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Economic Justification of Enlarging the Red River Floodway

A Discussion Based on the 1958 Report of the
Royal Commission on Flood Cost Benefit

C. Booy

FOREWORD

When the Royal Commission on Flood Cost Benefit compared the floodway with other means of providing flood protection for the City of Winnipeg, it wrote in its 1958 Report: ”Not only is the floodway more economical but it can also be expanded in size more easily.”

This possibility of expansion is important. The present 60,000 cfs capacity was selected for economic reasons, namely to maximize net benefits, but economic conditions change. In the year 2000 Winnipeg is expected to have a population of 700,000. Much more is at stake now than in 1958 when the population was only 410,000. Growth will likely continue. That makes a major inundation increasingly disastrous and its prevention more worth while.

A second reason for reviewing the adequacy of the floodway is that new information on the flood potential of the Red River has become available since the Commission wrote its report. The average return period of the design flood is now estimated to be 106 years rather than the 160 years the Commission assumed. These two factors suggest that the optimum capacity for the floodway is now considerably greater than it appeared in 1957.

Before embarking on the extensive study and data collection needed to determine how much the floodway should be enlarged, it is useful to review the information that is readily available, to examine how the present capacity was arrived at, and to determine what minimum enlargement can likely be justified. The investigation described in this report aimed at doing that. The optimum capacity was first re-calculated with the same figures for costs and damages used by the Royal Commission. Only the flood frequency curve was updated. To account for the growth of the City since 1957 the flood damage figures taken from the Report were then increased in simple proportion to the growth in population. With those new figures a new optimum was determined.

For 1957 conditions the calculations produced an optimum capacity of 80,000 cfs, which reflects the increased risk of flooding that is currently accepted. Taking the growth of the City into account raises the optimum capacity to 110,000 cfs. Based on the 1997 flood experience many of the detailed damage estimates used by the Royal Commission seem low, but in the absence of reliable information a more detailed updating was not attempted.

The results suggest that doubling the floodway capacity, and perhaps a significantly larger increase, can be justified on economic grounds alone. The review also shows that the economic analysis performed by the Royal Commission was deficient in that it did not include the cost of the flood easements needed to legalize raising upstream water levels above natural flood elevations even though the need therefore was foreseen in its report.

St. Adolphe, March 1999

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CHAPTER 1

BRIEF REVIEW OF PRESENT FLOOD PROTECTION POLICY

The operation policy for the floodway control structure determines what happens when the design discharge is exceeded. It must be reviewed before upgrading the flood protection for Winnipeg can be considered.[1]

Under emergency conditions, the operating rules give priority to preventing failure of the West Dyke, which is shown in the sketch of the floodway inlet on Figure 1. When the design capacity of the protection system (169,000 cfs) is exceeded, the upstream water level is allowed to rise above the natural flood level of 770.5 ft[2] so as to force more flow through the floodway. The level is not to exceed elevation 775.8 ft, which corresponds to a natural peak flow of 195,500 cfs and provides a 4.2 ft freeboard for wind and wave action. To cope with larger peak flows, the capacity of the river channel through the city is increased by constructing five-foot high emergency dykes on top of the Primary Dyking System. Only if this should prove insufficient, or impossible to achieve because of construction difficulties, may the water level at the inlet be raised further. Under no circumstances, however, is it to exceed elevation 778.0 ft, which is two ft below the crest of the dyke.

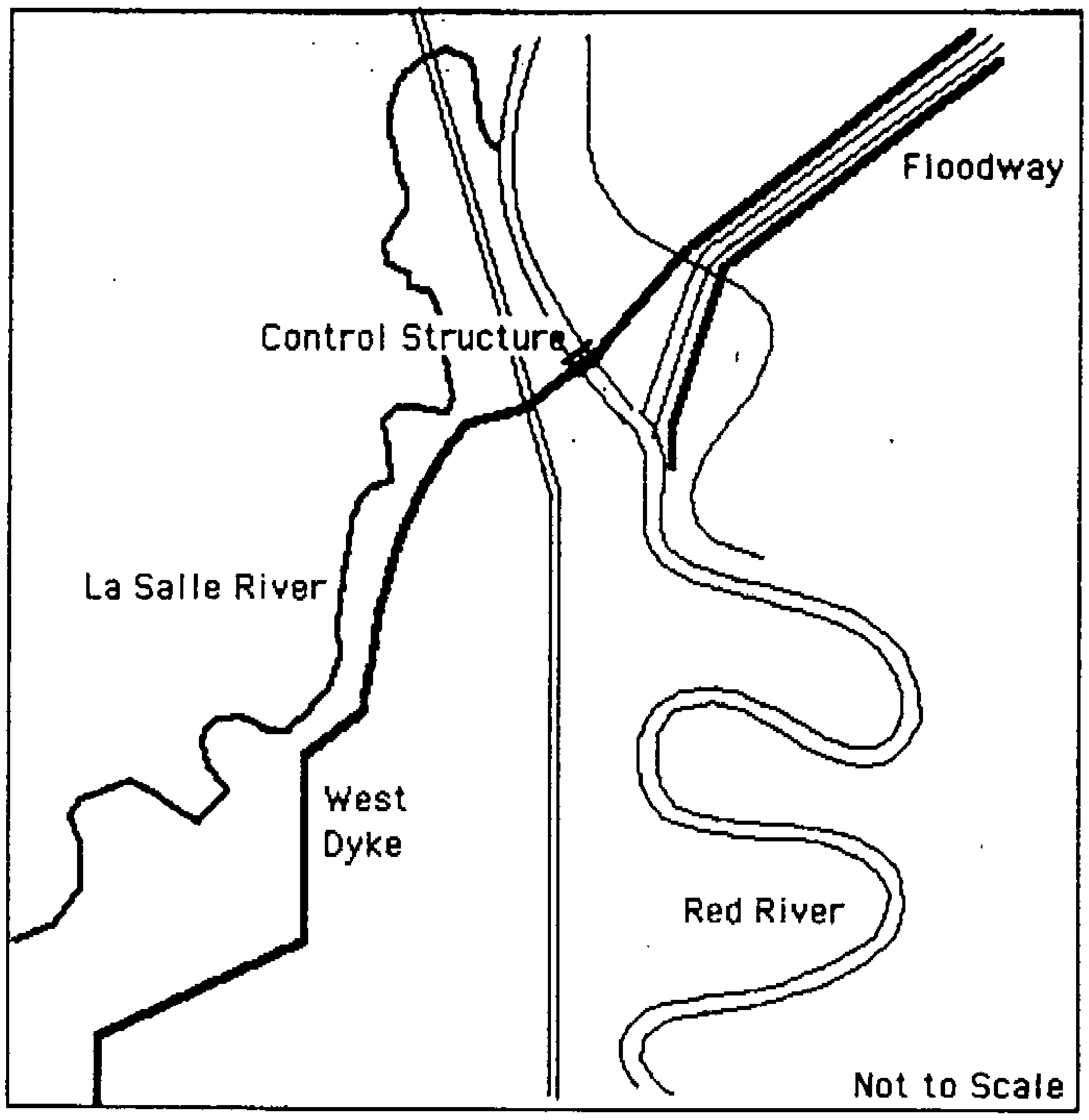

Figure 1

Overtopping of the Primary Dyking System in the city is thus preferred over failure of the West Dyke. This makes sense. In the situation envisioned by the operating rules, the West Dyke holds back the tremendous amount of water that would be stored up in what in

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[1] For a more detailed discussion of floodway operations under emergency conditions, see the report entitled: What If? , by C. Booy, of February 1999.

[2] This is the inlet elevation for 60,000 cfs obtained from the floodway rating curve in the Klohn-Crippen Report to the Manitoba Water Commission of June 30, 1998.

1997 was already called the Red Sea and which, with an inlet water elevation of 778.0 ft, would be up to 6.5 ft higher. Should the West Dyke be breached then a new water passage would be created to the La Salle River. As shown on Figure 1, this stream enters the Red River just downstream of the floodway control structure. The drop of up to 18 ft in only a few miles would cause rapid erosion and the city would soon be flooded. As the breach widened the flow in the floodway would be reduced. That would aggravate the flooding even more and prolong its duration.

The strategy behind the operating rules, which is aimed at preserving the integrity of the flood protection system, is therefore sound. But the rules overlook two important points. The first is the risk to the West Dyke posed by wind and wave action, and the second is the legitimacy of raising the upstream water level.

In his presentation to the International Joint Commission [3], professor Kuiper has demonstrated convincingly that two feet of freeboard is not nearly enough to ensure that wind and wave action will not breach the West Dyke. Increasing the freeboard by raising the dyke a few feet is, of course, not difficult. But would that solve the problem? The operators of the control structure could then raise the water level at the floodway inlet even more if that seemed necessary to prevent the water in the City from getting too high.[4]

The temptation for doing that is clear. Allowing the river to overtop the planned five-foot high emergency dykes amounts to permitting a major disaster to occur. At the place where the river first overflows the earth-fill emergency dyke, rapid erosion would take place and the concentrated current would likely undermine also the underlying pavement that now forms the crest of much of the Primary Dyking System.[5] A serious breach of the dyke would occur at the time when the river is at its highest. Faced with the choice of allowing this to happen or taking a chance on the wind that may or may not occur on the following days, those in charge may well choose to raise the gates and gamble that whatever freeboard is left on the West Dyke will prove to be sufficient. The system should be designed to discourage this gamble. Raising the inlet water level above a pre-set elevation should be precluded so that the freeboard of the West Dyke will be adequate under all foreseeable conditions.

That would be in line with standard engineering practice. When the floodway inlet level is raised above natural flood levels a vast reservoir is created. The higher the flood peak, the larger the amount of water that is temporarily stored. The West Dyke then functions like any earth-fill dam that holds back a large reservoir. It should meet the normal safety precautions for such a dam. Since a breach would threaten a major population centre, standard engineering practice undoubtedly demands the elimination of all foreseeable risk of failure. Overtopping by wave uprush would have to be prevented even if the probable maximum flood occurred.

But any consideration of raising the West Dyke gets us to the second point. The operating rules tacitly assume that the Province has the right to include in its flood protection plan raising the water level at the floodway inlet to elevation 778.00 ft. That is 3.5 ft higher than what the same rules take to be the natural flood level for the probable maximum flood. Doing that would be disastrous for many people living in the Red River

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[3] Submission to the International Joint Commission Regarding Red River Flood Control by Ed Kuiper. January 1998. The document was handed out at the public hearing.

[4] In 1997 the operators raised the inlet water level two feet higher than the natural level just to avoid some basement flooding in the city even though this was in violation of the operating rules for the control structure.

[5] The disastrous effect of a concentrated cross flow on road pavement was clearly demonstrated in 1997 on highway 75 south of St. Agathe , where it undermined the concrete road deck and created a deep and wide scour hole.

Valley. It would cause severe inundation in areas that to date have never experienced any flooding by the Red River. The Province could have obtained the right to do this, but only by securing the necessary flood easements[6] from all property owners affected by the increased water levels. It has not done so.

There is no question that in an emergency situation the government may have to sacrifice the interests of some persons for the sake of preventing a major disaster. But what we are discussing here is not an unforeseen emergency but the design of a flood control project. The point is that this design entails as a totally predictable feature the need of raising upstream water levels above natural flood elevations.

