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HYDRAULICS AND EFFECTIVENESS OF LEVEES FOR FLOOD CONTROL

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Abstract. Levees have been used as a means of structural flood protection for several thousand years. Their effect and effectiveness have been debated periodically, most recently during and after the 1993 Mississippi River flood. Based on hydraulic principles, it can be shown that for a given flood levees raise the water stage in the leveed channel and upstream of it. On the other hand, they may slightly lower the water stage downstream. Methods for channel capacity determination and identification of low-capacity bottlenecks suitable for levee or channel improvement are also discussed. The effectiveness of levees is site-specific. Usually it is more effective to use levees in conjunction with other structural and nonstructural flood control measures.

1. INTRODUCTION

Floods are natural phenomenon. In view of the climatic extremes and human interference, flood will continue to occur at different places and different times in the foreseeable future. Flood damage mitigation can be made through structural flood control or nonstructural measures.

Methods of structural control of floodwater can be grouped into four types; namely, storage, diversion, enhancing channel capacity, and constriction of the water within the channel. For a given river one or more of these methods may be applicable, but not necessarily all are beneficial. Historically, in the Neolithic age with limited resources and technical abilities, the options of channel improvement by clearing obstacles and flow diversion were first exercised, as was done on the Yellow River in China and the Nile River in Egypt more than four thousand years ago. Later, but still more than two thousand years ago, improved technology and resources permitted the building of levees along channels, allowing the use of flow constriction as a means of flood control. It was not until last century that storage through dam building became a viable infrastructure for flood control.

Heated debate on the effectiveness of the various means for flood control has erupted periodically throughout history. Often, such debates narrowed to a local and temporal scope and failed to visualize the problem in a broad, comprehensive time and spatial scale. Furthermore, the perspective on the threat of floods changes with time and the social-economic-political environment. Centuries ago when the flood threat was directly on human lives taming of the rivers was regarded as an undisputed necessity. The primary task was to find the resources and technology that could be used to accomplish this mission. There are numerous sources in Chinese literature spanning over two thousand years that argue on the methods to tame the Yellow River. Some people lost careers or even lives for their arguments; a German hydraulician even called the river the sorrow of China. Currently, floods are rarely a human-life threat in developed countries and the impacts of floods are mostly related to property damages, social interruptions, inconvenience, or merely a nuisance. For a prosperous society with ample useful land to spare like the United States, it is no wonder the 1993 Mississippi River flood generated talks of abolishing all the levees and reestablishing wetlands to take care of the flood.

History and long-time human experiences have shown that levees are an effective means of flood control if used properly. On the other hand, flood hazards can be considerably amplified if levees are improperly installed. In general, levees should be built to protect locations where the flood damages are high and should not be used to protect low-damage-site value areas. Levee effectiveness is site-specific and should be evaluated individually considering local hydrology and hydraulics of the river.

During and after the 1993 Mississippi River flood, the role of levees have been broadly discussed in general terms, but not in sufficient technical depth. Suggestions from the news media and the public ranged from building levees along the entire length of the river to totally abolishing all the levees. With such diversified views it is worthwhile to review how levees affect flood hydraulics as required basic information for the assessment of levee effectiveness in flood control.

2. HYDRAULIC PROBLEMS OF LEVEED RIVER FLOODS

The flood flow in a river changes with time. Therefore, it should be simulated with unsteady flow equations. In recent years, many computer-based models have been developed to simulate unsteady flow in river channels. Such models, if properly used, are indeed useful for routing floods caused by specific rainstorms that produce specific inflow hydrographs into the upstream end of the river channels. Thus, these models are useful to determine the effect of specific floods and are indispensable for real-time flood forecasting. Unfortunately, such unsteady models are not effective in answering the following four questions that the public often asks concerning flood control:

(a) What is the size of the flood that the channel can carry, i.e., what is the channel flow-carrying capacity?
(b) Where are the weak points (i.e. the bottlenecks of low capacity) along the channel?
(c) How much improvement can be gained from a proposed structural modification of the channel?
(d) How can we compare different improvement alternatives and how to select the optimum one for design and construction?

Unsteady flow routing is inflow-hydrograph specific. Hence, the computed solution of discharge and stage at a given location varies not only with the peak discharge and stage of the inflow but also with the shape of the hydrographs. Therefore the solution is not unique unless the inflow hydrography is totally specified, i.e., only for a particular storm flood. For the many possible storm floods in the future, numerous unsteady flow routing runs must be made to provide information that may be helpful to answer the aforementioned four questions. This is clearly an undesirable and impractical approach.

Fortunately, in all field conditions besides flash floods in very small streams, stepwise steady nonuniform flow simulation turns out to be an adequate hydraulic method for flood routing if the spatial and time scales for computation are properly chosen. This is especially true for flow rates near the peak of the hydrograph and it is mostly this part of the hydrograph that is particularly pertinent to the aforementioned four questions. By using this time-stepwise steady flow approximation the hydraulics of a leveed channel can be described as follows.

