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ENGINEERING AND LEGAL ASPECTS OF A DISTRIBUTED STORAGE FLOOD MITIGATION SYSTEM IN IOWA

by

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CERTIFICATE OF APPROVAL

MASTER'S THESIS

This is to certify that the Master's thesis of

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has been approved by the Examining Committee for the thesis requirement for the Master of Science degree in Civil and Environmental Engineering at the December 2011 graduation.

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ABSTRACT

This document presents a sketch of the engineering and legal considerations necessary to implement a distributed storage flood mitigation system in Iowa. This document first presents the results of a simulation done to assess the advantages of active storage reservoirs over passive reservoirs for flood mitigation. Next, this paper considers how forecasts improve the operation of a single reservoir in preventing floods. After demonstrating the effectiveness of accurate forecasts on a single active storage reservoir, this thesis moves on to a discussion of distributed storage with the idea that the advantages of active reservoirs with accurate forecasting could be applied to the distributed storage system. The analysis of distributed storage begins with a determination of suitable locations for reservoirs in the Clear Creek Watershed, near Coralville, Iowa, using two separate algorithms. The first algorithm selected the reservoirs based on the highest average reservoir depth, while the second located reservoirs based on maximizing the storage in two specific travel bands within the watershed. This paper also discusses the results of a land cover analysis on the reservoirs, determining that, based on the land cover inundated, several reservoirs would cause too much damage to be practical. The ultimate goal of a distributed storage system is to use the reservoirs to protect an urban area from significant flood damage. For this thesis, the Clear Creek data were extrapolated to the Cedar River basin with the intention to evaluate the feasibility and gain a rough approximation of the requirements for a distributed storage system to protect Cedar Rapids. Discussion then centered on an approximation of the distributed storage system that could have prevented the catastrophic Flood of 2008 in Cedar Rapids. There is significant potential for a distributed storage system to be a cost effective way of protecting Cedar Rapids from future flooding on the scale of the Flood of 2008. However, more analysis is needed to more accurately determine the costs and benefits of a distributed storage system in the

Cedar River basin. This paper also recommends that a large scale distributed storage system should be controlled by an entity be created within the Iowa Department of Natural Resources. A smaller distributed storage system could be managed by a soil and water conservation subdistrict. Iowa allows for condemnation of the land needed for the gate structures and the flowage easements necessary to build and operate a distributed storage system. Finally, this paper discusses the environmental law concerns with a distributed storage system, particularly the Clean Water Act requirement for a National Pollutant Discharge Elimination System permit.

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INTRODUCTION

Distributed storage is a developing and promising concept for flood mitigation. A distributed storage system accomplishes flood mitigation by replacing a single large reservoir with a series of tens, hundreds, or thousands of small reservoirs on the tributaries of the main channel. Ideally, the reservoirs are each individually controllable, allowing the controller of the entire system to determine the releases from each reservoir to maximize the flood protection of the system. The distributed storage reservoirs are expected to remain empty through most years, allowing the land on which they sit to remain productive the majority of the time.

The idea of distributed storage is not new. Andoh and Declerck (2009) demonstrates the value of using a passive distributed storage system for slowing down urban stormwater flow. Kurz et al. (2007) discusses a large scale passive distributed storage system in the Red River Basin, called the Waffle Concept. The Waffle Concept was an attempt to determine the effectiveness of utilizing existing low areas in the basin to store water by closing off the culverts running under elevated roads. The culverts would be closed in anticipation of a flood, and the water stored in the low-lying areas until the flood passed. The Waffle Concept was primarily concerned with capturing water before it reached the stream network. In addition, the distributed storage discussed in both Andoh and Kurz are passive storage systems. This thesis proposes an active storage system, where the water is captured and held in reservoirs after it has entered the stream network. The proposed storages would be individually controllable, allowing the releases from each reservoir to be managed in a way to maximize the flood control effectiveness for the entire system.

Forecasting is an essential part of a successful distributed storage system. The controller of the system needs accurate information regarding the expected timing and magnitude of flows in order to determine where to store water and where to allow it to flow downstream. An accurate forecast will allow the controller of the distributed storage system to hold water upstream and prevent excess water from arriving in one place at the same time. The held water can be released slowly during the flood to retain some storage capacity, or held until after the flood danger has passed.

A distributed storage system requires a selection of reservoirs located throughout the river basin. These reservoirs will ideally be located where the highest concentrations of downstream flow originate. In order to determine where the highest concentrations of downstream flow originate, the elevation data from the watershed can be analyzed to track the path of a drop of water from any individual point in the watershed. The areas in the watershed that include a high number of points that travel the same distance to the outlet are where the highest concentrations of flow originate. These areas create the highest flood risk because, assuming uniform precipitation, the rainfall in these areas will reach the stream outlet at about the same time. Therefore, it is essential to analyze these concentrated areas and locate distributed storage reservoirs to collect water that falls in these sites.

In addition, distributed storage reservoirs cannot be located where storing water in the reservoirs would cause extensive property damage. Preferably, reservoirs will be located only on pastures, woodlands, and crop lands. The only damage caused by filling the reservoirs will be to crops and pastures in the occasional year that the reservoirs are used. Once the reservoirs are located, the composition of the land potentially inundated by the reservoirs must be analyzed to determine whether the location is feasible for placing a distributed storage reservoir. Alternatively, the composition of the land could be included in a function for determining the suitability of a location for a reservoir, although this paper does not attempt this method of reservoir selection. Nonetheless, it is critical that the reservoirs be placed in the watershed with consideration for the land inundated by the reservoirs.

This paper includes a study of the difference between active, or controllable, reservoirs and passive reservoirs. Active reservoirs are required to maximize the storage efficiency of a distributed storage system, as the individual control will be necessary to coordinate the flows throughout the system. In addition, the effects of forecasting duration and accuracy were analyzed in order to demonstrate the advantages of a precise forecast for an active storage reservoir. Accurate forecasting, both of flow and precipitation, over a considerable time period is essential to confidently predict downstream flows resulting from upstream releases combining with precipitation and other flows in the system.

This thesis also includes the results of a small scale study on the Clear Creek Watershed in Eastern Iowa that analyzed suitable locations for distributed storage reservoirs. This study included determining reservoir locations using two similar algorithms. The first algorithm determined reservoirs according to the most storage volume per unit of area flooded. The second method attempted to place reservoirs with the goal of catching as much water as possible from two areas where rainfall would concentrate at the outlet at approximately the same time. Both of these techniques placed 33 reservoirs in the Clear Creek Watershed. Analysis of the types of land inundated by these 33 reservoirs resulted in removing several of these reservoirs, leaving 29 and 28 reservoirs for the first and second algorithms respectively.

Locating distributed storage reservoirs in the Clear Creek Watershed is useful for analyzing the properties of the reservoirs, but Clear Creek does not pose a substantial risk of urban flooding, and is therefore not an ideal location for a distributed storage system. However, Cedar Rapids, located approximately 19 miles north of Clear Creek on the banks of the Cedar River, is a more suitable location for a distributed storage system. Cedar Rapids was catastrophically flooded in 2008, and is in need of protection to prevent another such disaster from occurring.

This document is intended to provide a sketch for the possibilities of a distributed storage system on the Cedar River upstream of Cedar Rapids. The reservoirs analyzed in the Clear Creek example were extrapolated into the Cedar River basin to obtain a rough estimate of the number of reservoirs required to potentially protect Cedar Rapids from a flood like the one that occurred in 2008, and approximate the types of land that would be inundated by these reservoirs. In addition, this paper includes a ballpark estimate of the costs associated with constructing and using a distributed storage system in the Cedar River basin to protect Cedar Rapids. This estimate was compared with the U.S. Army Corps of Engineers' estimate of the damage caused by the 2008 flood in order to get a rough approximation of the potential benefits a distributed storage system could have for the Cedar Rapids area.

This initial overview of the potential for a distributed storage system in the Cedar River basin found that there is potential for significant benefits to Cedar Rapids. However, there are more studies that need to be completed to ascertain the full benefits of a distributed storage system, as well as to find the exact locations for the required reservoirs and ensure that they are placed in beneficial locations.

This thesis also evaluates several legal and policy issues associated with a distributed storage system. The focus of this paper is on Iowa, so these issues were analyzed with respect to Iowa law. The first legal and policy issue is determining the agency that would be responsible for constructing, maintaining, and operating a distributed storage system in Iowa. Ultimately, the Iowa Department of Natural Resources appears to be the most suitable entity for operating a large system, while soil conservation subdistricts can effectively manage a small distributed storage system. In addition, this document gives a brief overview of the land interests required for the system, and the feasibility of obtaining the land interests by eminent domain if necessary. Finally, this paper looks at the environmental law concerns, particularly the Clean Water

Act’s requirements for National Pollutant Discharge Elimination System permits and the likelihood that these will be required for distributed storage reservoirs.

PART ONE: ENGINEERING A DISTRIBUTED STORAGE SYSTEM

CHAPTER 1: SINGLE RESERVOIR DEMONSTRATIONS

Flood Protection Overview

Every year, floods cause significant damage to homes, businesses, and lives across the United States. In 2008, catastrophic floods in the state of Iowa on the Des Moines, Cedar, Iowa, and Mississippi Rivers caused billions of dollars in damage to river communities. In 2011, communities on the western border of Iowa were inundated by floods from the Missouri River, a flood which also caused damage in Nebraska, Missouri, Montana, and the Dakotas. The importance of protecting communities from floods has been demonstrated by nature in the past several years, particularly in the Midwest. Improved and more practical ways of reducing flood damage are crucial to prevent future flooding disasters.

Traditionally, flood protection was accomplished either by constructing a large dam and reservoir or by building a flood barrier. A flood barrier can be an earthen levee or a concrete floodwall, both of which reduce flood damage by preventing the water from flowing into areas where floods will cause significant damage. Levees and flood walls accomplish this by channeling the flow, preventing it from spreading out of the river and into sensitive areas in times of high water. A reservoir, on the other hand, is created by building a structure on a river or stream to reduce the flow on the river downstream. The water from the river or stream pools behind the structure, and the amount of water released is often controlled to prevent damage downstream. Any flow beyond the desired release collects in the reservoir to be released later, when the inflow to the reservoir has decreased to a safer level.

However, both of these flood control systems are ineffective when the water exceeds the designed maximums. A reservoir is limited to the volume that can be stored behind the structure before the water overtops the reservoir's spillway. Once the reservoir is full, the amount of water released downstream can no longer be controlled.

The water will flow over the spillway, negating any flood protection for the downstream communities. A flood wall or levee fails when the water overtops the barrier, allowing the flood waters to flow freely into the populated areas.

Reservoirs designed for the outflows to be controllable by a gate or other such structure are called active storage reservoirs. A passive reservoir, on the other hand, is one where the outflow cannot be controlled. A passive reservoir usually includes an outflow pipe or weir, and the amount of water released depends entirely on the height of the water in the reservoir. Active storage has the significant advantage that the amount of water released can be increased ahead of an impending flood wave to supplement the amount of storage available to hold such a flood wave.

Comparison of Active and Passive Storage

This section describes a simulation performed to analyze the advantage of active flood control over an identical reservoir using a passive flood control system. The simulation was run using Matlab code configured to model a single reservoir system. The input data was obtained from the USGS using the data from the Marengo stream gage on the Iowa River from March to August of 2008.[1] These dates were selected because they include the Flood of 2008, which caused considerable damage to Iowa City and Coralville along the Iowa River. Marengo is the last river gage upstream of the Coralville Reservoir, which is situated just upstream of Iowa City and Coralville. The Coralville Reservoir has capacity to store approximately 475,000 acre-ft. of water (United States Army Corps of Engineers, “Coralville Lake”). The reservoir used for this simulation was 50 feet deep, having an area 10,000 acres, for a total storage volume of 500,000 acre-ft, making it similar in size to the Coralville Reservoir. The simulation began with data from March 16, 2008, with the reservoir starting completely empty. For

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[1] Data obtained from the USGS Instantaneous Data Archive at http://ida.water.usgs.gov/ida/index_usgs.cfm

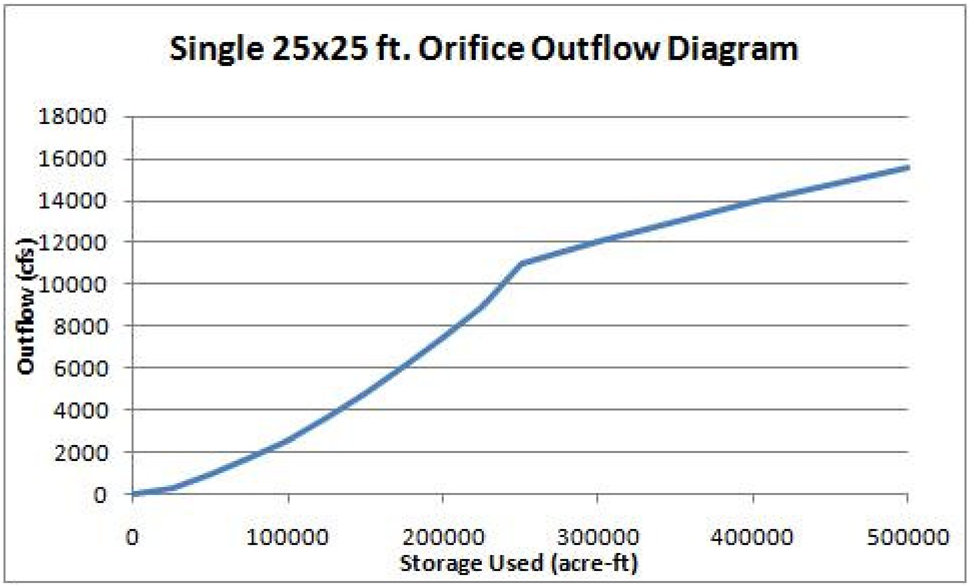

Figure 1-1: Outflow diagram for a single 25 ft. by 25 ft. orifice

simplicity, once the simulated reservoir was full, all water flowing in to the reservoir was released as outflow. This is a slight oversimplification. In reality, there would be lag time from inflow to outflow in a real reservoir of this size. In addition, there would be additional water stored above the spillway level because the spillway can only release a portion of the water above the spillway. Nonetheless, this simulation provides a reasonable demonstration of the functioning of an active storage system.

The passive storage reservoir was modeled using a single square outflow orifice with each side being 25 feet (7.6 meters) long, located on the bottom of the reservoir. This size of orifice was selected because it provided outflows in the range reasonably close to the normal outflows in the Coralville Reservoir. The size of the orifice was slightly unrealistic, but provides acceptable data for comparison. Figure 1-1 shows the release characteristics of the 25 foot square orifice.