This is a fundamental problem with the present system. When it was designed Flood Control like all Water Resources Engineering focused on specific projects with limited, well-defined targets. Accordingly, the Royal Commission on Flood Cost Benefit decided in 1958 that maximum benefits would be obtained with a project that protects Winnipeg against floods up to 169,000 cfs. To do this the Commission recommended a floodway with a 60,000 cfs capacity. The target of economic efficiency defined the project and its scope. The Royal Commission fully realized that some day the design flood would be exceeded but economically it made no sense to provide additional protection if the added cost was larger than the damage which the addition was expected to prevent. How to respond to the occurrence of those larger floods was a different story, not part of the project considered by the Royal Commission.

The narrow focus on the economic benefits expected from the project under consideration limited not only the design capacity but also the thinking about the operation of the control gates. In its 1958 report the Royal Commission discussed raising the water level at the floodway inlet so as to increase the discharge capacity and provide more protection for Winnipeg. But that alternative was rejected in favour of operating the gates so as to keep the upstream water level at the elevation it would have reached in the absence of a floodway.[7] In the context of the project itself that was a sound decision. Not having to involve upstream property owners certainly simplified getting the project underway. But the question what to do when the project limits are exceeded remained unanswered.

In the design stage it made sense to accept the small probability of flooding Winnipeg when the design flood is exceeded rather than spending more money to prevent it. But the situation is totally different in real time when exceeding the design flood becomes a reality. Then it makes no sense to allow Winnipeg to go under if it is at all possible to prevent this disaster. Then the target is no longer economic efficiency but saving Winnipeg. Then the inlet water level is raised as much as is consistent with that new target. That real time logic is clearly reflected in the operating rules that were formulated after the Commission had completed its design and the project was built.

It is not wrong to base the design flood on economic considerations. The weakness of the Royal Commission's approach was rather that it was inconsistent. The control gate operation, which the Commission assumed in the economic analysis, was abandoned in the discussion of what happens when the design flood is exceeded. The report observes that with a raise of three feet above natural levels at the floodway inlet "it would be possible to fight a flood up to 200,000 cfs in the Greater Winnipeg area".[8]. But that eventuality was apparently considered beyond the concern of the project.

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[6] A flood easement is entered as a caveat on the title of the property. It diminishes the property value. In a region where there is plenty of property that is not threatened with flooding, the reduction could be substantial. Obtaining easements is an obligation apart from whatever obligation exists to pay compensation for actual damage .

[7] See page 72, Report Royal Commission on Flood Cost Benefit, 1958.

[8] See page 89, Report Royal Commission on Flood Cost Benefit, 1958.

Obtaining flood easements for any foreseen raise in water levels above natural flood elevations should have been part of the project and the cost thereof, as well as compensation for actual damage, should have been included in the economic analysis. If that had been done then the capacity of the floodway would probably have been larger and there would be less need for raising the inlet level. More important, however, the property owners immediately upstream of the control structure would have been more aware of the high water levels they could expect. They could have prepared for them accordingly.

Another inconsistency in the Royal Commission's approach is that intangibles were not taken into consideration. It is, of course, difficult to put a dollar value on items such as insecurity, disruption of lives, human suffering, shattered prospects, etc. But that does not justify disregarding them. Most decisions in a person's life, minor as well as major, are based primarily on an evaluation of intangibles. There is no reason to assume that our collective value judgment is radically different. It is gratifying to know that the floodway proved to be a successful economic venture but that is not the reason the citizens of Winnipeg or even the responsible governments are quite happy with it.

A proper economic evaluation based on tangible costs and benefits is an indispensable factor in deciding what degree of flood protection we can afford. But rather than using it as the sole basis for the determination of the design flood it should be used to judge the economic implications (direct cost and monetary benefits) of whatever design flood is chosen for a host of other valid reasons. It is only one of the factors to be considered.

CHAPTER 2

STRATEGY FOR IMPROVEMENT

2. 1 The Alternatives.

Added protection for the City of Winnipeg can be obtained in a number of different ways. One could consider additional flood control on the Assiniboine River so as to decrease its contribution to the flow below the junction of the two rivers. That possibility, however, appears to be quite limited. Even the effect of the present control works on the flow at the James Avenue Pumping Station is to a degree uncertain. It depends on what discharge in the Assiniboine River coincides with the peak flow of the Red River. For the sake of simplicity, this study assumes that the combined effect of the Shellmouth reservoir and the Portage Diversion is and remains a reduction of 25,000 cfs at the James Avenue Pumping Station for all major flood events.[9]

Another possibility is raising the Primary Dyking System. This is not an attractive solution if overtopping can not always be avoided. The present low dykes have a crest of 26.5 ft, City Datum. They are mostly paved roads that can sustain a limited amount of general overflow without serious erosion. Raising the water level by one foot increases the capacity of the river channel through the city by about 5,000 cfs. The dykes would thus have to be made substantially higher to make a worthwhile contribution to the discharge that is controlled. But that would make overtopping also more dangerous. It would occur at a higher river level and most likely initiate a fast eroding breach. A large inundation would then occur rather suddenly and create a more hazardous situation.

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[9] An updated hydrologic study of the contribution of the Assiniboine to the flood problem in Winnipeg is overdue. For the purpose of this study, however, the uncertainty in the contribution is of minor importance.

From an economic point of view this alternative is also of questionable merit. The Royal Commission on Flood Cost Benefit examined the building of dykes through the City as a possible means of providing flood protection. It came to the conclusion that the benefit-cost ratio of dyking as a project by itself was low and that in combination with other projects it would undoubtedly be below 1.0.[10] This is not surprising because, unlike diversions, dykes make a difference for only a limited range of flow conditions.

More detailed studies may reveal that it is desirable to increase the flow that can be conveyed safely through the city. For the time being, however, it is assumed that no such attempt will be made and that the Primary Dyking System will continue to provide assured protection up to river water levels of 25.50 ft City Datum, which is one foot below the present crest elevation. This corresponds to a discharge at the James Avenue Pumping Station of 84,000 cfs.[11] The thinking behind this is that the prevention of flooding should be accomplished by means other than dyking. To the extent that flooding cannot be prevented provisions should be made to cope with it as best as possible. That can be done if dykes are kept low and erosion resistant. Preventable flood damage in the city is therefore assumed to start when the flow at James Avenue exceeds 25.50 ft.

With these assumptions the basic task of the review is restricted to determining whether there is economic justification for substantially increasing the floodway capacity. The remaining sections of this chapter analyze the economics of achieving the desired increase in different ways.

2. 2 Methods of Increasing the Capacity.

Increasing the floodway capacity can be achieved in two ways, by enlarging the cross-sectional area A and by raising the water level h at the floodway inlet. As will be shown below, the primary purpose of this study does not require deciding on the best combination. The optimum floodway capacity is the one for which the lowest *incremental* annual cost per cfs flow that is brought under control, equals the *incremental* annual flood benefits from that increase in control. The interest is therefore on *incremental* rather than on *total* costs. More specifically, the analysis is concerned with incremental costs in the neighbourhood of the optimum. As long as the benefit-cost ratio remains larger than one, the (probably substantial) initial cost associated with the capacity increase does not affect the optimum.[12] The following analysis aims therefore at determining a reasonable and conservative estimate of the lowest incremental cost of additional protection using readily available information.

Increasing the Cross-Section. Enlarging A must be done mainly by increasing the width. The depth of excavation is limited by the harder materials in the lower strata and by the need to avoid undue interference with ground water conditions. This is not to say that no significant increase in depth can be achieved either over the entire length or locally, but for the larger capacity increases the cost of enlarging A is expected to become proportional to the necessary increase in the surface width B. That proportionality also holds for the cost of lengthening the dozen bridges across the floodway. We thus write:

$$\Delta C_B = C_1 . \Delta B \qquad [1]$$

where ΔC_B is the increase in cost
C_1 is a constant
ΔB is the increase in floodway width.

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[10] Page 82, Report Royal Commission on Flood Cost Benefit 1958.

[11] According to the rating curve shown on Figure 4.5 of the Klohn Crippen Report.

[12] The issue of the overall benefit-cost ratio will be addressed briefly at the end of the study in section 5.2.

When the inlet water level h is kept constant, the increase in capacity is proportional to the increase in A and therefore roughly proportional to the increase in the surface width B. We write:

$$\Delta Q_B = C_2 . \Delta B \qquad [2]$$

where ΔQ_B is the increase in capacity due to the increase in B
C_2 is a constant.

The incremental cost, that is the cost per cfs associated with increasing B while keeping h constant, is the ratio of the two expressions:

$$R_B = \Delta C_B / \Delta Q_B$$
$$R_B = C_3 \qquad [3]$$

where R_B is the incremental cost associated with increasing B
C_3 is a constant.

Increasing the Inlet Water Elevation. When the inlet water level is raised by one foot without cross-section enlargement, the capacity of the present 60,000 cfs floodway increases by about 5000 cfs, or by about 8%. For a wider floodway the increase is of course larger in absolute terms. It is somewhat smaller as a percentage because the ratio of the surface width B to the average width is smaller for the larger floodway. As a first approximation, however, one could take the increase in capacity per foot of h to be proportional to B. We can then write:

$$\Delta Q_h = C_4 . B . \Delta h \qquad [4]$$

where C_4 is a constant
Δh is the increase in inlet water elevation.
ΔQ_h is the increase in capacity due to the increase in h.

On the cost side, increasing the inlet water level requires more, and more expensive, flood easements, as well as improvements of the West Dyke and raising the twelve bridges across the floodway. The flood easements are probably the most important limitation on raising h as far as incremental cost is concerned. Higher intake water levels increase not only the depth of flooding but also the extent and the frequency of flooding at any location that is affected. The actual cost is difficult to predict. The compensation is for the perceived reduction in property value and must be negotiated with the owners. But one can expect the cost to climb rapidly with Δh, possibly in proportion to the third or fourth power. We write therefore tentatively:

$$\Delta C_h = C_5 . \Delta h^4 \qquad [5]$$

where ΔC_h is the increase in cost
C_5 is another constant.

The incremental cost can then be written

$$R_h = (C_5 . \Delta h^4)/(C_4 . B . \Delta h)$$
$$R_h = C_6 . \Delta h^3 / B \qquad [6]$$

where C_6 is another constant,

Combining the Two. Neglecting the initial costs, since they are common to all enlargements, we can compare equations [3] and [6] to get some insight in the overall incremental cost. The comparison suggests that small raises of h are likely economical since they affect few people. Equation [6] shows, however, that when h is increased further, R_h will rapidly increase and approach R_B. Then it pays to enlarge the floodway width B.

Let us assume that we then increase B by a small amount. That will not change R_B but it will reduce R_h a little as can be seen from equation [6]. This reduction in R_h will then allow a small raise in h. Such an increase, however, will very soon get R_h back up to R_B. This shows that moving towards the optimum will involve increasing h as well as B. But the rapid increase of R_h with Δh suggests that for substantially larger capacities the incremental cost can be expected to remain at or close to R_B.

We should keep in mind that R_B is constant only for a constant h. When h is increased the value of R_B is decreased. One would expect the decrease to be in proportion to the increase in capacity caused by Δh as was mentioned above. A correction of the incremental cost for higher inlet elevations was obtained for modest increases in h by extrapolation using rating curve information as explained in the following chapter.

2, 3 Controlling the Flood Damage.

We now turn to the incremental flood damage. It will be assumed that flood damage is the result of overtopping of the Primary Dyking System and not due to failure of the West Dyke. This implies that the floodway can be counted on to remain fully operational and that it will, together with the flood control works on the Assiniboine River, reduce the flow at the James Avenue Pumping Station by the maximum possible amount. One can be certain of this only if there is an enforceable limit on the inlet water level. That is here taken for granted.[13]

It will further be assumed that once the Primary Dyking System is overtopped the extent of the flooding for a given peak flow at James Avenue is equal to what would have occurred with the same peak flow without any flood control works. For example, the extent of the flooding with a peak flow at James Avenue of 108,000 cfs would be the same as the damage that occurred in 1950 when that flow occurred at this location. The reason for stating this assumption is that the Royal Commission Report contains information on estimated damages for a return of several large floods under 1957 conditions. This information will be used to determine the incremental damage curve for successive increases in floodway capacity.

