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Siting and Design of Impoundments for Flood Control in the Red River Basin

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Impoundments are projects that store flood water. There are many possible variations in the design of impoundments and each site presents a unique set of problems and opportunities.

As with any project, the goals are to maximize the positive and minimize the negative impacts. In addition to flood control, potential benefits include erosion control, sedimentation, wetland development, stream flow maintenance, water supply, lake improvement, and recreation. In addition to direct cost, potential negative impacts include obstruction of fish migration, interruption of riparian corridors, unnatural stream flow regimes, sediment transport imbalance, loss of base flow, conversion of wetlands, and other vegetative changes.

Because of the wide variety of impacts there is a need for a multi-disciplinary approach. Proper site selection and design are critical.

Site Considerations

Sites with significant existing environmental or social values may present special problems when attempting to develop impoundment projects.

Site selection should consider compatible use relative to total watershed management objectives. Flood control, habitat preservation, connectivity, biodiversity, economic land uses, community stability, legal rights and social needs should all be considered. Achieving objectives that fully satisfy all public interests may be impossible. Yet, by following basic guidelines much controversy can be avoided.

Previously disturbed sites may be the most suitable for flood control impoundments. Best candidates may include drained or poorly drained wetlands, flood prone croplands, irregularly shaped fields, or other difficult to farm areas.

Sites with significant existing environmental or social values such as stable natural stream channels, virgin native prairie, unaltered natural wetlands or historical preservation areas deserve special consideration when planning a project. Such sites should not be impacted significantly without major justification.

On the other hand, such sites may present excellent opportunities for enhancement. For example, a native prairie site with a wetland complex might have adjacent restorable wetlands that may provide flood control or mitigation opportunities. If publicly owned, mutually beneficial cost sharing arrangements may be possible. Public lands located near a flood control impoundment might offer larger mobile species such as deer, fox and grouse alternate habitat during periods of flooding in the impoundment. If these areas are adjacent or connected by habitat corridors, they would be of highest value to wildlife.

Size

Impoundment size will generally be a function of watershed area and impoundment objectives. The amount of water that needs to be stored depends on the downstream channel capacity. The greater the channel capacity, the less storage required.

Control of flooding immediately downstream from an impoundment can often be accomplished by storing as little as 1" of runoff from the upstream drainage area. However, an impoundment to control flooding at points farther downstream will usually require storing a larger portion of the runoff that enters that impoundment to make up for other areas of the watershed that are not controlled.

The amount of storage required to control flooding on the Red River and its larger tributaries can be estimated from the stream gage records of historic floods. The 1997 disaster at Grand Forks could have been averted by a gate controlled reservoir immediately upstream from the City having a capacity of about 300,000 acre-feet. Of course, no potential reservoir site exists at this location. Even if it did, siting a reservoir there may not be the most desirable alternative due to dam safety concerns. It would also do nothing to reduce the extensive damages that occur upstream from Grand Forks.

A safer, and potentially more beneficial approach, would be to store the water further upstream, within the tributary watersheds. Doing so will require substantially more storage capacity to accomplish the same protection at Grand Forks. How much more depends on location and operation of the individual impoundments. A rough estimate of the amount required in 1997 would be 1,000,000 acre-feet of gated storage upstream from Grand Forks, which is equivalent to about 3/5" of runoff. An estimate of un-gated impoundment storage would be greater because it is less efficient at providing flood control.

The amount of storage required for flood control on the tributaries can be similarly estimated. For example, 100,000 acre-feet of gated storage upstream from Lake Traverse would have eliminated its major contribution to the 1997 spring flood peaks along the Red River. That, along with 75,000 acre-feet of gated storage in the remainder of the Bois de Sioux watershed, would have prevented the disaster that occurred at Breckenridge and the major flooding that occurred at Moorhead. 50,000 acre-feet of additional flood storage in the Thief River watershed might have controlled flooding on that tributary. This along with about 100,000 acre-feet of gated storage in the remainder of the Red Lake River watershed would greatly reduce the flood threat at Crookston. 65,000 acre-feet of un-gated storage has been proposed on the Maple River in North Dakota.