The orifice acts like a weir until the water level reaches the top of the orifice, at 25 feet, which corresponds to 250,000 acre-ft. stored. Water is released according to the

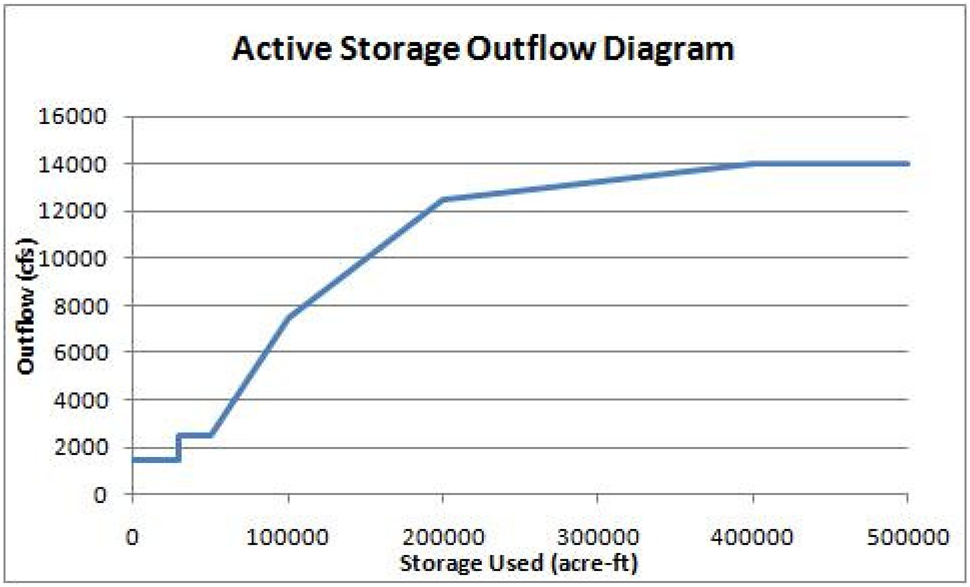

Figure 1-2: Outflow diagram for the active storage reservoir

weir equation in Equation 1.1 (Mays, 2005), where *w* is the width of the orifice opening (25 feet), and *H* is the water level in the reservoir:

$$Q = 3.33 * wH^{1.5} \qquad \text{(Equation. 1.1)}$$

Once the outflow passage is completely submerged, the release mimics orifice flow, represented by Equation 1.2 (ISU Institute for Transportation, 2009, “2C-12 Detention Basin Outlet Structures”), where h is the height of the orifice (25 feet), and the other terms are the same as above in Equation 1.1.

$$Q = 0.6hw * \sqrt{2g(H - {}^{h}/_{2})} \qquad \text{(Equation. 1.2)}$$

Figure 1-2 illustrates the outflow diagram for the active storage reservoir. The amount of water allowed to flow downstream at any given time in this simulation was selected according only to the amount of water in the reservoir. These release rules were chosen to allow for high releases under most circumstances, but also to limit the amount of damage caused by the releases in Iowa City. For this reason, the highest release allowed was 14,000 cubic feet per second (cfs), as this is the flow that begins to inundate

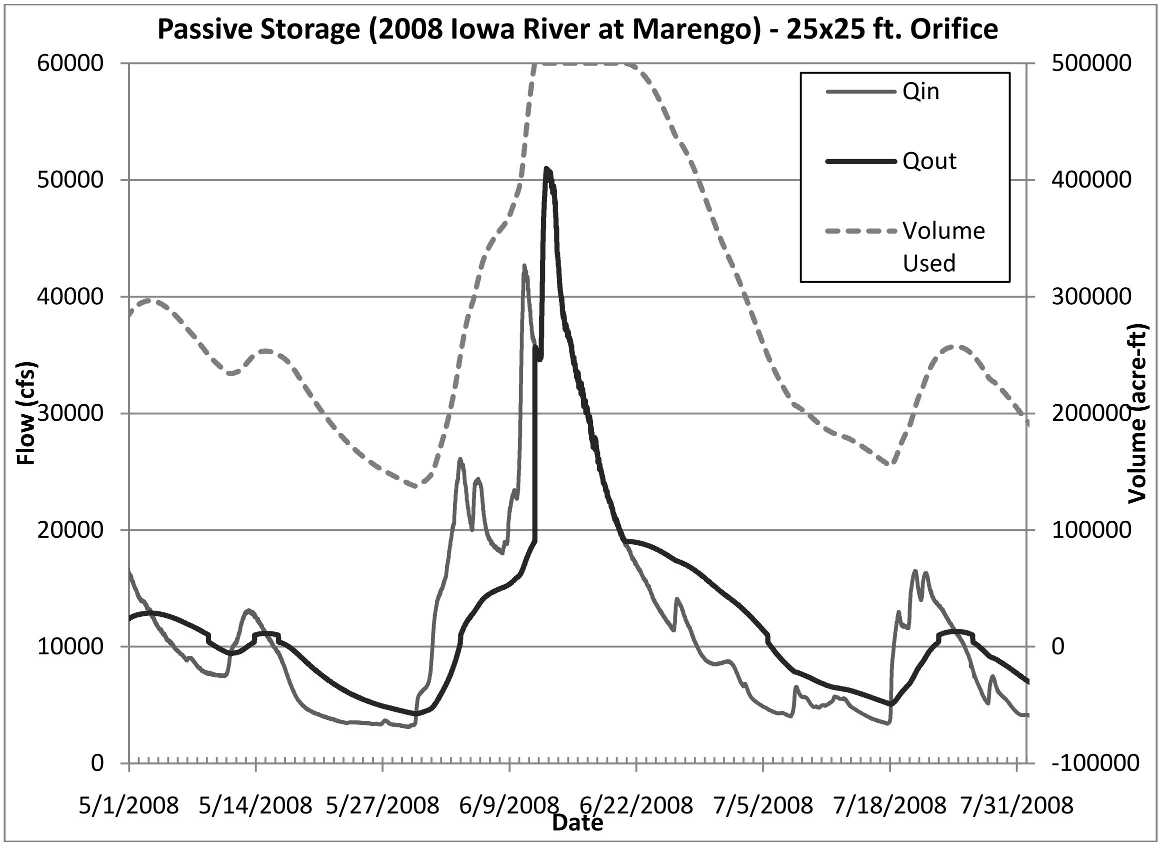

Figure 1-3: Passive storage reservoir with a single 25ft. by 25 ft. outflow orifice for the 2008 Flood.

roads and cause damage in Iowa City (Iowa Flood Center, Iowa Flood Information System). In a reservoir such as this one, a gate would be used to precisely control the outflow amounts. Although the temporal resolution of the input data was 30 minutes, for this simulation the gate was adjusted every four hours to avoid wearing out the gate's mechanical equipment.

The results of the simulation are shown in Figure 1-3 and Figure 1-4. Figure 1-3 illustrates the passive storage reservoir, while Figure 1-4 shows the active storage reservoir. The active storage was slightly more effective than the passive storage. The active reservoir did not fill completely until approximately one day later than the passive reservoir. However, neither reservoir was able to contain the largest portion of the flood

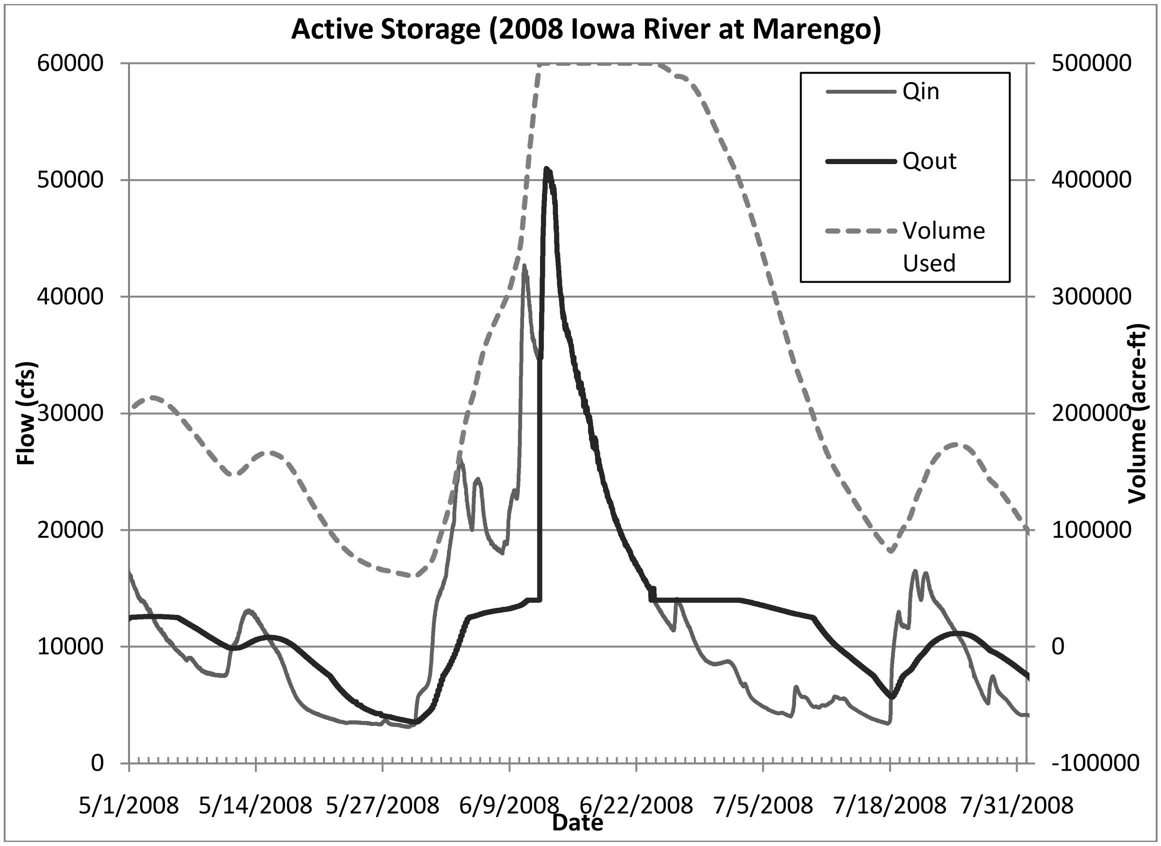

Figure 1-4: Active storage reservoir using the specified release rules for the 2008 Flood.

peak. The reason for the ineffectiveness of the reservoir is that the flood wave was extraordinarily large. Because the release rules used in this simulation were based solely on the amount of water currently in the reservoir, they could not anticipate the size of the impending flood. In order to have a more effective active storage system, it is necessary to forecast the impending flood so the reservoir level can be lowered in anticipation of the flood wave.

Demonstration of Flood Forecasting on a Single Reservoir System

Accurate and unbiased forecasts can significantly improve the effectiveness of reservoirs for flood mitigation (Yao and Georgakakos, 2000). However, even the most accurate forecasts are not useful for reservoir operation if not used intelligently to adapt to the conditions in the reservoir (Yao and Georgakakos, 2000). Therefore, this subsection seeks to utilize different simple forecast models to demonstrate the effectiveness of a forecast on a single reservoir simulation. The forecasts are input to an algorithm that decides the outflow of the reservoir based on the current volume and forecasted inflows. The goal of the simulation was to reduce the peak flow from the Flood of 2008 on the Iowa River at Marengo. The simulation compared persistence forecasts, perfect forecasts, and random error forecasts using one, seven, and fourteen day forecast periods. Unsurprisingly, the simulation demonstrated that a better forecast over a longer duration can significantly improve the operation of an active reservoir.

Simulation Set Up

As above, the simulation was run using Matlab code configured to model a single reservoir system. The stream gage data from the Iowa River at Marengo from March to August of 2008 was again used. The same 500,000 acre-ft. reservoir from the previous simulation was used, with the forecasts run and outflows modified every four hours.

A new set of release rules was used to account for the forecasting and to increase the outflows to better handle the large flood wave. To determine the amount of water released, a preliminary outflow ($Q_{preliminary}$) was calculated according to Equation 1.3:

$$Q_{preliminary} = \left(V_{forecast} + V_{stored} - V_{pool}\right) * \left(\frac{43560}{t_{fc} * 86400}\right) \qquad \text{(Equation 1.3)}$$

$V_{forecast}$ is the amount of volume forecasted to enter the reservoir over the forecast period, in acre-ft. The method of determining this variable will be discussed below, as it is calculated differently for each forecast model. V_{stored} is the amount of water in the reservoir at the time the forecast is made, in acre-ft., while V_{pool} is the desired amount of water in the reservoir storage pool, also in acre-ft. For this simulation, the storage pool was selected as 25,000 acre-ft., very near the 28,100 acre-ft. storage pool used for the

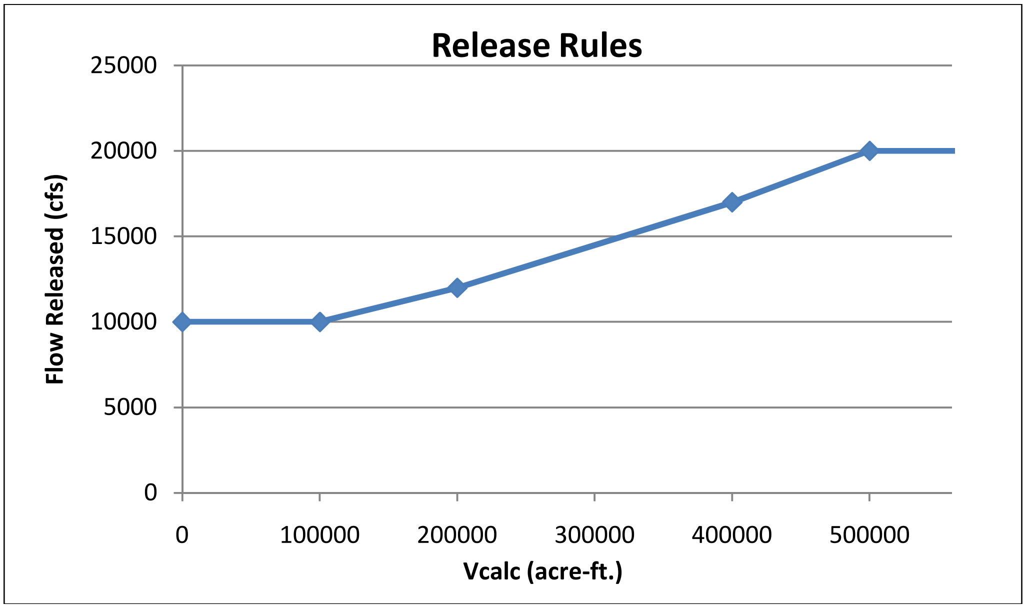

Figure 1-5: Release Rules as a function of forecasted volume (V_{calc}) when $Q_{preliminary}$ is calculated to be greater than 10,000 cfs.

Coralville Reservoir (U.S. Army Corps of Engineers, 2010). The term on the right converts volume in acre-ft. to flow in cubic feet per second, where t_{fc} is the forecast period in days.

If the calculated preliminary outflow is less than 10,000 cfs, then the outflow gate is set to the preliminary outflow value. This will keep the reservoir at the storage pool level when the forecasted inflows are low. If the preliminary outflow value is calculated to be more than 10,000 cfs, then the simulation uses Equation 1.4 to calculate the anticipated volume (V_{calc}) that will be in the reservoir using the forecast and assuming a 10,000 cfs outflow:

$$V_{calc} = \left(V_{forecast} + V_{stored}\right) - 10{,}000 * \left(\frac{t_{fc} * 86{,}400}{43{,}560}\right) \qquad \text{(Equation 1.4)}$$

This calculated volume is then used to set the gate outflows according to the release rules given in Figure 1-5. Thus, if the expected inflows are high but the anticipated volume in the reservoir is under 100,000 acre-ft., the outflow gate is set to 10,000 cfs. As the

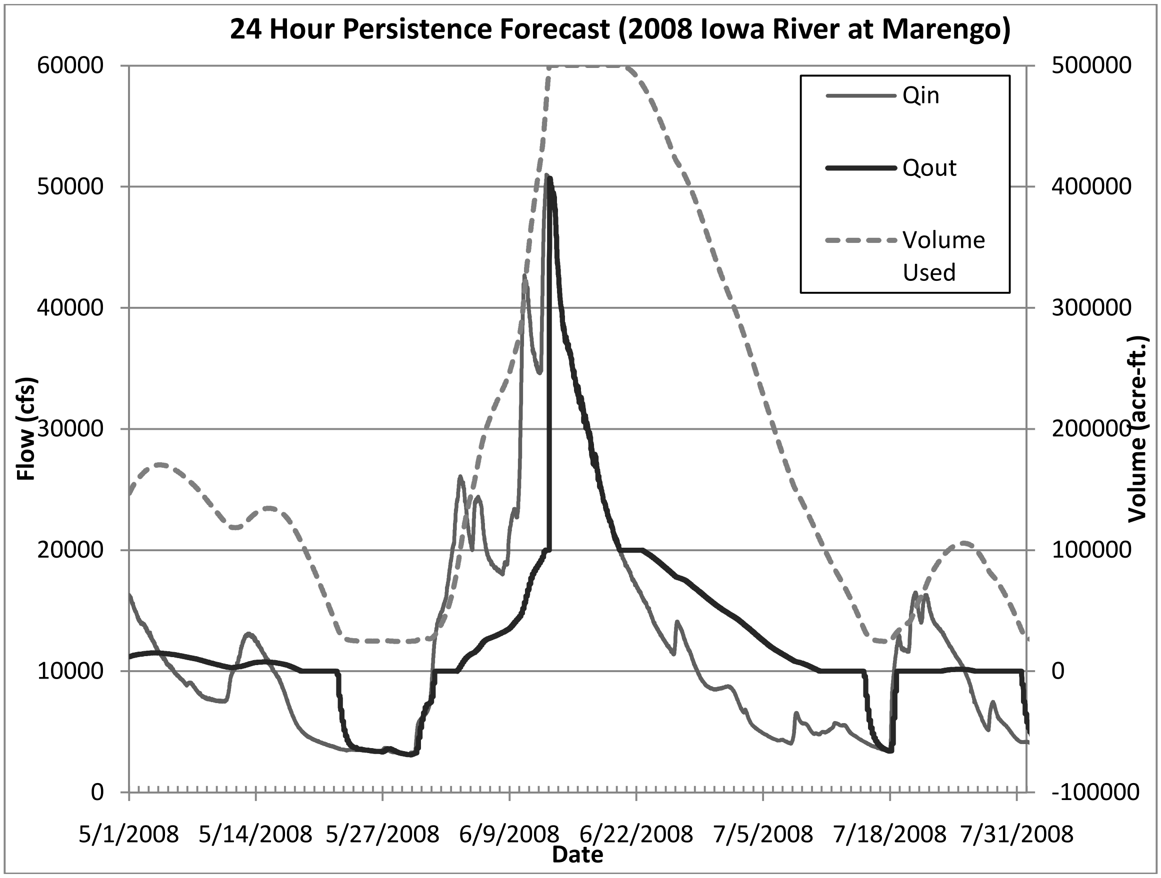

Figure 1-6: 24 hour persistence forecast simulation for the 2008 Iowa River flood.

forecasted volume in the reservoir increases, the outflows increase in a nearly linear fashion up to 20,000 cfs if the reservoir is forecast to fill completely.