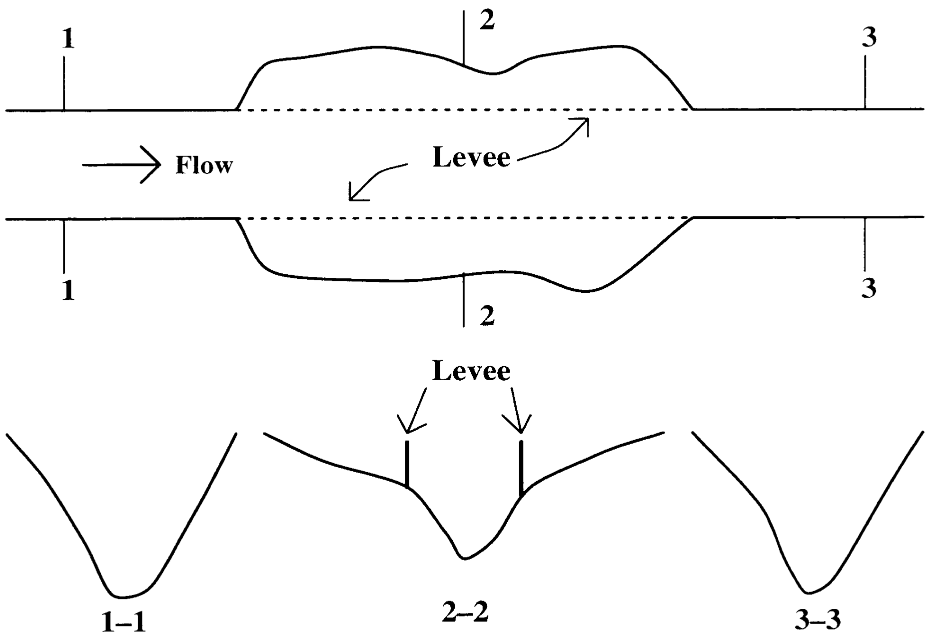


Figure 1. Schematic of a Flood Channel

As sketched in Fig. 1, a hypothetical river flows from a well-defined channel (section 1-1) into a flood plain (section 2-2) in its original natural condition. A leveed channel reach is shown (section 2-2) followed by an unleveed channel (section 3-3). The continuity relationship for this channel yields

$$Q_1 = Q_2 = Q_3 \tag{1}$$

or

$$A_1 V_1 = A_2 V_2 = A_3 V_3 \tag{2}$$

in which Q denotes discharge, V is velocity, and A is flow cross sectional area which is a known function of the flow depth Y for a given cross section geometry. The subscripts refer to the channel cross sections mentioned previously. The corresponding energy relationship is

$$Q_1\left(\frac{V_1^2}{2g}+Y_1+Z_1\right)=Q_2\left(\frac{V_2^2}{2g}+Y_2+Z_2+\Delta_{1-2}\right)$$

$$=Q_3\left(\frac{V_3^2}{2g}+Y_3+Z_3+\Delta_{1-2}+\Delta_{2-3}\right) \quad (3)$$

in which Z is the channel bed elevation and Δ is the head loss between cross sections. From these equations the depth and velocity of the floodflow in subsequent sections can be determined provided the inflow depth and velocity at cross section 1-1 are known.

The hydraulic effect of levees can be demonstrated qualitatively as follows. From Eqs. 1 and 3, the flow depth relationship between upstream section 1-1 and leveed section 2-2 for the leveed case is

$$Y_1+\frac{V_1^2}{2g}=Y_2+\frac{V_2^2}{2g}-(Z_1-Z_2)+\Delta_{1-2} \quad (4)$$

Likewise, for the same river in its original condition without levee, denoted with a subscript a,

$$Y_{1a}+\frac{V_{1a}^2}{2g}=Y_{2a}+\frac{V_{2a}^2}{2g}-(Z_1-Z_2)+\Delta_{1-2a} \quad (5)$$

The value of Z_1 - Z_2 is the bed elevation difference between the cross sections and is a constant. The values of Δ_{1-2} and Δ_{1-2a} are close, about the same magnitude as Z_1 - Z_2, and they are small if the channel reach is short. Furthermore, the difference in magnitude between $V_2^2/2g$ and $V_{2a}^2/2g$ is also negligible. Therefore, comparison of Eqs. 4 and 5 for the effect of levee can be made by considering only the major terms Y_1, Y_{1a}, Y_2, Y_{2a}, $V_2^2/2g$, $V_{2a}^2/2g$ in the two equations. For the same upstream depth $Y_1 = Y_{1a}$, V_{2a} is smaller than V_2 because of the additional flow area outside the levees. Therefore the velocity head is higher and the depth is lower for the leveed case i.e., $Y_2 < Y_{2a}$. Looking at this from a different viewpoint, if the stages at section 2-2 are held constant ($Y_2 = Y_{2a}$) the upstream depth at section 1-1 is higher for the leveed case than the natural channel, i.e., $Y_1 > Y_{1a}$. The above argument is approximated by assuming the discharge remains unchanged. In reality, for a given depth the discharge is also adjusted slightly with the levee, but it would not modify the qualitative result discussed.

