff: "We set the 3,000 cfs minimum because we want to be sure that salt *never, ever* gets into the Philadelphia system." As Robert Socolow observes in Essay 1: "Public discourse is dominated by solutions offered as risk free."

Despite the stout words of the DRBC staff, the 3,000 cfs standard is not absolute but probabilistic, and like all probabilistic standards it has an inevitable degree of arbitrariness. Moreover, it is not, despite appearances, a flow standard at all, but a *storage* standard. Its precise meaning is the following: it is the amount of reservoir storage required to maintain a minimum flow of 3,000 cfs at Trenton in an otherwise exact replay of the 1960s drought. Its guarantee, then, is not absolute: in the improbable event of a drought more severe than that of the 1960s the minimum flow at Trenton would be less than 3,000 cfs, and the chloride concentration at the mouth of the Schuylkill would presumably rise above 250 ppm. Thus the control of salinity by means of reservoir releases, like any other water use depending on finite storage, inevitably involves risk. And the level of risk that one deems to be acceptable or unacceptable is inevitably somewhat arbitrary.

Risk is always composed of two elements: (1) the nature and cost of the dreaded event, and (2) the probability of its occurrence. There are, therefore, two ways of dealing with risk: (1) by preparing to cope with the event if it should occur, and (2) by reducing the probability of its occurrence. If the event is taken to be the appearance of saline water high upstream, then the DRBC's proposal of providing reservoir water to hold it back is an example of the second way.

There is some arbitrariness in defining the dreaded event. One could, for example, define it to be the occurrence of a drought of given severity, or the actual contamination of water supplies, or some other event. The choice of definition affects the assignment of countermeasures to the categories (1) and (2) given above, but aside from this inessential semantic effect the choice is largely one of convenience. I will arbitrarily define a dreaded event to be the occurrence of salinity S at point P for duration T. Associated with each such event, i.e. with each triple (S,P,T) is a probability p. The risk is determined by the set of event-probability pairs, or, equivalently, by the function $p(S,P,T)$. Before turning to the probability side, let us consider the nature of the events and their consequences.

[e]This is only more or less absolute because factors other than inflow, such as wind, also have an effect.

A. Philadelphia Water Supply. One event of obvious interest is the occurrence of water containing 250 ppm of chloride at Philadelphia's Torresdale intake for a period of days or weeks. Water of this salinity can be approximated roughly by dropping a pinch of salt into a quart of pure water. What happens if the tap water gets that salty? According to a compendium of water quality criteria published by the State of California, "restrictions on chloride concentrations in drinking water are generally based on palatability rather than health."[37] Thresholds of taste, however, are apparently highly variable, as are other physiological effects. The California compendium lists the following reports for sodium chloride:

> . . . taste threshold values from 200 to 900 mg/1[f] have been reported. Water containing more than 500 mg/1 of sodium chloride may be unpalatable and cause appetite disturbances. Although an excess of sodium chloride induces thirst or can act as a diuretic, water containing up to 1,410 mg/1 has been used by some communities for many years without appreciable harm; however, 1,000 to 1,500 mg/1 of sodium chloride generally renders water unpalatable. It has also been reported that 7,500 mg/1 of salt is harmless and that 10,000 mg/1 causes vomiting.

These figures presumably apply to healthy people. Heart and kidney patients on low salt diets have other requirements not based on taste. For water uses other than drinking, problems would arise at a wide variety of salinities, some at levels below 250 ppm, others only at much higher levels. Many of these would depend strongly on the duration of high salinity. Salinization of tap water, then, is far from a sharply defined disaster; on the contrary, it shades off gradually through a series of diverse problems from mere inconvenience to real disaster over a wide range of salinities and and durations. It is unlikely that this range is adequately represented by a single standard based on taste.