Persistence Forecasts

The first type of forecasting model used was a persistence forecast. A persistence forecast uses data from the recent inflows to predict future inflows. For this simulation, the model used the flows from the previous 24 hours, and multiplied by the number of days in the forecast. For example, for a 1 day persistence forecast, the forecast assumes that the inflow over the next 24 hours will be the same as it was for the previous 24 hours. For a one week persistence forecast, the forecast assumes that the total inflow

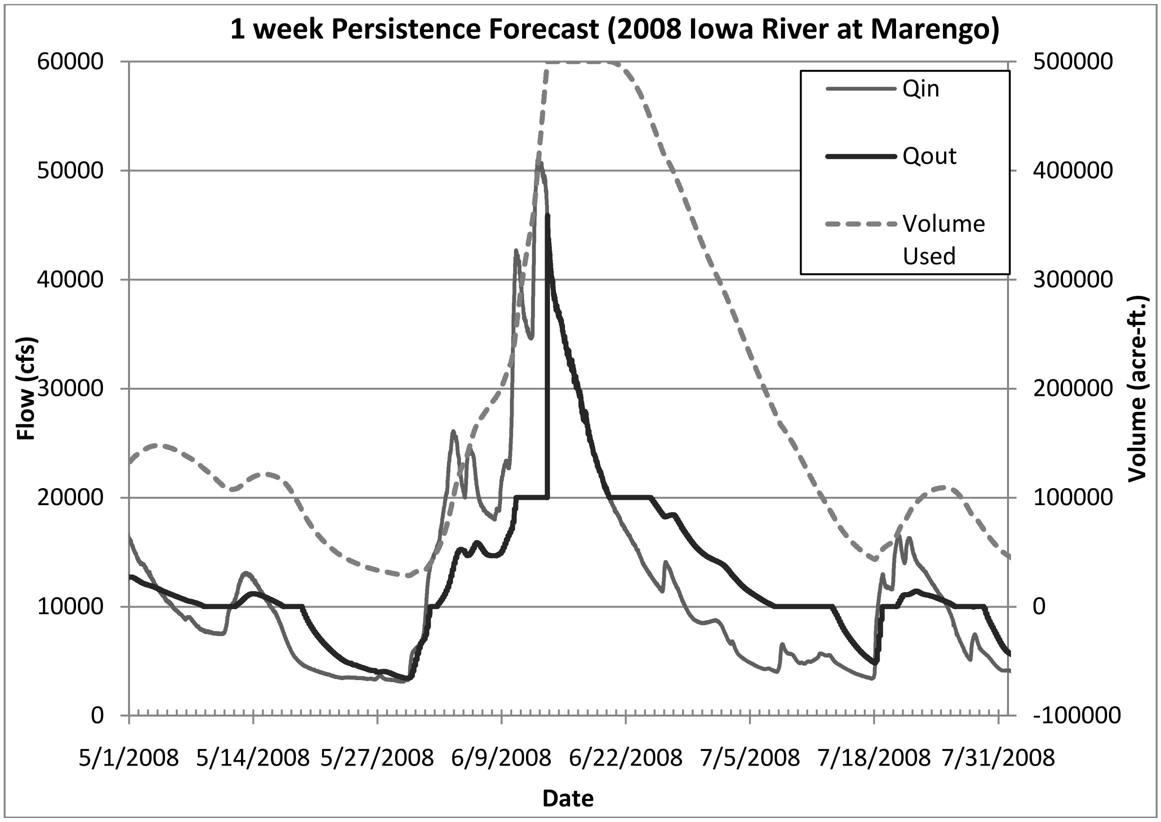

Figure 1-7: 1 week persistence forecast simulation for the 2008 Iowa River flood.

over the next week will be seven times the flow over the previous 24 hours. Thus, $V_{forecast}$ used in Equations 1.3 and 1.4 for a persistence forecast is equal to the total inflow over the previous 24 hours multiplied by the forecast period. Persistence forecasts are the simplest form of forecasting, and therefore generally yield minimal advantages for distributed storage control. The results of the simulation run with one day and one week persistence forecasts are shown in Figure 1-6 and Figure 1-7 respectively.

The one day persistence forecast had very little impact on the flood peak, as the peak flow was only reduced by 300 cfs, from 51,000 cfs to 50,700 cfs. The one week persistence forecast yielded slightly better results, reducing the peak flow from 51,000 cfs to 45,800 cfs. However, neither of these reductions is significant enough to appreciably reduce the damage caused by the flood. The reason for this is simple. Persistence

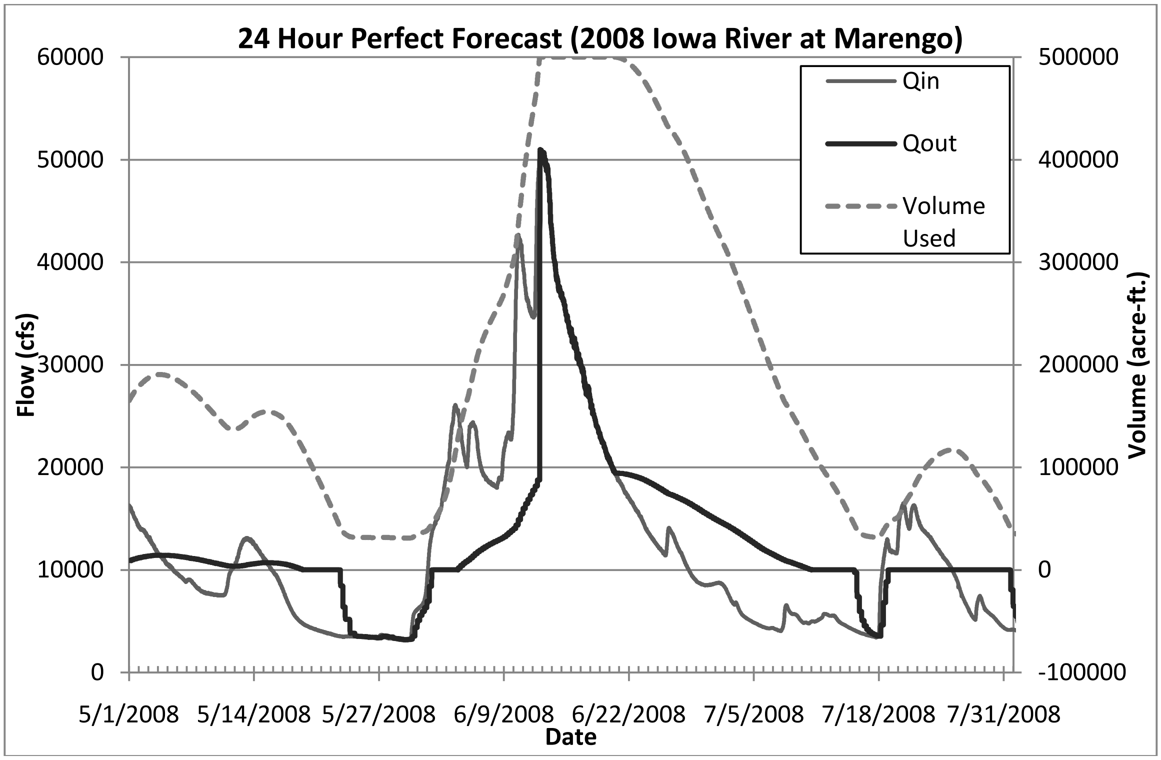

Figure 1-8: 24 hour perfect forecast simulation for the 2008 Iowa River flood.

forecasting is reactive to the flow in the system. To make a reservoir system more effective at mitigating floods, the system needs to be proactive. There must be an effective future forecast to aid in predicting the future flood wave.

Perfect Forecasts

The next simulation evaluated the effect of a perfect forecast on flood mitigation for a single reservoir. A perfect forecast is one in which the model uses the actual data from the forecast period to forecast the volume of flow that will flow into the reservoir over the period. For example, a 24 hour perfect forecast model uses the actual inflows over the next 24 hours to determine the forecasted inflow volume. While a perfect forecast is unrealistic using current technology, it provides a benchmark for the maximum possible impact a flood forecast can have on the system.

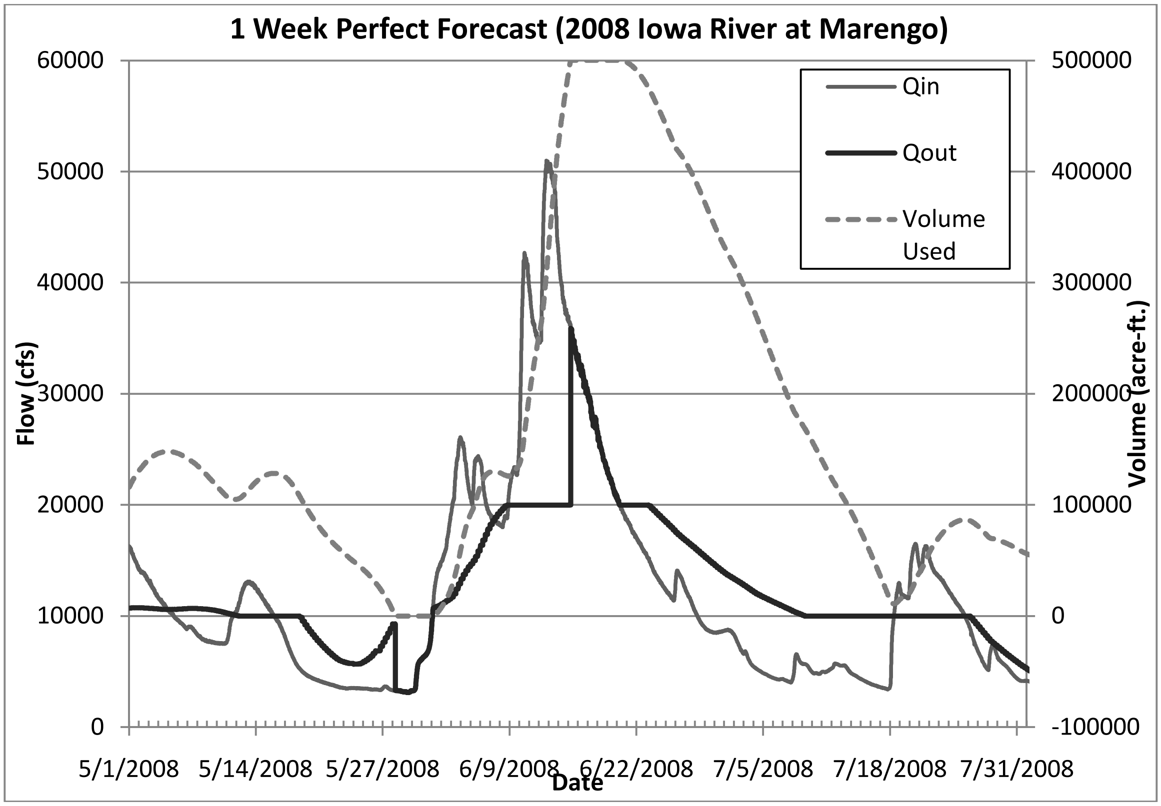

Figure 1-9: One week perfect forecast simulation for the 2008 Iowa River flood.

Perfect forecasts of 24 hours, one week, and two weeks were simulated to demonstrate the advantages of a perfect forecast and the impact that longer forecast periods have. The 24 hour perfect forecast simulation is demonstrated in Figure 1-8 below, while the one week perfect forecast is shown in Figure 1-9 and the two week perfect forecast is shown in Figure 1-10.

The 24 hour perfect forecast was ineffective at reducing the peak flow from the 2008 flood. The extreme flows from the 2008 flood lasted for nearly two weeks, and the magnitude of the impending flood was not recognized early enough by a forecast only looking 24 hours in advance. Under the release rules used, the reservoir failed to adequately anticipate the flood, as it did not empty the reservoir before the flood and it did not increase the releases fast enough to prevent significant damage.

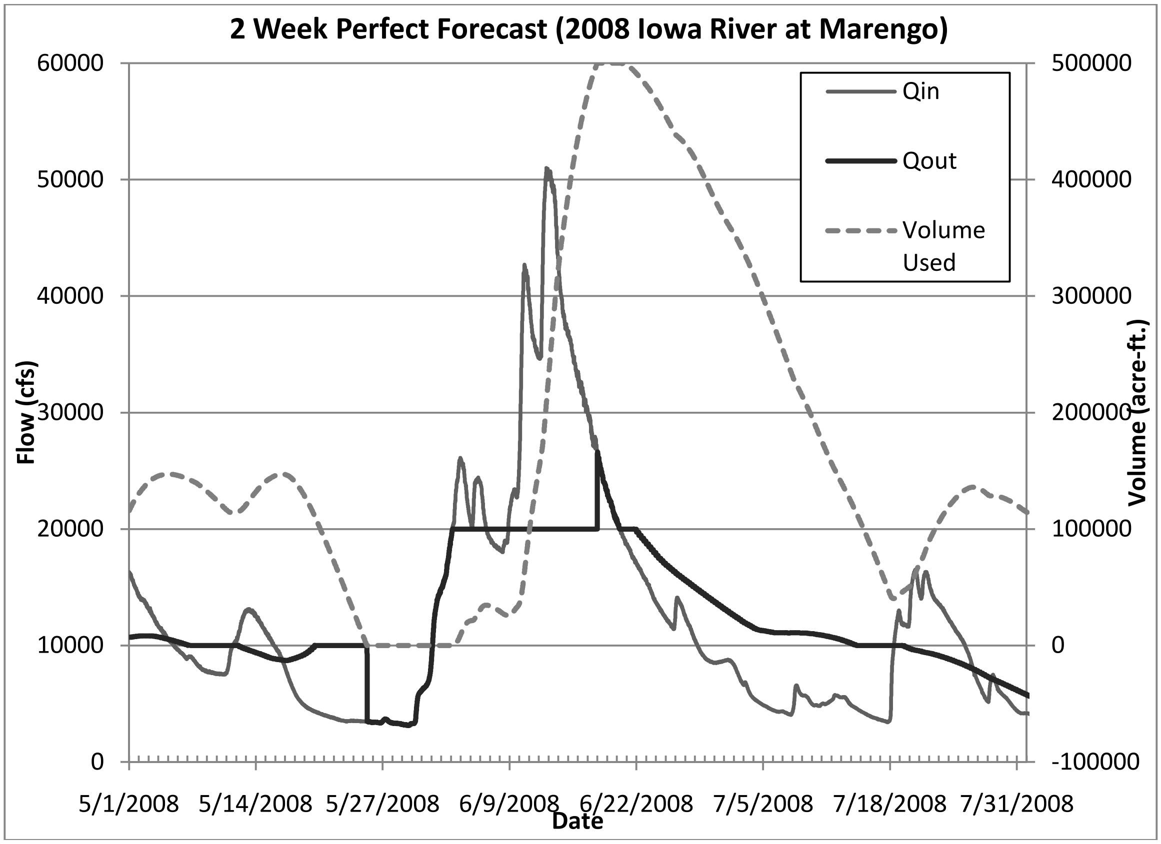

Figure 1-10: Two week perfect forecast simulation for the 2008 Iowa River flood.

The one week perfect forecast significantly reduced the peak flow from the flood. The peak was reduced from 51,000 cfs to 35,900 cfs. While this reduction would not prevent all damage from the flood in Iowa City, it would considerably reduce the area flooded and the damage caused. Notice that the release rules caused the simulation to completely drain the reservoir prior to the flood wave. Although this is unlikely for a large reservoir such as the one used here, for a multiple reservoir system it may be possible to empty the reservoirs ahead of a flood wave. However, once the flood wave arrived, the simulation was again too slow in recognizing the magnitude of the impending flood. The reservoir filled quicker than the reservoir allowed the water to release, and the reservoir was nearly a third full by the time the largest portion of the flood wave arrived.

The two week perfect forecast simulation attained the best results of all the simulations. The peak flow was reduced from 51,000 cfs to 26,600 cfs, which would radically reduce the damage caused by the flood in Iowa City and Coralville. Again, the system anticipated the flood wave and completely drained the reservoir in advance of the flood. However, this time the two week forecast allowed the system to immediately maximize the reservoir outflows, keeping the reservoir empty until the inflows reached the release cap of 20,000 cfs. Therefore, when the largest part of the flood wave hit the reservoir, the reservoir was still nearly empty, allowing the reservoir to absorb the peak of the flood.

Random Error Forecasts

Ideally, a perfect forecast would be available to assist in operating the distributed storage system. However, current technology is not capable of perfectly predicting the future flows in a river. There are too many variables to accurately predict, including the location and intensity of future rainfall, as well as the behavior of the water once it reaches the ground, from open land flow to the flow in streams and rivers. Therefore, the simulation was modified to include a random error in the perfect forecast in an attempt to create a more realistic forecasting model.