Similarly, by considering the energy relationship between the leveed cross section 2-2 and the downstream unleveed section 3-3, it can be demonstrated that due to the increased water surface slope at 3-3 created by levee constriction, a given discharge results in a slightly lower downstream depth (Y_3) for the leveed case.

The above argument demonstrates that for a given flood levees raise the water surface elevation at the levee and upstream of it. Also, it slightly lowers the water stage downstream of the levee, provided that the downstream flow control is far away. Field observations in many rivers (Parrett et al., 1993) agree with this analysis. The effect of levees on flood stage along a river is plotted schematically in Fig. 2 for typical sections upstream (1-1), at the levee (2-2), and downstream (3-3). This figure is drawn corresponding to the no-loop rating curve of stage vs.

discharge for streams. In the case of a looped rating curve for unsteady nonuniform flow, this figure should be modified accordingly.

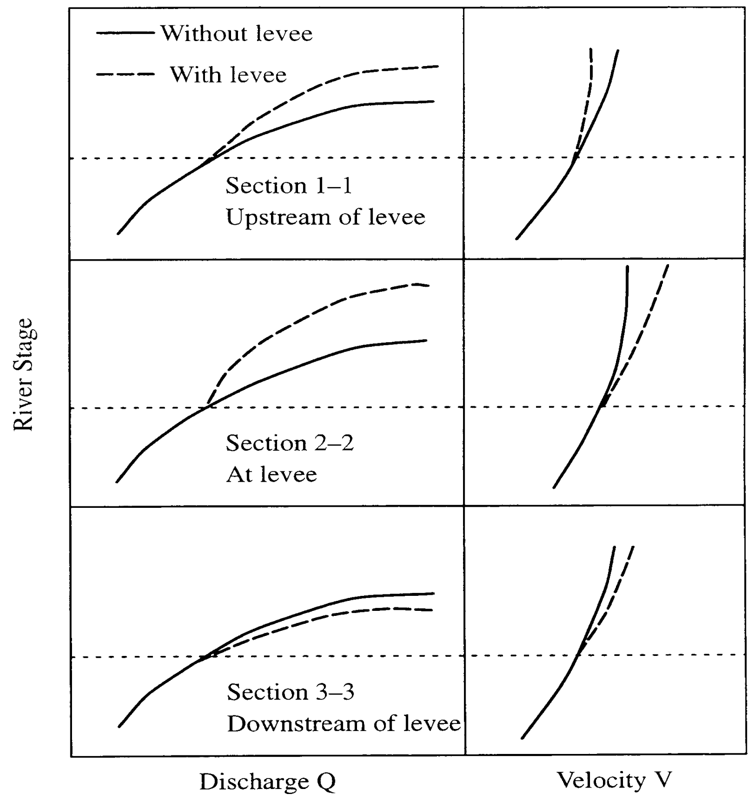


Figure 2. Effect of Levee on River Stage

3. HYDRAULIC EFFECTS OF LEVEE BREACHING

In flood management it is helpful to know the consequence of levee breaching. One recurring question regarding the 1993 Mississippi River flood is how high the flood stage at St. Louis could have been if those breached levees had remained intact and would St. Louis be in danger ("The flood that wasn't," 1993; Stephens and Dyhouse, 1994). Such questions on specific floods would be best answered using unsteady flow simulation for each particular case. However, general information can be obtained through the use of stepwise steady-flow approximation.

By referring to Fig. 1 the channel with breached levee carries the flow in two portions: the flow in the main channel, denoted by a subscript m, and the flow in the floodplain outside the breached levee, denoted by a subscript f. Part or the entire amount of floodplain flow at the breached levee may return to the river channel downstream at section 3-3 or the balance may flow elsewhere or be temporarily stored. The continuity and energy equations corresponding to Eqs. 1 and 3 are

$$Q_1 = Q_{2m} + Q_{2f} = Q_{3m} + Q_{3f} \tag{6}$$

$$
\begin{aligned}
& Q_1 \left(\frac{V_1^2}{2g} + Y_1 + Z_1 \right) \\
& = Q_{2m} \left(\frac{V_{2m}^2}{2g} + Y_{2m} + Z_{2m} + \Delta_{1\text{-}2m} \right) + Q_{2f} \left(\frac{V_{2f}^2}{2g} + Y_{2f} + Z_{2f} + \Delta_{1\text{-}2f} \right) \\
& = Q_{3m} \left(\frac{V_{3m}^2}{2g} + Y_{3m} + Z_{3m} + \Delta_{1\text{-}3m} \right) + Q_{3f} \left(\frac{V_{3f}^2}{2g} + Y_{3f} + Z_{3f} + \Delta_{1\text{-}3f} \right)
\end{aligned}
\qquad (7)
$$