If the remaining tributaries require similar flood storage to those mentioned above, it would appear that the volume of storage required on the tributaries is about equal to what is required to provide flood control on the Red River.

Location and Timing

Location of an impoundment within a watershed is an important factor in determining its potential for providing flood control benefits. Location, and other timing factors, are also important in determining appropriate design.

In a simple watershed with only one flood damage center, The hydrologically ideal impoundment location would be immediately upstream from the damage center. The design parameters are also relatively simple. The outlet should be sized to pass flows within the tolerable downstream limits and the impoundment should be large enough to store the excess.

If there is no suitable site immediately upstream from the damage center, impoundment site selection and design become more complicated. Areas that consistently contribute high flows to downstream flood peaks present the greatest opportunity for impoundment benefits. Conversely, areas that consistently pass flows ahead of the flood hydrograph may be poorer locations for an impoundment. Impoundments on lower tributaries can actually increase downstream main stem flood peaks if water stored early is released during the downstream flood peak.

When one damage site is downstream from another damage site the problem is further complicated. The ideal location becomes a compromise between what would have been best for each individual damage site. Because storing early water is counterproductive, the safest compromise locations tend to be within the middle to upper areas of the watershed. Sites in early water areas relative to one of the damage sites must be very carefully designed or operated to avoid increasing flood flows at that location.

When a basin such as the Red River has multiple damage centers and is climatologically large, the problem becomes extremely complicated. Timing factors other than location, such as weather, play very important roles. Optimum flood control requires large storage capacity and small outlets or gate control to ensure proper timing of storage and release, which varies from flood to flood.

A basin wide strategy of flood control by impoundment would suggest that impoundments should be located upstream from all significant flood damage areas. This would provide the greatest possible total flood control benefit. However, for remote upstream impoundments to be effective in controlling mainstem flooding, they must be designed and operated accordingly. In general, this means including gate control or very long drawdown times.

On-Channel vs Off-Channel

Impoundments may be located on-channel, where all stream flows enter the impoundment, or off-channel, where only a portion of the flow enters the impoundment. Either type can be designed to provide flood control benefits. On-channel impoundments are more traditional and potential sites are relatively easy to identify. Off-channel impoundments may be less disruptive to the stream environment. The advantages of one type or the other are generally site specific.

On-channel storage involves the construction of a dam across a river valley or drainageway. In flatter areas, they may include wing dikes on either side to increase storage capacity. If properly located and designed, on-channel impoundments are ideal for flood control because they can capture and control as much of the flow as necessary or possible.

The greatest environmental concerns with on-channel impoundments are related to location. Sites within deep valleys offer efficient storage potential. But they also frequently have high gradient streams that are very important for fish reproduction or migration and valuable riparian habitat. Steep gradient streams also have potential for downcutting of the downstream channel caused by interception of the normal sediment supply. These problems can be minimized by design considerations. However, alternative sites or strategies may be more appropriate.

Off-channel impoundments can avoid or minimize the negative impacts to base flows, sediment transport, fish migration, and riparian wildlife corridors.

A simple form of off-channel storage can be provided by a levee separating a channel from a flood plain area. The height of the levee overflow would determine the stage at which storage would begin to occur. Such an impoundment would not increase the amount of available storage over existing, but could beneficially alter the timing of storage and release. Agricultural diked storage is an example of this type. It may work well where widespread agricultural areas are frequently flooded. The dikes can reduce the frequency of flooding yet retain the available flood storage for use during critical periods of large floods.

The capacity of an off-channel storage site can be increased by adding an inlet channel to bring water into the impoundment from a higher elevation. Impoundments of this type often have dikes on all four sides and a diked inlet channel. The advantages of this type are that they may require less land, and storage can occur while flow in the channel is at or below flood stage.

Gated vs Ungated

Impoundments may have *gated* outlets, which can be operated in response to conditions anywhere in the watershed, or *ungated* outlets, which release a designed amount of water based on the elevation of water in the reservoir.