One week forecasts were run with 10 percent error and 25 percent error. The simulation produced a random number according to the normal distribution (a z-score, from approximately -3 to 3, weighted such that numbers closer to zero were more likely). This z-score was weighted with the three prior z-scores in an attempt to correlate the forecasts. The newest z-score was given a weight of 40%, while the prior ones had a weight of 30%, 20%, and 10% respectively. The total perfect forecast volume was multiplied by the weighted z-score and either 10 or 25 percent, depending on the simulation to obtain the forecast error. The forecast error was then added to the perfect

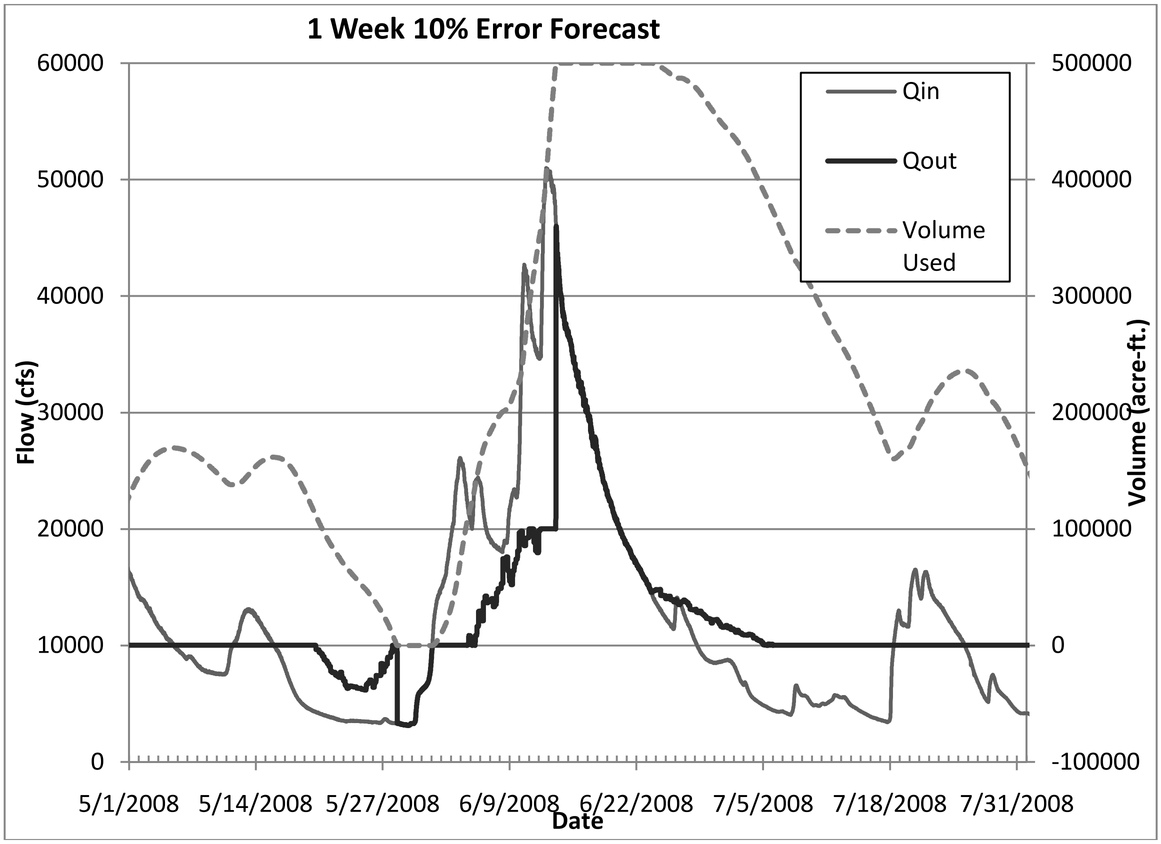

Figure 1-11: One week 10 percent error forecast simulation for the 2008 Iowa River flood.

forecast to obtain the forecast volume ($V_{forecast}$), which was used for determining the amount released for that period.

The 10 percent error forecast is shown below in Figure 1-11. The ten percent error forecast had about the same results as the persistence forecast, but was less effective than the perfect forecast. The releases generally mimic the trend of the perfect forecast, but jump around as the forecast errors are recalculated. The peak flow for the one week ten percent error forecast simulation is 46,000 cfs, about 10,000 cfs more than the one week perfect forecast and about 200 cfs more than the one week persistence forecast.

The 25 percent error forecast is shown in Figure 1-12. There is a noticeable difference between the 25 percent error forecast and the ten percent error forecast.

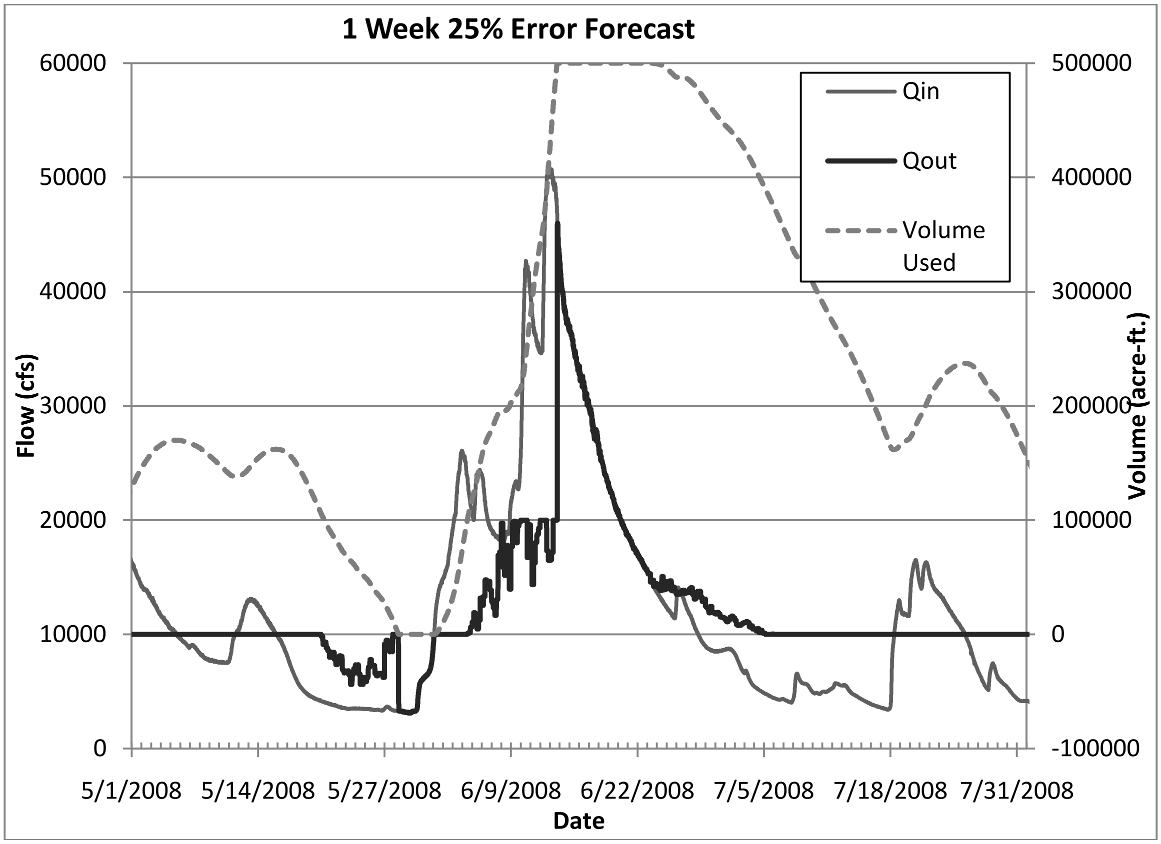

Figure 1-12: One week 25 percent error forecast simulation for the 2008 Iowa River flood.

However, the random nature of the forecast errors caused the positive and negative errors to generally balance out, negating the effects of the larger error. Even with the increased error, the peak flow was again 46,000 cfs, identical to that of the ten percent error forecast.

Discussion

At present, inaccuracies of precipitation forecasting severely limit the accuracy of river forecasts. The travel time for the Iowa River basin is currently about seven days (Krajewski and Mantilla, 2010). Therefore, attaining the benefits of a two week perfect forecast requires a perfect precipitation forecast for between one and two weeks, depending how far up in the basin the predicted rainfall is located. The Hydrometeorological Prediction Center, part of the National Weather Service, currently forecasts the areas where certain set amounts of precipitation are expected. These forecasts are given for up to one week, but their accuracy is lacking. The 4-5 day forecasts have an average monthly threat score[2] of 0.02 to about 0.43, with forecasts of larger precipitation quantities generally having lower threat scores (Hydrometeorological Prediction Center, 2011).

The error from precipitation forecasts weakens the potential to accurately forecast river stages days or weeks in advance. The National Weather Service's Advanced Hydrologic Prediction Service issues river forecasts using precipitation data and forecasts, as well as stream gage data, in the river stage forecasts currently issued (Mason and Weiger, 1995). However, these forecasts can be no more accurate than the input data. When a river is over flood stage, forecasts as short as three days presently have skill barely better than a simple persistence forecast (Welles, 2005). In order to obtain the greatest benefits for a single or a multiple reservoir system, significant improvements in river and precipitation forecast accuracy are necessary.

The above simulation demonstrated the value of accurate forecasting for a single reservoir system. The 500,000 acre-ft. reservoir managed to essentially contain a flood wave that was about 643,000 acre-ft. of water volume from the point flow exceeded 10,000 cfs until the flow dropped below 10,000 cfs. Forecasting is even more important for a multiple reservoir distributed storage system, as multiple reservoirs must be controlled over a wide area with pinpoint accuracy. Accurate forecasting can allow the

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[2] Threat score is a measure of the error associated with area forecasts, ranging from 0 to 1, with 1 being a perfectly accurate forecast. The threat score is calculated by the formula Correct/(Forecast+Observed-Correct), where "Correct" is the correctly predicted area, "Forecast" is the forecasted area, and "Observed" is the actual area that received the forecasted rain amount (Hydrometeorological Prediction Center, Verification).

smaller storages to be more efficient than a single larger reservoir. If the operator can predict when and where water is coming through the system, excessive water can be held by upstream reservoirs with excess capacity until the flood danger downstream has diminished. However, without accurate forecasting of both future precipitation and river flow, the operator of the distributed storage system will not be able to use the scattered smaller reservoirs more efficiently than a single large reservoir.

CHAPTER 2: SMALL SCALE DISTRIBUTED STORAGE ANALYSIS IN THE CLEAR CREEK WATERSHED

A distributed storage system is one in which the system includes many smaller reservoirs instead of a single large dam and reservoir. In an active distributed storage system, the outflow from each individual reservoir can be controlled for widespread management of the water level on the river throughout the watershed. The distributed storage reservoirs are spread throughout the watershed so that the water flow can be controlled at all points on the river. Each distributed storage reservoir is ideally located on undeveloped land, and is intended to remain unfilled except in a flood event. Therefore, the land within the reservoir area can remain productive in most years, and is only inundated when a large flood is predicted to occur downstream.

This research focused on an analysis on the Clear Creek Watershed to determine potential locations for distributed storage reservoirs and examine the usage of the land inundated by the reservoirs. Clear Creek was chosen because it is a small basin with a significant amount of hydrologic and elevation data available. The Clear Creek Watershed is approximately 263 square kilometers (65,000 acres), and is located in Iowa and Johnson Counties, west of Iowa City, as shown in Figure 2-1.

The purpose of this analysis was to use readily available digital elevation mapping ("DEM") data[3] to determine where reservoirs could be placed along Clear Creek and its tributaries. This was done first by determining the most efficient reservoirs, or those with the highest average depth. The program was run again to implement the concept of travel bands, and find the reservoirs that maximize the storage in certain areas of the watershed where there is a high risk of downstream flooding. Once placed, this chapter analyzes the

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[3] Processed DEM data obtained from Ricardo Mantilla of the Iowa Flood Center. The DEM data used was the portion of the Clear Creek Watershed upstream of the USGS stream gage at Coralville.

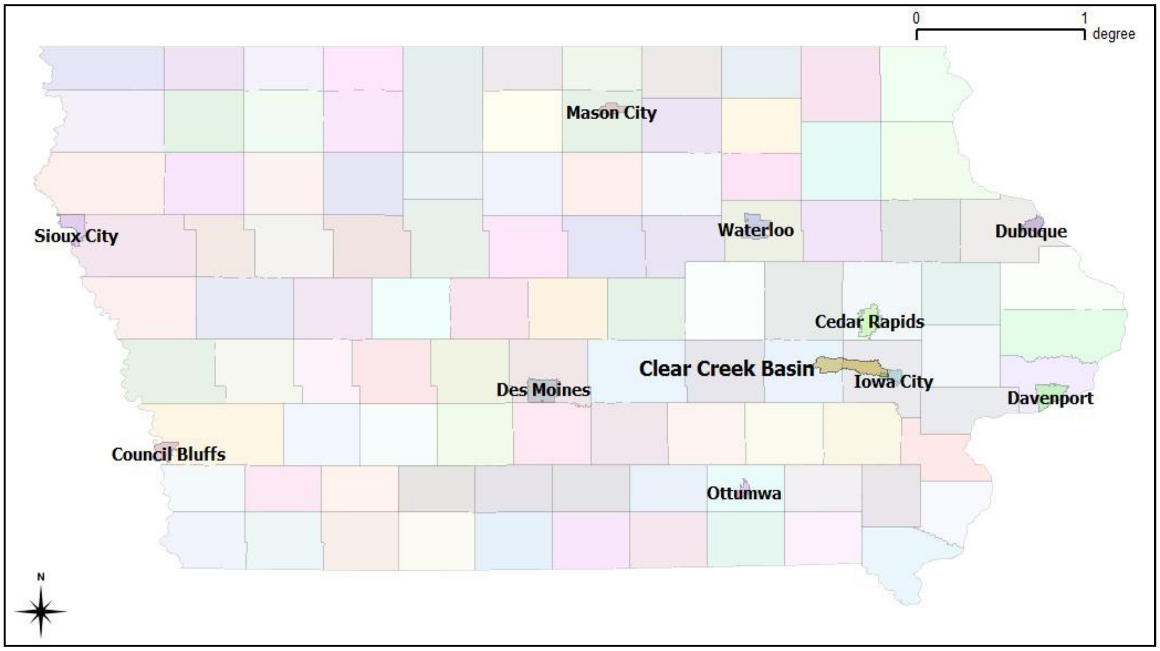

Figure 2-1: Location of the Clear Creek Watershed in Eastern Iowa.*

reservoirs to determine the land that would be flooded by the reservoirs when full and the amount of water storage available in the reservoirs. This analysis demonstrates that several of the reservoirs were impractical because they result in flooding developed areas. However, the majority of the reservoirs were considered suitable locations for distributed storage reservoirs.

Calculation of the Most Efficient Reservoirs

The first determination involved calculating the most efficient reservoirs in the Clear Creek Watershed. Efficiency was evaluated as the highest volume stored per unit of area flooded. The reservoirs were located according to a program created in Matlab that analyzes the DEM data for Clear Creek. The program first traced the stream,

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* GIS data used to create Figure 2-1 retrieved from the Iowa Geological and Water Survey's Natural Resources Geographic Information Systems Library at http://www.igsb.uiowa.edu/nrgislibx/

locating all the points in the stream that were of the desired Horton stream order.[4] The simulation was run on order 2, 3, and 4 tributaries, with the size of the reservoirs heavily dependent on the level of the stream tributaries. For this illustration, the reservoirs on the order 4 tributaries are shown, as the order 4 reservoirs are on average double the size of the order 3 reservoirs, while the order 2 reservoirs were significantly smaller.

Once the stream was traced and all the points in the stream stored, the program calculated the size of the watershed upstream of each relevant stream point and the size of a reservoir created by placing a three meter wall at that point. Three meters was chosen because that size allows for substantial volume in the reservoirs without requiring massive dam structures. The program saved the most efficient reservoir (the reservoir with the highest average depth, or storage volume to inundated area ratio) that can store at least 30,000 m^3 (24.3 acre-ft.) on each of the 33 order 4 tributaries. Table A-1 in Appendix A lists the location and size of each of the 33 reservoirs.

The 33 reservoirs on order 4 tributaries have a total storage volume of 7.59 million cubic meters (6,150 acre-ft.) when at the full 3 meter depth. The geographic locations of the reservoirs are shown below in Figure 2-2. This storage is approximately 11.5% of the total volume with a ten inch rainfall in the watershed. A ten inch rainfall is approximately the ten day, 100-year storm rainfall amount (ISU Institute for Transportation 2009, “2C-2 Rainfall and Runoff Analysis”), and is a very conservative estimate of the maximum rainfall that can reasonably be expected over the watershed. However, some of these reservoirs are not feasible because they flood developed

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[4] The Horton stream order is a measure of the size of a stream or river at a certain point based on the size of the tributaries feeding the stream. A stream that originates with no tributaries is order 1, and remains order 1 until it joins with another order 1 stream. At that point, the combined stream becomes an order 2 stream, and remains order 2 until joining with another order 2 tributary. Clear Creek is order 7 at the outlet into the Iowa River, but has Horton order 1-6 tributaries.