In Eq. 7, flood stages in the main channel and the floodplain are usually the same ($Y_{2m} + Z_{2m} = Y_{2f} + Z_{2f}$.) If all the floodplain flow returns to the channel downstream at section 3-3, $Q_{3f} = 0$. If the loss function for Δ is given and a supplementary function relating a variable of the main channel to the floodplain is defined (such as a side weir formula for a breached levee or an energy relationship between the main flow and the floodplain), the depth and velocity in these equations can be solved provided the inflow at cross section 1-1 is specified.

The aforementioned stepwise steady flow approximation is not good for a short period immediately after the levee breach, during which time the flow is highly unsteady and a significant amount of additional discharge is drawn from the water in the channel upstream, which causes a drop in the water surface and increase in velocity at that point. A schematic of the time variation of flow for the simple hypothetical case of constant upstream inflow is shown in Fig. 3. It should be noted that the flow is passing from the no-breach stage-discharge rating curve to the breached stage-discharge curve as indicated by the arrow in the graph. Likewise, the corresponding time variation of the flow downstream of the breached levee (section 3-3) is also shown in the figure. Curve (a) is for all the flow, main channel and floodplain, returning to the channel at section 3-3 ($Q_{3f} = 0$). Curve (b) is true if part of the floodplain flow does not return to the main flow (Q_{3f} 0 in Eq. 7). In this case, the non-return flow could be a diversion or it could indicate a large storage of flood water beyond the levee. For the latter, it usually implies that effective levee protection would have been provided had it not breached.

4. FLOOD CHANNEL CAPACITY AND BOTTLENECK DETERMINATION

For flood control purposes, it is useful to know the capacity of the flood channel and the location and degree of deficiency of the bottlenecks in passing future floods of different sizes. As mentioned previously, unsteady flow routing is inflow specific, requiring numerous simulation runs for different inflow hydrographs; and hence, is not suitable for the determination of bottleneck capacity. On the other hand, given channel geometry, Eqs. 2 and 3 can be solved to determine the channel capacity; but they are ineffective for locating the bottlenecks because that can be done only through trial-and-error. Perhaps it is for this reason that the questions of channel capacity and bottlenecks have not been addressed quantitatively in flood control planning and design.

A new open-channel hydraulic performance graph (HPG) method recently developed by the author (Yen and Gonzalez, 1994) permits direct capacity and bottleneck determination of river channels, with or without levees. An HPG is essentially a summary of all the channel flow backwater information in terms of the corresponding upstream and downstream stages for different discharges. With such a summary graph available there is no need to perform repetitive steady or unsteady flow backwater profile computations to determine the channel capacity and location of bottlenecks. A typical HPG for a hypothetical channel with levees is shown in Fig. 4. The corresponding HPG with one levee completely breached is shown in Fig. 5. A set of such HPGs can be used to evaluate and compare flood stages upstream and downstream of a levee before and after breaching. Figure 6 shows the location of the bottlenecks and the corresponding flooding threshold capacity for a reach of Boneyard Creek, on the campus of the University of Illinois at Urbana-Champaign, using the HPG method. Details on the theory and methods used to establish the HPGs and the procedure to apply the HPGs for capacity and bottleneck determination can be found in Yen and Gonzalez (1994).