What are the real threats? To understand the nature of the event we are trying to deal with, we should examine each of the diverse problems in the series in its own right. And this should be done not only for sea salt, but also for soluble industrial substances, which, unlike sea salt, might *suddenly* appear in the river through some accident. How much does it cost to get pure water (or a substitute beverage) to people with special sensitivities or to feed fussy boilers in a pinch? We should know. The amounts of water needed for some

[f]One mg/l (milligram per liter of water) is the same as one ppm (part per million by weight). Because of the extra weight of the sodium, the drinking water standard, 250 ppm of chloride ion, is equivalent to about 400 mg/l of sodium chloride.

purposes, such as drinking, are miniscule compared to the whole supply.

Although Philadelphia has elaborate and effective plants for purifying the river water it uses, it lacks facilities for removing salts. As we saw above, desalting requires an expensive plant, and, for fundamental reasons, considerable energy. The energy required for dilute solutions such as 250 ppm of chloride or even 1,000 ppm, however, is much less than that required for sea water. One way Philadelphia could protect itself against salt would be to build a standby desalting plant. The probability of its being needed, even without Tocks, is so small, however, that this solution is unattractive. Much simpler alternatives are available in any case.

The salinity of tap water in Philadelphia would not necessarily be as high as that in the Delaware River. Philadelphia takes about half its water from the Schuylkill River, which is isolated from the Delaware estuary by a dam, and the water department is able to mix the water from the two sources. This mixing could provide a reduction in salinity by as much as a factor of two. It should be noted, however, that the Schuylkill has limited capacity. At one point during the 1960s drought the entire fresh flow was being taken so that no water at all went over the dam.

In 1950 an engineering firm, as part of one of the many Delaware development plans, proposed among other things an aqueduct running straight north from Philadelphia's Torresdale intake to a point just upstream of Trenton.[38] The purpose was not to avoid salt water, which was not considered a serious problem in those predrought days, but to avoid some of the manmade pollution in the lower part of the river. An alternative plan in the same report proposed a much longer aqueduct all the way to Wallpack Bend, some 70 miles away. An aqueduct to avoid salt water would not need to be as long as either of these.

A permanent aqueduct might not be necessary, however. During the drought, the Army Corps of Engineers made plans for constructing a temporary pipe of rubberized material stiffened by steel hoops to be submerged in the river itself. Fortunately, saline intrusion is not a sudden event, but one that develops gradually during the spring and summer, generally reaching its peak in the fall. In drought years the normal movement is merely exaggerated; thus there is time to undertake temporary construction, particularly if well prepared in advance. The temporary pipe has the economic advantage that much of its cost can be discounted by a factor depending on the probability of its being needed. Since this probability is very small, the discounting is heavy. To make a rational economic choice, one needs to compare the discounted cost of the temporary pipe with the cost of providing reservoir storage to achieve equivalent risks.

B. Ground Water in the Nearby Aquifers. From the vicinity of the Delaware estuary, where it is near the surface, the bedrock slopes gently downward to the southeast under southern New Jersey. It is overlain by a wedge-shaped series of unconsolidated strata that are saturated with water. The billions of gallons contained in these strata constitute by far the largest reservoir of ground water in the region. Virtually all the towns and industries along the New Jersey side of the river below Trenton take their water from wells.

Originally, the ground water, derived from precipitation, flowed out of the aquifers into the rivers and streams. In many places along the lower Delaware, however, pumping from nearby wells has reversed the gradient, causing water to flow from the river into the ground. Most of the water from wells very close to the river is in fact river water. Such wells are using the aquifer simply as a filter to remove some of the river's pollution. While the ground is very effective in removing bacterial and other suspended particles, it does not remove dissolved substances such as salt. The DRBC staff feared that if the river became saline, nearby wells would also.

Unfortunately, sea salt is not the only substance that passes through aquifers. Nitrates from septic systems and agriculture, as well as acids, metallic salts, some organic compounds, and other substances produced by industry all seep into the ground, forming blobs of contaminated ground water that slowly expand and drift down-gradient over periods of years or even decades. Nassau County on Long Island has recently issued bonds to construct a plant to remove the nitrates that have slowly accumulated in the ground water from the thousands of septic systems that dot the surface.[g]