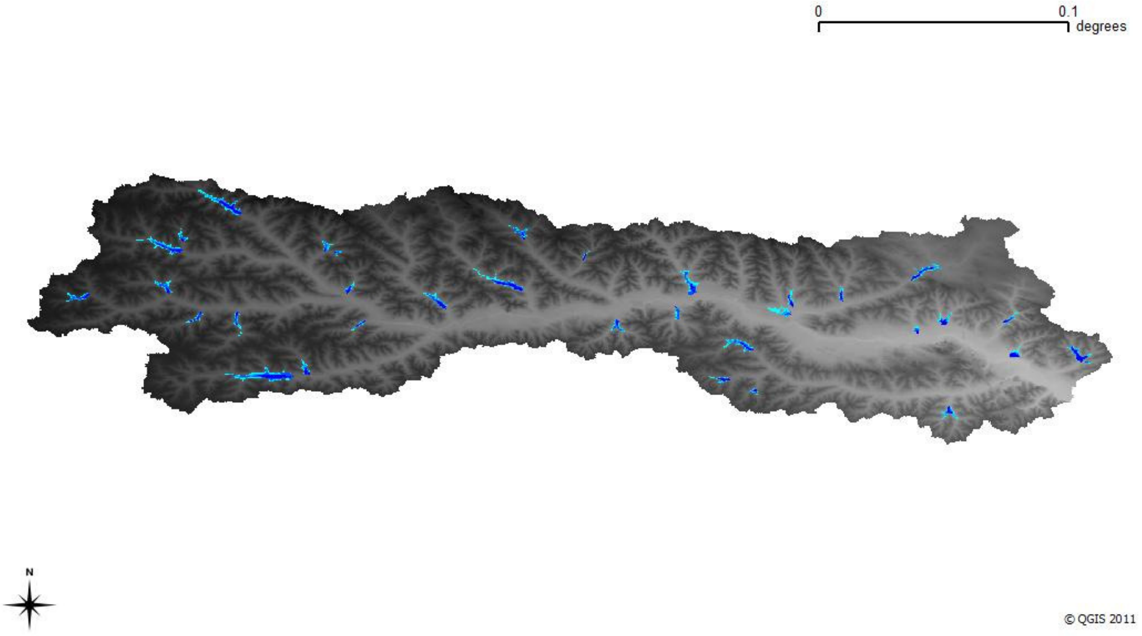

Figure 2-2: Locations of the 33 reservoirs on Horton order 4 tributaries of Clear Creek.

residential or industrial areas. Therefore, an analysis of the flooded land cover, discussed below, is needed to determine which of the reservoirs are potentially usable for a distributed storage system.

Analysis of Travel Bands

Flooding is frequently caused by high waters on multiple upstream tributaries combining at the confluence of a river. When high waters arrive at the confluence of streams at the same time they create a “traffic jam” of water. This traffic jam can result in serious flooding downstream of the combination of the waters. It is possible to reduce the risk of flooding with smaller overall storage volumes by storing the water originating from places where there is a particular danger of a river traffic jam.

Precipitation flows downhill from the point where it lands until it reaches a stream or river. The water then continues to flow in the stream or river until it reaches the river or stream outlet. It is possible to estimate the path that a drop of rain will travel from

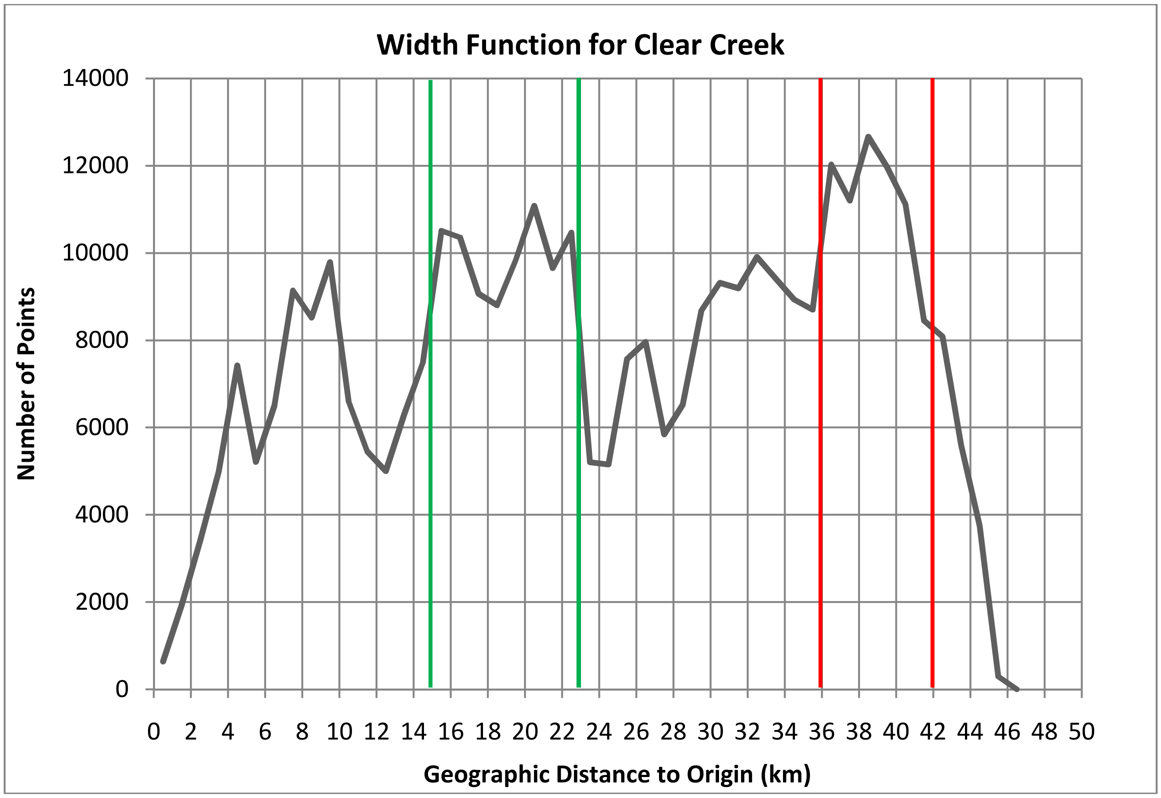

Figure 2-3: Width function for the Clear Creek Watershed

every point in the watershed using the DEM data. The water is assumed to flow from one point to the lowest adjacent elevation point until it reaches the end of the river. The distance that the water will travel from any given point to the outlet is determined from the path of the water from each point. This distance is referred to as the geographic distance to the outlet, or GDO. Assuming relatively uniform flow speeds throughout the watershed, the GDO is a proxy for the time that it will take for a rain drop to travel from any given point to the outlet of the watershed.

A histogram of the GDO values at every point in the Clear Creek Watershed was created to find the areas where a danger of a traffic jam is highest. This histogram, called the "width function," is shown below in Figure 2-3. From the width function, it is apparent that the region with the highest concentration of GDO lies between 36 and 42 km upstream of the origin. There is also a risk area, with a slightly lower peak but a larger number of included GDO's, between 15 and 23 km upstream. Although there are other potential risk areas, this research focuses on these two areas because they represent the areas of highest flood risk.

Assuming that the rain falls uniformly across the watershed and that it all falls at the same time, which is a reasonable assumption for a small watershed like Clear Creek, the areas creating the highest risk of floods are located in these two "travel bands." Precipitation that falls in these two bands is likely to arrive at the outlet at substantially the same time. It would be advantageous, therefore, to attempt to store as much water as possible from these two travel bands so that the water concentrating downstream can be spread out, reducing the flood peak.

The reservoir selection algorithm was performed again to maximize the storage of water that falls in the travel bands between 15-23 km and 36-42 km upstream from the stream gage. The program was very similar to the above reservoir selection program, except that instead of selecting the most efficient reservoir for each order 4 tributary, the program stored the reservoir from each order 4 tributary that held the most water from either or both of the travel bands. The maximum amount held from the travel band was calculated according to a ten inch rainfall over the basin area within in the travel band. If the reservoir stored more than the volume of the ten inch rainfall within the basin area and travel band, then the travel band storage amount was capped at the ten inch travel band volume. If there were no reservoirs in a tributary with part of its upstream basin area in the travel band, or there were two or more with the same travel band storage volume, then the reservoir with the larger total storage volume held was selected. It was assumed that the reservoir could be controlled to store as much water as possible from the travel band, while ignoring the water flowing through the reservoir from outside the travel band.

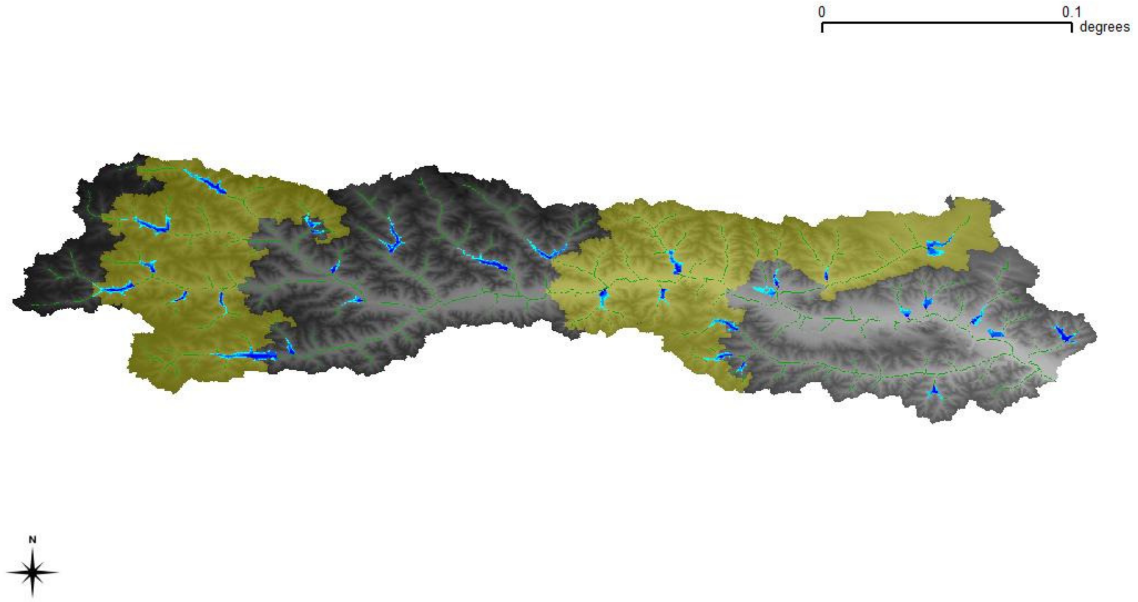

Figure 2-4: Locations of the 33 reservoirs on level 4 tributaries maximizing the storage from the travel bands, which are shown in yellow.

A list of the travel band reservoirs is given in Table A-2. The 33 reservoirs store a total of 8.49 million cubic meters (6,880 acre-ft), with 5.67 million cubic meters (4,600 acre-ft.) of that storage in the travel bands. These reservoirs can therefore store approximately 16.3% of the 34.8 million cubic meters (28,200 acre-ft.) of total ten inch rainfall volume in the travel band. This may seem like a small amount, but some of that rainfall volume will infiltrate into the ground, and arrive at the stream later. In addition, holding the water in a reservoir will allow for more of the water to evaporate, reducing the total volume of water flowing through the river. The Waffle Concept estimated additional evaporation in that distributed storage system at approximately 38% of the stored water volume (Kurz et al. 2007). This amount would necessarily vary depending on the length of time the water is stored, as well as the weather conditions present while the water is stored, but it could be a significant amount. Furthermore, ten inches is a massive rain event for Clear Creek, and the ability to stop 16.3% of such a large event is a significant step.

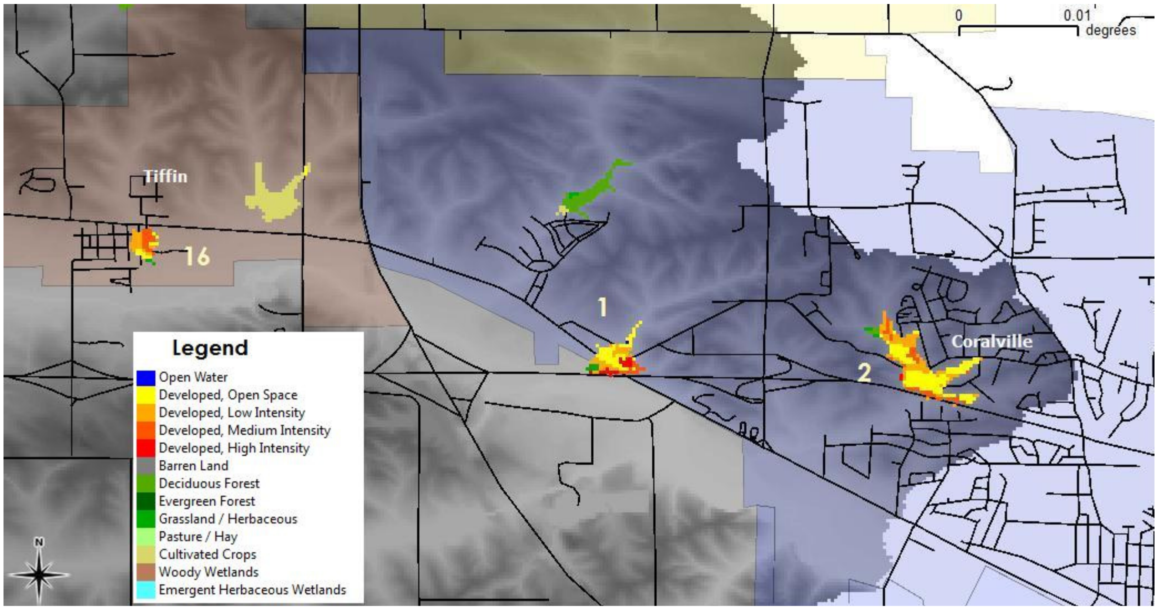

Figure 2-5: Land cover shown for the efficient reservoirs in the Coralville and Tiffin areas.

Land Cover Analysis

Next, the 33 reservoirs from each of the above algorithms were analyzed to determine the land uses of the land inundated by the reservoirs. Obviously, a reservoir cannot be located in a populated area because it would cause damage to property and infrastructure. Therefore, the area flooded by each reservoir was cross-referenced with the land cover grid to determine the amount and class of each land type flooded by each individual reservoir.[5] Reservoirs flooding too much developed area must be removed from the list as impractical. The flooded land cover tables are given in Appendix A, with the table for the efficient reservoirs in Table A-3 and the flooded land cover for the travel band reservoirs in Table A-4.

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[5] Land cover data obtained from Ricardo Mantilla at the Iowa Flood Center. A listing of the land cover class definitions is given in Appendix B. The land cover database was last updated in 2002, and therefore the land uses in some areas may have changed.

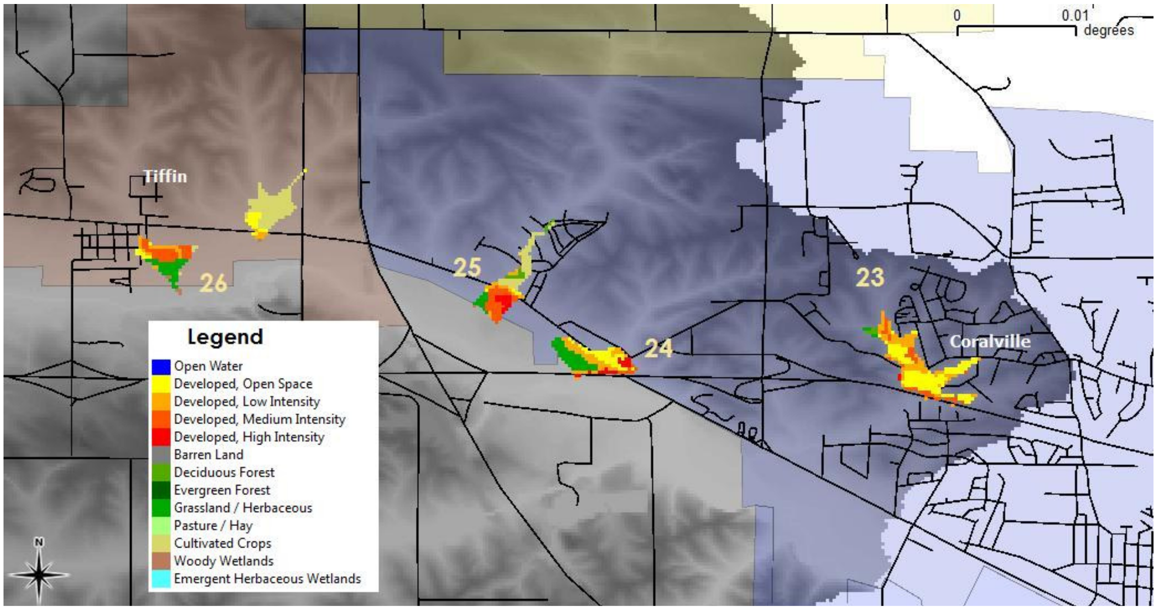

Figure 2-6: Land cover flooded by the travel band reservoirs in the Coralville and Tiffin area.

