



Floods and People

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On Friday night, June 10, 1972, a flash flood descended upon the city of Rapid City, South Dakota. At least 10% of the city's homes were destroyed with 235 people killed and over 5000 made homeless. The following quotes were obtained from residents of Rapid City by B. Drummond Ayers and published in the *New York Times* of June 13, 1972.

Frustrated by the lack of success [at pulling buried automobiles out of sand and gravel], Mr. [Dennis] Waltz fell to his knees in the muddy water and started clawing at the sand and rocks with his bare hands. "They say a woman and her baby are in one of these cars," he yelled over his shoulder.

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"You know this is a terrible thing to be involved in, but since I've been in the [National] Guard, this is the first time I've ever felt I was doing anything worthwhile."—National Guard private

* * *

"We're down on our hands and knees like animals. I've had enough of the smell of death in this awful, awful mire."—Rapid City housewife

* * *

"It's unbelievable. Everybody is pitching in, giving us more equipment and help than we know what to do with. I've done construction work all over the world but I've never seen people like the folks in Rapid City."—State Highway Department employee

I. THE URGE TO CONTROL

Most people have a reasonably clear image of what is meant by the phrase "natural disaster." Under this rubric we usually include earthquakes, forest fires, hurricanes, tornadoes, and floods. The pejorative connotation of the word "disaster" used in this context is very potent, and society's image of these natural events has been formed over a period of some five thousand years, since human beings first organized themselves into large, complex, urban societies.

It does not take a great deal of thought to recognize that these events are "disasters" only to the extent that they interfere with the aspirations and tranquility of human societies. An earthquake is a disaster in San Francisco or Anchorage but is little more than a curiosity along the sparsely populated coast of Baja California. A brush fire is a disaster in the hills above Los Angeles but provides an ecological service to a redwood forest by periodically burning away accumulated underbrush and saving the large trees from really serious fires.

A flood is somewhat like a forest fire in this respect. Periodic flooding of a river serves to bring beneficial deposits of sediment to the flood plain and to clear away accumulated debris in the channel. There is now good evidence that the river and its flood plain form an interdependent ecosystem and that the prevention of floods and augmentation of low flows may distort and oversimplify the river's ecosystem and possibly do it irreversible damage. However, it is difficult for normal people to keep this subtle, ecological principle in mind when entire cities are inundated by floods causing hundreds of millions of dollars in damage or when, for example, vacationers, most of them children, are swept away and killed, as they were by the raging flood waters of Brodhead Creek near Stroudsburg, Pennsylvania, in 1955. (The story of the 1955 flood is told in Essay 2.)

The loss of homes, jobs, or possibly even of loved ones and friends in a flood can cause severe psychological and emotional damage to people. Noticeable increases in divorce and suicide occurred in the aftermath of the great spring floods on the Mississippi River in 1973,¹ and some of these same effects were noted after the Rapid City, South Dakota disaster in 1972. At the same time other observers have noted the tendency for people to draw together in mutual aid and sympathy when such disasters strike, and there are many inspiring stories of courage and strength that renew one's faith in human resourcefulness. In no way do I wish to make light of these effects. Nevertheless, it is clear that floods are disasters only because people choose to live, work, or play on flood plains. They do so for

very old reasons: the river is a source of food, drinking water, and water for irrigation; it is a transportation route, a recreation area, and, of course, a sewer.

There was a time, before the great technological civilizations of the Bronze Age, when the human response to the periodic flooding of rivers was primarily adaptive. The flood plain was kept extremely fertile by the floods, and the neolithic societies which farmed the flood plains learned to predict the floods and move to high ground to avoid them, returning to their farms as the waters receded. There are many areas in the world, including the United States, in which this kind of behavior still goes on to some degree.

But as human technological capabilities grew and as civilizations became increasingly urbanized and specialized, this kind of adaptive behavior became less and less convenient, and the motivations toward controlling and managing the flood cycle for human benefit grew apace. The Egyptians and Sumerians devised and constructed elaborate flood control and irrigation projects, whose purpose was to maximize the benefits and minimize the costs of the yearly flood cycle.² As a result of these projects, great cities were built on the flood plains of the Nile or the Tigris-Euphrates, and, as has occurred with every flood plain development since that time, these cities must have occasionally suffered severe damage in those years when the flood discharge exceeded the design capabilities of the control works. One can even speculate that the biblical story of Noah may have originated in what might now be called the "1,000-year" flood of the Tigris and Euphrates Rivers.³

One might reasonably expect modern societies, with this 5,000-year backlog of bitter experience, to approach flood plain development with considerable caution and to demonstrate a healthy respect for the river and the awesome and unpredictable devastation of which is capable. In "primitive" cultures such respect is often expressed in worship, in which the river is a god, to be placated and appeased rather than challenged and manipulated. But "civilization" has repudiated belief in such natural deities and has substituted instead a belief in its own technological omnipotence. The enormous economic benefits to be derived from exploitation of the river and its flood plain have led to a chronic shortness of memory and what dramatists might call a willing suspension of disbelief in the efficacy of flood control technologies.

In the United States the flood control problem has evolved with the parallel growth of agriculture and urbanization. The conversion of vast areas of highly water retentive forest to easily eroded farmland has caused large increases in the ratio of runoff to infiltration in

most major drainage basins. At the same time cities on downstream flood plains have grown rapidly, placing an ever increasing number of people in the direct path of flood discharges. And through it all the few voices warning that flood plain development should be controlled have been overwhelmed by the far greater number of voices demanding that the floods be controlled instead.

Engineers who build dams take great pride in their accomplishments. Their dams are usually designed with great care and with large margins for safety, and, as a result, the failure rate in the United States has been very small.³ The desire to build spectacular, enduring, and socially beneficial projects is a very human one and one that gives the agency responsible for construction a powerful motivation to advocate the building of large dams. One ought not to be too critical of these motivations, especially in the light of our entire society's preoccupation with spectacular technological feats.

The excitement and awe inspired by a great dam is captured well in this selection from *Rivers in Harness* by Allan H. Cullen:

[Hoover] Dam's hydroelectric facilities are open for inspection. First you can look out at Lake Mead and see the four intake towers, 390 feet high, jutting into the lake. Then you can descend, in an elevator that goes right down through the heart of the dam, and visit the powerhouses. The elevator ride is somehow a disturbing one, for you know that leaping, straining masses of water are only a matter of yards from you. You feel a sense of apprehension at the fragility of man and his works. But it gives way, as you continue to descend, to a new feeling of exhilaration and confidence, as you realize that the dam will protect you after all. You feel sudden wonder at the knowledge that small weak creatures very much like yourself somehow succeeded in damming this potent river. By the time you reach the bottom of the shaft, you feel like a giant, holding back the rush of water yourself with one contemptuously outstretched hand!⁴

It would be difficult to find very many engineers who would express these feelings, as Mr. Cullen has, in such openly emotional terms. Most engineers are not given to this kind of hyperbole. One senses, however, that these feelings must exist in even the most outwardly reserved of dam builders. But it would be unfair to attach too much importance to these subjective motivations. The building of big dams has for many years been seen as a socially useful and laudable activity by all but a small minority of our society. The majority emphasizes the role of a dam in protecting life and property and its

³The Washington office of the Corps of Engineers claims that there has never been a failure of a Corps constructed dam and that there have been no major levee failures.

contribution to the economic growth and well-being of the river basin in which it is built.

As discussed much more fully in Essay 4, only a dam's role in protecting property is quantified in the conventional benefit-cost analyses performed by the water resources professionals. The benefits from lives saved and from disruption and anguish avoided are treated as "intangibles," incapable of being quantified in dollar terms in any satisfactory way. The benefits from promoting regional development are not included in benefit-cost analyses because these benefits typically occur beyond the project's boundaries and also because the economist worries that development in one region may occur at the expense of development in another, with no net benefit in "national income" accounts.

Yet it is clear that both a dam's role in reducing the toll on human beings and its role in promoting regional development loom large in the decision to build it, far larger than does its role in protecting property.^b In the case of the Delaware Valley, everyone who has ever read the heartbreaking story of the 37 people who were killed at Camp Davis in 1955 finds it unforgettable and wants to have something done to prevent a recurrence of such a tragedy.^c And anyone who has watched the debate over the decision to build the Tocks Island Dam knows that among the strongest supporters of the dam are the labor unions, who see in the control of the Delaware River a major spur to new jobs. Their position was well captured in the Corps of Engineers' basic report on the valley back in 1958:

Whether or not this region can achieve the high level of economy projected for it over the next half century will depend on the favorable operation of a highly complex set of factors. The historical and projected levels of economic development show that a potential for major expansion already exists within the region as well as for the country as a whole. One factor upon which the service area will rely to sustain and nourish its growth will be the reasonable exploitation of its water resources.⁵

Over the twenty years since the great floods took place, memories of these floods have been slowly fading. In order to help reinforce these memories the Corps conducted a study of Hurricane Agnes,

^bThe most recent cost-benefit study done by the Corps of Engineers for the Tocks Island Dam project states that flood control will provide only about 13 per cent of the annual benefits to be gained from construction of the dam (see Essay 4, Table 4-1, p. 128)

^cAs explained in more detail in Essay 2, Camp Davis is located on a tributary that enters the Delaware just below Tocks Island. The proposed dam would have had no effect on that tributary.

which struck eastern Pennsylvania in 1972 and caused severe flood damages. The Corps made an estimate of the flood damages that would have resulted had Agnes centered over the upper Delaware Valley instead of over the Susquehanna Basin and estimated that Agnes would have caused about \$190 million in damage in New Jersey and Pennsylvania. Then the Corps went one step further and calculated that about 80 percent of this hypothetical damage would have been prevented by the hypothetical Tocks Island Dam. That the Corps saw fit to publicize this report and give it wide circulation among responsible officials in the Delaware Valley lends further support to the assertion that flood control has played a role in the dam's promotion far in excess of its purely quantitative importance.

In the next two sections I concentrate on the quantitative tools used by the water professionals to describe floods and the damage they do to property. Any participant in a controversy about flood control is at a disadvantage if he or she has no familiarity with the concepts in use, and the important concepts are considerably less difficult than I had first thought. (There are no introductory science textbooks on floods that I am aware of.) Section II explains how one can estimate the amount of flooding associated with a storm, given its location and intensity. Probabilistic aspects of calculations of flood damage, derived of necessity from statistical treatment of the historical records, are discussed in section III. The two sections contain the essential ideas that lie behind the dollar figure for flood damage that gets reported in a benefit-cost analysis. Section IV describes some nonstructural alternatives to dams that offer protection, in varying degrees, against the monetary and human toll of floods. And in section V, I take a try at sorting out what seems to be at stake in choosing between structural and nonstructural approaches to flood control.