Under southwest Philadelphia there is a blob of ground water several square miles in extent that is contaminated with sulphates. It is thought to have originated many decades ago with the dumping of sulphuric acid by a company that has long since gone out of business. But more recent accretions are thought to have occurred also. It is slowly expanding toward the south under the river and may ultimately pollute many wells in Camden. Chromium salts from within Camden itself forced the closing of a municipal well in January 1973. Other local spots of pollution have been discovered all up and down the heavily industrialized strip along the river. Camden is currently

[g]Removal of nitrates is essentially desalination, which, as we have seen, consumes a good deal of both capital and energy. Both of these are in short supply. Thus a technical fix of one problem aggravates another.

looking outside its city limits for new places to drill wells. As far back as 1955 the engineering firm TAMS,[39] in a comprehensive report on the Delaware Basin, suggested the possibility of running an aqueduct from Camden some 25 miles back into the pine barrens where water could be taken from the very large and still pure Cohansey aquifer.

Virtually all the wells within a few miles of the river draw from the Raritan-Magothy formation, which is near the surface there. It is this formation also which is suffering pollution under the industrial areas. Thus the possibility of saline intrusion into it from the river during a severe drought is only one of the threats to its purity—and by no means the most urgent. Protection of ground water from all sources of pollution should be given at least as much attention as the protection of surface water. But as one geologist remarked, ground water is not visible; you can't swim in it and you can't paddle a canoe in it. It is easy to ignore.

Drought induced saline intrusion from the river differs from most other ground water pollution in that it is temporary. During the 1960s drought, brackish water lay in the river for many days opposite nearby wells that were believed to draw much of their water from the river. Yet the well water did not become seriously brackish. In some cases the salinity rose temporarily, but only to a much lower level than that observed in the river. This was probably due to time averaging, which is explained in a USGS report with regard to a particular well as follows:[40]

> [T]he water reaching the well at any time is probably a composite of water that left the river at various earlier times over a period of as much as several months, depending on the length of flow paths over which individual particles of water traveled.

Such averaged water would be much less saline than that momentarily in the river.

In order to devise a rational plan for protecting the aquifers against the effects of drought, it would be necessary to determine how severe conditions would have to get—i.e., how saline the river would have to be for how long—before any wells would be seriously contaminated. More generally, one would need to know how many wells would be affected to what degree and for what period over a range of river conditions. Since actual conditions have never been severe enough to provide this information directly, it would have to be obtained by indirect means. The problem does not appear to be beyond the power of modern mathematical techniques.

The movement of ground water (along with any contaminants) is governed by the gradient of the head,[h] and this in turn is strongly influenced by the pattern of pumping from wells. By coordinating pumping rates at many wells over an extended area, it is possible to some degree to guide or stop the movement of contaminants. This technique is now used and will be needed increasingly to control industrial pollution.

In the case of temporary salt intrusion from the river, one has the additional parameter of time. To minimize the intrusion of saline water into the aquifer, one would want to minimize the gradient of head at the junction of river and aquifer during the period of high salinity. One might be able to do this, for example, by leaving nearby wells idle for some period ahead of time, replacing their yield with direct withdrawals from the river. During the idle period the aquifer would tend to fill and its gradients to diminish. Alternatively, inland wells could be substituted temporarily or permanently for those strongly connected to the river. As in the case of Philadelphia, the alternatives need to be examined quantitatively and their costs and risks compared to the costs and risks of salinity control by reservoir storage.

Let us turn now to the second element of risk—the probability that a dreaded event will occur. The probability of observing a drought of given severity in a randomly selected year is difficult to estimate. By definition, a "severe" drought is one whose like has rarely occurred, and about which, therefore, little is known. As with floods, one is faced with estimating the tail of a probability distribution with very little to go on. Moreover, human intervention (e.g., deforestation) may cause the probability distribution itself to change over time.

The severest drought of record in the Delaware Valley is that of the 1960s. According to an estimate made by TAMS, apparently conservative enough to justify positive language: "It is quite certain that the runoff in the driest year has a return period of at least 100 years and may increase to several hundred years in the lower reaches of the main river."[41] During this rare event, salty water reached higher up the river than had ever been recorded before, but it did not reach high enough or remain long enough to contaminate water supplies.