The efficient reservoirs include three reservoirs in populated areas of Coralville and Tiffin. Figure 2-5 shows the land cover flooded by these three reservoirs in the Coralville and Tiffin areas, overlaid with the road network in black.[6] Reservoir 2 is in a residential area in Coralville just north of Interstate 80, while reservoir 1 is in an industrial area near the intersection of U.S. Highway 6 and Interstate 80. Reservoir 16 is located in a residential area in Tiffin. None of these locations could be used for a distributed storage reservoir, as flooding these areas would cause significant property damage.

The travel band reservoirs include four reservoirs located in the Coralville and Tiffin areas, shown in Figure 2-6. Reservoir 23 is in the same residential area of

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[6] Road network and city boundary data obtained from the Iowa Geological and Water Survey's Natural Resources Geographic Information Systems Library at http://www.igsb.uiowa.edu/nrgislibx/

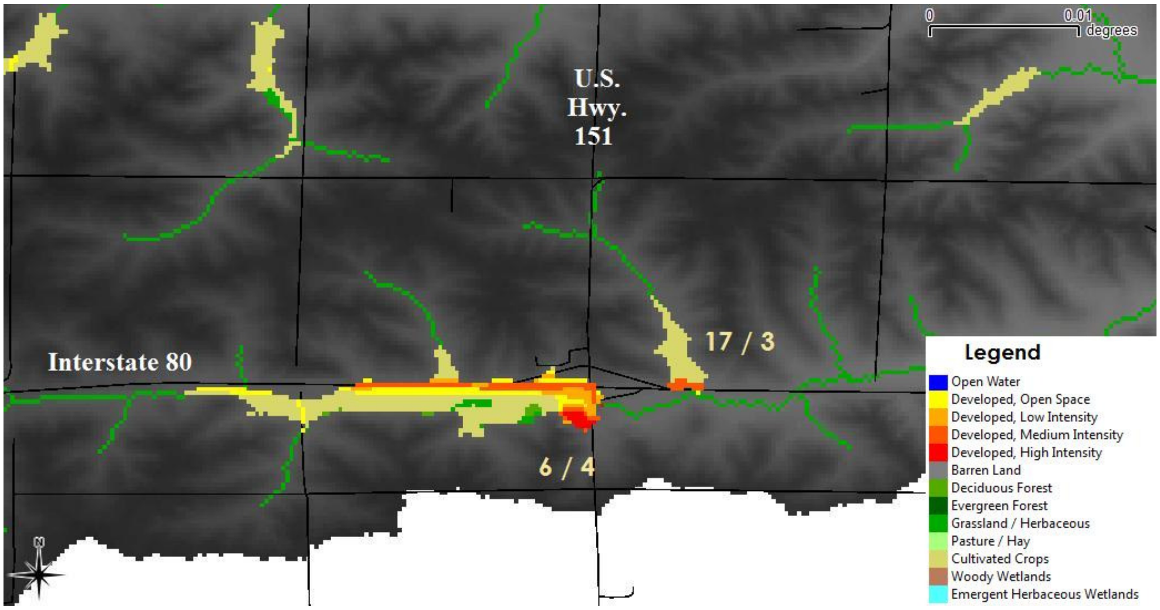

Figure 2-7: Land cover flooded near the Highway 151 exit off of Interstate 80.

Coralville just north of Interstate 80 as the above efficient reservoir 2. Reservoirs 24 and 25 are in an industrial area on U.S. Highway 6 just north of Interstate 80 and east of Interstate 380. Reservoir 26 is in a largely residential area of Tiffin. Again, none of these reservoirs can be used as a distributed storage reservoir because of the damage inundating these areas would cause.

Both the efficient and travel band algorithms included the same two reservoirs near the U.S. Highway 151 exit from Interstate 80. These reservoirs are shown in Figure 2-7. The large reservoir is reservoir 6 for the efficient reservoirs and 4 for the travel band reservoirs. This large reservoir would potentially flood a stretch of Interstate 80, as well as a commercial area just south of the Highway 151 exit. This reservoir is not viable, as it would cause too much damage to buildings and infrastructure in the commercial area south of Interstate 80. The smaller reservoir is number 17 for the efficient reservoirs and 3 for the travel band reservoirs. This reservoir could potentially flood a portion of Interstate 80, but due to the inaccuracy of the 30 meter elevation data used, it is unclear

Table 2-1: Volume stored and area inundated by the calculated reservoirs after removing the reservoirs flooding important areas.

	Reservoirs	Volume Stored (m^3)	Area Inundated (m^2)	Travel Band Volume Stored (m^3)
Efficient	29	5,789,000	4,352,000	--
Travel Band	28	6,436,000	5,224,000	4,629,000

whether it would flood the highway or merely inundate the low lying land around the highway. For this analysis, it will remain as a potential reservoir location, but further study would need to be undertaken before implementing the reservoir to ensure that it did not flood Interstate 80. If it were found that the reservoir would in fact flood Interstate 80, the reservoir could still be used if an additional barrier were used to protect the highway from the water.

A summary of the remaining reservoirs after removing the unusable reservoirs is given in Table 2-1. There are 29 reservoirs remaining from the efficient calculation, totaling 5.79 million cubic meters (4,700 acre-ft.) of storage volume. The travel band calculation is left with 28 reservoirs totaling 6.44 million cubic meters (5,190 acre-ft.) of storage, 4.63 million cubic meters (3,730 acre-ft.) of which is located in the two travel bands. As indicated in Table A-2, the total ten inch rainfall volume in the travel bands is approximately 34.9 million cubic meters (28,300 acre-ft.). The travel band storage is therefore about 13% of the total rain volume for a 10 inch storm. Again, although this may seem small, a ten inch rainfall in the Clear Creek Watershed is extraordinarily rare. Furthermore, some of that rainfall would seep into the ground and flow into the river slower, while some of the stored water would evaporate. The distributed storage reservoirs would provide more flood protection for flood events smaller than the ten inch rainfall.

CHAPTER 3: DISTRIBUTED STORAGE POTENTIAL FOR THE CEDAR RIVER WATERSHED

The Clear Creek Watershed provides a valuable small scale demonstration on how reservoirs can be chosen, as well as the potential impact of such reservoirs. However, the ultimate goal is to establish a distributed storage flood mitigation project on a large watershed to protect the lives and property in a city. The Cedar River is currently severely lacking in flood protection upstream of Cedar Rapids. These flood control inadequacies were exposed by the Flood of 2008, which flooded over ten square miles of Cedar Rapids (City of Cedar Rapids, Iowa, “Flood of 2008 Facts and Statistics”). According to the U.S. Army Corps of Engineers, the Flood of 2008 caused an estimated $2.4 billion in damage to the city, with an additional $3.3 billion in economic losses (U.S. Army Corps of Engineers, “Cedar River, Cedar Rapids, Iowa, Frequently Asked Questions”). The Cedar Rapids flood was exacerbated by a flood “traffic jam,” where the flood wave approaching Cedar Rapids from far upstream combined with recent rainfall just upstream of Cedar Rapids, causing a catastrophic flood in Cedar Rapids. The Cedar River upstream of Cedar Rapids would therefore be an ideal place for a distributed storage flood mitigation project to protect the city from a future traffic jam type flood.

Scaling the Clear Creek Simulation to the Cedar River Watershed

The flood protection offered by a series of smaller passive reservoirs is generally equivalent to the sum of the flood protection offered by each reservoir upstream (Loucks et al., 1981, pp. 242-245). Therefore, a series of passive reservoirs, each the size of one of the reservoirs calculated above for Clear Creek, offers essentially the same amount of flood protection as a single reservoir of the same total volume. This assumption will be used for this section, with the understanding that the ultimate system should be actively

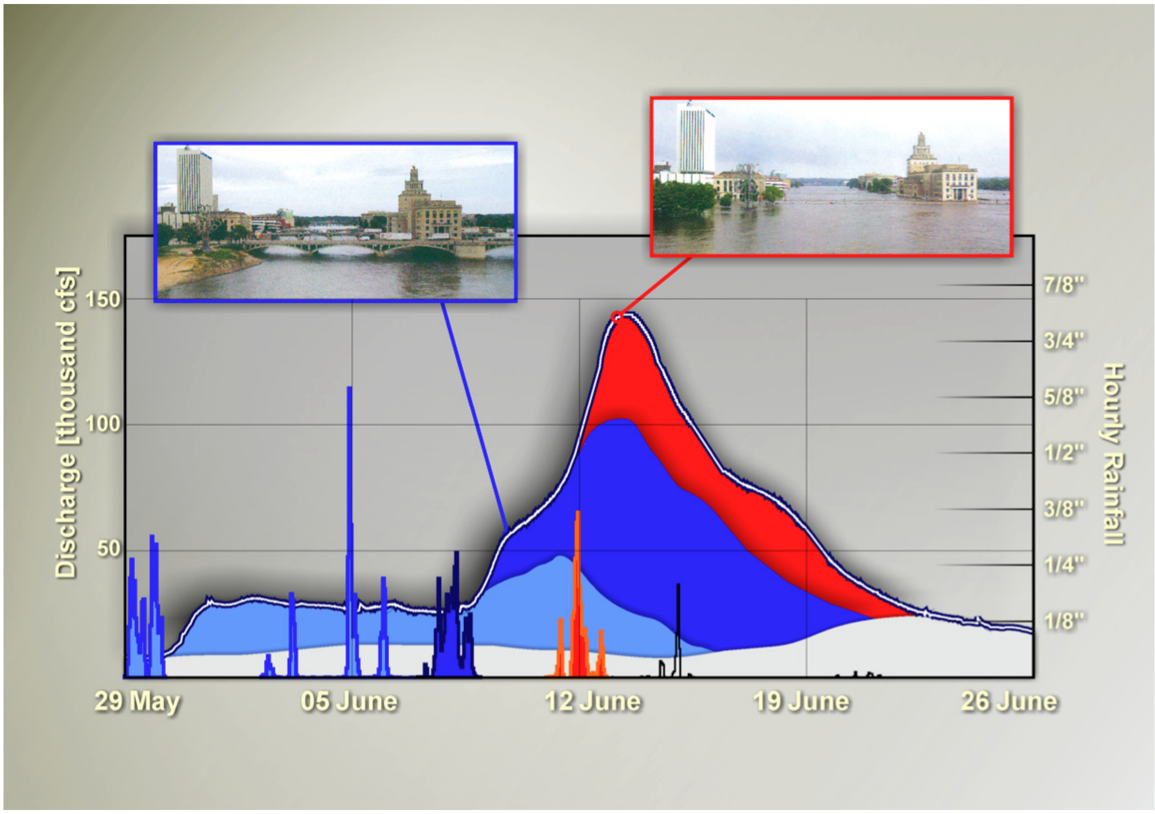

Figure 3-1: Figure showing the portion of the flood wave in Cedar Rapids caused by the rainfall events leading up to the flood.*

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* Figure 3-1 courtesy of Witold Krajewski and Ricardo Mantilla of the Iowa Flood Center.

controlled, and therefore would offer greater benefits, or require less reservoirs, than the conservative estimates given here.

Figure 3-1 shows the stream gage data from the Cedar River at Cedar Rapids, with the volume resulting from each of the three rainfall events leading up to the 2008 flood shown in a different color. This figure illustrates the “traffic jam” that occurred in Cedar Rapids, escalating what would have been a moderate flood into a disaster. The red and dark blue peaks arrived in Cedar Rapids at approximately the same time, resulting in a peak significantly larger than each individual peak. A distributed storage system that

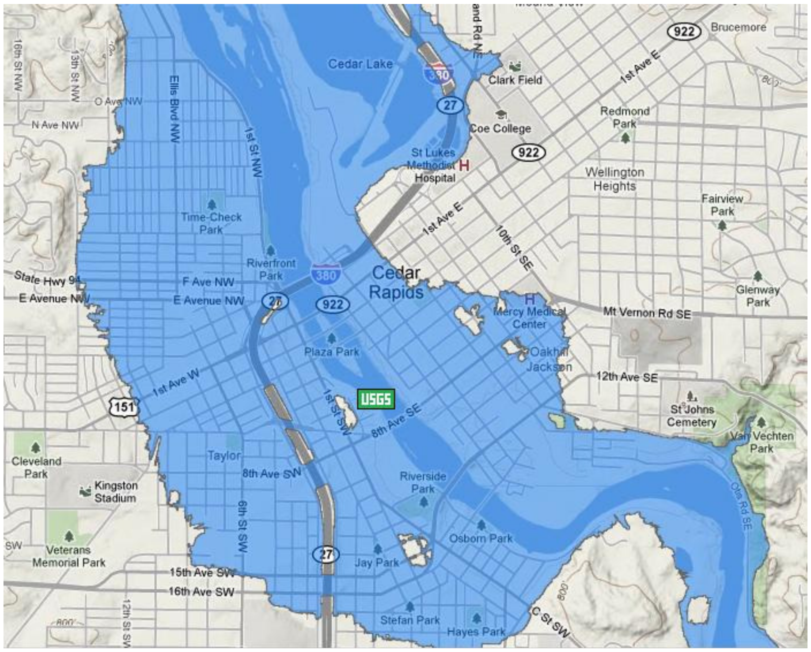

Figure 3-2: Cedar Rapids flood map for a flow of 142,630 cfs, or a stream gage height of 31.5 feet.

could prevent the red peak would reduce the maximum flow from 140,000 cfs to about 110,000 cfs. Figure 3-2 shows the land inundated in Cedar Rapids by a flood with a peak of 142,630 cfs, or 31.5 feet at the USGS stream gage. Figure 3-3 shows the flood if the peak was reduced to 110,000 cfs, or 26.5 feet at the USGS gage. This reduction in the flood peak would have radically reduced the amount of damage caused to Cedar Rapids by the 2008 flood, but not entirely eliminated it. Figure 3-4 illustrates the 20 foot flood level in Cedar Rapids, which was the record flood in Cedar Rapids prior to the Flood of 2008. At this level, there would be essentially no damage to the city of Cedar Rapids. In addition, if the dark blue region could be held in a series of reservoirs, then the 2008 flood would have peaked at 50,000 cfs, securely held within the banks of the Cedar River, as shown in Figure 3-5.

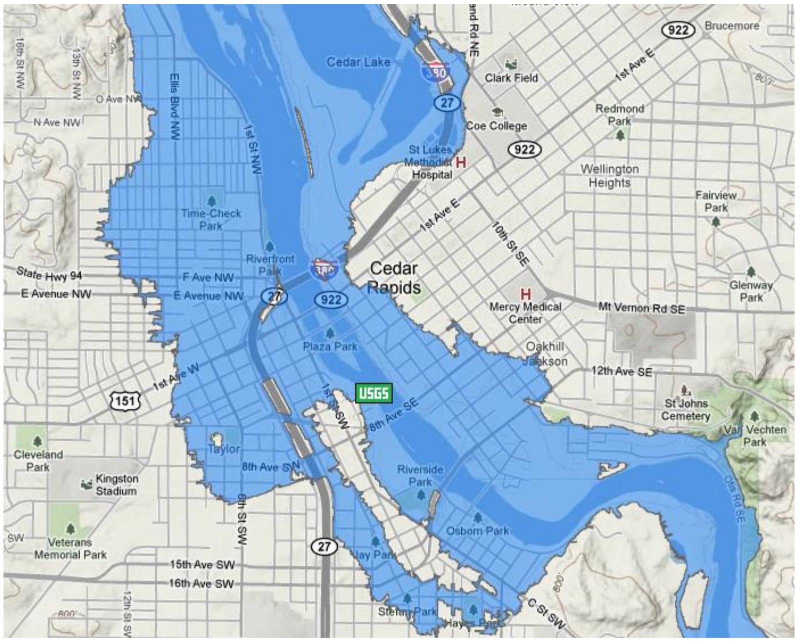

Figure 3-3: Cedar Rapids flood map for a flow of 110,000 cfs, or a stream gage height of 26.5 feet.

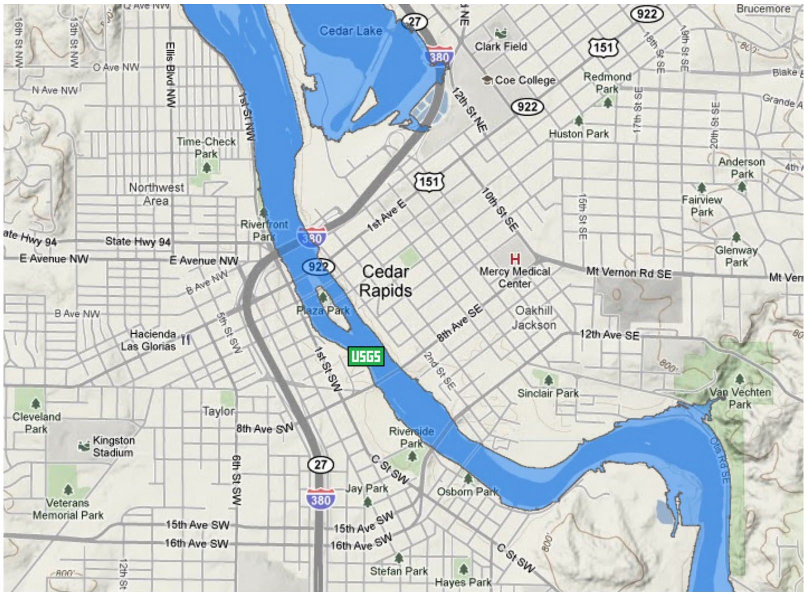

Figure 3-4: Cedar Rapids flood map for a flow of 73,000 cfs, or a stream gage height of 20 feet.