No emergency dyking will be assumed in the economic analysis even though there is little doubt that, given the opportunity, attempts will be made to ward off impending flooding by emergency dyking. The reason is that emergency dyking is a risky approach compared to providing equivalent protection by floodway enlargement.[14] It should not take the place of control measures one can depend on.

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[13] How this is to be achieved can be judged better when a more complete review of the flood protection is made.

[14] See page 79 of the Royal Commission Report for a clear analysis of the risk that emergency dykes will not provide the intended protection.

CHAPTER 3

DEALING WITH PROBABILITY IN THE ECONOMIC ANALYSIS

3. 1 Parameter Estimation.

The study of flood risk for the City of Winnipeg, described in the report: "The Risk of Going Under"[15], recommended using a risk function in which the parameter uncertainty[16], observed in the distribution of the Red River peak flows, is taken into account. The uncertainty does not affect the estimated value of the mean peak flow but it makes the estimate of the mean[17] more uncertain. This increases the risk that extreme values occur. The question arises whether this parameter uncertainty should also be taken into account in the economic analysis described in this report. The answer is negative. Why that is so can be illustrated with a simple example.

Let us assume that a person wants to wade across a muddy river. He is informed that, while the mean water depth is 4 ft, the actual depth could vary from this average by as much as 1.5 ft. Being 6 ft tall, the wader runs no risk of going all the way under. Suppose, however, that in addition he is told that the mean depth at any particular location is not that well known. It is estimated to vary between 3 ft and 5 ft. The "best " estimate may still be 4 ft but the uncertainty in the mean evidently increases the risk of encountering a depth of over 6 ft. Parameter uncertainty should therefore be considered in risk assessments involving extreme values.

Now suppose that the person does not want to wade across the river but rather calculate the discharge having observed the width of the river and the average velocity. The variability of the mean depth makes the discharge calculation uncertain but still the best estimate is commonly understood to be the one using the overall mean depth of 4 ft. The practice of using the mean as the best representative of a random variable, in this case the local mean, is theoretically justified because it minimizes the expected (squared) error.

The economic analysis, which is the subject of the present study, uses the estimated mean annual flood damage for various levels of flood protection. The variability of the parameters that define the peak flow probability distribution makes this damage estimate to a degree uncertain. In a strictly economic analysis, however, overestimating and underestimating the flood damage are considered to be equally undesirable. One should therefore take the parameter values that minimize the error that can be expected. This also avoids bias in the calculations. The calculations needed to determine the economic optimum should therefore be based on mean parameter estimates. In other words, the parameters must be estimated from the record in the customary way[18]. There is no reason for taking the variability caused by parameter uncertainty into consideration.

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[15] Report by C. Booy. August 1998.

[16] Since the parameters (mean and standard deviation of the variable or its logarithm) are estimated from the record of peak flows that happens to be available, they are always to a degree uncertain. When the peak flows are independent of each other the basic, indeed the only, variability is the year-to-year, or short term variability. The uncertainty in the parameters because of this variability is small in a record that spans a good number of years. But the sequence of flood peaks on the Red River shows also a marked variability between successive decades or multiples of decades. Some periods have significantly more high peaks than one would expect from a pure chance phenomenon, others have less. This long-term variability increases the parameter uncertainty. It can be quantified and taken into account in a statistical analysis.

[17] The sample mean is more affected by the long-term variability than the sample standard deviation.

[18] Technically this estimation method is known as the method of moments.

3.2 Using Mean Annual Flood Damages.

It is not always recognized that the procedure that is used in the economic analysis for dealing with uncertain events is somewhat problematic for other reasons. To arrive at an economic decision involving uncertainty, one must add together the monetary consequences of future events, all having different probabilities of occurrence, and compare the sum with an expenditure that is 100% certain. That is, in a sense, comparing apples and oranges. To get around this difficulty in a decision situation, there has to be agreement on how the probabilities associated with the various consequences ought to function in the decision. It seems rational to assume that the more probable events should be given relatively more weight. That can be done best by giving each event a weight equal to the probability of its occurrence. A certain event, like incurring the unavoidable cost of the engineering works, is given the weight of one. This means that in arriving at the proper decision this event is taken for 100% into account. An impossible event is given the weight of zero, which means that it is totally disregarded. An event that has a probability of 50% of occurring is given a weight of 0.5, and so on. In the problem at hand this means multiplying all damages in dollars by the probability of their occurrence before adding them up. It is clear that this comes to the same thing as substituting for the entire series of possible but uncertain damages the mean value of the series. Indeed the practice is often justified by the claim that the mean is what one can expect "in the long run".[19] Whatever the justification, the procedure seems quite reasonable. Yet, few people act as if $100,000 with an annual probability of 0.01% is fully equivalent to a certain $10 per year. Certainly neither the many gamblers nor the innumerable buyers of insurance among us do so.

There are several reasons for this discrepancy. There is, of course, a nuisance value attached to chance losses and a euphoria value to lucky gains. More important for our discussion is the fact that the assumed linearity between real value and monetary value breaks down for exceptionally large losses as well as for exceptional gains.[20] An exceptionally large loss may have a crippling effect that justifies paying more for prevention than the strict monetary value multiplied by the (small) probability that the loss occurs. Another way of putting this is that the sheer magnitude of exceptional losses (as well as exceptional gains) introduces intangibles that deserve separate consideration in the decision. Large scale flooding of Winnipeg could carry a price tag in the tens of billions of dollars. The crippling effect of such a loss could permanently hamper recovery. One may well question the adequacy of treating a project aimed at preventing such a catastrophe as an economic venture that aims at maximizing expected net benefits. The insurance model may

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[19] Treating the mean of a series of uncertain monetary values as if it were a fixed constant number of dollars is justified, of course, for the very large populations of realizations that the insurance business deals with. There the temporal variability of the mean becomes indeed practically negligible. The mean annual flood damage, however, remains an extremely variable quantity within any realistic time frame. The assignment of probability weights offers a better justification than the argument one often hears about what can be expected "in the long run". Galbraith noted: "In the long run we are all dead." Hydrologists might prefer: "In the long run climate change will overtake all our predictions". Or, to avoid speculation completely: "What the future will bring is in God's hand. What we do is attempt to deal responsibly with uncertainty through a rational evaluation of the risk that we can discern and that we can quantify on the basis of past experience".

[20] The old Petersburg paradox illustrates the problem. Suppose you are offered to participate in a game of chance in which a coin is tossed repeatedly. If heads turns up the first time you are paid $2^1(\$1) = \$2$. If it also turns up the second time you are paid $2^2(\$1)$ or $4. The third time you are paid $2^3(\$1)$, or $8. The fourth time you get $16 and the n-th time you are paid $\$2^n$. As soon as tails turns up the game ends. What are you willing to pay for participating? For each term in the series the pay-out multiplied by the probability equals $1. Since there are an infinite number of terms the mean pay-out is infinite! But if you are not interested in winning more than a thousand billion dollars you should not pay more than $39 for participation.

then be more appropriate. In that model the basic problem is, of course, determining the value of added security.

This report is not the place for pursuing the question of how to evaluate the intangible consequences of flooding. It is probably better not to attempt setting a dollar value on them in advance. When for the entire range of design floods under consideration one has established the monetary consequences (cost and damage prevented) and one has a clear picture of the intangibles involved in each particular choice, then one can put the question whether the intangible benefits of additional protection are worth the extra expense needed to reduce the risk of flooding beyond what corresponds to the economic optimum. But to do that one first needs the economic analysis and that is what this study is about.

3. 3 The Probability Function.

The probability function used in this study is taken from the report: "The Risk of Going Under".[21] It is a two-parameter log-normal distribution that plots as a straight line on logarithmic probability graph paper. The function can be expressed as:

$$\mathrm{Ln}Q = 10.4682 + 0.6679\, Z \qquad [7]$$

in which

LnQ is the natural logarithm of the peak flows at James Ave

Z is a normally distributed variable with zero mean and unit variance.

The constants in the equation are the mean and the standard deviation of LnQ.

This distribution gives practically the same results as the three-parameter Log-Pearson Type III distribution currently used by the Water Resources Branch for the Red River at the James Avenue Pumping Station. The two-parameter distribution is preferred here for simplicity. It fits the data very well and it facilitates the necessary spreadsheet calculations discussed in Chapter 5. The choice is discussed more extensively in the report mentioned.

CHAPTER 4

USING THE INFORMATION FROM THE REPORT OF THE ROYAL COMMISSION

4. 1 General

The Royal Commission on Flood Cost Benefit conducted an extensive study of the flood damages that would occur if under 1957 conditions there was a recurrence of the largest floods they knew of. For these they took the 1948, 1950, 1861, 1852 and 1826 floods, as well as what was then estimated to be the probable maximum flood. The Commission considered damage to all types of buildings: dwellings, apartments, commercial buildings, institutional buildings, etc. It also considered damage to the infrastructure, the cost of flood fighting, evacuation, etc. and the loss to income caused by the flooding. The estimates were used to prepare flood damage curves that relate flood damage to high water levels. These in turn were used to prepare detailed estimates of the reduction in expected annual damage that could be associated with various projects, combinations of projects and degrees of protection.

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[21] The Risk of Going Under, by C. Booy , page 7.

The Commission had to make a choice between a variety of projects and combinations of projects that could alleviate flooding in Winnipeg, Brandon and the rural areas in the Red River drainage basin. Compared to this, the present study is much simpler. It only seeks to determine whether a substantial increase in the floodway capacity is economically justified. For this limited purpose it is sufficient to consider only damage to Winnipeg. This damage can be expressed as a function of the peak flow at the James Avenue Pumping Station which, everything else being the same, is reduced by the same amount the floodway capacity is increased. The information contained in the Royal Commission's Report was used to derive a simple mathematical expression that approximates the relationship between the James Ave peak flow and the flood damage. The derivation of the expression is explained in the next section.

Should the figures used by the Royal Commission be updated?