It is difficult to estimate how much rarer a drought it would have taken to actually cause contamination. In any case, the DRBC wished to provide a very large amount of reservoir storage—more

[h] "Head" at a point is the elevation to which water would rise in a well drilled at that point; "gradient of head" is the rate of change of head with position. Water moves in the direction of steepest downward gradient of head.

than all of Tocks, according to the DRBC's study (Fig. 5—7)—to reduce even further the probability of high salinity. In view of the already low probability and in view of the alternative means for dealing with salinity, the DRBC's proposal seems, on the face of it, excessively conservative and costly.

There is, however, in addition to the uncertianty of nature expressed in estimates of drought probabilities, a human uncertainty that needs to be taken account of. That is the uncertainty of New York City's behavior under the pressure of a water shortage. The Supreme Court decree requires New York City to maintain a certain minimum flow in the Delaware under all circumstances, but that is, despite its august auspices, only a human rule, which can be and has been broken by humans (see Essay 2). If one looks only at the map and the unbreakable rules of nature, then the direct conflict between New York and Philadelphia is clear. Any drop that New York takes is unavailable to rush down the river and help drive the salt from Philadelphia's door. During the 1960s drought the Supreme Court rule was temporarily suspended and the DRBC refereed the conflict by imposed compromises.

In the event of a severe drought, maintenance of a high minimum flow at Trenton, such as 3,000 cfs, might seem wasteful to competing water users, since it might mean sending several gallons of water down the river for each gallon protected. There is merit in policies that would tend to defuse such a conflict, and more particularly to decouple New York in a physical rather than a merely legal sense from Philadelphia, Camden, and other lower Delaware users. Displacement of Philadelphia's intake upstream, on either a permanent or a standby basis, management of the aquifers along the lower Delaware with conjunctive use of the river and nearby wells, provision by New York City for standby use of the Hudson all would have a decoupling effect.

3. The Consultants' Study of 1975[i]

Among the few pieces of new research done by the consultants who carried out the million-dollar study mandated by Congress in late 1974, was an attempt to estimate salt intrusion probabilities. This was undertaken largely through the efforts of an unusually ambitious and energetic young engineer name Charles Kohlhaas. The analysis made use of a sophisticated statistical technique on which Kohlhaas enlisted the aid of a respected expert, Michael Fiering of Harvard, with whom he had worked before.

[i] URS/Madigan-Praeger and Conklin-Rossant.

The results of the analysis were startlingly unfavorable to the dam, and appeared to constitute a major break for the opponents. Indeed, for a short while it appeared that a technical analysis, done at the eleventh hour, might decide the issue in a dramatic fashion, almost as if it had happened in the imagination of Walter Mitty. But in the end, the breakthrough did not occur after all, for reasons that shed light on the limitations of analysis in the pressure of controversy.

As noted above, the DRBC had set the absolute-sounding salinity standard of 250 ppm of chloride at the mouth of the Schuylkill, but had neglected to estimate the probability of its being violated. Moreover, there remained a substantial margin between this standard and actual salinization of important sources. The really pertinent information was the probability of actual damage of a given extent. And to determine this it was first necessary to find the probability of the occurence of salinity of given concentration, duration, and location along the river. It was to this question that Kohlhaas addressed himself.

The problem fell into two parts: first, finding the relation between river flows and the distribution of estuarine salinity, and second, estimating the probabilities of different river flow patterns. Putting the two parts together, one could estimate the probability that any specified salinity event would occur—for example, finding more than 250 ppm of chloride, the accepted maximum for drinking water, at Philadelphia's Torresdale intake.

A number of circumstances render the problem less straightforward than it might seem, most notably these: (1) the salinity distribution at any time depends not just on the momentary river flow at that time, but on the past pattern of flows extending back at least two or three months; (2) the historical record is not long enough to give a statistically adequate sample of the more unfavorable flow sequences that occur during droughts; (3) river flows are not determined entirely by nature, but in part by the human operation of tributary dams, both present and future. Although circumstances such as these complicated the analysis, they were by no means insurmountable.