II. HOW DO FLOODS HAPPEN?

A flood is a dramatic manifestation of a very simple physical principle—the conservation of water. In order to illustrate this in a quantitative way let us consider a highly simplified model of a river drainage basin and ask what happens to the rainwater during and after a heavy rainstorm.

Let us choose a moderately sized basin of area 1,000 square miles. If it is roughly circular in shape it would have a diameter of about 36 miles. Examples of basins of this size in the Delaware Valley are the Lehigh River basin above Bethlehem, Pennsylvania (1,279 square miles) and the Schuylkill River basin above Pottstown, Pennsylvania

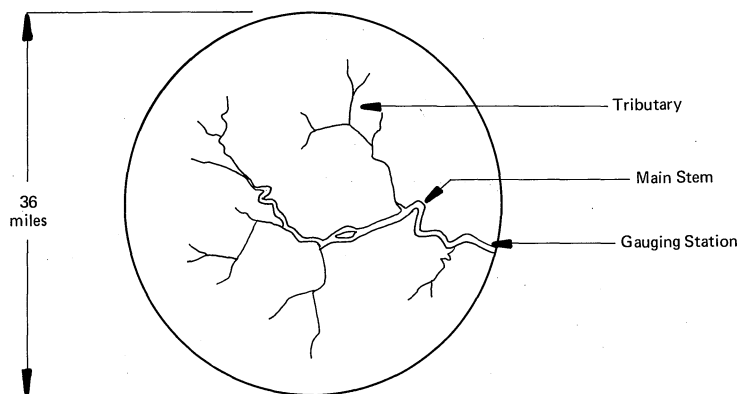


Figure 6-1. A Model Basin – Perfectly Circular

(1,147 square miles). Next let us suppose that a rainstorm completely covers this area and drops four inches of rain uniformly onto the basin during a period of five hours. We can easily compute the total amount of rain that falls on the basin by multiplying the rain's depth by the basin's area, and we obtain a total of 9.3 billion cubic feet of water. The average rate at which it fell is obtained by dividing by the duration of the storm (five hours) and this rate is called the *intensity* of the storm. In our example the intensity is 0.8 inches per hour, which yields for the whole basin 516,000 cubic feet per second (cfs).^d

We have obviously chosen a very simple storm pattern, and it should not surprise the reader to learn that real storms are a great deal more complicated than this. One real storm, which figures prominently in the planning for flood control in the Delaware Valley, is discussed in Box 1 below.

Hydrology textbooks characterize storms by three quantities: intensity, duration, and area. The complex structure of a real storm is usually smoothed out by averaging all of these quantities over the area under consideration, usually a particular drainage basin. If the basin is small this averaging is a reasonable technique, but for very large basins taking an overall basin average can obscure important local effects. To avoid substantial errors, the big basin must be broken into smaller basins.

Four things can happen to the rain: (1) it can infiltrate into the soil, (2) it can be stored on the surface in puddles and ponds, (3) it

^dA useful conversion factor in this type of calculation is one inch per hour = 645 cfs per square mile.

Box 1 The Basin Project Storm

Figure 6-2 is a picture of the "basin project storm" used by the Corps of Engineers in the design of the Delaware Basin flood control system.¹ The general shape and rainfall values of this storm are based on an actual storm that occurred over the Basin in May of 1942. It is a reasonable prototype of the kind of large, severe storm which can occur over the Delaware Basin.

The lines of constant total rainfall are called *isohyetal* lines (iso = same, hyetos = rain) and these are obtained by connecting all rainfall gauges which record the same total rainfall. In 1958, when the report was written, there were 153 official rain gauges in the basin. This averages out to about 80 square miles per gauge, which means that local variations in rainfall patterns of a smaller scale than this cannot be detected. So the isohyetal pattern which is plotted for any given storm is only an approximation of the gross features of the storm.

The rainfall depths, which are shown on the map, are total depths and therefore, unless we know something about the duration of the storm, we cannot obtain the intensities along the isohyets. Intensity is as important as total depth, because the faster the rain falls, the less the ability of the ground to soak it up. A given depth of rainfall produces more total runoff if it falls in a short period than if it falls over a long period.

A second variable absent from the map is the direction of motion of the storm over the basin. A storm that moves *down* a river basin piles the runoff water upon itself, and increases the severity of the flooding, relative to the flooding that would result from the same storm hovering over the basin. Although we assume there is no such nonuniformity of rainfall pattern over time in our model storm, the avid reader may want to enlarge the treatment in Appendix 1 to this Essay, to incorporate this potentiality.

The central role of the "basin project storm" in water resource planning should give us pause. If one concentrates on designing structures to meet one single threat, in what sense can one claim to be optimizing the basin's ability to withstand the variety of storms that will in fact occur? The basin project storm, although clearly a convenient mechanism to force some reality on planning, can be a dangerous concept if given too much emphasis. With high speed computers it becomes at least conceivable to try to optimize a basin's flood control strategy relative to a variety of threats, each with some associated probability of occurrence, and thereby to avoid the pitfalls of designing defenses against a single form of attack.

1. Taken from House Document 522, U.S. Army Corps of Engineers, Delaware River Basin Report, vol. 6, Appendix M, Plate #70.

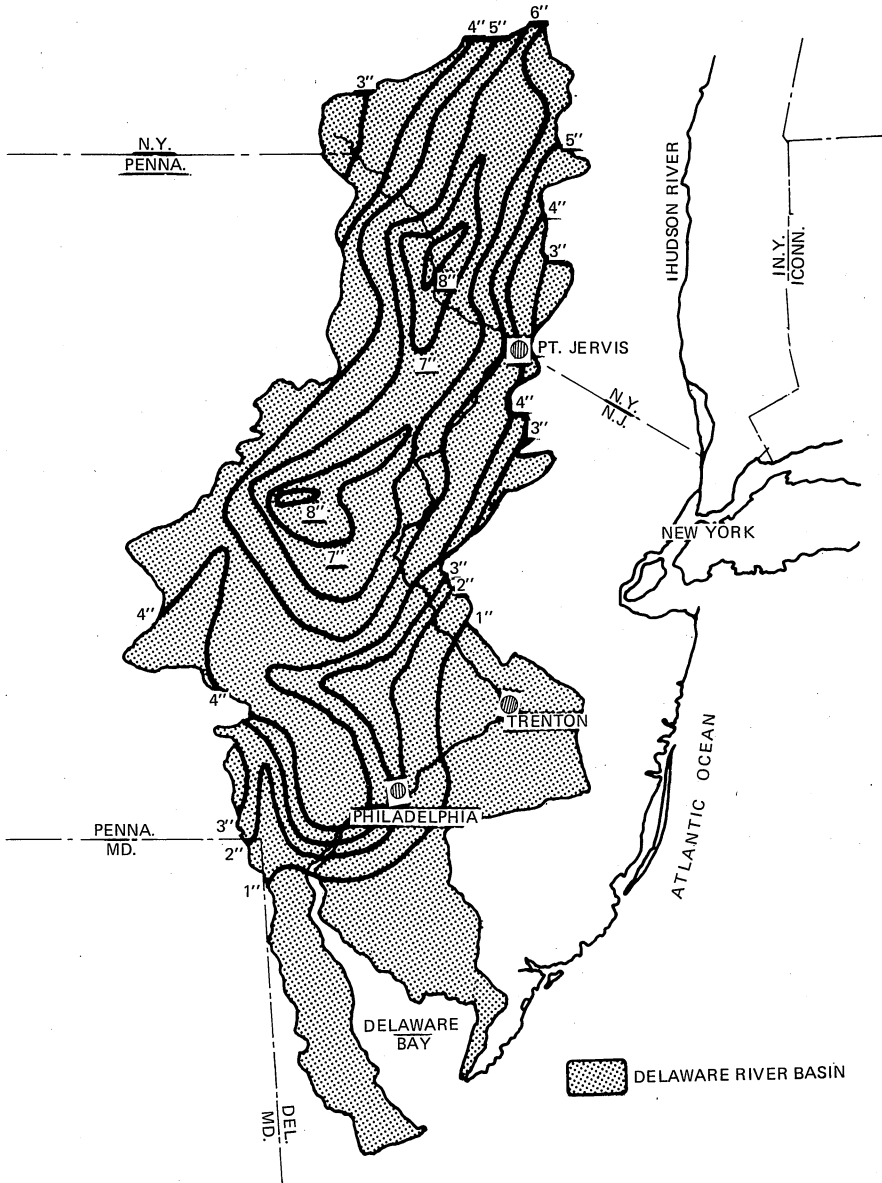


Figure 6-2. Basin Project Storm. (Contours show inches of rainfall.)

can evaporate or be transpired back into the atmosphere through the leaves of plants, and (4) it can run off over the surface of the ground into the stream system of the basin. Only the last factor contributes to flooding; the first three contribute to reducing the amount of runoff. Of these three the least important in a large storm is evapotranspiration, which takes place too slowly to have any appreciable effect on the runoff during the hours of a single storm. Evapotranspiration is important, however, in considerations of long term water balances, since losses due to this mechanism can, and often do, exceed total runoff over the period of a year.

The ability of the ground to absorb and store water is called its infiltration capacity, and it is usually given in units of inches of rainfall per hour that can be absorbed.^e Infiltration capacity is a very strong function of the nature of the soil and ground cover. At one extreme would be a shopping center parking lot, which has an infiltration capacity of zero, and at the other extreme would be a dense tropical rain forest with several distinct layers of vegetation overhanging a soft, spongy soil covered with fallen leaves and other organic material.

We will assume that our model basin has an average infiltration capacity of 0.15 inches per hour during the storm we have postulated. This is a number typical of the Lehigh and Schuylkill river basins in the regions mentioned earlier, as reported by the Corps of Engineers in H D 522. In our sample storm, where rain falls at 0.8 inches per hour, the infiltration and storage are holding back 0.15/0.8 or 19 percent of the rain from participating in the runoff. Note that we have implicitly assumed that the infiltration capacity is constant during the storm. This assumption is often made in hydrologic modeling, for the sake of simplicity, but it is a weak one: the infiltration capacity is lowered drastically if the ground has already been saturated by a previous storm; even during a single storm the infiltration capacity drops as the soil saturates, and therefore rainfall of a given intensity is far more effective at producing runoff at the end of a storm than at the beginning. Any flood prediction model that aspires to reasonable accuracy must incorporate sufficient data on the properties of soil and ground cover to take these factors into account.^f

^eIt is customary to lump surface storage and infiltration capacity together for the purpose of runoff calculations. Water stored on the surface eventually either infiltrates or evaporates, but this is clearly irrelevant in flood calculations.