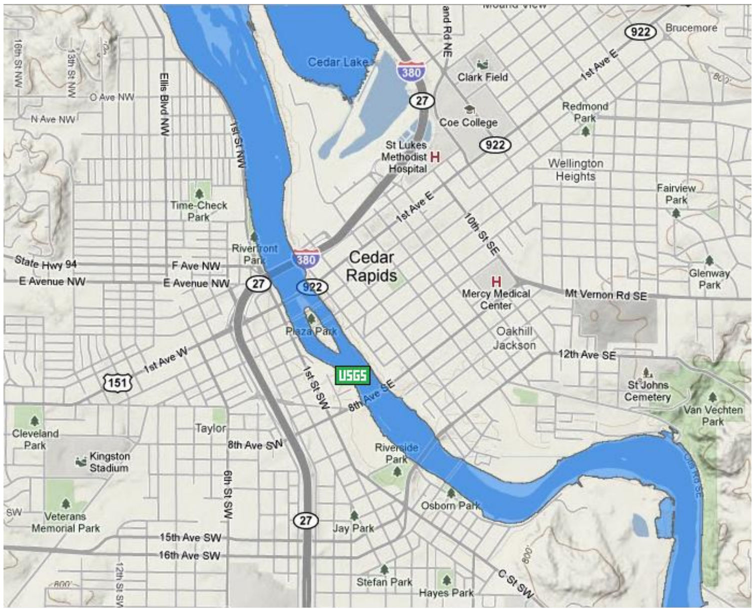

Figure 3-5: Cedar Rapids flood map for a flow of 52,300 cfs, or a stream gage height of 16.5 feet.*

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* Figures 3-2, 3-3, 3-4, and 3-5 obtained from the Iowa Flood Center's Iowa Flood Information System Cedar Rapids flood maps.

The rain event around June 11-12 (red area) caused an estimated 5.31(10^8) cubic meters (430,000 acre-ft.) to flow through Cedar Rapids. The June 7-8 rain event (dark blue area) resulted in an estimated 1.17(10^9) cubic meters (952,000 acre-ft.) through Cedar Rapids. The total Flood of 2008 volume of water above the 20 foot level is approximately 5.85(10^8) cubic meters (474,000 acre-ft.). The present discussion focuses on the red and dark blue rainfall bands, with the acknowledgement that the focus on the dark blue rainfall band may be overly conservative. In reality, the amount of water storage needed to fully protect Cedar Rapids is somewhere between the red area plus the dark blue area and the total flood volume above the 20 foot level.

Although the landscapes in the Cedar River Watershed and the Clear Creek Watershed may not be exactly the same, it is safe to assume that they are relatively similar due to their geographic proximity. This is especially true near Cedar Rapids, which is located approximately 30 km (19 miles) north of the Clear Creek Watershed. Assuming that the landscapes in the Cedar River Watershed are similar to those in the Clear Creek Watershed, the data obtained above for the Clear Creek distributed storage reservoirs can be used to estimate the number of reservoirs needed in the Cedar River Watershed to protect Cedar Rapids from a flood like the one in 2008.

The size of the basins must also be considered before extrapolating the Clear Creek data to the Cedar River basin. In the Clear Creek Watershed, it is reasonable to assume uniform rainfall across the entire watershed. In the Cedar River basin, there will almost never be uniform rainfall in the entire basin. This assumption will affect an analysis of the travel bands in the Cedar River basin, as the precipitation falling in one area might combine downstream with precipitation that fell later. The effectiveness of the reservoirs depends on the placement of the reservoirs, not merely the quantity of reservoirs. The red area from Figure 3-1 was caused by concentrated precipitation barely upstream of Cedar Rapids. Therefore, reservoirs to capture such an event would be needed close to Cedar Rapids. The reservoirs needed to capture the dark blue rainfall event, on the other hand, could be further upstream because the rain fell higher in the basin. The actual placement of the reservoirs in the Cedar River basin is beyond the scope of this discussion, but would need to be considered before implementation of a distributed storage system.

The mean values for the efficient reservoirs from the Clear Creek Watershed simulation above, which were selected according to the maximum average depth, or volume per unit of area flooded, will be used to scale to the Cedar River Watershed. Each reservoir is therefore estimated to contain 200,000 cubic meters (162 acre-ft.) of water, while flooding 150,000 square meters (37 acres) of land. In order to contain the $5.31(10^8)$ cubic meters (430,000 acre-ft.) from the red area of Figure 3-1, there would need to be 2,660 of these reservoirs in the basin. These 2,660 reservoirs would inundate approximately 398 square kilometers (98,400 acres) of land in the basin. The size of the Cedar River basin upstream of Cedar Rapids is nearly 16,900 square kilometers. Therefore, the 2,660 reservoirs required to hold back the red band from Figure 3-1 would inundate only about 2.36% of the total basin area upstream of Cedar Rapids.

In order to hold back the dark blue area from Figure 3-1, approximately $1.17(10^9)$ cubic meters (952,000 acre-ft.) of storage would be needed. This would require 5,870 of the 200,000 cubic meter (162 acre-ft.) reservoirs. These reservoirs would inundate about 881 square kilometers (218,000 acres) of land, or about 5.21% of the total basin area upstream of Cedar Rapids.

It is worth noting again that these numbers are preliminary estimates. The actual number of reservoirs and their locations requires extensive study before implementation. Consideration must be given to the actual terrain within the Cedar River basin, as well as the travel bands within the basin, with special thought given to the likelihood of differential rainfall across the basin. Based on the extensive study, it could be determined that larger or smaller reservoirs would be more effective. In addition, these are conservative estimates that fail to take into account the active nature of the distributed storage system. Accurate forecasting and intelligent control of the reservoirs may be able to make more efficient use of the storage volume.

Economic Analysis

The feasibility of a distributed storage project hinges on whether the economic value of the property saved from flooding outweighs the economic cost of constructing the reservoirs and flooding the land. Table 3-1 shows an estimate of the land cover flooded by the reservoirs discussed above to stop the red band and the dark blue band from Figure 3-1. The land cover flooded was assumed to include the same percentages as the total of the efficient reservoirs from the Clear Creek discussion. Table 3-1 also gives an estimate

Table 3-1: Break down of the costs for the areas inundated by the reservoirs necessary to protect Cedar Rapids.

		Cost/acre	Cost/km^2	Red Band		Dark Blue Band		Both
			(x10^3)	km^2	Cost (x10^6)	km^2	Cost (x10^6)	Cost (x10^6)
Developed, Open Space	1.99%	$50,000[a]	$12,355	7.90	$97.6	17.5	$216	$314
Developed, Low Intensity	0.83%	$100,000[b]	$24,710	3.29	$81.3	7.29	$280	$262
Developed, Medium Intensity	0.52%	$100,000[b]	$24,710	2.06	$50.8	4.55	$113	$164
Deciduous Forest	4.09%	$0[c]	$0	16.3	$0	36.1	$0	$0
Grassland/ Herbaceous	7.51%	$200[d]	$49	29.9	$1.48	66.1	$3.27	$4.76
Pasture/Hay	19.0%	$200[d]	$49	75.8	$3.75	168	$8.29	$12.1
Cultivated Crops	65.6%	$684[e]	$169	261	$44.1	578	$97.6	$142
Woody Wetlands	0.43%	$0[c]	$0	1.73	$0	3.83	$0	$0
Total				**398**	**$279**	**881**	**$618**	**$897**

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[a] The open space cost was estimated to be $50,000/acre, or about the cost of a reasonable residential structure on every two acres. There is probably less structural damage than this in the flooded area, but the higher estimate was chosen to allow for damage to roads and yield a conservative estimate.

[b] Low and medium intensity were estimated at a cost of $100,000/acre to account for the cost of a residential structure on every acre. Again, a high property value was chosen for this conservative estimate.

[c] It was assumed that the monetary damage to forests and woody wetlands is negligible.

[d] The value of damage to grasslands and pasture was estimated as $200/acre, an average estimate for replanting grass (Iowa State University Extension 2008).

[e] The value of cultivated crop loss was estimated by weighting the value of corn and soybean revenue per acre (Purdue University Extension 2010) by the percentage of corn and soybeans grown in the North Central, Northeast, and East Central Iowa counties in 2010 (USDA 2010). The estimated revenue per acre was based on rotating corn and rotating bean crops with average productivity.

of the cost of flooding the land needed for distributed storage reservoirs upstream of the Cedar River.

As shown in Table 3-1, using only the reservoirs needed to eliminate the red peak from Figure 3-1 would cost approximately $279 million. This would significantly reduce the area flooded in downtown Cedar Rapids, as shown in Figures 3-2 and 3-3. However, a large portion of the Cedar Rapids area would still have been inundated. Protecting Cedar Rapids completely and reducing the peak of the flood to approximately 50,000 cfs would require all 8,530 reservoirs. It would cost an estimated $897 million to flood all of these reservoirs.

For initial costs, the reservoir structures were assumed to be a ten inch wall (0.254 meters) three meters high and 30 meters wide (the size of a single pixel in the DEM data). Although some reservoirs would be larger, the majority would likely need to be much smaller than 30 meters wide. Using these estimated dimensions, the structures would each require 22.9 cubic meters (29.9 cubic yards) of concrete. A cast-in-place concrete wall of this size is estimated at $23,400, assuming a concrete cost of $1,023 per cubic meter (Craftsman Book Co. 2007. page 366, ten inch single story structural wall in Cedar Rapids, IA). A motor to operate the gate was estimated at $4,419, including installation labor costs (Craftsman Book Co. 2007. page 564, three phase 125-200 hp weatherproof motor, 270 amps in Cedar Rapids, IA.). Table 3-2 summarizes the construction cost estimates for the distributed storage system.

The total construction costs are therefore estimated at $74 million for the 2,660 reservoir system, and $237 million for the entire 8,530 reservoir system. The total cost for construction of the 8,530 reservoir system and fully using the reservoir system once is estimated at approximately $1.13 billion. Therefore, the reservoir system, even if only used once to stop a flood on the scale of the Flood of 2008, could be able to save an estimated $2.4 billion in damage, and prevent potential economic losses in excess of $3 billion at an approximate cost of just over $1.1 billion. Thus, this conservative estimate

Table 3-2: Estimated initial construction costs for distributed storage reservoirs.

Reservoirs	Concrete ($x10^3$)	Gate Motors ($x10^3$)	Total ($x10^3$)
1	\$23.4	\$4.42	\$27.8
2,660	\$62,000	\$12,000	\$74,000
5,870	\$137,000	\$26,000	\$163,000
8,530	\$199,000	\$38,000	\$237,000

approximates the net benefit of the system at more than \$4 billion. More studies would be needed to determine exact locations where distributed storage reservoirs could be located in the Cedar River basin, and to determine whether there would be enough suitable locations to place distributed storage reservoirs. In addition, further study is needed to determine both long-term and short-term costs and benefits more accurately to conclude that the project would be advantageous. However, this preliminary analysis indicates that a distributed storage system could be a cost-effective flood prevention system on the Cedar River upstream of Cedar Rapids.

PART TWO: LEGAL AND POLICY ASPECTS OF THE DISTRIBUTED STORAGE SYSTEM

CHAPTER 4: ORGANIZATIONAL ASPECTS OF CONSTRUCTING, MAINTAINTING, AND OPERATING A DISTRIBUTED STORAGE SYSTEM

In order for a distributed storage flood mitigation project to be implemented, a single organizational entity will be needed to fund the construction of the reservoir gates, maintain the gates and reservoirs, and determine when and how the gates must be operated. In Iowa, there are several ways that a distributed storage system could be organized. The Iowa Code allocates jurisdiction over flood plains in the state to the Iowa Department of Natural Resources.[7] In addition, there are soil and water conservation districts and subdistricts, as well as drainage and levee districts with flood control authority. The Water Resources Coordinating Council and Watershed Planning Advisory Council were recently established by the Iowa legislature to consider flood mitigation, and have the potential to assist with a distributed storage project. Finally, an agreement between two or more of these entities could be made under Chapter 28E of the Iowa Code for the agencies to work together on a distributed storage system.

Iowa Department of Natural Resources

The Iowa Department of Natural Resources (DNR) is given statutory jurisdiction to manage flood plain development and construct flood control works.[8] The goal of the DNR in coordinating flood control works is to “effect the best flood control obtainable throughout the state.”[9] This primarily involves the requirement that all proposed flood

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[7] Iowa Code § 455B.264(1) (West)

[8] “The [D]epartment [of Natural Resources] has jurisdiction over the public and private waters in the state and the lands adjacent to the waters necessary for the purposes of carrying out this part. The department may construct flood control works or any part of the works.” Iowa Code § 455B.264(1) (West).

[9] Iowa Code § 455B.277 (West)

control works must be submitted to the DNR for approval.[10] Even flood control works proposed by drainage districts, soil and water conservation districts, or other political subdivisions must be submitted to the DNR for approval.[11] The DNR approves such a flood control work if it does not adversely interfere with the flood control in the state, or adversely affect the water resources of the state.[12]

The Iowa DNR is permitted to delegate its authority over flood plains and flood control works to a local government entity, such as a city or county.[13] The DNR delegates its authority simply by approving of locally proposed regulations in writing.[14] Local government officials are encouraged to consult with the DNR in drafting local regulations to ensure that the local regulations meet the state standards and can be approved quickly.[15]

There is a provision within the Iowa DNR statutes allowing for the creation of watershed management authorities by a Chapter 28E agreement.[16] Watershed management authorities involve Political subdivisions within a single USGS unit code 8 watershed.[17] These watershed management authorities have the power to assess flood

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[10] *Id.*

[11] *Id.*

[12] *Id.*

[13] Iowa Administrative Code § 567-75.7 (West). *See also* Iowa Administrative Code § 567-75.1(2) (West).

[14] Iowa Administrative Code § 567-75.7(1) (West).

[15] *Id.*

[16] Iowa Code § 466B.22 (West)

[17] The USGS unit codes are a system of identifying individual watersheds with a code. Shorter codes are used to identify larger watersheds, which are then broken down by longer codes. For example, the Upper Mississippi region is designated by 2 digit code 07, while the Upper Mississippi-Iowa-Skunk-Wapsipinicon subregion is designated by 4 digit code 0708. The Iowa River Basin is designated 070802, and includes 9 different code 8 watersheds. Six of these code 8 watersheds within the Iowa River Basin are in the Cedar River Basin.

risks, options for reducing flood risk, and allocate money made available to the authority for purposes of flood mitigation.[18] These watershed management authorities can execute contracts and agreements, but are specifically prohibited from using eminent domain authority.[19] Several watershed management authorities have been created in Iowa in 2011 with state funding, including one on the Upper Cedar River Basin (Gravelle, 2011). These watershed management authorities allow the authority to make recommendations and act on the recommendations as much as the enabling local governments allow.

The Iowa DNR appears to be a suitable governing authority capable of managing and operating a large scale distributed storage system, such as the one suggested above for the Cedar River Watershed. However, a specialized sub-department would likely be necessary in order to properly manage, maintain, and control the system. The watershed management authorities are a potential step toward to the desired solution, but are severely limited by the lack of condemnation authority. A watershed management authority would have problems if any landowners of the potentially inundated land held out from voluntary participation. Obtaining all the property interests needed for a system may be too difficult because of the inability to use eminent domain.

Currently, the DNR includes three divisions: an Energy and Geological Resources Division, an Environmental Protection Commission, and a Natural Resources Commission.[20] The Environmental Protection Commission is responsible for protection of flood plains and flood control works.[21] A flood control sub-division within the Environmental Protection Commission would have the authority to evaluate and

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[18] Iowa Code § 466B.23 (West)

[19] Iowa Code § 466B.23(7) (West)

[20] Iowa Administrative Code § 561-1.3 (West).

[21] Iowa Administrative Code § 567-75.1 (West).

construct flood control structures, as well as maintain and control the reservoirs once built. Therefore, such a sub-division is a suitable entity capable of managing a distributed storage system on a large scale.

For distributed storage projects on a smaller scale, like Clear Creek, the DNR is likely not the best entity to construct, operate, and maintain the project. In this instance, a smaller and more localized government entity would be better suited to manage the system. Watershed management authorities are limited by the lack of condemnation authority, but might be able to run a small distributed storage system if landowners agreed to voluntary participation. The DNR could also delegate its authority to manage flood control works to a local entity pursuant to the provisions of the Iowa Administrative Code, allowing that local entity to manage the distributed storage system.[22]

Soil and Water Conservation Districts and Subdistricts

Chapter 161A of the Iowa Code creates a soil conservation division within the Iowa Department of Agriculture and Land Stewardship.[23] The soil conservation division oversees soil conservation districts, and has the duty to assist the districts in formulating conservation plans to protect soil and water resources in the state by measures including controlling floods.[24] The districts are tasked with preventing soil erosion caused by, among other things, floodwaters.[25] In addition, the districts may construct, improve, and maintain structures as needed to carry out the goals defined by Chapter 161A.[26] Soil conservation districts are authorized to cooperate in exercising any and all powers given

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[22] Iowa Administrative Code §§ 567-75.7 (West) & 567-75.1(2) (West).