The first part of the problem—the relation between flow and salinity—had been much studied, and although the available results were not in a form Kohlhaas could use, the tools were there. In fact, two different sets of tools were there, offering a fundamental choice of method. On the one hand there was a mathematical model of the estuary that expressed the governing physical mechanisms as differential equations; on the other hand there was a group of standard statistical techniques for establishing a purely empirical relationship between flow and salinity.

A similar choice confronts almost every analyst of a complex system. The first approach has the great conceptual advantage that it embodies the best theoretical understanding of the phenomenon being modeled and the great practical advantage that it is adaptable to hypothetical variants of the real situation or to parameter values outside the observed range. The second approach has the advantage that it reflects all the real world effects, including those that are necessarily neglected for the sake of simplicity in the mathematical-physical model. It often has the added advantage of being quick and simple to apply.

It is not difficult to cite cases in which either one of the approaches is better than the other. In the present case, in which the physics is well understood, there can be little doubt that the mathematical-physical model was the best for Kohlhaas's purpose,[j] and he did, in fact, prepare to use a computer version of a respected model of the Delaware estuary. But before these preparations were complete, he ran across some statistical work that convinced him that he could do the job more simply by means of a regression empirically relating past average flows at Trenton with measured salinities at the Torresdale intake.

This empirical relationship turned out to be a weak link in the argument. The difficulty was that significant amounts of sea salt had never really reached as high upstream as the Torresdale intake. It was therefore difficult to separate definitively the changes in salinity due to sea salt movement from changes in the background salinity due to varying pollution. Kohlhaas also used salinity observations at points downstream of Torresdale, where the sea salt effects were much larger, but it was difficult to extrapolate these results back upstream with sufficient confidence. This was a case where the practical advantage of the mathematical-physical model—its adaptability to hypothetical variants of the real situation (more extreme salinity events than had ever really occurred)—would have been especially helpful.

The second part of the job—estimating the probabilities of different river flow patterns—could not be done directly from the historical record because the record was too short and because future flow patterns would be influenced by future tributary or main stem dams. To solve this problem, Kohlhaas, in cooperation with Fiering

[j]For an opposite example, see Daniel Goodman's discussion of eutrophication models in Essay 9.

and with the aid of a computer, constructed a "synthetic streamflow sequence"that is, a sequence of numbers that had the same statistical characteristics as the sequence of historical natural flows and that conformed to the known behavior of river basins. Such a sequence, made sufficiently long, will in theory display all possible flow patterns of given length (say three months) with the right statistical frequency.

This sequence represented the natural flows as they would occur in the basin without dams. To get the effect of existing and possible dams, Kohlhaas ran the synthetic sequence through an existing computer model that can simulate any flow regulation scheme. When Kohlhaas put this together with his flow-salinity regressions, he found that the probability of even the most minimal salt intrusion in the Philadelphia-Camden area in any given year was only one in several hundred (the exact number depending upon the assumptions about upstream regulation), and further that the Tocks Island Dam would only reduce the probability moderately.

The opponents, needless to say, were jubilant. But the New Jersey state officials, who bore the burden of making a decision, were more cautious. Recognizing the potential importance of the result, they arranged for the DRBC to call a meeting of eminent hydrologists and others with a knowledge of the Delaware. For the reasons mentioned above, these experts were unwilling to accept Kohlhaas's relationship between Trenton stream flows and Torresdale salinity. Thus his startling results were largely nullified for political decision making.

This did not mean, however, that the experts thought that Kohlhaas's probability estimates were necessarily too low, only that they were not convincingly established. As one of them pointed out, the flows at Trenton in 1965 were not only below the DRBC standard of 3,000 cfs but in fact were below 2,000 cfs for several weeks without causing contamination of the Philadelphia and Camden water supplies. Moreover, the Kohlhaas-Fiering synthetic streamflow analysis assigned a very low probability to this flow event. That much could be said without the regressions.