^fResponsibility for the acquisition of such data in the United States rests with the weather service.

Now let us follow the runoff, starting when the storm begins and continuing until long after it stops. If we keep track of the discharge at the mouth of the basin, we will see it first grow and then diminish. We are able to work out a complete description of the runoff for our model basin if we assume that the runoff travels down the basin at a constant average velocity. A typical average velocity for sluggish basins is about 0.5 miles per hour and for flashy basins is about 1.5 miles per hour. We choose an intermediate velocity, such that a drop of water will travel a distance equal to the radius of our basin (eighteen miles) in twenty hours; its velocity is 0.9 mph.

A graph of water flow versus time for any single point on a river is called a hydrograph, and it is one of the standard tools of the professionals who assess the relationship between storms and flood damage. The hydrograph of the flow at the mouth of our model basin for our model storm is shown in Figure 6-3. It has the general features of hydrographs measured at real gauging stations following real storms. The essential features of the hydrograph can be deduced from a relatively simple geometric model, and this is presented in Appendix A.

The principle of conservation of water tells us that the area under the discharge curve must equal the total runoff. Since the area under the curve is fixed, it is obvious that a flashy basin that discharges all the water very rapidly must have a hydrograph with a very high peak discharge. In Figure 6-4 a hydrograph for a flashy basin with a sixteen-hour lag time is superimposed on the more typical hydrograph from Figure 6-3. One sees that a given rainstorm will produce a far more serious flood in a flashy basin. Some of the small tributaries of the Delaware, like Brodhead Creek, lie in flashy basins. It was on Brodhead Creek, during Hurricane Diane in 1955, that the water level at Camp Davis rose some 25 feet in about one-half hour and swept 37 people to their deaths.

If we choose our stream to be 250 yards wide at the gauging station, assume that the water is flowing by at a rate of about 5 mph (7.5 feet/second), and assume that the banks rise vertically at the edge of the stream (so that the width of the stream is fixed), we can compute how much the river will rise when the peak discharge of 75,000 cfs comes past. (We simply divide the total discharge by the width and by the average velocity.) The result is a rise of 13.3 feet in the river at the mouth of the basin.

Notice what happens if we assume no infiltration capacity for the basin. (This situation could arise if the storm we are considering followed closely upon the heels of a previous storm which had

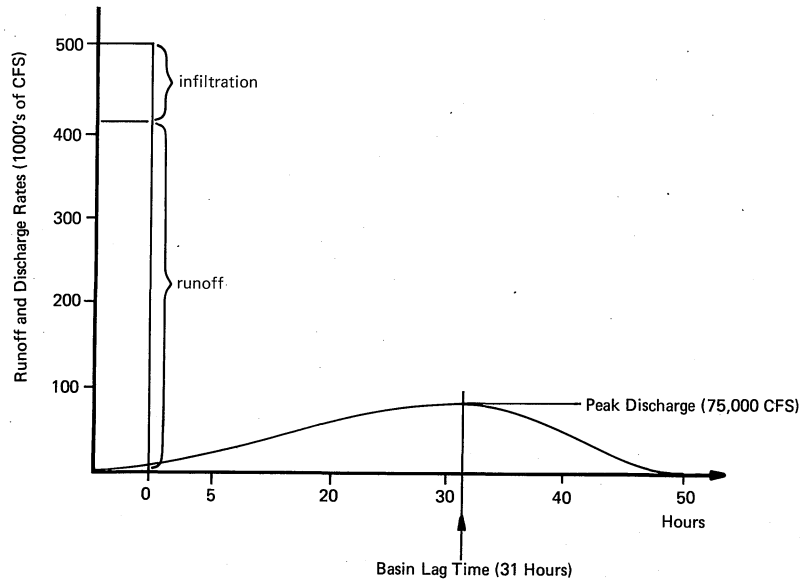


Figure 6-3. Hydrograph for a Five-Hour Storm at the Edge of a Circular Basin

saturated the ground, as happened in the Delaware Basin in 1955.) A total absence of infiltration would mean 19 percent more water appearing as runoff, so that all points on the hydrograph would have to be raised by 19 percent. This would give a peak discharge of 89,250 cfs and a maximum depth of 15.8 feet, an increase of 2.5 feet in gauge height. It is usually unrealistic to assume that the river will stay within vertical banks while it rises thirteen to sixteen feet above its normal gauge height. However, this is the situation if levees or dikes are in place, and thus we see how engineers go about determining how high dikes should be built. They use the information we have so far analyzed plus one other important datum, the frequency with which floods of this magnitude are expected to occur. This important step is probably the weakest link in the entire chain, and we will return to analyze it in more detail in the next section.^g

If there are no local flood protection works and the river is not in a

^gThe flood we have just calculated would be classified by the Corps of Engineers (using 1956 data) as a 35-year flood on the Lehigh River at Bethlehem, Pa. and about a 200-year flood at Pottstown on the Schuylkill. If we assume zero infiltration capacity in the Lehigh basin then the 89,000 cfs discharge is equivalent to a 70-year instead of a 35-year flood. (An N -year flood is a flood whose severity is expected to be exceeded once in N years.)

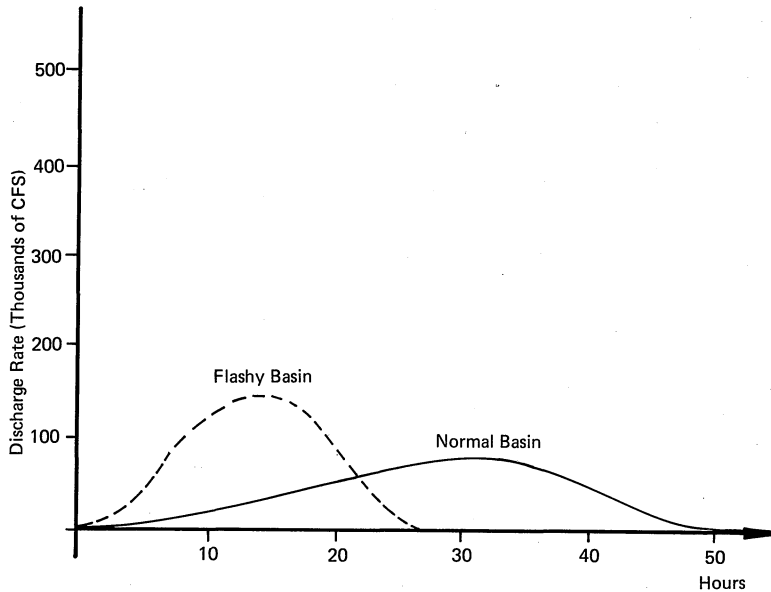


Figure 6-4. Hydrograph for a flashy basin superimposed on the hydrograph from Figure 6-3. Because the runoff has to flow out of the basin eventually, the areas under both hydrographs are equal to the area of the runoff rectangle (Figure 6-3). The flashy basin produces higher floods, sooner after the storm, but of shorter duration.

deep channel, the river will spill over its banks and spread the excess discharge over a larger area. This larger area, whose boundary varies with the discharge, is called the flood plain, and it is here that flood damage occurs if humans have built structures or planted crops close to the river. When the water spreads out over the flood plain, its velocity generally decreases. Relative to vertical banks, moreover, its depth does not increase nearly so rapidly with increasing discharge because the width of the effective stream bed keeps growing.

For any given point on a stream it is possible to plot a curve, called a *stage-discharge* relation, which displays the stage (depth) of the river corresponding to any value of its flow; in particular, this curve allows the peak stage to be predicted if the peak discharge is known. The stage-discharge curve is more or less constant over time, being determined essentially by the topography of the river bed and flood plain; it evidently can be altered rapidly by the passage of very high discharges or slowly with sediment accumulation. The stage-discharge relation is very difficult to derive from first principles, and

it is determined empirically, for any fixed location along a river, using topographic maps and devices that can monitor the instantaneous flow velocity of the water. In order to predict flood stages at all significant points on a river, one generally needs a great many stage-discharge relations, and this implies a very substantial data acquisition program.

When the river overflows its banks there is not only a substantial decrease in the average flow velocity but also a substantial increase in the effective surface storage. Both consequences are highly beneficial for points downstream, because the warning times in the basin are increased and the effective storage-infiltration rate is also increased. Conversely, local flood control works (such as channel straightening, levees, and dikes) often have just the opposite effects and make downstream locations more susceptible to flooding than they were before. Furthermore, if a levee ever is overtopped, it becomes downright harmful, since it prevents the flood waters from draining back into the stream bed when the stage falls.

Let us now use the model drainage basin we have been analyzing to show how a dam will reduce flooding downstream. We build our dam at the point where we have calculated the hydrograph in Figure 6-3, and we embed our model basin within a larger basin. Downstream of the dam, at the mouth of the larger basin, we place a city (see Fig. 6-5). At the location of our city the river has been swollen by the addition of water from other tributaries downstream of the dam, so that the 75,000 cfs peak discharge that passes the dam site is only a fraction of the expected peak discharge at the city. Just how large this fraction is will be determined by the dimensions in space and time of the storm and its location over the larger basin. This is why it is impossible to make any general statements about the downstream effects of the dam. For any particular storm, the analyses performed for each subbasin may be combined, in what is called a routing study.