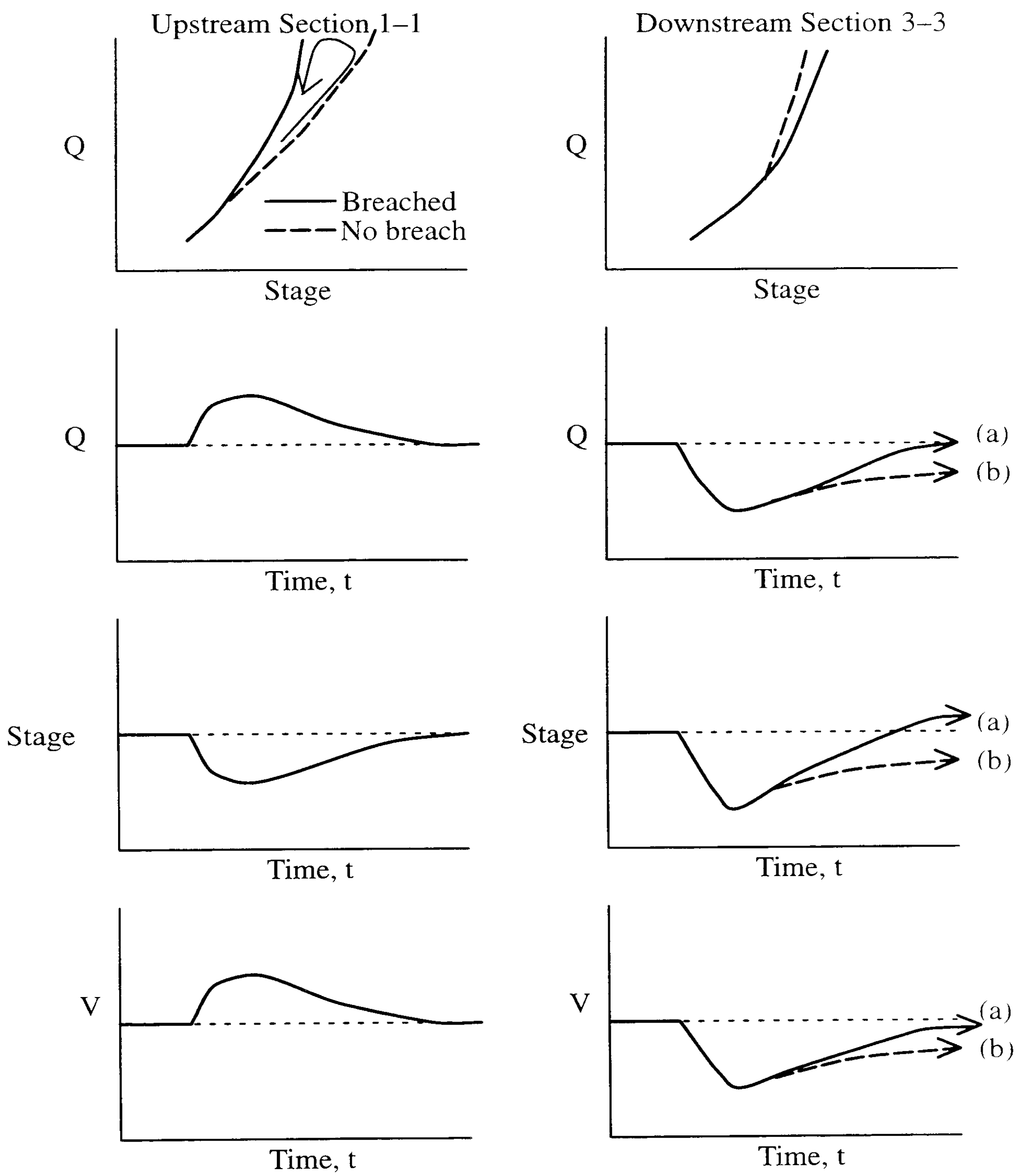


Figure 3. Effect of Levee Breach