Gated outlets provide greater flood control benefits because the timing and amount of storage and release can be adjusted based on existing or predicted conditions downstream in the watershed. They may also result in less adverse impacts within the flood pool area because water is normally stored only when necessary or beneficial and can be quickly released after downstream flooding conditions have subsided. Gated outlets allow a wider range of control which provides the enhanced flood control, but also may result in more abrupt and significant changes in downstream flows. This may negatively impact the stream environment. But those impacts should occur infrequently and only during major flood events.

Most gated impoundments also include ungated outlets as emergency spillways for dam safety when the design capacity of the reservoir is exceeded.

Types of outlets include weirs and orifices. Weirs are overflow devices. Because outflow increases rapidly with increasing stage, weirs are used where level control is the primary concern. Orifices are underflow devices. Because outflow varies less with increasing stage, orifices are used where flow control is the primary concern. An impoundment outlet may include both weirs and orifices and both devices may be gated or ungated . An example of a gated weir would be a stoplog bay. An example of a gated orifice would be a sluice gate.

Gate control is most beneficial when timing of storage and release are critical. This is often the case when the flood is of long duration and when the location of the storage is far upstream from a point of flood control interest. If water from an area would precede the downstream flood peak, storage would not be advisable and the gate should be open. It should be closed to avoid contributing to peak flows and kept closed until flood conditions have subsided. Because gated storage is more efficient, it should always be considered when flood storage capacity within the watershed is limited.

The main disadvantages of gate control are the potential for improper or unauthorized operation and added expenses of operation. The larger the impoundment the more practical gate control will be.

Ungated outlets are less expensive to build and do not require operation. Ungated storage is most appropriate for small impoundments in the upper reaches of a watershed. These are areas where detention is almost always beneficial and where precise operation may not be possible or practical. Such impoundments should be designed with long drawdown times to ensure that releases do not substantially contribute during downstream flooding.

The size of the outlet is a very important design feature of an impoundment. In most cases, gated outlets will be larger than ungated outlets. Ungated outlets must be small enough to control downstream flows to less than bank full until the reservoir is almost full. Gated outlets may be large enough to pass bank full flows without filling the reservoir. This is especially important on higher order streams and when storage capacity is limited.

The operating plan of a gated impoundment is also very important. It should be linked to current or predicted flood elevations at damage points downstream. It is designed to optimize flood control benefits. It may also be designed to minimize adverse environmental impacts. Some projects may require a very detailed plan, while others may not. In every case, the operating plan should be an integral part of the project design and establishment. Changing the operating plan may require both legal proceedings and permit amendments.

Single vs Multi-Purpose

A single-purpose flood control impoundment would simply detain the flood water and release it all as quickly as possible after the flood. Multi-purpose impoundments may retain a portion of the water to be used for other beneficial purposes. They may have permanent pools as for wildlife or recreation, or semipermanent pools as for water supply or stream flow maintenance. Multi-purpose impoundments can be as beneficial for flood control as single-purpose impoundments if the total storage capacity is increased to compensate for the permanent or semipermanent storage volume, and if the operating plan allows unrestricted use of the reservoir for flood storage when needed . Multi-purpose impoundments may be more economical to build because a portion of the cost can be assigned to other benefits and supported by other interests.

Because retained water is totally removed from the flood hydrograph, it may be more beneficial for flood control than water detained for only a short period of time.

Flood Control Water Supply Impoundments

The average annual runoff from the Minnesota side of the Red River Basin is only about 2". Most of the runoff occurs in the spring, and intermittent stream flows are the norm throughout the remainder of the year. Impoundments present an opportunity to store spring runoff and make it available to augment stream flows during the drier seasons.

The most beneficial locations would be within the watersheds of intermittent streams that have potential for high quality stream habitat and upstream from potential high value water users.

The design goals include minimizing reservoir evaporative losses and providing high quality water. Evaporative losses are proportional to surface area. Therefore, deep reservoirs with relatively smaller surface areas are preferred. Desirable water quality features include sedimentation of incoming suspended solids, minimal resuspension of sediments, adequate dissolved oxygen, and suitable trophic conditions. In general, water quality is also better in relatively deep reservoirs.