We will assume that the storm we have used so far forms a portion of some larger storm over the basin above the city, and that a routing study of this storm has shown that flooding at the city can be held to acceptable levels if the peak discharge at the dam can be held below 20,000 cfs. (Not only is the magnitude of the peak important ordinarily, but so is its timing; the inclusion of time dependent effects requires a full routing study.) This requirement is enough to tell us the short term storage capacity that must be allowed for. Referring to Figure 6-6 we can see that the required short term storage capacity, represented by the shaded area, reflects the difference between the discharge expected from the project storm in

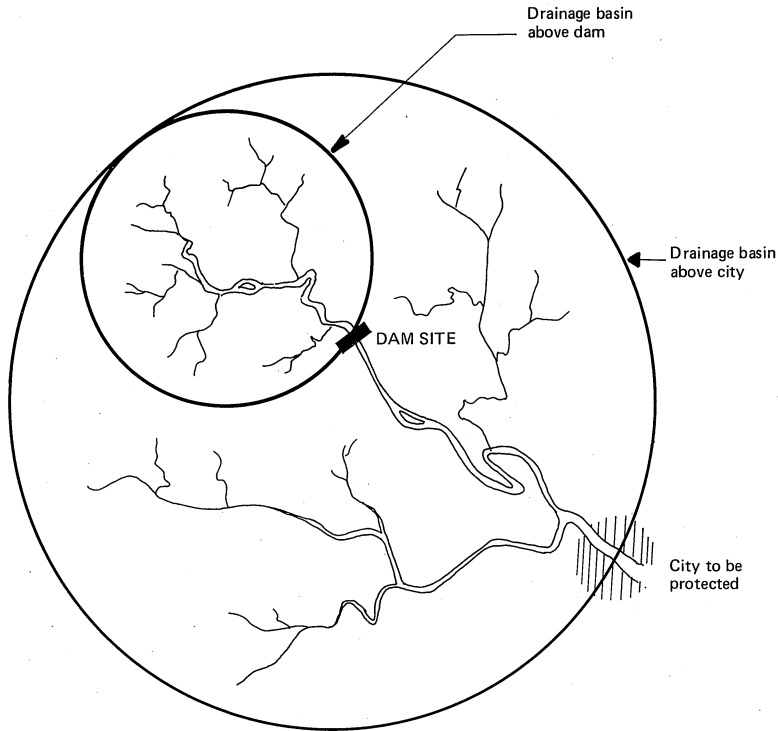


Figure 6-5. The drainage basin of Figure 6-1 embedded in a larger basin, and a dam placed where the gauging station was.

the absence of a dam and the discharge permissible with the dam in place. The stored water continues to flow out of the reservoir considerably beyond the time when the river, in the absence of a dam, would have fallen back to its base flow. In this way the natural discharge in excess of 20,000 cfs is spread out over a longer time and made harmless.

Either from the formulas in Appendix A, or by graphical methods applied directly to Figure 6-6, one may verify that the short term storage capacity of our dam must be about three billion cubic feet, or 69,000 acre feet. This much water would create a lake with an average depth of twenty feet and a surface area of 3,450 acres or 5.4 square miles. If this water is now discharged at 20,000 cfs the flow must be maintained for about another 40 hours, as seen in Figure 6-6.

In Appendix A, the Tocks Island Dam is subjected to a similar analysis, and, indeed, the required storage capacity calculated by the

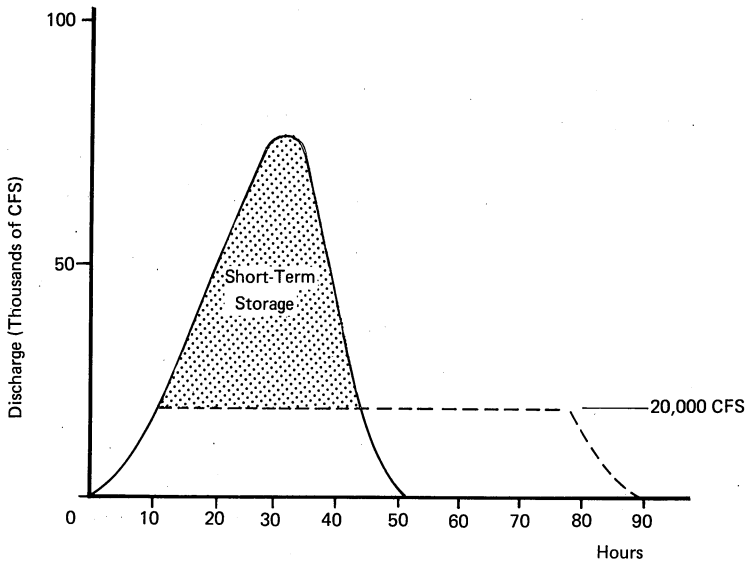


Figure 6-6. A dam delays the flow. The solid curve is the same as the hydrograph in Figure 6-3 (rescaled). The dashed curve shows the flow past the dam when the maximum flow is constrained to be 20,000 cfs.

Corps of Engineers is found from a few simple properties of the drainage basin. Thus, simple models have a certain usefulness in gaining intuition about how floods arise and about how big they get. But the reader should not be unduly impressed with such drastically oversimplified models—predicting floods from real rainstorms is far from a simple process. There are a great many complications that can arise in a real flood, such as sudden local fluctuations in rainfall or in infiltration rates, that make prediction far more difficult in practice than in theory. These difficulties increase rapidly as the size of the basin increases.

III. PREDICTING ANNUAL FLOOD DAMAGES

The techniques used in the previous section are necessary in the development of an accurate flood prediction program, but they do not nearly suffice to decide whether it is worthwhile to build a flood control dam on a particular river. One clearly must know something about how often and with what severity floods occur on the river and what damages can be expected from these floods. Such informa-

tion is used to quantify the annual dollar benefits from flood control associated with the building of the dam in the benefit-cost analyses that are the subject of Essay 4. In this section I outline how these benefits are conventionally calculated; some further details are found in Appendix B to this Essay.

If next year a flood causing one million dollars worth of damage had one chance in ten of occurring, and a flood causing five million dollars worth of damage had one chance in one hundred of occurring, the expected value of the damage for the year would be \$150,000.^h More generally, if we know the numerical probability associated with every possible level of damage to a basin from flooding, we can calculate the expected value of the damage in an analogous fashion. The art of producing damage-frequency curves, which contain just these probabilities, proceeds in three steps.

1. Discharge-Frequency Relations. The historical record of large floods is restated mathematically so that every value of peak discharge from a future storm has an associated probability. Actually, one conventionally plots not the probability that a flow of given magnitude will occur, but the probability that a flow of a given magnitude will be exceeded (the exceedence frequency), during any year-long interval.

2. Stage-Discharge Relations. As discussed in the previous section, the topography and soil characteristics of a basin, as well as the historical records of floods, are used to associate a given peak discharge with a given "stage" or height of the river.

3. Damage-Stage Relations. The physical structures in the flood plain are surveyed, and the dollar damage each can be expected to sustain when the river is at various heights is estimated. The possible appreciation or depreciation in the value of these structures over time, and the possibility that new structures will be built, are handled separately.

The first step is the most difficult and unreliable. There is almost by definition no reliable way to determine the frequency of rare events, and it is just the rarest (and most damaging) events that are most important.

Typical graphs for each of the three steps are presented in Figures

^h $0.1 \times \$1,000,000 + 0.01 \times \$5,000,000 = \$150,000$. We assume these two floods are the only ones conceivable, in this highly oversimplified example.

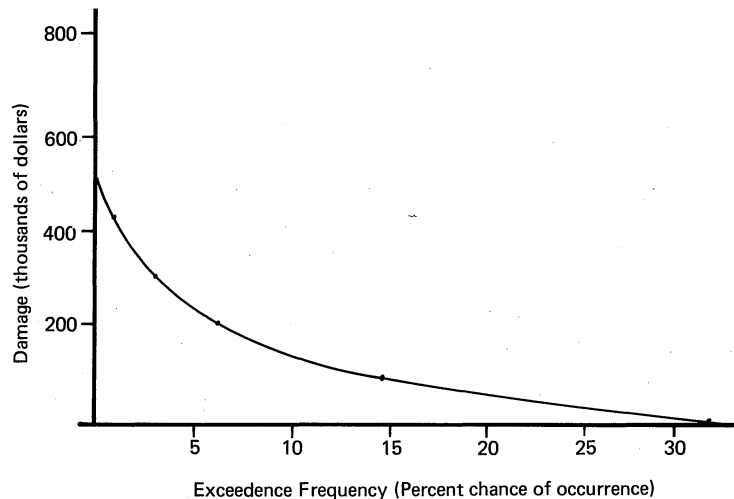


Figure 6-7. Damage Frequency Curve

6B-1, 6B-2, and 6B-3 in Appendix B. When the three are combined Figure 6-7 results. This figure gives the percent chance that a storm will occur in the basin in the next year that will produce an amount of damage to property (in dollars) in excess of the damage shown on the vertical scale.

It may be seen from Figure 6-7 that completely negligible damage has about two chances in three of occurring. It may also be seen that, as almost always, severe damage is associated only with rare events.¹ The largest source of unreliability of estimates of "flood benefits" quite generally can be traced to the fact that rare events are intrinsically difficult to treat statistically. (For further evidence, see Box 2, below.)

Damage-frequency relations must be calculated both in the presence and in the absence of control structures if the benefit associated with a structure is to be estimated. The construction of a levee at a damage center, or of a dam upstream of this center, will generally cause the damage-frequency curve to be displaced downwards, thereby reducing the expected annual damages from floods. The problem is to attempt to estimate just how much the damage-frequency curve will be displaced.

¹By a rough measurement of the relevant areas under the sample damage frequency curve shown on Plate 7 of Appendix D of H D 522, I find that 70 percent of the expected yearly damages from flooding on the Delaware is caused by floods with greater than ten-year recurrence intervals.

Box 2 Rare Events

To get a feeling for the uncertainties involved, I compared six different methods that have been designed for attaching recurrence intervals to rare floods. I applied all of them to the historical data for the Lehigh River at Bethlehem, Pennsylvania.¹ The six methods were (1) a simple fit to the normal distribution, (2) the Beard Method,² (3) the Gumble Method,³ (4) the log-Pearson type III method,⁴ (5) the method used by the Corps in H D 522 employing a joint distribution of normal and hurricane discharges, and (6) the simplest method of all, simply assuming that the previous period of record will be repeated, on the average, in the future, the period of record being 1902-1970 (data for 1906-09 not available). The results are shown in Table 6-1 below.

Table 6-1. Recurrence Interval for Worst Flood or Record (approx. value)

<i>Method of Computation</i>	<i>No. of Years</i>
Fit to normal curve	180
Hurricane + normal	75
Beard	95
Gumble	160
Log-Pearson type III	70
Repetition of previous period of record	66

This wide range of recurrence intervals obtained by differing but basically reasonable methods cannot provide a quantitative measure of the range of uncertainty, but it does serve to give the reader some feeling for the difficulties involved in making even approximate statements about the probabilities of rare events.