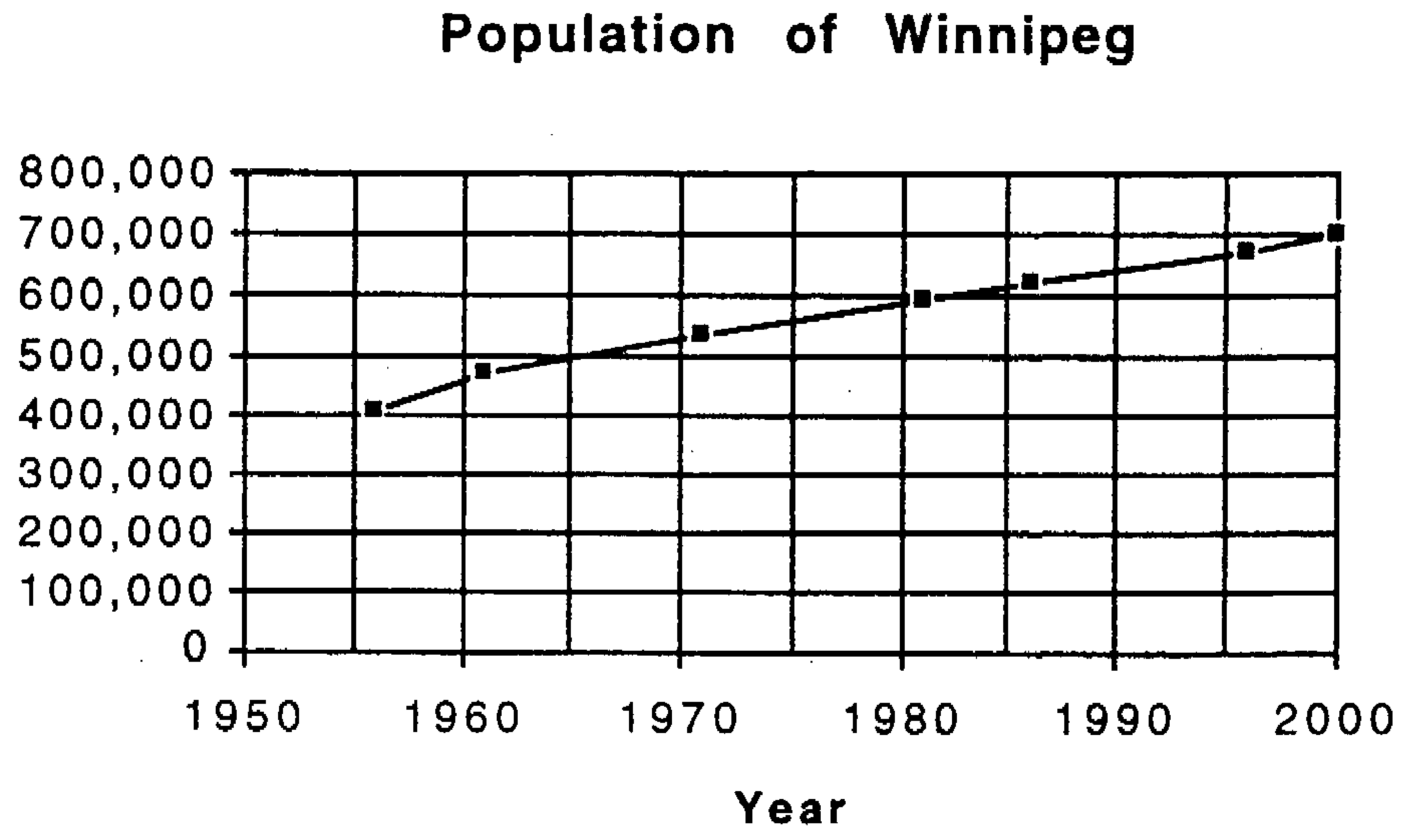

Figure 2

The answer is, of course, yes. Since its report was written, Winnipeg has grown from a population of 410,000 to nearly 700,000. as is shown on Figure 2. Moreover, the Commission expressed cost and damages in terms of 1957 dollars. Comparable goods and services are now about ten times as expensive. And, finally, several damage estimates arrived by the Commission seem far too low in the light of the 1997 flood experience.

Changing the individual damage figures in the Royal Commission's Report, however, requires specific information that is being sought but not yet available. It seemed undesirable to make the results of the study questionable by relying on arbitrary estimates. It was decided therefore to limit the investigation in this report in two ways.

In the first place, the report seeks to answer only whether the cost and damage figures found in the Royal Commission would justify a substantial increase of the floodway capacity. No attempt was made to determine the size of the capacity increase definitively. In the second place, only two, quite defensible, changes were introduced. The updated probability function given in equation [7] was used rather than the frequency curve used by the Royal Commission. And the damage figures used by the Royal Commission were increased in proportion to the population increase from 1957 to the year 2000.

All costs and damages remain expressed in 1957 dollars so as to facilitate reference to the Commission's report. This is not expected to change the optimum because the inflation that has occurred since 1957 affects costs and damages largely to the same degree.

4. 2 Flood Damage Estimates

As mentioned, the Royal Commission estimated the flood damages to Greater Winnipeg that would have been caused had the floods of 1948, 1950, 1861, 1852, 1826 or the probable maximum flood, occurred in 1957. They presented these damage figures, broken down into various categories, in a table together with the peak discharges at Redwood Bridge that occurred as a result of those floods. The peak flows range from 69,000 cfs to 270,000 cfs. [22]

Figure 3 shows the damage estimates for flows larger than 84,000 cfs as discrete points plotted against the corresponding peak flows at the James Avenue Pumping Station. The current estimate of the 1950 peak flow of 108,000 cfs was used rather than the 103,500 cfs assumed by the Royal Commission.

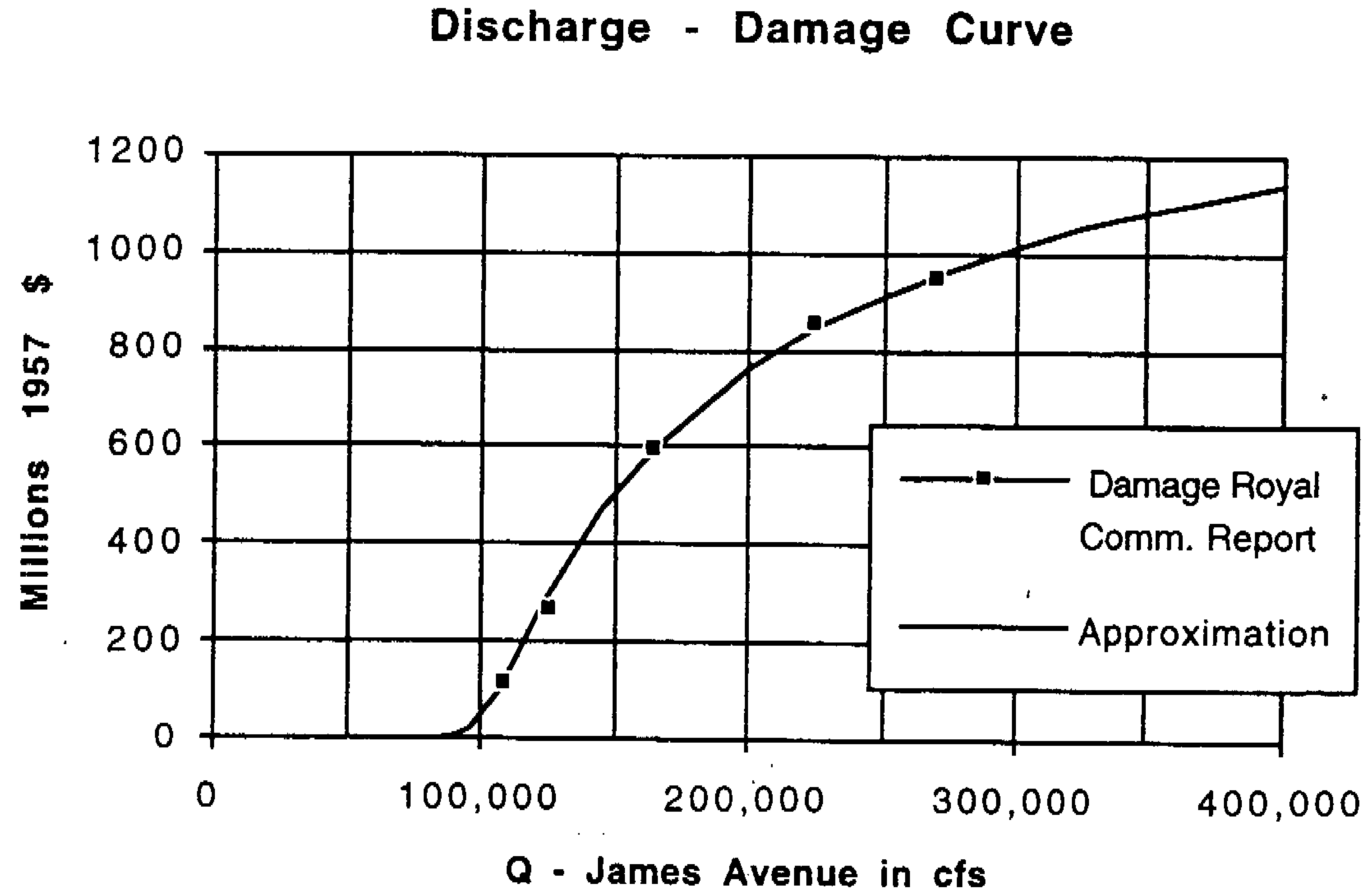

Figure 3

A mathematical curve was fitted through the data to obtain an approximate relationship that could be used for spreadsheet calculations. To arrive at the shape it was assumed that for the smaller floods the damage increases rapidly with increasing peak flows since progressively larger low lying areas are affected. For the larger floods, however, the depth of flooding, and therefore the damage, can be expected to follow the rating curve of the river, which tends to curve down. Finally, there is, of course, a limit to the total damage that can occur in a city.

For discharges smaller than 108,000 cfs the shape was more or less arbitrarily based on the assumption that the damage increases from zero to the reported $114,200,000 of the 1950 flood in proportion to the square of the discharge over 84,000 cfs. For the larger discharges a simple expression was obtained by assuming that the damage has a definite limit and that reductions from this limit are inversely proportional to the flood peak.

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[22] Royal Commission Report page 38, Table 6.2.

This led to:

$$D = A\,(1 - B/Q)$$

where: D is the damage
Q is the flood peak
A and B are constants.

As can be seen from Figure 3 a very reasonable fit is obtained with:

$$D = 1520\,(1 - 100{,}000/Q) \quad \text{million \$} \qquad [8]$$

For flows between 84,000 cfs and 108,000 cfs a quadratic expression was used:

$$D = 114.2\,(Q - 84{,}000)^2/(108{,}000 - 84{,}000)^2$$

$$D = 0.19826\,(Q - 84{,}000)^2 \quad \text{million \$} \qquad [9]$$

The damage estimates were not updated. To account for the population increase the figures must be multiplied by the ratio of 700,000 over 410,000 or about 1.7.

4. 3 The Cost of Enlarging the Floodway

The report of the Royal Commission contains cost estimates for floodways with capacities ranging from 20,000 cfs to 145,000 cfs and inlet elevations ranging from 766 ft to 773 ft.[23] They were obtained from the earlier Red River Basin Investigation and updated for 1957 price levels.[24] The cost figures were converted to annual costs using an interest rate of 4% interest and an amortization period of 50 years.