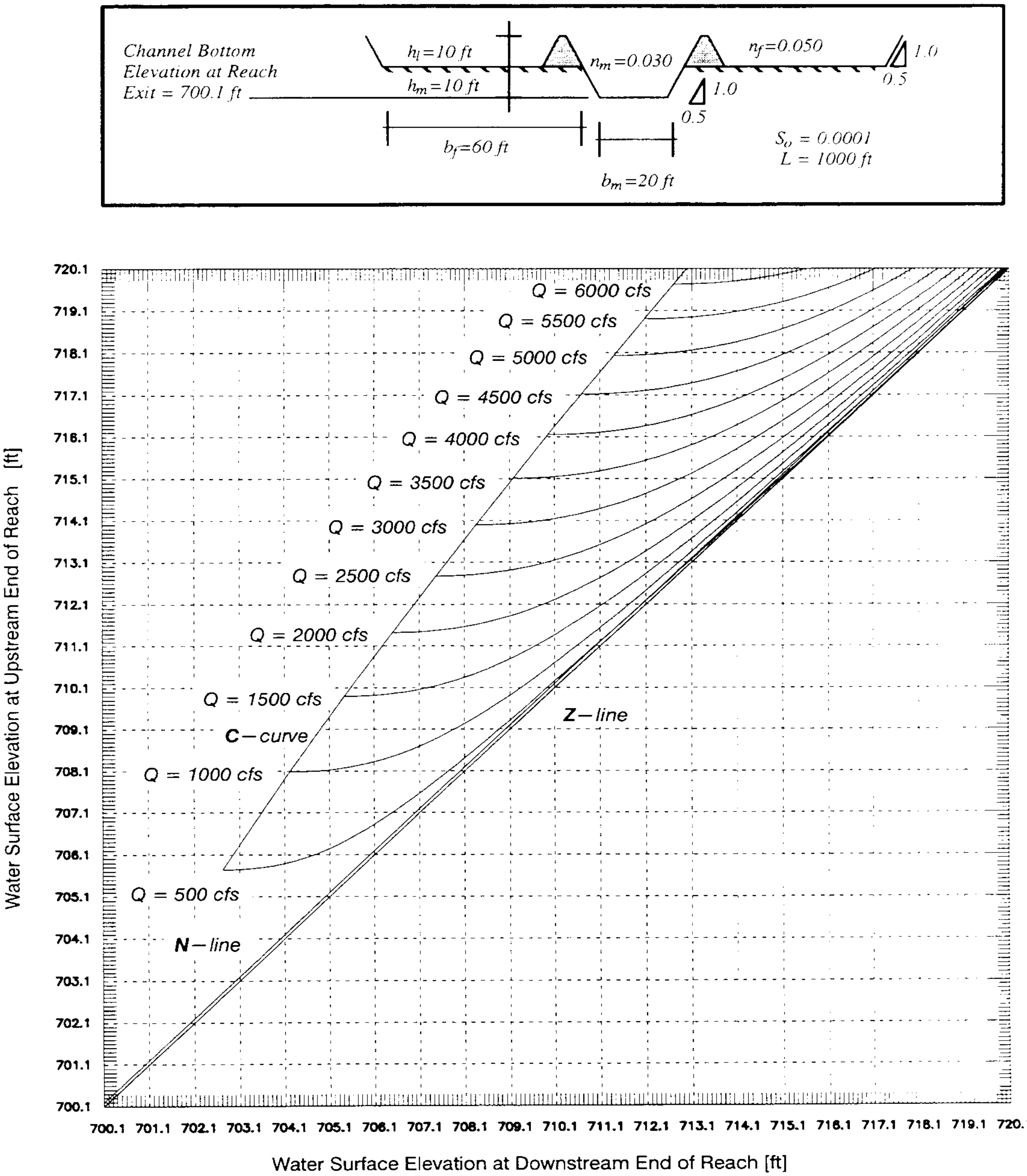
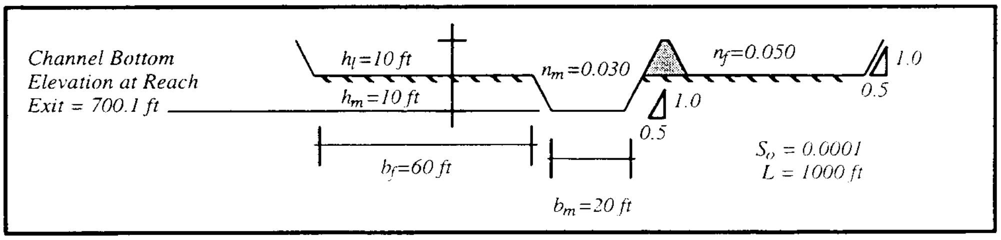