1. USGS Water Supply Papers, #1672 and #1902.
2. See H D 522, Appendix M.
3. See, e.g., R.D. Linsley and J.B. Franzini, *Water-Resources Engineering*, 3rd ed. (N.Y.: McGraw-Hill, 1972), p. 127. This method is used by the U.S. Geological Survey.
4. *Ibid.*, p. 128. Since 1967 this has been the standard method used by the Corps of Engineers.

For a levee this problem is relatively easy. The presence of a levee will alter both the stage-discharge and the stage-damage relations in obvious ways, and this causes no difficulty. The derivations of both the "altered" and the "natural" damage-frequency curves proceed in exactly the same fashion. A dam, on the other hand, is considerably more complicated, because its effect is on the discharge-frequency

curve at the damage site and this effect depends on the nature of the storm that produces the flood. Two discharges must be known—at the dam site and at the damage center—and these discharges are not necessarily strongly correlated. In general, the greater the separation between the two sites the smaller the correlation (see, for example, Fig. 6-2).

The result of the calculation described in this section is an estimate of the expected amount of damage that will be prevented by the dam during its lifetime. As seen in Box 6 of Essay 4 (p. 139), this constitutes the greatest part of the flood control benefit of the dam.

IV. NONSTRUCTURAL ALTERNATIVES

Unless a dam is already justified exclusive of its role in flood control, it is not usually an efficient method of achieving the benefits provided by flood control. Addressing exclusively the concern for human lives saved, E. F. Renshaw wrote:

... It would be difficult to find any large scale investment that reasonably can be expected to save as little life per dollar expended as the typical flood control projects, which are inadequate to cope with the rare and particularly disastrous floods.⁶

In the United States, between 1936 and 1970, the average annual death toll from floods was 95,⁷ and it has shown no tendency to decrease with time. During this same period more than nine billion dollars has been spent for structural flood control projects,⁸ an average of over \$250 million per year.

The great majority of flood fatalities occur during flash floods on small, supposedly benign tributaries, two instances of which we have already mentioned: Brodhead Creek in the Delaware Valley in 1955 and Rapid Creek in Rapid City, South Dakota, in 1972. The latter flood killed 235 people even though a massive flood control dam had recently been completed only fifteen miles upstream. The problem in this case was that the storm that produced the flood happened to center over a portion of the basin not protected by the dam, rendering the dam virtually useless. The flood was also made worse by the failure of a smaller dam just upstream from Rapid City. It provides little comfort to the homeless and bereaved survivors of the flood to point out that it was a highly improbable event.^j

^jThe rainstorm that caused this flood dropped over seven inches of rain in six hours and was tentatively labeled a "100-year" rainstorm by the U.S. Weather

To call a dam "inefficient" as a saver of lives, one must have other alternatives in mind. Among these are zoning regulations, accurate crest prediction capability, and strong emergency relief capability. Although they are probably no less attractive a set of programs in the presence of a dam, in fact they constitute an increasingly respected alternative to a dam. They, along with flood insurance, are known collectively as nonstructural alternatives.

A. Flood Plain Zoning

Of course, the simplest and most direct means of preventing flood damage is to declare the flood plain off limits for all human activities. But the apparent simplicity of this scheme is quite deceptive since the flood plain is not so easy to define precisely. In addition, such a plan would be very wasteful, because a valuable source of human welfare and enjoyment would be lost. An awareness is growing in many a waterfront city (e.g., Pittsburgh, Philadelphia, St. Louis) that the quality of urban life would have been greatly improved if the city had been conscious of the esthetic and recreational value of its rivers and had planned its growth both to preserve and to utilize these values.

Probably the major reason why flood plain zoning has been so slow to develop in the United States is that the responsibility for zoning has been left in the hands of the smallest, least powerful, and most easily influenced units of government: the county and municipal. At this level of government there is generally only a dim awareness of the scope of the flood problem, there is virtually no capability for data acquisition and analysis, and there is no effective means of controlling developments in upstream communities. In addition there is the nearly universal tendency for such local governments to be controlled by business interests, which see the river and flood plain almost entirely in terms of their economic potential, and which tend to assume that they will be taken care of by the state and federal governments should a flood disaster occur. This faith has been amply justified in the past.

Buildings in the flood plain have moderately deleterious effects during a flood, because they present obstruction to the flow of flood waters, which results in the backing up and diversion of water into areas that would not otherwise be flooded. They also can be very destructive when they break loose and wash downstream. Piles of

Bureau's local hydrologist. The flood discharge at Rapid City was 28,500 cfs which was over ten times the 2,600 cfs of the previous flood of record! This discharge was eight times as large as the 50-year flood estimated from previous data by the U.S. Geological Survey.

debris, forming into mini-dams and then breaking loose suddenly, worsened the effects of the Rapid City flood. A building, bridge, or dike in the floodway is therefore a kind of public nuisance, and this has been one of the traditional legal justifications for flood plain zoning laws. Our legal system tends to assume that people and companies are not to be compensated for damage they do themselves, but it attempts to protect those who suffer damages resulting from the negligence or errors of others.⁹

In recent years a few states, including Wisconsin, Minnesota, and New Jersey, have instituted flood plain zoning laws, and this concept seems to be gaining popularity. Consider the following, of many possible examples:

- Rapid City, South Dakota, has instituted a new plan for flood plain usage in the wake of the 1972 flood, and certain housing tracts that had been built near Rapid Creek will not be rebuilt. They will be replaced by a park.
- The Corps of Engineers has proposed an entirely nonstructural plan for the Charles River in Massachusetts.¹⁰
- The people of Littleton, Colorado, on the South Platte River, in response to a proposal of the Corps of Engineers to channelize the river through Littleton (as part of a larger flood control plan for the South Platte), proposed that the money appropriated for channelization be used instead to acquire property in the flood plain that would be converted into a park. The Corps has agreed to support this plan.¹¹
- Burlington, N.J., combining urban renewal with flood plain zoning, demolished tenements in the flood plain and replaced them with new housing on higher ground.

The first and most important component of a flood plain zoning plan is an accurate delineation of the flood plain itself. An excellent example of such a study is the report on the Raritan River done by Anderson-Nichols and Company for the New Jersey Division of Water Resources.¹² This study presents a careful and precise survey of the Raritan flood plain and delineates two distinct regions: the floodway and the flood fringe.

The floodway is that portion of the flood plain which is subjected to relatively frequent floods and within which the typical water velocities are large enough to cause serious damage to unprotected

structures. The flood fringe is a region in which floods are relatively infrequent and in which water velocities are significantly slower. These descriptions are, of course, far too qualitative to be of much use, but the actual quantitative distinctions are made with the aid of a rather complex, standardized procedure that uses many of the statistical hydrology methods we have described in previous sections. The procedure involves determining a mean annual flood discharge and then multiplying it by appropriate factors to determine the discharge that defines the floodway and the flood fringe. The factors are obtained by statistical analyses of historical flood data and, for example, the outer boundary of the floodway might be defined by the ten-year flood and the flood fringe by the 100-year flood.

Of course, exactly the same kinds of statistical uncertainties are involved in defining the boundary of the flood fringe as in designing a flood control dam. If housing tracts and trailer parks and other vulnerable developments are constructed just outside the flood fringe, a risk is being taken that the public should be aware of. This is where an accompanying insurance program plays an important role, since insurance by its very nature assumes a permanent situation of risk.

The Raritan River study cost the State of New Jersey about one million dollars to delineate 331 miles of flood plain. The greatest portion of this money was spent doing precise surveys to determine the contours of the land and the distribution of structures, so that stage-discharge and stage-damage relations can be made as accurate as possible. Although these costs are large, they are still considerably smaller than those required to erect dams or levees.

The Raritan study makes a number of recommendations, among them: (1) that communities along the river adopt "properly worded land management regulations," (2) that "no fill or structure be permitted within the floodway limits which would alter the natural flood flow," (3) that "all efforts be made to make people aware of the potential dangers associated with the improper use of flood-prone areas," (4) that structural control methods be considered for regions in which they are appropriate, and (5) that flood insurance be obtained under the National Flood Insurance Act of 1968. The building of flood control structures is not excluded, but is recognized as one element of a more comprehensive program.

B. Flood Insurance

By all accounts every past attempt at creating a workable private flood insurance program has been a failure. As we have seen, the major portion of flood damage occurs during the large, rare floods,

and it has usually taken only one such major event to wipe out completely whatever insurance reserves had been set aside. The smaller, more common types of floods might be more predictable, but in this case the insurance rates cannot be raised sufficiently high, for occupants of the flood plain have a clear incentive to gamble and carry no insurance: they can count on the federal government to step in with relief measures, grants, and low cost loans in the wake of a flood.

It is not an easy thing to argue against such economic aid to flood victims. The financial losses and the emotional and physical suffering of these unfortunate people are genuinely tragic, and to respond with compassion and aid seems to be the least the rest of us can do for them. The natural tendency is to help the victims replace and rebuild what they have lost and to minimize their dislocation. But we must ask ourselves whether this policy is really helping anyone in the long run. Are we not setting up both the victims and ourselves for a replay of the same scene at some future date? Would it not be more sensible to introduce incentives to relocate out of the flood plain rather than to encourage a return to the precarious situation of the past? Would it not also seem reasonable to demand of those who choose to remain in the flood-prone area that they plan realistically for the possibility that they will experience the same problems again? It is not society's obligation to continue to subsidize clearly unwise and uneconomic choices by some of its members.

There are several ways in which flood insurance can play a role in forcing people to pay the real costs of their occupancy of the flood plain. The government could adopt a policy of refusing to provide aid for flood victims, thereby putting the burden of protection on the flood plain occupants themselves. This would, I believe, be a grossly unfair policy to adopt at this time, given the severe economic inequities that already exist in our society and the fact that most people who now live in flood plains moved there at a time when these questions were not considered worthy of serious consideration.

A more sensible approach would seem to be to accept the fact that society will have to bear the cost of past mistakes, but to insist that any *new* flood plain development and any rebuilding of flood damaged areas be done with the clear understanding that the residents, businesses, and industries that occupy that area are expected to anticipate and make a reasonable effort to pay the costs of any future damages. The best way to do this is with insurance, and this insurance should be mandatory. Mandatory insurance is the only viable alternative to simply turning our backs on the flood victims and saying "we warned you." Human beings do not feel good about

themselves when they behave this way. Many states already require auto insurance, and adequate fire insurance is required by all mortgage lenders. A program of compulsory health insurance is considered by many to be a sensible way to handle the country's health care problems. Compulsory flood insurance would fall within this same category and would seem to be in the best interests of both the flood plain residents and the society as a whole.