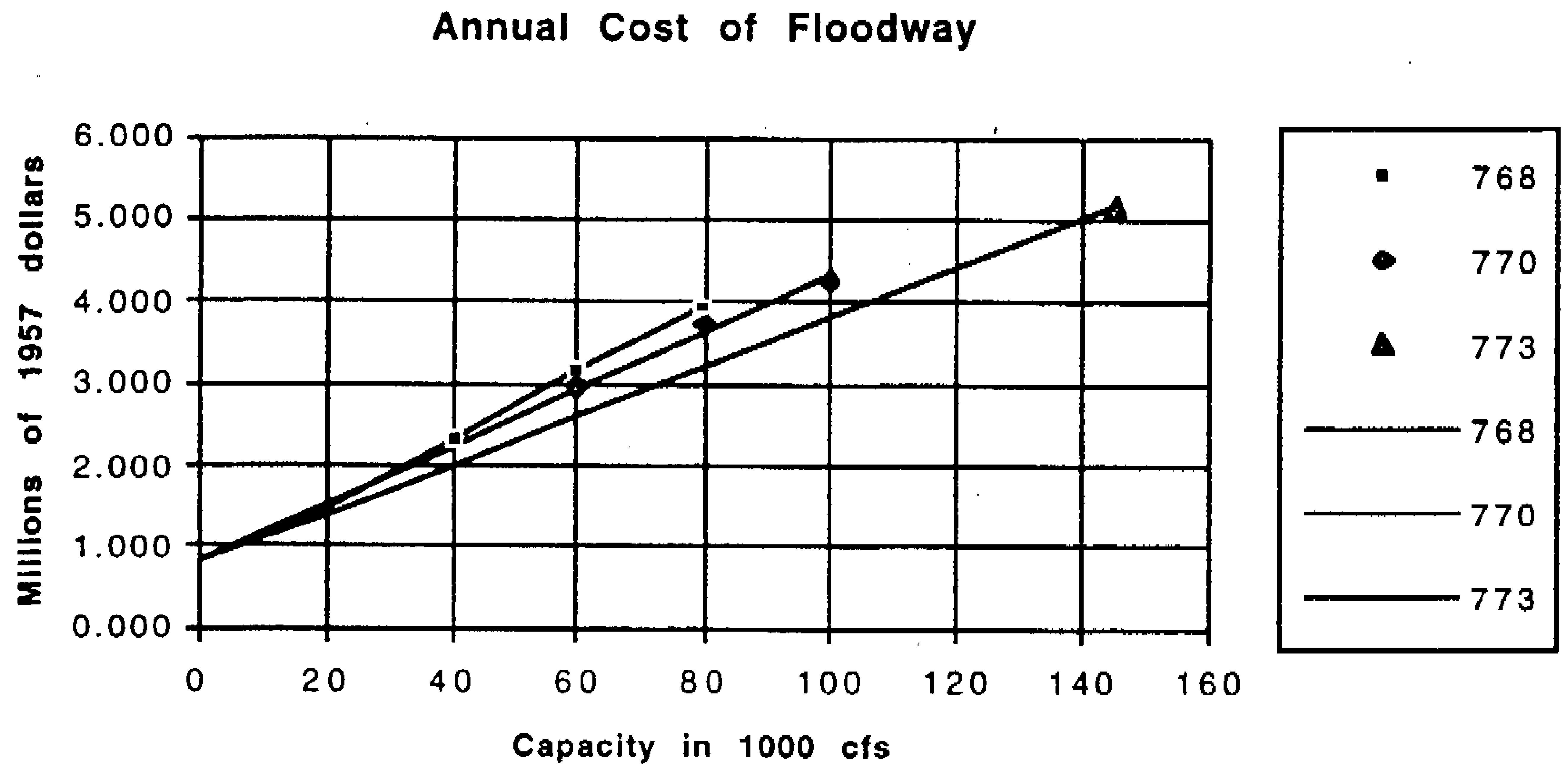

Figure 4

Only the inlet levels of 768 ft and higher and only the capacities of 60,000 cfs and more are of interest for this study. These data were plotted as discrete points on Figure 4. The points suggest linear relationships, as was predicted in the pervious section. Straight lines were therefore fitted through the data points for the inlet levels of 768 ft and 770 ft.

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[23] The elevations refer to the designs prepared by the Red River Basin Investigation, which assumed the control structure to be somewhat farther downstream.

[24] Royal Commission Report page 30, Table 4.4

Since the lines were close to meeting at a point on the vertical axis of the diagram, the line representing elevation 773 ft was also drawn through that point.

The slope of the lines represent the incremental costs. For inlet elevation 768 ft the incremental cost is \$39.33 per cfs, for elevation 770 ft it is \$35.00 per cfs and for elevation 773 it is \$29.88 per cfs. To be able to estimate the incremental cost for other inlet elevations the relationship between the increase in water level and the incremental cost was approximated by a curve using these figures. The results are shown in Figure 5.

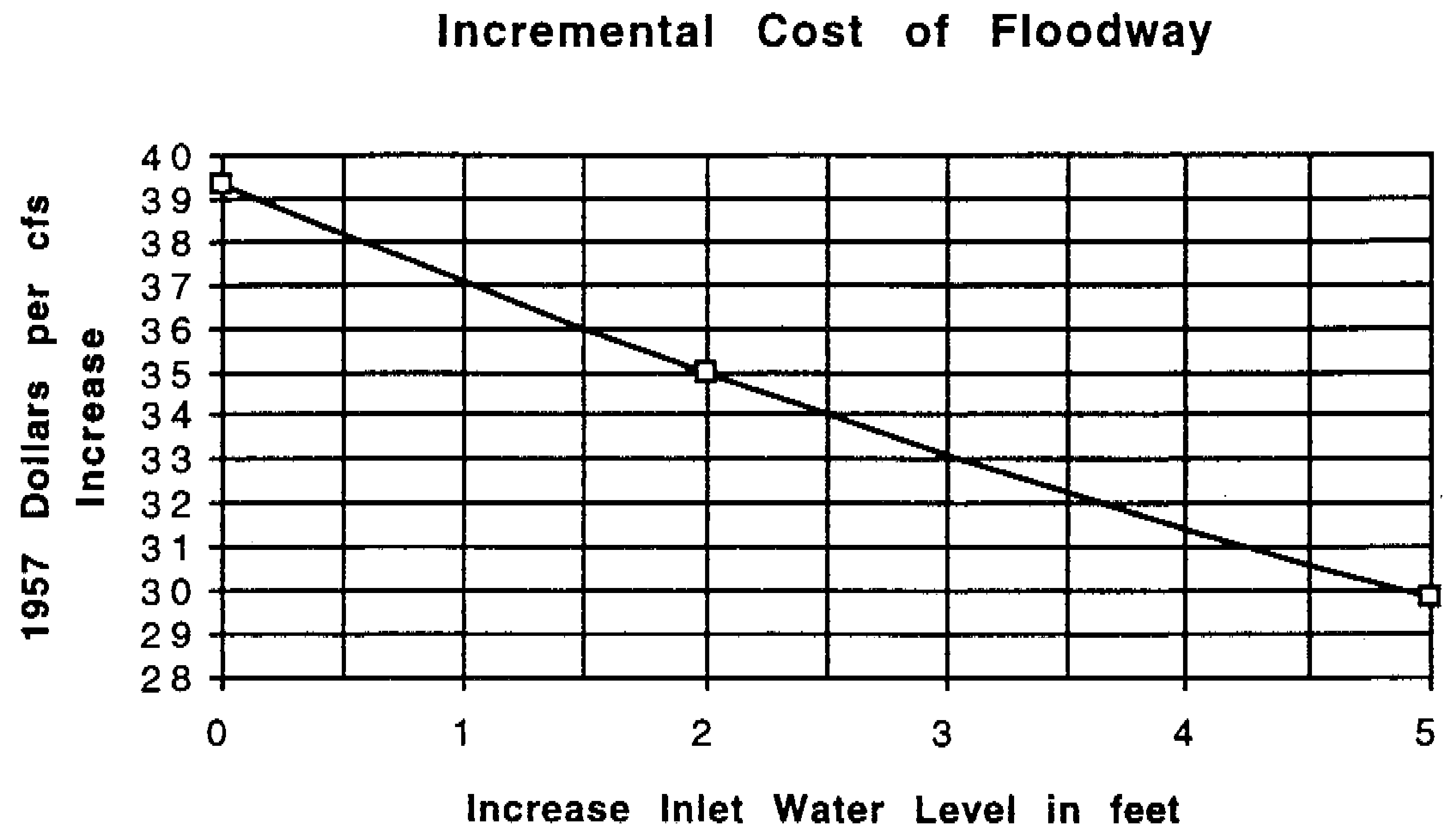

Figure 5

CHAPTER 5

INCREMENTAL BENEFIT COST ANALYSIS

5. 1 The Procedure

The first goal was to determine the mean residual annual flood damage for the set of floodway capacities under consideration. This was done by first calculating the expected damages for a range of peak flows as modified by a given degree of flood control. These damages were then multiplied by the probability associated with the peak flow. The values thus obtained were then added. Finally, the procedure was repeated for the range of floodway capacities considered. The calculations were performed on a spreadsheet.

The mean residual annual damage figures were used to determine the incremental flood control benefit, that is the damage prevented per cfs floodway capacity. This incremental benefit was expressed as a function of the increased floodway capacity. The figures were corrected for the growth of the City by multiplying with the population ratio.

Next the incremental cost of the floodway was determined as a function of the increased flood capacity. The capacity for which the incremental cost equals the incremental benefit is the optimum. Finally, some consideration was given to the effect of the initial cost on the results of the analysis.

5. 2 The Mean Annual Flood Damage

The residual flood damage for each floodway capacity used in the calculations was based on the peak flow that occurs at the James Avenue Pumping Station. It will be called *Q-James*. This peak flow is obtained by subtracting from the natural peak flow, called *Q*, both 25,000 cfs to account for the flood control works on the Assiniboine River, and the floodway capacity for the particular floodway enlargement under consideration. Table 1, which is included in the back of the report, shows the columns of the spreadsheet values obtained and will be referred to in the explanation that follows.

To start the calculations, the probability equation [7] was used to determine the annual probability that the present design flood, $Q = 169{,}000$ cfs, is not exceeded. This turned out to be a little more than 99.06%. This limit then defined the range of floods to be considered in this study.

In accordance with standard statistical practice the floods were identified by their non-exceedance probabilities *F(Q)*. A set of values for *F(Q)* was entered in the first column of the spreadsheet, (see Table 1) ranging from 99.06% in increments of 0.01% to near 100% . Since the normal distribution extends all the way to infinity the value of 0.99999 was arbitrarily chosen as the last entry for *F(Q)*.[25] Equation [7] was then used to determine the natural peak flow *Q* corresponding to each value of *F(Q)*. These were entered in the second column. It is not certain whether the last value of a little more than 600,000 cfs is still physically possible but for the calculations that is not important since the contribution of the final interval to the average annual damage is very small.

The flows at James Avenue corresponding to the values of *Q* were then calculated for the present floodway capacity of 60,000 cfs. They were entered in the third column called *Q-James-60*. Equations [8] and [9] were then used to determine the residual flood damages corresponding to each entry in *Q-James-60*. These flood damages are listed in the fourth column called *Damage-60*. To obtain the average annual damage for the floodway capacity of 60,000 cfs all damage figures in this column, except the last entry, were multiplied by the probability interval of 0.01% and added. The last value was multiplied by 0.005% instead of by 0.01% before adding, to account for the fact that the listed damages are associated with the upper interval boundary, instead of with the middle. The effect of this correction is, of course, very small. The average annual damage came to $2,721,302. That figure was entered below the other figures in the column *Damage-60*.

The procedure was then repeated for capacities of 70.000 cfs to 180,000 cfs. The average annual damage values are shown graphically on Figure 6 in the back of the report.

5.3 Incremental Flood Control Benefits

The average annual damage, which we will call *D*, is a function of the floodway capacity. The latter will be called *F*. To determine the relationship the natural logarithms of *D*, *LnD*, were plotted against *F* in Figure 7. The relationship is nearly linear.[26] We can therefore write:

$$LnD = a + b.F$$

where: a and b are constants.

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[25] In Table 1 the value is shown rounded off to 100%.

[26] This is perhaps not surprising. With the floodway a whole array of damages associated with stages at James Avenue remains possible. A larger capacity merely shifts all damages towards smaller probability values. The effect on the mean reflects the shape of the cumulative probability function of the peaks.

The incremental flood benefit is the damage prevented per unit of F. It will be called ΔD. Mathematically it is the derivative of D with respect to F. To determine it we take the derivative of both sides of the equation with respect to F:

$$(dD/dF)\,/\,D = b$$
$$\Delta B = b.D$$

In words: For a given capacity F, the incremental benefit is proportional to the corresponding damage D. The coefficient of proportionality is equal to the (absolute value of the) slope of LnD on Figure 7.