The experts were unanimous in the view that a probabilistic streamflow model could and should be joined to the mathematical-physical model in order to obtain estimates of the probabilities of salinity events.[k] They agreed that Kohlhaas had identified and formulated an important question amenable to technical analysis. Thus Kohlhaas's energetic effort did achieve what rushed studies

[k]The DRBC has asked its staff to look into this. Another case of the fox guarding the chicken coop, though eminently logical according to the organization chart.

sometimes do: it forced a new question into the arena. This is not to say, of course, that the golden numbers (250 ppm at the mouth of the Schuylkill, or, more or less equivalently, 3,000 cfs at Trenton) will tarnish easily. Old hands among the dam's proponents were at pains to restore the gilt that Kohlhaas had temporarily knocked off. Said one: "The 250 ppm standard must be regarded as a fact of life."

Kohlhaas's effort did not achieve what rushed studies practically never achieve, namely the resolution of an outstanding question. Under the press of controversy, there never seems to be enough time to undertake the kind of sustained research that the resolution of issues usually requires. A most ironic instance was Tom Cahill's plea (in the McCormick Report on eutrophication) for the collection of nutrient data over several seasons. Since the Tocks decision seemed continuously imminent, it never seemed worthwhile to launch such a long term effort. Yet the decision remained hanging in part because of the missing data. Had the data collection been begun back in 1971, when Cahill recommended it, we would now be a long step ahead on the eutrophication issue.

The incident brought together in one room a group of scientists with intimate knowledge of the Delaware, and inevitably the discussion went beyond the narrow question at hand and raised the more basic one: How much do we *want* to deplete the river? The conservationists want to take as little additional water as possible (just as they want to pollute as little additional air as possible and pave over as little additional land as possible, etc.). Their opponents, the promoters of growth, want to take as *much* additional water as possible, with compensating releases from a dam.

The trouble is that the compensation is not complete, since it applies only to low flow: both the average flow and the variance of the fluctuations are necessarily reduced. The estuarine biologists among the experts were convinced that these effects could only be detrimental to the aquatic life. Inevitably, the issue came down to the costs and benefits of growth, or at least of conventional growth. The answer to the salinity question, if it were known, would set one of the terms of this trade-off.

NOTES

1. For a discussion of the economics of this sort of situation, see Coase, "The Problem of Social Cost," *Economics of the Environment*, ed. Robert Dorfman and Nancy Dorfman, (New York City: Norton, 1972), p. 100.

2. "The decision not to use the Hudson River was based on the poor quality of water in that source. As treatment processes could have been provided to

correct the quality deficiencies at far less cost than that of importing mountain water, it is reasonable to assume that a high value was placed on the esthetic quality of the more remote source." C.H.J. Hull, "Control of Raw Water Characteristics," Proceedings, 11th Sanitary Engineering Conference on Influence of Raw Water Characteristics on Treatment, University of Illinois, February 5, 6, 1969, p. 82.

3. *Ibid.*

4. Russell et al. *Drought and Water Supply, Implications of the Massachusetts Experience for Municipal Planning* (Baltimore: Johns Hopkins Press, 1970).

5. 1,400 gal/ton of steel vs. 35,000 gal/ton of steel. Ray K. Linsley and Jos. B. Franzini, *Water Resources Engineering*, 2nd ed. (New York: McGraw-Hill, 1972) p. 426. Presumably these figures represent net forward diversion.

6. Linsley and Franzini, *op. cit.*, p. 425.

7. A. C. Twort, *A Textbook of Water Supply*, (New York: American Elsevier, 1963).

8. Ultraflo Corp., Sandusky, Ohio.

9. Jack Hirshleifer, James C. De Haven, Jerome W. Milliman, *Water Supply, Economics, Technology and Policy*, (Chicago: University of Chicago Press, 1960), pp. 261–263.

10. Linsley and Franzini, *op. cit.*, p. 427.

11. Hirshleifer, et al., *op. cit.*, p. 264.

12. E.B. Weiss, "International Responses to Weather Modification," *International Organization* 29 (3) (Summer 1975): p. 805.

13. Appendix on Economic Analysis, prepared as part of Northeastern U.S. Water Supply Study (NEWS), Contract No. DACW-52-69-C0002, by the Institute of Public Administration, 55 W. 44th St., New York, pp. 30–31. This report, which is highly critical of conventional water resources planning, was not included in the published version of the NEWS study.