Of course, as with each of the alternatives considered here, flood insurance by itself is not a complete solution. An intelligent insurance plan would promote zoning and warning systems in order to minimize losses. This is precisely the conception of the National Flood Insurance Act of 1968, in which federal flood insurance is sold only to those communities that meet certain minimum standards for zoning, warning systems and relief capabilities. It seem reasonable to demand that the entire society share the cost of past overdevelopment on the flood plains of our rivers. This concept is embodied in the Flood Insurance Act through federal subsidization of rates, so that present flood plain occupants will be encouraged to purchase the insurance.

The insurance program is being administered by a pool of private companies and the limits of subsidized insurance are \$17,500 for a single-family dwelling, \$30,000 for two- to four-family structures, and \$30,000 for small business properties. An owner who wishes to have extra insurance must pay full actuarial rates. The rate subsidies are seen as a transitory device to ease the readjustment to new land use patterns. New or substantially modified structures pay full actuarial rates. This national insurance plan contains incentives to dedicate the flood plain to parks, beaches, and certain industrial and low intensity residential uses (e.g., properly floodproofed vacation cottages) for which it is economically most suited. Only a small number of communities have so far made the necessary efforts to qualify for this insurance, but one senses a growing awareness and appreciation of this option in many floodprone communities.

C. Flood Warning Systems

Neither flood plain zoning nor insurance presents severe technological problems. When we get to flood warning systems, however, we encounter a fundamentally technological problem that could serve to siphon off some of the creative engineering effort which has traditionally gone into designing flood control structures. The data acquisition and processing problem, the communications problem, the various hydrology and hydraulics problems are all amenable to technological solutions, and depending on how much money one

wished to spend, one could conjure up flood warning systems with enough fancy technology to satisfy even the most hardware oriented engineer.

In a flood warning system the most important variable is the time delay between the warning signals and the actual flood. A flood warning system to predict the crest of the Mississippi River at St. Louis should be expected to make predictions several days in advance. For the Delaware River at Trenton one has a time period of the order to ten to twenty hours over which accurate predictions can be made. For flashy tributaries, a time delay of more than a half-hour could cost lives. Clearly the system one designs will be quite different for each of these three cases.

The state of the art of long term crest prediction seems to have reached a reasonably high level. By measuring discharges on major tributaries and using empirical lag times, a crude routing analysis can be done to estimate the height of the crest and its time of arrival at downstream locations. According to an official of the New Jersey Division of Water Resources, the crest at Trenton can be predicted to within one-half foot up to twelve hours in advance. In this official's opinion, there is no excuse for any loss of life in a main-stem flood on the Delaware.

It is on flashy tributaries that rapid early warning systems are necessary. Even when the flood plain of such a tributary has been zoned and its residents insured, a warning system is still required as a hedge against errors in drawing zoning lines. Where it is too late to prevent flood plain development, the warning system is essential so that at the least death and injury and easily preventable property damage can be minimized.

A very simple example of an early warning system has recently been installed on Green Brook near Scotch Plains, N.J. It consists of a device that monitors the gauge height at a certain point upstream, and when this reaches some critical value a warning light flashes in the local police department. This provides an earlier warning than what a local official has called the old "yell and holler system," especially at night.

Areas of the central United States that are subject to tornadoes are familiar with a similar type of early warning system. The sighting of funnel clouds in an area, or even just the appearance of characteristic weather phenomena, are enough to cause tornado warnings to be broadcast urging people to take safe shelter. It is not too difficult to conceive of analogous arrangements for flash floods. Data on the relevant characteristics of a drainage basin (infiltration capacities, lag times, base flows, etc.) could be monitored at frequent intervals and

stored in a data bank. Using modern radar and other microwave techniques the location, size, motion and intensity of an approaching storm could be fed into a computer program, which would predict the resulting flood much further in advance than a sensing device ten miles upstream.

There is clearly the possibility for error in predicting flood crests, and the tolerance for error increases as the warning time increases. This presents a rather tricky optimization problem. A warning system should be designed conservatively so that the only result of an error is inconvenience and whatever costs are associated with evacuation procedures. But if the system is too conservative, and people are inconvenienced too many times with no apparent justification, the system is likely to be discredited.^k Perhaps two signals could be given: first a "yellow light" (possible danger), then a "red light" (imminent danger).

Historically there has been a tendency for communities downstream of a new flood control dam to overestimate the protection it provides. One should expect the same misperception to accompany the introduction of a new warning system. Care must be taken to inform residents of the flood plain both about the threat of flash floods and about the details of the warning system. One way to do this would be to include an easily understandable description of the flood threat and warning system in the documentation accompanying the sale of homes or businesses in the flood plain. Of course, a clear presentation of the flood threat might discourage some people from moving into the area. So much the better!

V. FINAL THOUGHTS

For most of its journey from upper New York State to Trenton, New Jersey, where it begins the transition from an inland river to an estuary, the Delaware flows between fairly steep banks, and its flood plain is narrow. Occasional towns and cities occupy the few reasonably flat areas where the flood plain widens. The Corps of Engineers calculates that, in the 1955 flood of record, about 9,200 acres were flooded between Tocks Island and Trenton, and about 27 million dollars in damage was done.¹³ In its benefit calculation the Corps assumed that development on the flood plain would continue at previously experienced rates for the entire basin and that conse-

^kIn this connection it would be interesting to find out how effective the tornado warning system is. I am not aware of any sociological studies of the degree to which people actually take the warnings seriously.

quently damage in a future repetition of the 1955 flood would be substantially greater.

This prediction has not been borne out by events in the first fifteen year after H D 522 was written. Burt and Eisel showed that several communities, including Burlington, New Jersey; Easton, Pennsylvania; and Riegelsville, Pennsylvania, have substantially reduced the number of structures on the 1955 flood plain and that the total number of structures on the flood plain in the eight major damage centers has been reduced by over 40 per cent from 2,420 to 1,414.¹⁴

Thus, nonstructural techniques have already begun making a serious contribution to the prevention of flood damages along the Delaware River, and it would seem that this alternative will be even more important in the future, especially in New Jersey, which has a new flood plain zoning law. Contrary to the assumption in the Corps of Engineers' benefit-cost analysis, expected rates of growth in the Delaware Valley as a whole should not be reliable predictors of rates of growth in the flood plain itself.

It seems clear that the flood control function of the Tocks Island Dam easily passes a benefit-cost test as long as the dam is justifiable anyway for other purposes.¹ But it is most unlikely that a pure flood control dam could be justified. The relatively small damage potential between Tocks Island and Trenton^m coupled with the high ecological and esthetic value of a freely flowing river and the observed trends toward more judicious use of the flood plain would seem to argue against a Tocks Island flood control dam. It is important that this point be clearly understood by both the public and political leaders, because flood control has continued to act as a powerful emotional impetus behind the promotion of the dam. This impetus has been waning in recent years as the memory of 1955 fades, but it

¹The formal method of judging the merits of adding an additional purpose to a project that is already economically justifiable is to consider the "separable" costs and benefits of this addition. At the time of House Document 522 (1962), the annualized separable costs of providing flood control at Tocks Island Dam were only \$207,000. (Largely, this is the annualized cost of making the dam higher above the level of the reservoir than would be warranted by its function for water supply; in effect, the dam is perceived as a wall to contain a flood surge built on top of a wall to store water.) Even allowing for the inflation by more than a factor of two which has overtaken *both* costs and benefits between the analysis in House Document 522 and the analysis reported in Essay 4, this annualized separable cost is far smaller than the annualized benefit from expected reductions in property damage, \$3.8 million.

^mBelow Trenton the flooding of the river is dominated by tidal effects in the estuary.

could return to full strength overnight with the occurrence of another major flood on the Delaware. One suspects that if this were to occur, the flood control function of the dam would again become a powerful selling point, independent of the benefit-cost analysis.

Neither a structural nor a nonstructural approach to flood control can provide a perfect guarantee against flood damage, and uncertainties in flood frequency prediction make the long range benefits of a zoning law just as hard to predict as the long range benefits of a dam. Moreover, the magnitude of the impact of a flood on any community depends critically on the effectiveness of the system of emergency relief. It may be that, currently, dollars and effort spent on simplifying the relief system—which now confronts the flood victim with a bewildering array of public and private agencies having overlapping responsibilities—would yield the largest return, in terms of reduced anguish in the flood plain. Clearly, the choice of approach to flood control involves esthetic and moral judgments as much as economic and technical judgments.

We are now presented in part with a choice between two fundamentally opposed views of the proper relationship of human beings to nature. A dam or a levee symbolizes humanity's desire to dominate and control nature, and thereby to provide new options for development. A flood plain zoning law, a flood warning program, and a flood relief program symbolize a desire to adapt to nature and to confine humanity's options within the limits imposed by natural phenomena, thereby preserving the natural environment. Both seek to enhance the general quality of life.

Underlying the conservationist's clear preference for a nonstructural approach is the belief that "nature knows best" and that man is too stupid and clumsy to be able to grasp the subtleties of nature's mechanisms and manipulate them without risking irreparable damage. But this characterization is too negative by itself. There is also the positive reverence for nature in both her benign and violent moods, and a strong tendency to equate beauty with virginity. To the naturalist, beauty can be found in widely diverse places: a barren desert populated chiefly by dry mesquite and lizards, a high mountain pass covered with snow, a coral reef teeming with aquatic life, or a lonely stretch of wild river lined with green forests and rushing over rapids and falls. The only feature these various scenes have in common is their isolation from man and the fact that they have existed substantially as we view them now for millions of years without change, and that they will continue to exist for millions more if only they are left alone.

Theodore Roosevelt captured the essence of this esthetic in his preface to a collection of hunting stories:

There are no words that can tell of the hidden spirit of the wilderness, that can reveal its mystery, its melancholy, and its charm. There is delight in the hardy life of the open, in long rides, rifle in hand, in the thrill of the fight with dangerous game. . . . [We need] the silent places . . . the wide waste places of the earth, unworn by man, and changed only by the slow change of the ages through time everlasting.¹⁵

Aside from the references to hunting, this might very well serve as the credo of the modern day Sierra Club. The reader is urged to compare this quote with that of Allan H. Cullen in section I of this essay. These two quotes give an accurate measure of the philosophical gulf separating the conservationists from the technologists.