This relationship was used in another set of spread sheet calculations to determine the incremental damage as a function of F. The relationship was plotted on Figure 10 in the back of the report. In the interest of accuracy the coefficient of proportionality was equated to the local slope instead of to the overall slope. This makes very little difference.

A good approximation of the relationship can be obtained by taking the difference in flood damage between successive floodway capacities and dividing it by the capacity increase. The incremental benefit obtained this way must then, of course, be plotted in the middle of the capacity interval.

5.4 Incremental Costs

To obtain the incremental cost, that is the cost of the increase per cfs, the relationship between this cost and the inlet level, shown in Figure 5, was used. The inlet level was made dependent on the floodway capacity, as is shown in Figure 8.[27]

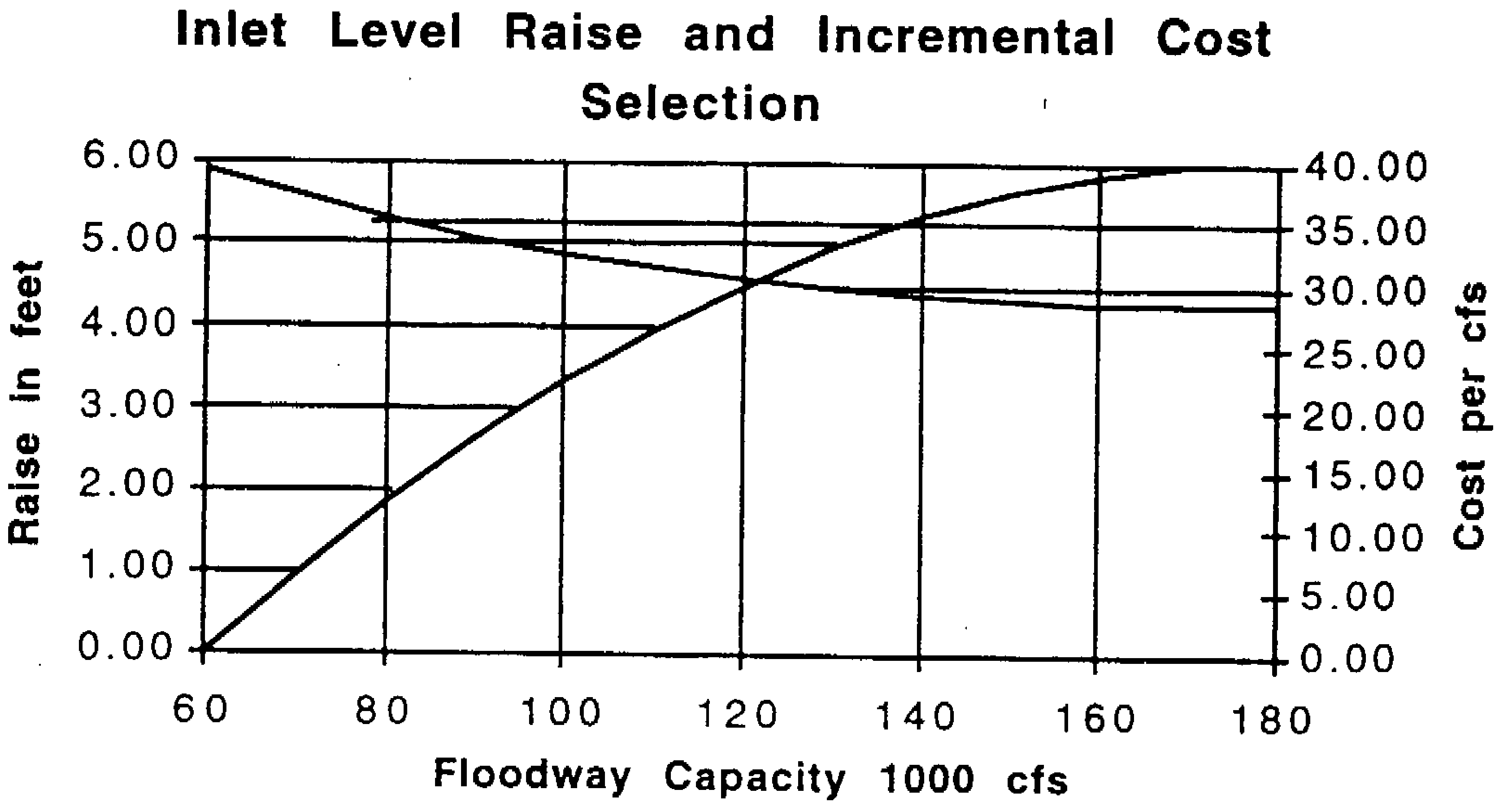

Figure 8

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[27] It was decided not to get involved in this report in the thorny issue of raising the upstream water level higher than the level adopted for flood proofing after the 1997 flood. According to the Klohn-Crippen report, referred to above, the 1997 level at the floodway inlet was 771.5 ft., which is one foot above the inlet elevation of the present floodway when it passes the design flow of 60,000 cfs. This would mean that the flood proofing would protect the adjacent property owners for a raise of up to three feet. But at this stage in the planning process it would not make sense to use the existence of local flood proofing as a binding constraint on the design.

The choice was based, first of all, on the assumption that for the larger design floods a greater increase in level would be justified because of the higher natural flood levels that would accompany the more severe floods. It was tentatively assumed that the level would not be raised by more than 6 ft even for an increase to 180,000 cfs. Keeping in mind that the effect of the increase is not only to increase the cost of any flood easement but that it also extends the number of easements required, a quadratic relationship with F seemed appropriate. This is shown on Figure 8. The figure also shows the corresponding incremental cost corresponding to the relationship of Figure 5.

The incremental cost curve was also plotted on Figure 10. This figure shows then that the optimum capacity would be around 110,000 cfs.

5. 5 Discussion of the Results

The residual flood damages associated with the non-exceedance probabilities *F(Q)* are shown graphically on Figure 9 for the range of floodway capacities investigated. The picture is instructive in that it presents graphically and to scale the magnitude and the distribution of the mean annual flood damages that remain with each of the floodway capacities. A comparison with the discharge-damage curve of Figure 4 shows that any error introduced by extrapolating this curve beyond the data obtained from the Royal Commission's report has no appreciable effect on the results.

The optimum capacity of 110,000 cfs is based on the very conservative damage estimates obtained from the report of the Royal Commission. The Commission estimated, for example, the loss of income in the City after a recurrence of the 1826 flood without flood protection. This loss accounts for about a quarter of the total damage. The Commission assumed that it would be 85% in the first two-and-one-half months, 35% in the next two-and-one-half months and 10% in the next six months. Thus the Commission assumed a return to normal conditions in a mere 11 months, which seems far too optimistic. The conclusion seems justified, therefore, that a substantial increase in floodway capacity can be defended on economical grounds alone.

One should keep in mind that this analysis is based on estimated incremental costs only. The undoubtedly substantial initial cost must also be considered. Bridges are to be lengthened and raised and the widening of the floodway may involve displacing large quantities of previously excavated and deposited material. In addition, there may be a substantial up-front cost for flood easements.

To address this issue globally we will consider a floodway capacity increase from 60,000 cfs to 80,000 cfs. From the figures in Table 1 one can calculate that the capacity increase reduces the average annual damage for 1957 conditions by $920,285. The figure must be increased by a factor of about 1.7 because of the population increase. That raises it to $1,571,000. Based on 4% interest and a 50-year amortization period this figure represents a present value of $33,753,000. The total cost of the enlargement, in terms of 1957 dollars, must thus remain below this figure in order to obtain a benefit-cost ratio larger than one. This seems rather likely, considering that the total cost of the present 60,000 cfs floodway in the same dollars was estimated by the Royal Commission at $57,361,000. If the benefit-cost ratio is larger than one for the increase to 80,000 cfs then it certainly remains so for all increases up to the optimum.

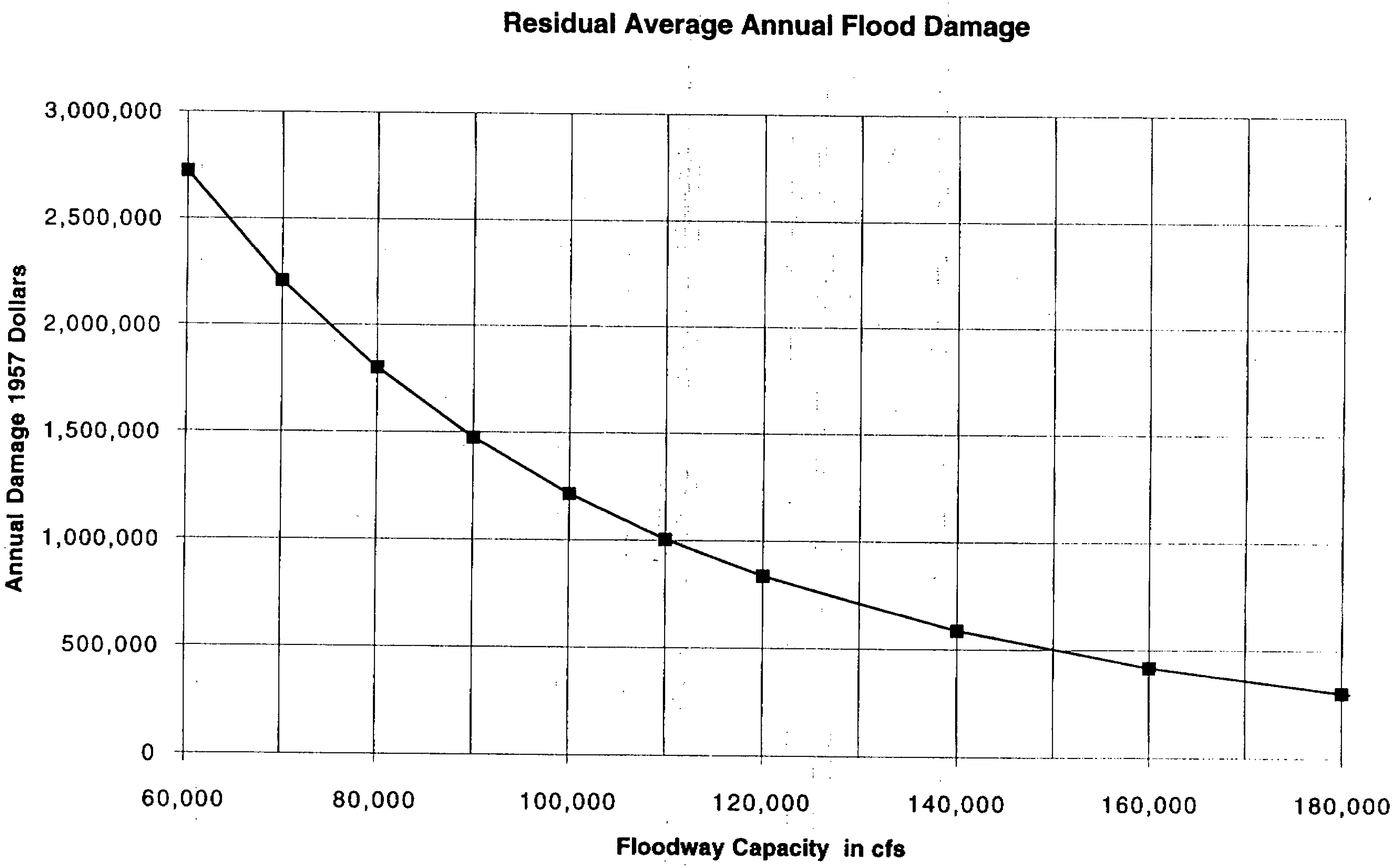

Residual Average Annual Flood Damage
Annual Damage 1957 Dollars
3,000,000
2,500,000
2,000,000
1,500,000
1,000,000
500,000
0
60,000
80,000
100,000
120,000
140,000
160,000
180,000
Floodway Capacity in cfs