Figure 4. Hydraulic Performance Graph of Example Channel Reach with Levees



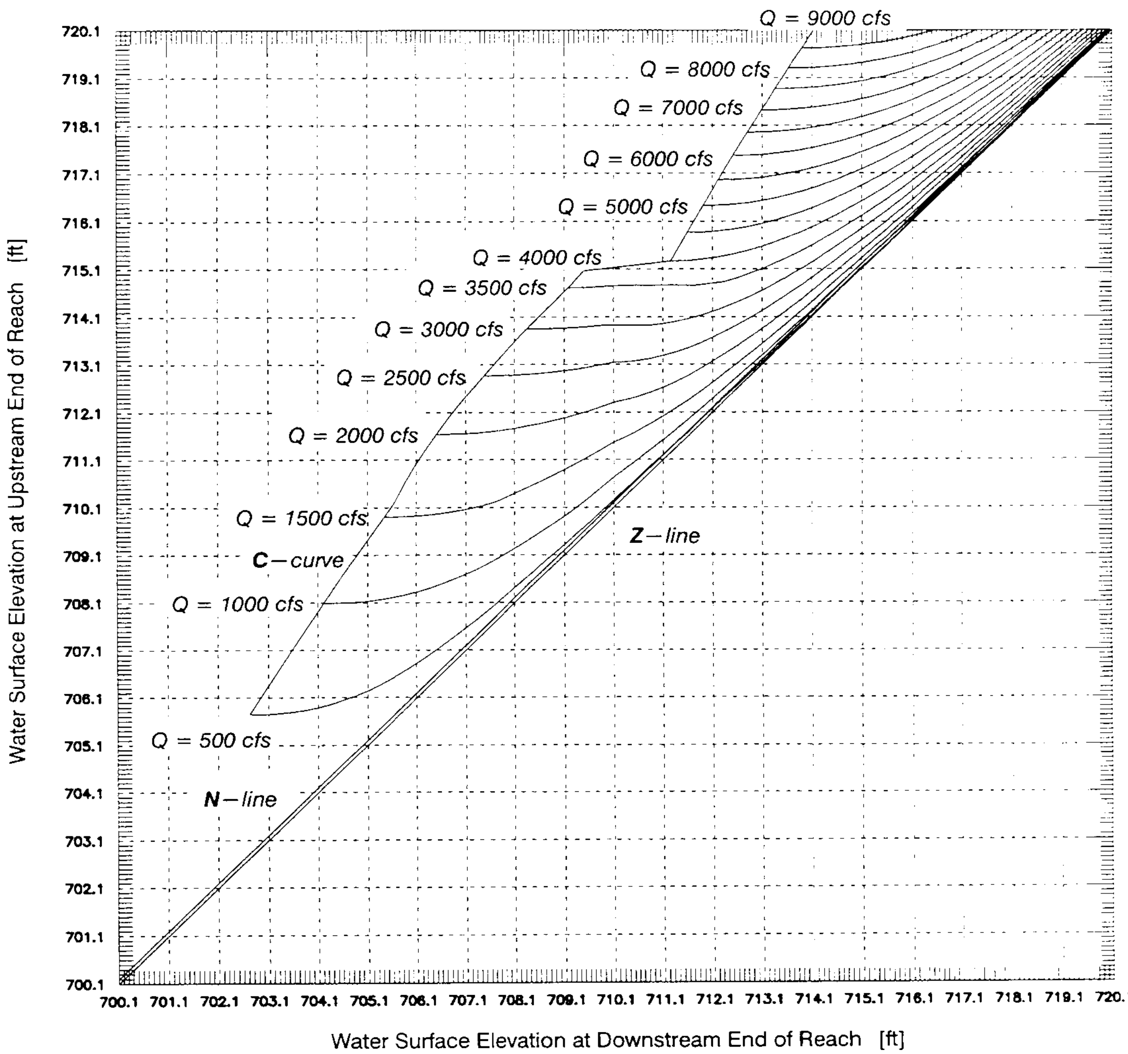


Figure 5. Hydraulic Performance Graph of Example Channel Reach with One Levee Breached