Most of us, including this author, can identify to some degree with the sentiments expressed by both writers. There may be some engineers who will not be content until every stream more than five feet wide is dammed, and there may be some conservationists who will not be content until we all return to living in caves, but for most of us it is extremely difficult to form a firm ideological commitment to one side or the other. We can, however, make one statement about attitudes toward flood problems with which most people would agree. It does seem that on too many occasions in the past the choice that has been examined has been between controlling floods by structural means or doing nothing at all. The adaptive alternative has been, with few exceptions, ignored. The right choice is between control and adaptation rather than between control and inaction.

Although in most cases I would prefer a combination of control and adaptation, I incline toward adaptation. Adaptive approaches are inherently more flexible than control approaches. Zoning lines can be redrawn or insurance rates can be changed as new information becomes available, but a 160-foot-high, 3,200-foot-wide dam will be around for a long, long time to come. One does not casually move aside three-and-one-half million cubic yards of earth and rock if one has second thoughts on the matter.

This flexibility is critical in the face of uncertainty. It is not possible for human beings, even with the most careful and objective analysis, to foresee all the ecological consequences of a major project. In the case of the Tocks Island Dam, even if it were determined that the lake would not eutrophy and that the shad would be able to climb the fish ladders to spawn, there could still be any number of serious, even disastrous, ecological effects which, if we had been able to

predict them in advance, would have caused us to abandon the dam.

It is often argued that if everyone thought this way nothing would ever get done. I would state this in the slightly weaker form that if more people thought this way, a lot less would get done. That would almost certainly be a good thing, especially with regard to massive projects such as the Tocks Island Dam.

APPENDIX A

The hydrograph in Figure 6-3 has two critical features: (1) a peak discharge, which is related to how high the water will rise at the crest of the flood, and (2) a lag time, which expresses how long after the start of the storm the crest of the flood arrives at the mouth of the basin. Both of these features can be understood quantitatively using the geometrical model in Figure 6A-1. In this figure, runoff is assumed to flow in a straight line. In each of the situations in Figure 6A-1, the shaded area shows where rain can fall in the basin such that it arrives at the mouth of the basin at a single time.

Runoff from rain falling at the left-hand edge of each shaded region at the beginning of a storm and runoff from rain falling at the right-hand edge at the end of the storm will drain across the basin together. The width of the shaded region is the distance that runoff will flow, moving at the basin's average velocity (v) during the duration of the storm (T). In the case where v is constant everywhere in the basin, the boundaries of the shaded region are fractions of circles centered at the mouth of the basin. If the rain starts suddenly, falls uniformly over time, and then stops suddenly, the shaded area is proportional to the discharge which will eventually appear at the mouth. The hydrograph, therefore, is generated by calculating the shaded area as the shaded area sweeps to the left.

Elementary calculus is required to calculate the areas in Figure 6A-1, and thereby the full hydrograph. But the peak discharge can be estimated using only geometry. The peak discharge corresponds to that particular shaded area of width vT that is centered on the diameter of the circle, as in the middle drawing. Given that the radius of the basin is R , the radius of the circle passing through the middle of the shaded region corresponding to the peak discharge is $R\sqrt{2}$, since such a radius is a chord traversing 90 degrees of the circle. If the thickness of the shaded area, vT , is much less than the radius of the basin, R , then, *approximately* (1) the inner radius of the shaded region is $R\sqrt{2} - vT/2$, and (2) the outer radius is $R\sqrt{2} + vT/2$, and

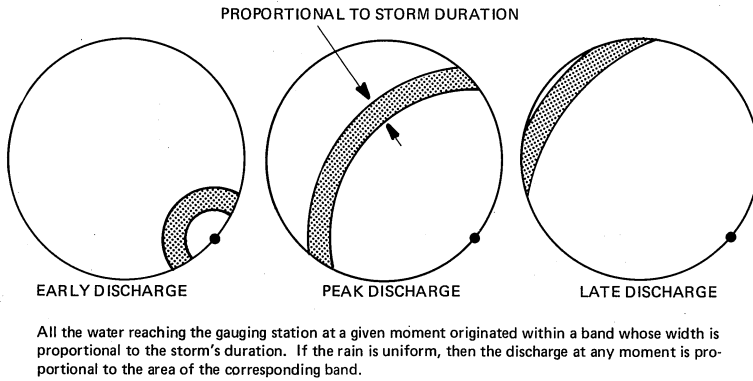
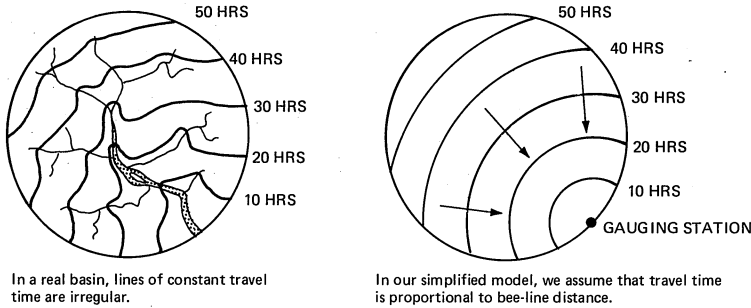


Figure 6A-1. Progress of Storm Runoff

(3) the shaded area (one-quarter of a thin ring) is $(\pi/2) (R \sqrt{2}) (vT)$.

The lag time, T_L , is defined as the time from the start of the storm to the peak discharge. Thus, it is the time for runoff to flow from the outer radius to the mouth of the basin:

$$T_L = \frac{1}{v} \left[R\sqrt{2} + \frac{vT}{2} \right] = \frac{R}{v} \sqrt{2} + \frac{T}{2} \quad (A1)$$

The peak discharge, D_{max} , is the product of the intensity of the runoff produced by the storm (P) (measured, for example, in inches per hour) times the shaded area, which is one-fourth of a thin ring:

$$D_{max} = P \frac{\pi}{2} (R\sqrt{2}) vT \quad (A2)$$

If we use precise data for our model storm, $R = 17.8$ miles, $v = 0.89$ mph, $T = 5$ hours, $P = 0.65$ inches per hour, we find that the lag time is 31 hours and the peak discharge is 74,000 cubic feet per second.

If a storm is of long enough duration to invalidate the assumption that vT is much less than R , then the approximate formulas written above will be inaccurate. If one must analyze a storm of long duration, it may be convenient to treat the storm as a series of short storms and sum the hydrograph corresponding to each short storm.

We can reexpress the formula for the peak discharge by introducing a quantity, Q , the total runoff produced by the storm. Since $Q = P\pi R^2 T$, we may write:

$$D_{max} = Qv/R\sqrt{2} \quad (A3)$$

or, including the lag time as well:

$$D_{max} = Q/(T_L - T/2). \quad (A4)$$

Since the lag time is much longer than the duration of the storm, we thus have the nice result that the total runoff from the storm is approximately the product of the peak discharge and the lag time.

The exact formulas for the shaded areas in the general case are not given here but were used to generate the hydrograph in Figure 6-3.^a It must be remembered that, unless the stream bed is initially dry, the flows we are calculating should be added to the flow already present (called the base flow). Here, too, conditions existing prior to the storm (the magnitude of the base flow) can be crucial in determining whether or not a flood occurs.

We may try to apply these formulas to the basin above the site of the proposed Tocks Island Dam. The area of that basin is 3,827 square miles. Assuming the drainage basin is circular (a rather poor assumption in this case), its radius would be 35 miles. The Corps reports in H D 522 that the design storm, with a total runoff of 586,000 acre feet, would produce a peak discharge of 211,000 cfs at

^aThe exact formula for the peak discharge yields a value of 75,000 cfs for our model storm, only one percent different from what we have found here using an approximation.

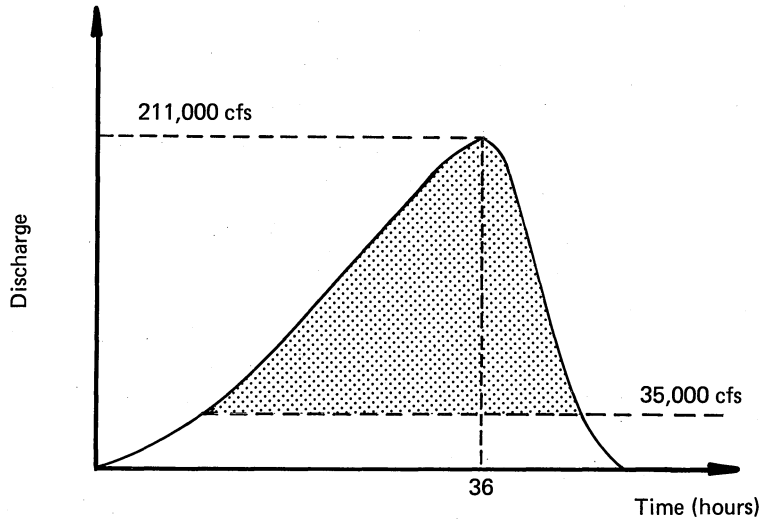


Figure 6A-2. Approximate Hydrograph for Tocks Dam Site.

the dam site in the absence of the dam.^b The corresponding storm duration is not specified, but it would be short; let us assume it is four hours. Using equation (A4) to solve for the lag time (since T , D_{max} , and Q are specified), one finds that $T_L = 36$ hours.

Using equation (A1) to solve for the average runoff velocity (since R , T , and now T_L are known), one finds that $v = 1.6$ miles per hour. Evidently, the basin above Tocks Island is relatively flashy, presumably because it is largely mountainous and the water runs off steeply sloped land.

The dam is designed to discharge at 35,000 cfs for most of the natural hydrograph period. To obtain a rough estimate of the needed storage in the design storm, I have drawn Figure 6A-2, a very crude hydrograph, but arranged to have the lag time and the peak discharge just calculated. A very rough graphical estimate of the shaded area in the figure gives a short term storage of 287,000 acre feet, which compares remarkably well with the figure of 275,000 acre feet given by the Corps in H D 522.

^bOne acre foot = 43,560 cubic feet. The total basin runoff corresponds to 2.87 inches of runoff (rainfall minus infiltration) when averaged over the whole basin.