Figure 6

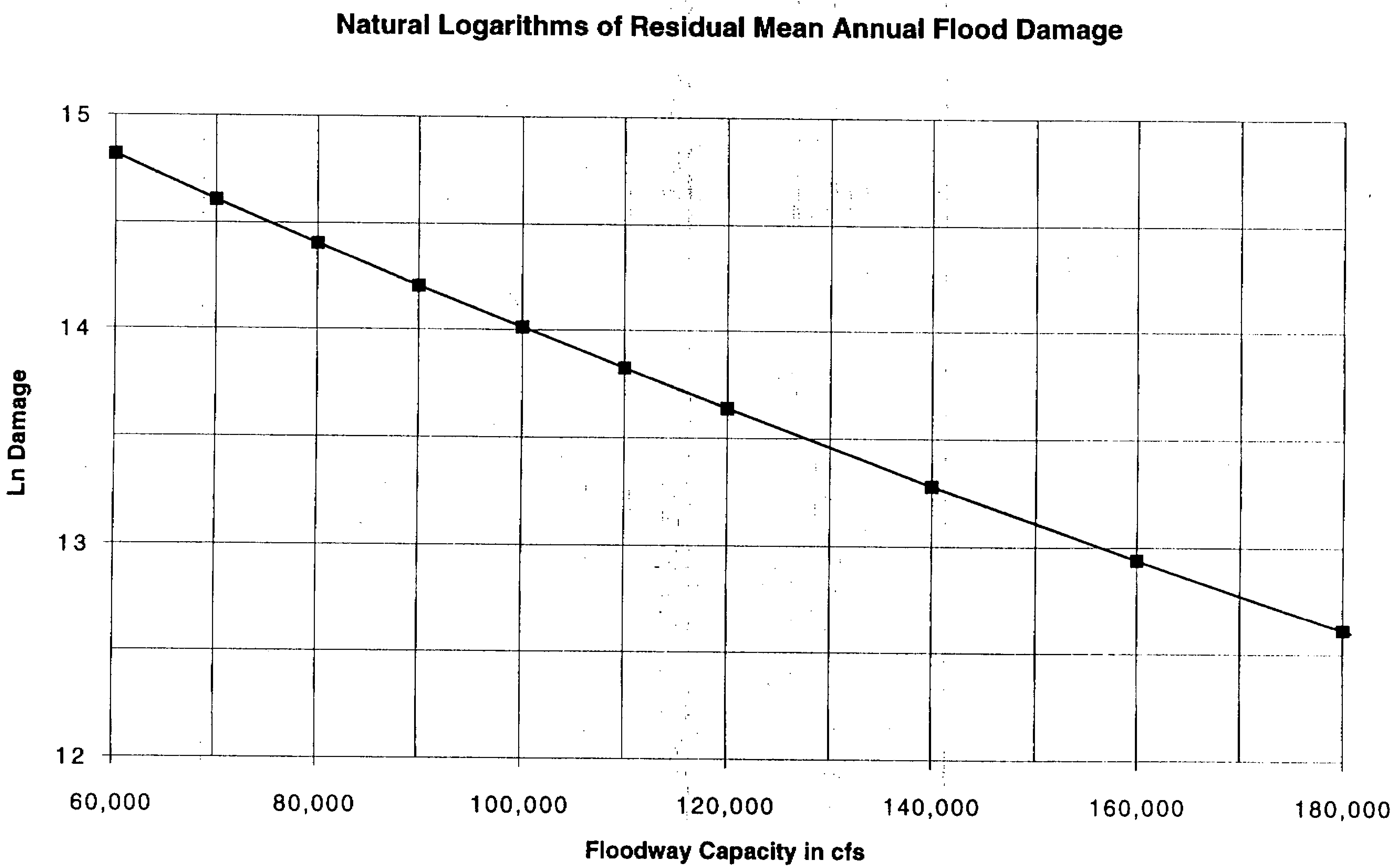
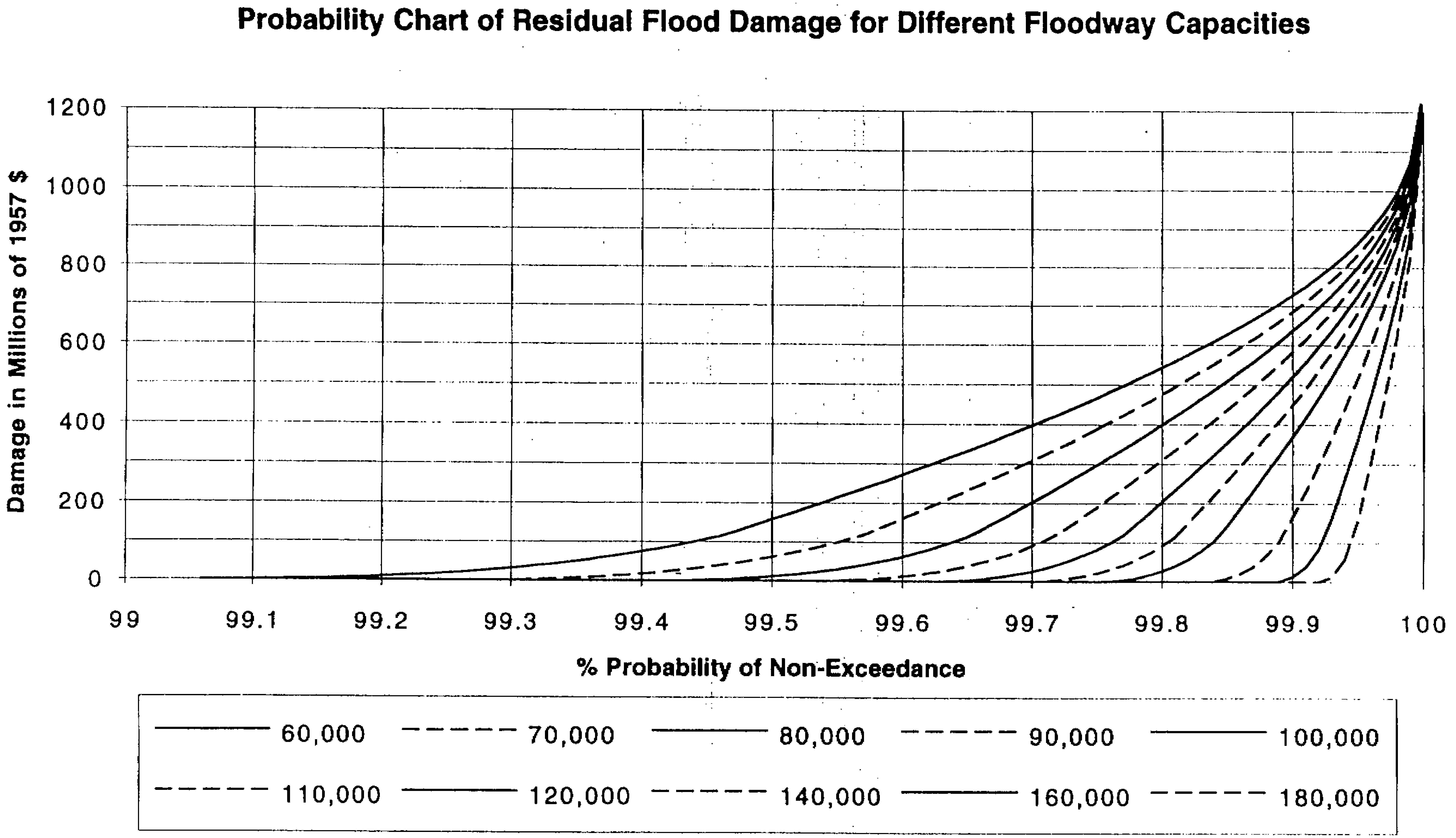

Natural Logarithms of Residual Mean Annual Flood Damage
Ln Damage
15
14
13
12
60,000
80,000
100,000
120,000
140,000
160,000
180,000
Floodway Capacity in cfs

Figure 7



Probability Chart of Residual Flood Damage for Different Floodway Capacities

Figure 9

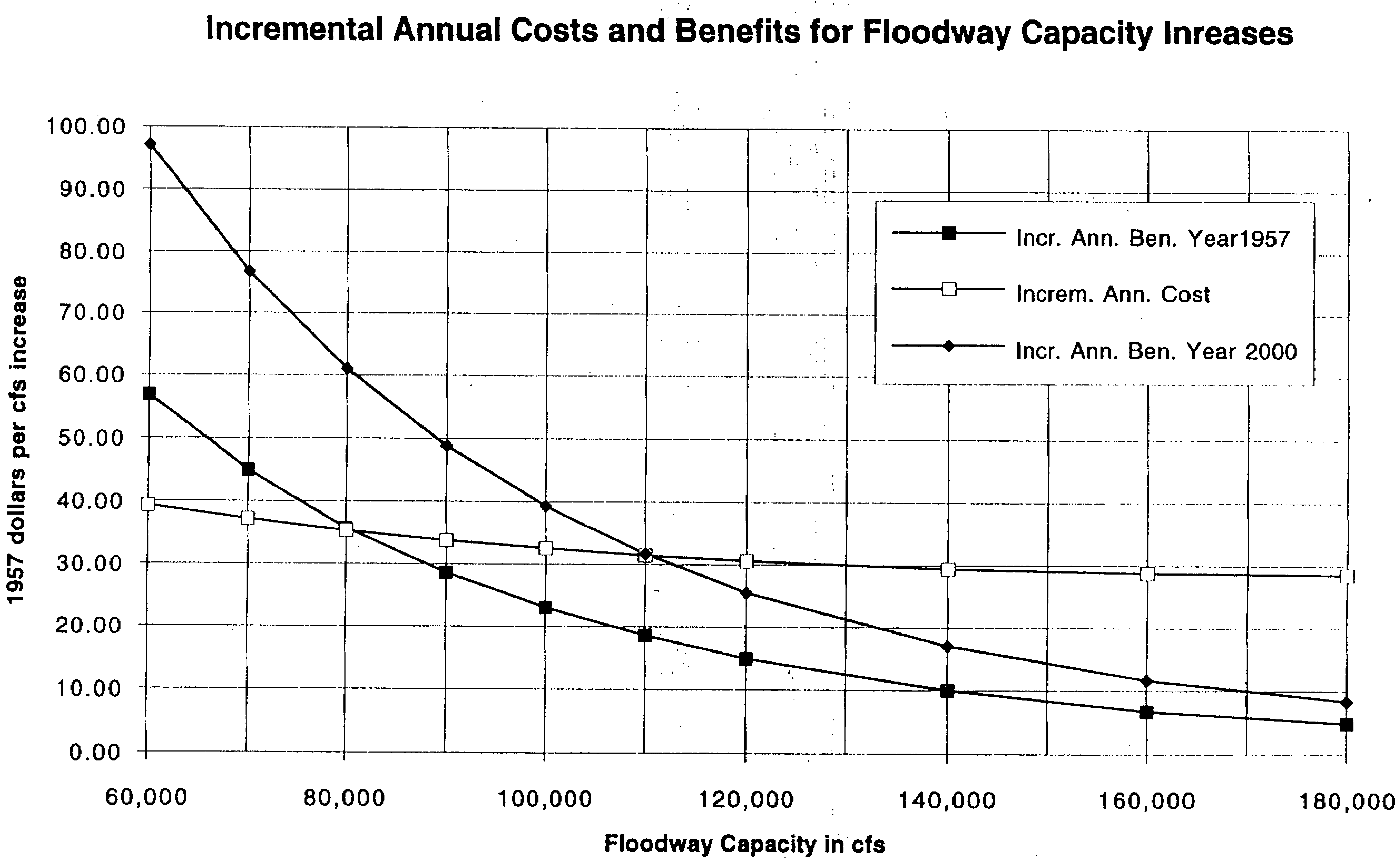

Incremental Annual Costs and Benefits for Floodway Capacity Inreases
1957 dollars per cfs increase
100.00
90.00
80.00
70.00
60.00
50.00
40.00
30.00
20.00
10.00
0.00
60,000
80,000
100,000
120,000
140,000
160,000
180,000
Floodway Capacity in cfs
■ Incr. Ann. Ben. Year1957
□ Increm. Ann. Cost
◆ Incr. Ann. Ben. Year 2000