Reliable water supply can be provided without significantly detracting from flood control if the retained amount is limited to what is normally available on an annual basis. As an example, assume that a reservoir has capacity to store 3.7" of runoff from its watershed area, which is typical of a 10 year spring flood. If 1" of runoff is retained, the reservoir would still have capacity to store all of a typical summer 100-year, 24 hour rainstorm runoff of 2.6". In an average year, the 1" of runoff that is retained would be used for water supply and stream flow maintenance. If greater reservoir capacity is available, some water could be carried forward from year to year as a drought contingency.

The amount of water normally available for water supply would depend on pool losses. If half the water were assumed to be lost, the remainder could still provide a continuous outflow of 3.5 cfs from a 100 square mile watershed.

Flood Control Wetland Impoundments

Impoundments can be designed to incorporate wetland benefits. Additional design goals include a semi-permanent wetland pool and control of pool bounce.

The size and depth of the wetland pool would depend on the type of wetland desired. In general, wetlands are relatively shallow water bodies. The size of the wetland is dictated by topography and may be limited by the availability of water to replenish evaporative and seepage losses. Assuming a pool drawdown of 2 feet by spring, the level could be restored by 1 to 2 inches of runoff from a watershed 12 to 24 times the size of the wetland. If the watershed to pool ratio is less than 10, there is likely to be a significant pool deficit in drier years. If the watershed to pool ratio is much greater than 20, the pool may be subjected to high bounce during summer runoff events.

Pool bounce may adversely impact nesting wildlife and wetland vegetation. It is desirable to keep bounce to a minimum during frequently occurring summer runoff events. This can best be accomplished by a weir type outlet. On the other hand, flood control requires bounce during major runoff events. This can best be accomplished by an orifice type outlet.

A good compromise that provides benefits to both interests can be provided by a combined outlet that would include both a weir and an orifice. The weir would be positioned upstream from the orifice. It would control levels to minimize bounce during the minor, frequent runoff events. During major events, the downstream orifice capacity would be exceeded resulting in submergence of the weir and control of downstream flows.

The optimum type of outlet depends primarily on the watershed to pool ratio. If the ratio is less than 20, the pool bounce will be relatively minor during frequent floods even with a small piped outlet. To illustrate, the runoff from a 10-year, 24 hour rainstorm is about 1 1/4 inches which is equivalent to 25 inches on a pool area equal to 5% of the upstream drainage area. Such a pool could have a very small outlet that would fully control the 10 year flood while limiting bounce to less than a 2 foot wetland impact goal. Higher ratios than 20 may warrant the more expensive combined outlet or gate control to minimize bounce and optimize flood storage.

Wetland flood control impoundments with ungated outlets should be located in the middle and upper areas of the watershed. Those with gated outlets can be located anywhere if they have an appropriate operating plan.

Wetland areas can also be developed within a larger flood control impoundment area. If they can be located in higher elevations, they may be less impacted by bounce. Compartmentalization of a flood control impoundment can also protect critical areas from frequent excessive bounce.

Cost

The cost of building impoundments is highly variable and may depend on the size and on multi-purpose aspects of the project. In general, larger projects have a lower cost per acre-foot of storage. Average cost is also less with projects that can store a high proportion of the runoff because the outlet works can be smaller. Impoundments with gate controlled outlets are more expensive than ungated impoundments.

The average cost of the 33 impoundments funded by the Red River Watershed Board since 1976 has been $182 per acre-foot. The average storage per project was 3000 acre-feet while the median project size was 1250 acre-feet. Approximately 40% of the 100,000 acre-feet of storage built is gate controlled. Future cost are likely to be higher due to inflation and the fact that projects are becoming more difficult to build. A reasonable estimate of current average cost may be about $500 per acre-foot for gate controlled storage.

Summary

Impoundments can provide substantial flood control benefits if properly located and designed. Proper location and design can also help to avoid or minimize adverse environmental impacts. Opportunities exist for projects that provide multiple benefits. Partnership in addressing flood control and other environmental issues may result in the most cost effective and beneficial solutions.