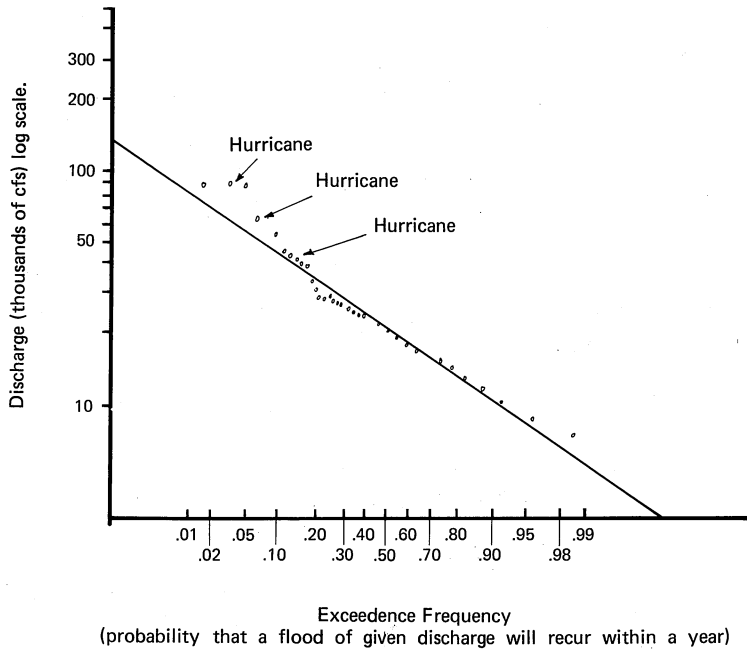


Figure 6B-1. Discharge-Frequency Curve for the Lehigh River at Bethlehem, Pa. The distorted horizontal axis is characteristic of "probability paper." Note: Some points have been deleted for clarity in the portion of the curve above 40 percent exceedence frequency.

APPENDIX B

The Corps begins its analysis with stream runoff data which is gathered by the U.S. Geological Survey from 108 stream gauging stations in the Delaware Basin. Most of these are equipped to convert the stage (level) of the stream into a discharge (cfs) figure. The yearly peak discharges are used in a flood analysis. In a statistical analysis of droughts, one would use the yearly minimum discharges.

The annual peak discharges for the N year period of record (typically $N = 40$ – 50 years) are next rank ordered according to their magnitudes, the largest being numbered one and the smallest, N . The recurrence interval of a given discharge is then given by N/m where m is the rank order of the given discharge.^c For example, the

^cThe Corps actually used a slightly different method, called the Beard method, which tends to assign longer recurrence intervals to the very rare floods. However, it is quite similar in principle to the simple method we use here.

second largest peak discharge in a 40-year record would be called a 20-year flood.

The logarithms of the peak discharges are then plotted against the exceedence frequencies^d on special probability paper, as shown in Figure 6B-1. This paper is designed so that if the logarithms of the peak discharges are normally distributed then the points will form a straight line, with the mean discharge at 50 percent exceedence frequency and the slope of the line equal to the standard deviation of the distribution.

If peak discharges are in fact log-normally distributed, this must ultimately be related to the fact that the peak discharge in any year is determined by a number of independently varying multiplicative factors that are more or less randomly distributed. One thinks immediately of storm intensity, storm location, infiltration capacity, previous stream depths, amount of snow cover, etc., as variables that would help determine the peak runoff.

The Corps of Engineers found that the assumption of a log-normal distribution for the peak discharges was a poor one for the Delaware Valley. There seem to be two quite distinct populations of peak discharges: those caused by ordinary storms and those caused by hurricanes. The hurricane-created discharges are rarer but tend to be considerably more severe than would be predicted by fitting the annual data to a single log-normal distribution. Accordingly, the smaller peak discharges are not much help in predicting the recurrence frequencies of the rarest and most devastating floods. In a 40-year record there are at most thirteen or fourteen hurricane discharges. This is statistically equivalent to having only a fourteen-year record of annual peaks, an awfully short record from which to estimate future recurrence intervals with much confidence.

This procedure was followed in generating a discharge-frequency record for each of the 108 gauging stations in the basin. The Corps found that, given the area drained by each stream and the average slope of the stream bed (e.g., in feet of descent per mile of run), the main features of the record of each stream could be reasonably well predicted. This enabled the Corps to estimate the discharge-frequency record for the many streams within the Delaware Basin which have no gauges. At this point in the analysis the Corps had a discharge-frequency curve for any point in the basin at which flood damage might occur. Wherever the stage-discharge relation for a location is known, relating height of a stream to its rate of flow, it

^dExceedence frequency is the inverse of the recurrence interval. A twenty-year discharge would have a 5 percent exceedence frequency—i.e., a probability of .05 that it would be exceeded in any given year.

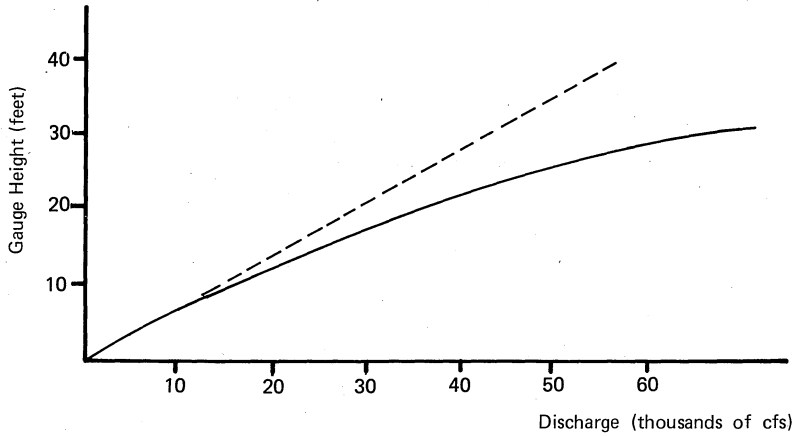


Figure 6B-2. Typical Stage-Discharge curve
Doubling the discharge less than doubles the height of the river, because the river spills over its banks.

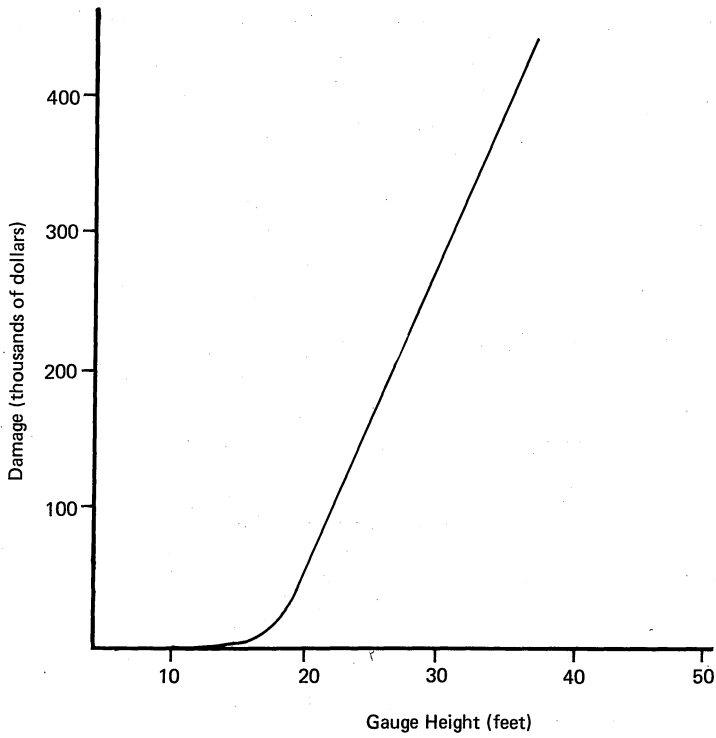


Figure 6B-3. Typical Stage-Damage curve

becomes straightforward to construct a stage-frequency curve, i.e., a curve showing the probability that a given gauge height will be exceeded in any year.

Figure 6B-2 shows a more or less typical stage-discharge relation. Note that the dotted straight line corresponds to the discharge being contained within perfectly vertical banks and moving with a constant velocity. Most stage-discharge relations deviate from this extreme because the channel has a sloping boundary.

The final step is to combine the stage-frequency curve with a stage-damage curve to produce a damage-frequency curve from which expected annual damages (in dollars) can be calculated. A fairly typical stage-damage curve is shown in Figure 6B-3. Note that for the first fifteen feet in gauge height little damage is done but that damage rises rapidly for stages higher than this. This is what one expects intuitively and we might denote fifteen feet as the flood stage at this particular location since a "flood" occurs only if the stage is exceeded.

The results of combining the three graphs in this Appendix is the damage-frequency curve in the text, Figure 6-7. Damage is plotted against exceedence frequency (probability per year that a given level of damage will be exceeded), because in that form the expected annual damage can be estimated graphically: it is just the area under this curve. The expected annual damage, in turn, is entered into the cost-benefit analysis.

NOTES

1. Calvin Kentfield, "The River Did Not Stay Away," *New York Times Magazine* July 15, 1973, pp. 14-19.
2. Allan H. Cullen, *Rivers in Harness*, (Philadelphia: Chilton Books, 1962).
3. For some other examples see W. G. Hoyt and W. B. Langbein, *Floods*, (Princeton: Princeton University Press, 1955), p. 3.
4. Allan H. Cullen, *op. cit.*, p. 57.
5. House Document 522, *U.S. Army Corps of Engineers Delaware River Basin Report*, vol. I, 1958, p. 48.
6. Edward F. Renshaw, "The Relationship between Flood Losses and Flood Control Benefits" in *Papers on Flood Problems*, Gilbert F. White (ed.) University of Chicago, Dept. of Geography Research Paper #70, 1961.
7. *Statistical Abstract of the U. S.*, (Washington: Dept. of Commerce 1972)
8. Laurie Burt and Leo M. Eisel, "Flood Control and the Delaware River," Environmental Defense Fund publication, April 1973.
9. These matters are discussed in greater detail by E. W. Beuchet in "A Legal View of the Flood Plain," Harvard Law School (1961), reproduced by the Tennessee Valley Authority for limited distribution.

10. Laurie Burt and Leo M. Eisel, *op. cit.*
11. The Corps' position is stated by Harry A. Dolphin, Chief, Public Affairs Office, Missouri River Division, Omaha, Nebraska in a letter to the editor of "Not Man Apart," the magazine published by Friends of the Earth.
12. Flood Hazard Report No. 2, "Delineation of Flood Hazard Areas, Raritan River Basin," Anderson-Nichols & Co., Inc. as consultants for the State of New Jersey, Dept. of Environmental Protection, Division of Water Resources, March 1972.
13. H D 522, Appendix D, Tables 2 and 4.
14. Laurie Burt and Leo M. Eisel, *op. cit.*
15. *African Game Trails, Works*, vol. 5, xxvii, quoted in Roderick Nash, *Wilderness and the American Mind*, (New Haven: Yale University Press, 1967), p. 150.