14. Clair Engle Plant, Calif.; see California Department of Water Resources, Bulletin #134–69, "Desalting State of the Art," June 1969. See also John Harte, Robert H. Socolow, *Patient Earth*, (New York: Holt, Rinehart & Winston, 1971), p. 174.

15. Northeast Desalting Team (B. Johnson, et al.), "Potentialities and Possibilities of Desalting for No. N.J. and N.Y.C.," February 1966, Clearinghouse for Federal Scientific and Technical Information, Dept. of Commerce, Springfield, Va. PB170568.

16. V.A. Koelzer, "Desalting," National Water Commission, National Technical Information Service, Dept. of Commerce, Springfield, Va. PB 209942.

17. John D. Bredehoeft and Robert A. Young, "Digital Computer Simulation for Solving Management Problems of Conjunctive Groundwater and Surface Water Systems," *Water Resources Research* 8 (3) (June 1972): p. 536.

18. *North Atlantic Regional Water Resources Study*, Appendix D, North Atlantic Division, U.S. Army Corps of Engineers, May 1972.

19. John D. Bredehoeft and Robert A. Young, "The Temporal Allocation of Groundwater—A Simulation Approach," *Water Resources Research* 6 (1) (February 1970): p. 5.

20. Appendix P, "Gross and Net Water Needs," *Delaware River Basin Report*, House Document 522, Vol. IX, 1960.
21. H D 522, vol. IX, Appendix P, Plate 17.
22. H D 522, vol. IX, Appendix P, Table P-10.
23. H D 522, vol. III, Appendix C, p. 230.
24. H D 522, vol. I, Main Report, p. 59.
25. H D 522, vol. I, Main Report, p. 51.
26. Memorandum from L.J. Warns to H.A. Howlett of the DRBC, dated April 2, 1974.
27. Survey of New Jersey Water Resources Development, for State of New Jersey, Legislative Commission on Water Supply, by Tippetts-Abbett-McCarthy-Stratton (TAMS), December 1955.
28. H D 522, vol. II, Appendix A, Exhibit C, p. 11.
29. H D 522, vol. I, Main Report, p. 49.
30. H D 522, vol. VI, Appendix M, p. M-96.
31. "New Jersey Water Supply, Alternatives to Tocks Island Reservoir," M. Disko Assoc. (West Orange, N.J., October 1973). See also, Smith Freeman, Edwin Mills, David Kinsman, "High Flow Skimming," Chapter 2 of *Papers in Support of a Free-flowing Delaware River*, Save-the-Delaware-Coalition, 1973.
32. Joint Legislative Air and Water Pollution Control and Conservation Committee, Hearing on Tocks Island Project, East Stroudsburg, Pa., October 28, 1971, pp. 4–6.
33. Draft Environmental Impact Statement for Newbold Island Generating Station, Atomic Energy Commission. Discussion prepared by DRBC staff for AEC.
34. Englesson, G. A., and Anderson, R. H., "The Impact of Consumptive Use of Water on the Salinity Distribution in the Delaware Estuary," United Engineers (Subsidiary of Raytheon Co.), June 1974.
35. Federal Water Pollution Control Act, Amendments of 1972, Public Law 92-500, Section 102 (b) (1).
36. Water Quality Control Study, Tocks Island Reservoir, Delaware River Basin, Federal Water Pollution Control Administration, Department of Interior (New York, June 1966), Figure VII-1.
37. J. E. McKee and H. W. Wolf, "Water Quality Criteria," California State Water Quality Control Board, Publication No. 3-A, 1963, 2d ed. p. 160.
38. Report on the Utilization of the Waters of the Delaware River Basin, for INCODEL, Malcolm Purnie Engineers–Albright and Friel, September 1950.
39. Survey of New Jersey Water Resources Development, *op. cit.*
40. Barksdale, et al., Groundwater Resources in the Tri-State Region adjacent to the Lower Delaware River, N.J. Div. of Water Policy and Supply, Special Report 13, 1958, p. 123.
41. *Water Resources Study for Power Systems*, Tippetts-Abbett-McCarthy-Stratton New York, March 1972.