Figure 10

Table 1

Calculation of Average Annual Flood Benefits Based on 1957 Conditions

For Given Floodway Capacities

F(Q)	Q cfs	Q-James-60	Damage-60	Damage-70	Damage-80	Damage-90	Damage-100	Damage-110	Damage-120	Damage-140	Damage-160	Damage-180
99.06%	168,959	83,959	0.0	0	0	0	0	0	0	0	0	0
99.07%	169,409	84,409	0.0	0	0	0	0	0	0	0	0	0
99.08%	169,864	84,864	0.1	0	0	0	0	0	0	0	0	0
99.09%	170,325	85,325	0.3	0	0	0	0	0	0	0	0	0
99.10%	170,791	85,791	0.6	0	0	0	0	0	0	0	0	0
99.11%	171,263	86,263	1.0	0	0	0	0	0	0	0	0	0
99.12%	171,741	86,741	1.5	0	0	0	0	0	0	0	0	0
99.13%	172,226	87,226	2.1	0	0	0	0	0	0	0	0	0
99.14%	172,717	87,717	2.7	0	0	0	0	0	0	0	0	0
99.15%	173,214	88,214	3.5	0	0	0	0	0	0	0	0	0
99.16%	173,717	88,717	4.4	0	0	0	0	0	0	0	0	0
99.17%	174,228	89,228	5.4	0	0	0	0	0	0	0	0	0
99.18%	174,746	89,746	6.5	0	0	0	0	0	0	0	0	0
99.19%	175,270	90,270	7.8	0	0	0	0	0	0	0	0	0
99.20%	175,802	90,802	9.2	0	0	0	0	0	0	0	0	0
99.21%	176,342	91,342	10.7	0	0	0	0	0	0	0	0	0
99.22%	176,889	91,889	12.3	0	0	0	0	0	0	0	0	0
99.23%	177,444	92,444	14.1	0	0	0	0	0	0	0	0	0
99.24%	178,007	93,007	16.1	0	0	0	0	0	0	0	0	0
99.25%	178,579	93,579	18.2	0	0	0	0	0	0	0	0	0
99.26%	179,159	94,159	20.5	0.0	0	0	0	0	0	0	0	0
99.27%	179,748	94,748	22.9	0.1	0	0	0	0	0	0	0	0
99.28%	180,347	95,347	25.5	0.4	0	0	0	0	0	0	0	0
99.29%	180,954	95,954	28.3	0.8	0	0	0	0	0	0	0	0
99.30%	181,572	96,572	31.3	1.3	0	0	0	0	0	0	0	0
99.31%	182,199	97,199	34.5	2.0	0	0	0	0	0	0	0	0
99.32%	182,837	97,837	38.0	2.9	0	0	0	0	0	0	0	0
99.33%	183,485	98,485	41.6	4.0	0	0	0	0	0	0	0	0
99.34%	184,144	99,144	45.5	5.2	0	0	0	0	0	0	0	0
99.35%	184,815	99,815	49.6	6.7	0	0	0	0	0	0	0	0
99.36%	185,497	100,497	54.0	8.4	0	0	0	0	0	0	0	0
99.37%	186,191	101,191	58.6	10.3	0	0	0	0	0	0	0	0
99.38%	186,898	101,898	63.5	12.4	0	0	0	0	0	0	0	0
99.39%	187,618	102,618	68.7	14.7	0	0	0	0	0	0	0	0

F(Q)	Q cfs	Q-James-60	Damage-60	Damage-70	Damage-80	Damage-90	Damage-100	Damage-110	Damage-120	Damage-140	Damage-160	Damage-180
99.40%	188,351	103,351	74.2	17.3	0	0	0	0	0	0	0	0
99.41%	189,097	104,097	80.1	20.2	0.0	0	0	0	0	0	0	0
99.42%	189,859	104,859	86.3	23.4	0.1	0	0	0	0	0	0	0
99.43%	190,635	105,635	92.8	26.8	0.5	0	0	0	0	0	0	0
99.44%	191,427	106,427	99.7	30.6	1.2	0	0	0	0	0	0	0
99.45%	192,234	107,234	107.0	34.7	2.1	0	0	0	0	0	0	0
99.46%	193,058	108,058	114.3	39.2	3.3	0	0	0	0	0	0	0
99.47%	193,900	108,900	124.2	44.0	4.8	0	0	0	0	0	0	0
99.48%	194,759	109,759	135.1	49.2	6.6	0	0	0	0	0	0	0
99.49%	195,637	110,637	146.1	54.9	8.7	0	0	0	0	0	0	0
99.50%	196,535	111,535	157.2	61.0	11.3	0	0	0	0	0	0	0
99.51%	197,453	112,453	168.3	67.5	14.2	0	0	0	0	0	0	0
99.52%	198,392	113,392	179.5	74.6	17.5	0	0	0	0	0	0	0
99.53%	199,354	114,354	190.8	82.1	21.3	0.0	0	0	0	0	0	0
99.54%	200,339	115,339	202.1	90.3	25.5	0.4	0	0	0	0	0	0
99.55%	201,348	116,348	213.6	99.0	30.2	1.1	0	0	0	0	0	0
99.56%	202,383	117,383	225.1	108.4	35.5	2.3	0	0	0	0	0	0
99.57%	203,444	118,444	236.7	118.4	41.4	3.9	0	0	0	0	0	0
99.58%	204,533	119,533	248.4	132.3	47.8	6.1	0	0	0	0	0	0
99.59%	205,652	120,652	260.2	146.3	55.0	8.8	0	0	0	0	0	0
99.60%	206,802	121,802	272.1	160.5	62.8	12.1	0	0	0	0	0	0
99.61%	207,985	122,985	284.1	174.7	71.5	16.0	0	0	0	0	0	0
99.62%	209,202	124,202	296.2	189.0	80.9	20.6	0.0	0	0	0	0	0
99.63%	210,455	125,455	308.4	203.5	91.3	26.0	0.4	0	0	0	0	0
99.64%	211,747	126,747	320.8	218.0	102.6	32.2	1.5	0	0	0	0	0
99.65%	213,080	128,080	333.2	232.7	114.4	39.3	3.3	0	0	0	0	0
99.66%	214,456	129,456	345.9	247.6	131.3	47.4	5.9	0	0	0	0	0
99.67%	215,878	130,878	358.6	262.5	149.1	56.5	9.4	0	0	0	0	0
99.68%	217,350	132,350	371.5	277.7	167.1	66.8	13.8	0	0	0	0	0
99.69%	218,874	133,874	384.6	292.9	185.2	78.3	19.3	0	0	0	0	0
99.70%	220,453	135,453	397.8	308.4	203.4	91.2	26.0	0.4	0	0	0	0
99.71%	222,094	137,094	411.3	324.0	221.9	105.7	34.0	1.9	0	0	0	0
99.72%	223,799	138,799	424.9	339.9	240.5	122.9	43.4	4.6	0	0	0	0
99.73%	225,573	140,573	438.7	355.9	259.4	145.3	54.5	8.6	0	0	0	0
99.74%	227,422	142,422	452.7	372.2	278.4	168.0	67.3	14.1	0	0	0	0
99.75%	229,353	144,353	467.0	388.7	297.7	190.8	82.1	21.3	0.0	0	0	0
99.76%	231,373	146,373	481.6	405.4	317.2	213.9	99.2	30.4	1.1	0	0	0
99.77%	233,487	148,487	496.3	422.4	337.0	237.2	118.9	41.6	4.0	0	0	0
99.78%	235,709	150,709	511.4	439.8	357.1	260.8	147.0	55.4	8.9	0	0	0
99.79%	238,047	153,047	526.8	457.4	377.5	284.7	175.4	71.9	16.2	0	0	0

F(Q)	Q cfs	Q-James-60	Damage-60	Damage-70	Damage-80	Damage-90	Damage-100	Damage-110	Damage-120	Damage-140	Damage-160	Damage-180
99.80%	240,512	155,512	542.6	475.4	398.3	309.0	204.1	91.7	26.3	0	0	0
99.81%	243,118	158,118	558.7	493.8	419.5	333.6	233.2	114.1	39.5	0	0	0
99.82%	245,884	160,884	575.2	512.6	441.1	358.7	262.6	149.2	56.5	0	0	0
99.83%	248,827	163,827	592.2	531.9	463.2	384.2	292.5	184.6	77.9	0	0	0
99.84%	251,969	166,969	609.7	551.7	485.8	410.3	322.9	220.5	104.6	1.7	0	0
99.85%	255,340	170,340	627.7	572.0	509.0	436.9	353.8	256.9	142.4	8.0	0	0
99.86%	258,972	173,972	646.3	593.0	532.8	464.2	385.4	293.9	186.3	19.7	0	0
99.87%	262,906	177,906	665.6	614.7	557.4	492.3	417.8	331.6	230.8	38.3	0	0
99.88%	267,192	182,192	685.7	637.3	582.8	521.3	451.0	370.2	276.1	65.6	0	0
99.89%	271,899	186,899	706.7	660.8	609.3	551.2	485.3	409.7	322.2	104.0	1.7	0
99.90%	277,110	192,110	728.8	685.3	636.8	582.4	520.7	450.4	369.4	164.2	13.0	0
99.91%	282,938	197,938	752.1	711.2	665.8	614.9	557.6	492.5	418.1	231.2	38.5	0
99.92%	289,534	204,534	776.8	738.6	696.3	649.1	596.2	536.4	468.3	299.4	83.6	0.1
99.93%	297,125	212,125	803.4	768.0	728.8	685.4	636.9	582.5	520.8	369.6	164.4	13.1
99.94%	306,035	221,035	832.3	799.7	763.9	724.3	680.4	631.3	576.1	442.3	264.2	57.5
99.95%	316,771	231,771	864.2	834.6	802.2	766.7	727.4	683.8	635.1	518.5	366.5	160.1
99.96%	330,225	245,225	900.2	873.8	845.1	813.8	779.3	741.4	699.4	600.0	473.3	306.2
99.97%	348,078	263,078	942.2	919.4	894.7	867.9	838.6	806.6	771.5	689.8	587.9	457.6
99.98%	374,237	289,237	994.5	975.7	955.4	933.7	910.1	884.6	856.9	793.6	716.8	621.9
99.99%	421,722	336,722	1,068.6	1,054.8	1,040.1	1,024.4	1,007.7	989.9	970.7	927.9	877.9	818.6
100.00%	607,142	522,142	1,228.9	1,223.2	1,217.3	1,211.1	1,204.7	1,198.1	1,191.1	1,176.2	1,159.9	1,142.0
Mean Annual Damage Millions of 1957 $			2,721,302	2,207,842	1,801,017	1,476,786	1,216,752	1,007,101	837,496	586,187	416,775	300,609