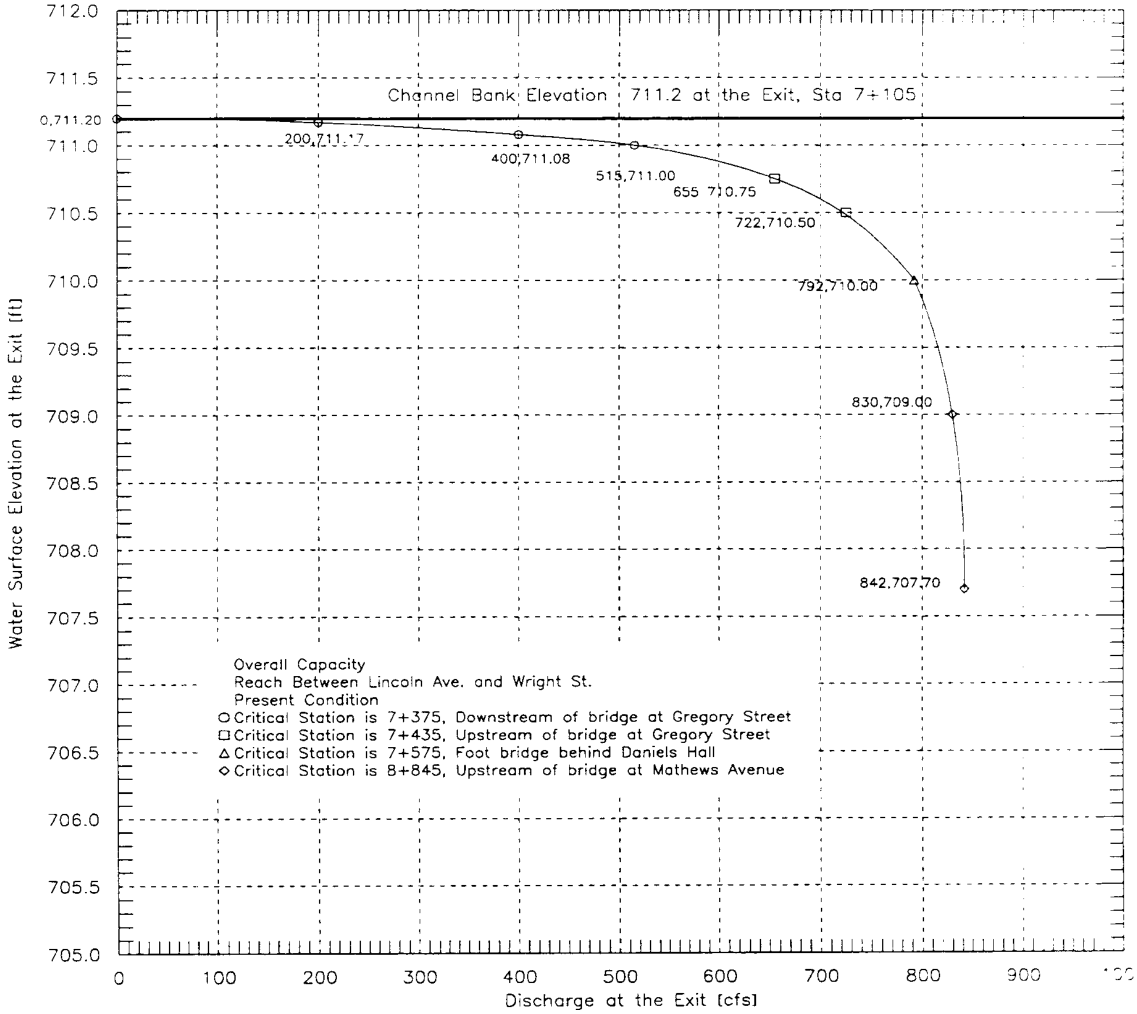


Figure 6. Hydraulic Capacity and Bottleneck Determination for Boneyard Creek

5. LEVEE AS EFFECTIVE FLOOD CONTROL MEANS

During the 1993 Mississippi River flood, a reporter asked me if it be better if the entire Mississippi is leveed. If everywhere along the river human life were at high risk during floods, this may have been the way to go. With today's advanced warning and evacuation systems, flood damages are mostly economic and social losses, human life is rarely at risk. Economically levee effectiveness can be measured by comparing the benefit gain through the reduction of flood damage with the total cost of levee construction, operation, and maintenance. The flood risk damage loss C_R is calculated as

$$C_R(D)=\int_D^\infty p_f(D) \quad L(D) \; dD \tag{8}$$

in which D is the levee design size, L(D) is the damage cost should the levee fails at size D, and p_f is the probability density function of failure. If the levee is not built, D = 0 and p_f is large. If a large levee is built, p_f is small. If the land in the flood plain or behind the levee is developed, the value of L increases. The economic benefit of the levee is C_R (D = 0) - C_R (D = d), where d is a specified levee size.

Thus, levees should not be built where the potential damage is small (e.g. farmlands), it is cheaper to let the land flood and accept the small losses than to spend the money to build the levee. On the other hand, levees are effective in protecting high economic risk areas (e.g. urban lands.) If levees are built all along the river, it would increase both p_f and L making the project less effective. Two effective alternatives are building low design sized levees around farmlands and other low economic risk areas and using a "fuse-plug" type levee that would fail when the flood exceeds a certain level. The low-damage-loss land will be protected from frequent, relatively small floods but it will be inundated during major extreme floods to prevent water from flooding high-value strategic areas. Variations of this basic principle have been practiced for many years around the world, including induced breaching, as in one case during the 1993 Mississippi River flood.

One cause of the levee effectiveness controversy is that there has not been a comprehensive investigation on the benefit and costs of the levees in the reduction of damages for past major floods. A hydrologist or an economist alone cannot do such a study. It requires a joint effort of at least the two professions. Until such creditable quantitative information becomes available, the “beauty” will still be in the eyes of the beholder (Tobin, 1995).

Levees are only one of the tools available for flood control. Levees should be used wisely in conjunction with other structural and nonstructural flood control measures. It appears that this holistic view was indeed in the mind of many past successful river engineers. In the training of river engineers in the second half of the Twentieth Century, the engineers learned the technical details without understanding the holistic view. Furthermore, history of flood control practice indicates that even if a holistic approach is taken in the planning and design and the structural flood control part is property exercised, the desired benefit cannot be achieved because the nonstructural measures component cannot be properly formulated or carried out. In flood control perhaps one can learn from the long struggle the Chinese have had with the Yellow River, a river far more shrewd than the Mississippi, the Rhine, or the Po, a river with vast human imposed environmental and ecological changes no other large river can match.

6. SUGGESTED RESEARCH TOPICS

There are numerous research topics on levees that are important to pursue. In the following a selected few are listed in random order:

- Development, evaluation and comparison of flood routing methods for leveed channels and breached channels.
- Evaluation and application of channel capacity determination methods.
- Demonstration of channel bottleneck determination and hydraulic improvement with levees.
- Investigation of levee breaching hydraulics.
- Investigation of necessary non-structural measures that should be implemented in conjunction with levees for effective flood control.
- Investigation of the risk damage costs (Eq. 8) to establish criteria rating areas for levee

protection for specific flood frequency levels and land uses.

- Investigate the socio-political factors involved in levee protection.
- Investigate the ecological effects of levees.
- Document and translate literature on flood control practices used on major rivers around the world, especially the Yellow River.

7. REFERENCES

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