[23] Iowa Code § 161A.1 (West) et. seq.

[24] Iowa Code § 161A.4 (West)

[25] Iowa Code §§ 161A.5 & 161A.7 (West)

[26] Iowa Code § 161A.7(g) (West)

to them, and all state agencies may cooperate with the conservation districts.[27] In addition, soil and water conservation districts may receive money from the Watershed Improvement Fund, which creates a pool of money that can be used by local entities for flood mitigation projects like a distributed storage system.[28]

Soil and water conservation subdistricts may be formed to carry out watershed protection and flood prevention projects.[29] Subdistricts have all the powers of the soil and water conservation districts supplemented by additional powers conferred only on the subdivisions.[30] The subdistricts may include portions of more than a single district and may span multiple counties.[31] A subdistrict could therefore be created that would cover only the watershed for which the improvement is intended for. Subdistricts may collect an annual tax or special benefit taxes and bonds from the areas included to cover the operations of the district and improvement works needed.[32] The Iowa Code also allows for the subdistricts to pay for projects by levying assessments against landowners in proportion to the benefit received by the landowner.[33] Subdistricts have statutory authority to condemn land as necessary for flood control and watershed protection projects.[34]

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[27] Iowa Code §§ 161A.8 & 161A.9 (West)

[28] Iowa Code §§ 466A.2, 466A.4 (West)

[29] Iowa Code § 161A.13 (West)

[30] Iowa Code § 161A.22 (West)

[31] Iowa Code § 161A.16 (West) et. seq.

[32] Iowa Code §§ 161A.20, 161A.22, 161A.23 (West)

[33] Iowa Code §§ 161A.23, 161A.24 (West)

[34] Iowa Code § 161A.21 (West)

The soil and water conservation division and districts are not likely to be particularly useful for a distributed storage system. The districts and the division are focused primarily on soil and erosion control, with ancillary powers of flood control. For example, Iowa Code § 161A.4(2)(g) indicates that the division may use flood control measures "to preserve and protect the public interest in the soil and water resources of [Iowa] for future generations." The only mention of flood control in the soil conservation division's administrative regulations echoes the above language.[35] The regulations are silent on flood control measures in discussion of the content of soil and water resource plans.[36] The policy goal of protecting the soil may conflict with the goal of a distributed storage project, which is primarily to prevent flooding.

However, the soil and water conservation subdistricts are an interesting potential solution for smaller scale distributed storage systems. Soil and water conservation subdistricts have condemnation authority, which, as discussed in Chapter 5, would likely be needed to implement distributed storage. Furthermore, the subdistricts can receive tax money or levy assessments against property benefitted by the distributed storage project. Thus, the cost for a small distributed storage project could potentially be paid by the city or landowners who would be benefitted by the flood control project. Those whose land would be flooded or otherwise disadvantaged by the project could be compensated by those advantaged. Alternatively, the conservation subdistrict can fund the project from taxes received from the county or governmental entity or entities in which the subdistrict is located, or potentially through the Watershed Improvement Fund.

Soil and conservation districts and subdistricts would not be well suited for a large scale distributed storage project. There are 100 soil conservation districts within

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[35] Iowa Administrative Code § 27-22.30 (West)

[36] *Id.*

Iowa; one for every county except Pottawattamie County, which has two districts. The Cedar River Basin is located in part of 24 Iowa counties and 5 Minnesota counties (Cedar River Watershed Coalition, ”Watershed”). It would therefore require coordination of far too many soil and water conservation districts to create a subdistrict. However, for a small distributed storage project approximately the size of the Clear Creek study discussed above, a soil and water conservation subdistrict would be feasible because the Clear Creek Watershed only includes portions of two counties.

Levee or Drainage Districts

Another entity that could control a small scale distributed storage project are levee and drainage districts. Levee or drainage districts are organized similar to the soil and water conservation districts discussed above, except that their primary goals are to facilitate drainage of surface waters from land.[37] Levee or drainage districts are created by a county board of supervisors, and may be jointly created by the boards of two or more counties.[38] In addition, landowners may petition the county for the creation of drainage districts or subdistricts to build a flood control improvement.[39] The county has three assessors determined the damage caused by the proposed improvement on private property and the benefits conferred on properties.[40] The county board then approves the drainage district if it determines that the costs and damages caused by the project are reasonably borne by the benefitted landowners.[41] The benefitted landowners are levied

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[37] Iowa Code § 468.1 (West)

[38] Iowa Code §§ 468.1 & 468.281 (West)

[39] Iowa Code § 468.6 (West)

[40] Iowa Code §§ 468.24 & 468.40 (West)

[41] Iowa Code § 468.27 (West)

for the benefits conferred on their land, which is used to pay the damages to the injured landowners.[42]

Levee or drainage districts are an entity that could only control very small distributed storage projects. For small projects, a drainage district would be a very efficient and localized method of creating a distributed storage system. The procedures outlined for assessing the costs and damages to the benefited landowners ensures that the injured landowners are compensated at the expense of those who receive the benefits of the project. However, all current drainage districts are smaller than the county scale, and generally much smaller. A drainage district could potentially be organized on the level of the Clear Creek Watershed, but anything larger would likely be difficult because the entire county board of supervisors for each included county is involved in decisions on the drainage districts.

Water Resources Coordinating Council and Watershed Planning Advisory Council

In 2008, the Iowa Legislature created the Water Resources Coordinating Council ("WRCC") by the Surface Water Protection and Flood Mitigation Act. The WRCC was originally created within the office of the governor, but has since been moved to the department of agriculture and land stewardship.[43] The WRCC is comprised of 13 members from academia and state agencies, including the director of the DNR and the director of the soil conservation division.[44] The WRCC coordinates water resource functions, including reviewing current flood plain management, identifying problems,

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[42] Iowa Code § 468.31 (West)

[43] Iowa Code § 466B.3(1) (West)

[44] Iowa Code § 466B.3(4) (West)

and considering solutions.[45] However, at present the WRCC lacks any actual authority to solve problems, and is only able to present recommendations to the legislature for reducing the impact of future flooding.[46] For this reason, the WRCC would not be an effective entity to run a distributed storage project, but it could be beneficial for the entity controlling the distributed storage system to work with the WRCC.

The Watershed Planning Advisory Council ("WPAC") was organized by the state legislature in 2010.[47] It is comprised of a variety of agencies and private interest groups, and includes city stakeholders, agricultural interest groups, economic interest groups, and water interest groups (including the soil and conservation division and the DNR).[48] The WPAC also does not have any actual authority, but submits recommendations to the Iowa Legislature for, among other things, watershed improvement and flood mitigation.[49] Again, the WPAC is not a controlling entity, but could be beneficial to work with in planning a distributed storage system.

Chapter 28E Agreements

Chapter 28E of the Iowa Code provides a mechanism for state and local governmental entities within the state to cooperate with other state and local governmental entities, as well as agencies from other states and federal agencies.[50] Chapter 28E allows public agencies in Iowa, which includes all state and local

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[45] Iowa Code § 466B.3(6) (West)

[46] Iowa Code § 466B.3(6)(c) (West)

[47] Iowa Code § 466B.31 (West)

[48] *Id.*

[49] *Id.*

[50] Iowa Code § 28E.1 (West) et. seq.

governmental entities,[51] to exercise their statutory powers or authority jointly with another agency having the same powers.[52] Chapter 28E also permits public agencies to enter into agreements with public or private agencies for joint action.[53] These agreements can include the creation of a separate entity to carry out the purpose of the agreement.[54]

A chapter 28E agreement could be used to create an entity to oversee the construction, maintenance, and operation of a distributed storage project. The agreement could be created between two or more counties for a smaller distributed storage project. For a larger distributed storage project, multiple drainage districts, soil and water conservation districts, or even watershed management authorities could make an agreement to work together for the flood protection project. This agreement could include the Iowa DNR as well. However, the decision making process for operating the reservoirs must be free of bureaucracy, as the operation decisions must be made quickly during floods. Therefore, the entity created by the chapter 28E agreement must have a single decision making unit that is equipped to forecast potential floods and decide how best to mitigate the damage.

Recommendation

For a smaller scale distributed storage project around the size of the Clear Creek Watershed, a soil and water conservation subdistrict is the best entity to manage the system. The soil and water conservation subdistrict has condemnation authority to acquire the lands and easements needed for reservoirs and their associated structures. In

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[51] Iowa Code § 28E.2 (West)

[52] Iowa Code § 28E.3 (West)

[53] Iowa Code § 28E.4 (West)

[54] *Id.*

addition, the subdistrict can either levy the costs against the properties benefitted by the project or obtain tax funds from the counties involved. A soil and water conservation subdistrict would be small enough and localized enough to effectively control the reservoirs when a flood occurs.

For a large scale distributed storage project like the one proposed on the Cedar River Watershed, Iowa does not currently have a governmental entity well suited to construct, maintain, and operate a distributed storage project. Soil and water conservation districts and subdistricts, as well as levee or drainage districts, are too small and localized to be effective for a large distributed storage project. The Iowa DNR has the power necessary to build and control a distributed storage system, but there is currently no entity within the DNR capable of doing so. The best solution is to create an entity within the DNR specifically tasked with managing a distributed storage system. The entity would need to have eminent domain powers in order to acquire the land and easements necessary for the reservoirs. In addition, the entity would need a source of funding to buy the land and easements, and construct and maintain the reservoirs. There would likely need to be a legislative grant of funds for the entity to fund a distributed storage project, as the Iowa DNR does not currently have the funds available for a large scale distributed storage project.

CHAPTER 5: PROPERTY LAW AND EMINENT DOMAIN CONSIDERATIONS

Land Interest

In order for the distributed storage project to be implemented, the controlling entity must be able to store water in a variety of locations throughout the basin of the river. In addition, the controlling entity must be able to purchase land to construct the gate structures, and have access to the structures for construction and maintenance. The Iowa DNR requires, in the application for a dam project, that the applicant obtain ownership or perpetual easements[55] for areas occupied by the dam embankment, spillways, other structures, and the permanent or maximum normal pool.[56] The controlling entity need not acquire full ownership in the lands that are intermittently flooded, as an easement to allow flooding of the land is sufficient.[57] The DNR requires ownership or easements for "temporary flooding of areas which would be inundated by the flood pool up to the top of dam elevation and for spillway discharge areas.[58] Thus, to put it simply, DNR regulations require that the controlling entity must buy the land where the structures are located, and obtain at least an easement to flood the land upstream of the dam up to the high water mark of the dam.

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[55] "An easement creates a nonpossessory right to enter and use land in the possession of another[,] obligates the possessor not to interfere with the uses authorized by the easement," and is irrevocable by the easement grantor. Restatement (Third) of Property (Servitudes) § 1.2 (2000). An easement only allows the easement owner to perform the specified activities on the land, and reserves all remaining activities and use of the land to the grantor. In this instance, easement would allow the land to be used by the distributed storage reservoir to store water without the landowner being able to interfere. When the land was not being used to store water, the land owner would be able to use the land for his or her own benefit.

[56] Iowa Administrative Code § 567-72.3(b)(1) (West)

[57] *Phelps v. Board of Supervisors of Muscatine County*, 211 N.W.2d 274, 276 (Iowa 1973), *quoting United States v. Cress*, 243 U.S. 316, 329 (1917).

[58] Iowa Administrative Code § 567-72.3(b)(2) (West)

For the land potentially inundated by the distributed storage reservoir when full to the top of the dam structure, a flowage easement is sufficient to compensate the land owner. A flowage easement allows the grantee “the right and privilege to flood the land, but expressly reserves title and beneficial use of the lands (except for the flowage rights) to the grantor.”[59] The flowage easements must include provisions that prohibit the landowner from erecting and using of any structures in the area potentially inundated.[60] The controlling entity will also need to acquire a right-of-way easement over the land to gain access to the dam for construction and maintenance.

Ideally, the required land interests will be obtained voluntarily from the property owners through bargaining. These agreements would likely involve payment for diminished land value up front, with the inclusion of liquidated damages for harm caused when the reservoirs are used. In addition, the easements must restrict the ability of the landowner to build in the reservoir area. However, if landowners refuse to voluntarily sell the easements, the controlling entity may need to condemn the required land and easements through eminent domain powers.

Eminent Domain

The Takings Clause of the Fifth Amendment of the United States Constitution mandates that “private property [shall not] be taken for public use without just compensation.”[61] This imposes two specific limits on governmental takings of private land: (1) the property can only be taken for “public use,” and (2) the landowner must receive just compensation for the taking of his or her land. This section will also give a brief overview of the eminent domain procedures in Iowa.

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[59] *Anderson v. Bell*, 433 So.2d 1202 (Fla. 1983)

[60] Iowa Administrative Code § 567-72.3(b)(3) (West)

[61] U.S. Constitution Amdt. 5

Public Use

The public use requirement has been interpreted broadly by the courts. It does not mean that the property taken must be open to the public, like a park or a road.[62] Rather, the governing body effecting the taking must only believe that the taking would promote the legislature's objective, and that objective primarily serves a public benefit.[63] The Supreme Court has also held that the public use prong is "coterminous with the scope of a sovereign's police powers" to regulate for health, safety, and public welfare.[64]

There is no doubt that flood control is a public use, even where the land is taken only for a flooding easement. The Iowa legislature has specifically authorized eminent domain for flood control projects by soil and water conservation subdistricts,[65] and the Iowa Constitution expressly allows condemnation for drainage districts.[66] Thus, the only issue with using eminent domain for distributed storage reservoirs is whether compensation is required, and how much must be paid.

Just Compensation

When a governmental uses or damages private lands for a public purpose, the landowner is entitled to compensation for the fair market value of the land. This applies even where the land is not permanently taken for public use, but merely damaged intermittently, or where an easement is taken.[67] A taking requires compensation when

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[62] *Kelo v. City of New London*, 545 U.S. 469, 480 (2005)

[63] *Id.* at 483

[64] *Hawaii Housing Authority v. Midkiff*, 467 U.S. 229, 240 (1984).

[65] Iowa Code § 161A.21 (West)

[66] Iowa Code § 18 (West)

[67] *Bormann v. Board of Supervisors for Kossuth County*, 584 N.W.2d 309, 316 (Iowa 1998) (citations omitted), *cert. denied* 525 U.S. 1172

the landowner is “substantially [deprived] of the use and enjoyment of his property or a portion thereof.”[68] Even if some land would be flooded without the improvement, compensation is required where the flooding is greater as a result of the improvement.[69]

In Iowa, the just compensation requirement is geared toward making the landowner whole. The goal is to place the landowner in as good a monetary position as if the land had not been taken.[70] For a taking of part of the land, or part of the property interest, the correct measure of damages is “the difference between the fair market value of the entire tract immediately before and immediately after condemnation.”[71] For a distributed storage reservoir, the easement is a partial taking of the land interest, and would be valued as the difference in fair market value of the entire parcel with and without the easement. To make the landowner whole, the easement would likely need to include liquidated damages to compensate the landowner for lost crop income, applicable only when the reservoir is used and the productivity of the land is destroyed. This would be more desirable than an up-front payment of the entire expected value of the easement, as the landowner would be protected from potentially ruinous monetary losses when the reservoir is inundated. In addition, the costs of the project would be somewhat deferred, as an easement providing for the payment of damages would reduce the amount of compensation that would be required initially because the land value would not be reduced as much by the easement.

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[68] *Phelps v. Board of Supervisors of Muscatine County*, 211 N.W.2d. 274, 276 (Iowa 1973) (citations omitted)

[69] *Id.*

[70] *Aladdin, Inc. v. Black Hawk County*, 562 N.W.2d 608, 611 (Iowa 1997)

[71] *Powers v. City of Dubuque*, 176 N.W.2d 135, 138 (Iowa 1970)

Eminent Domain Procedure in Iowa

In Iowa, eminent domain proceedings are commenced by the state attorney general if the project uses state funds, the county attorney if the project uses county funds, or the city attorney if the project uses city funds.[72] The condemning authority must give notice and opportunity for comment to the affected landowners,[73] and must make a good faith effort to obtain the land through negotiation.[74] Upon failure to obtain the necessary land through negotiation, condemnation proceedings are commenced in the county where the property is located and the compensation is determined by a compensation commission.[75] The compensation commission is a six member panel chosen by a judge from a pool of 28 persons that the county board of supervisors has selected as eligible for the compensation commission.[76] The commission is comprised of two agricultural land owner-operators, two city property owners, a real estate agent or broker, and a person who has knowledge of property values by virtue of his or her occupation, such as a banker, appraiser, or loan officer.[77] The selected compensation commission appraises the value of the real and personal property taken, as well as any personal property damaged and any moving expenses required, and the compensation is awarded as this appraised value.[78] Either party may appeal the award to the district

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[72] Iowa Code § 6B.2 (West)

[73] Iowa Code § 6B.2A (West)

[74] Iowa Code § 6B.2B (West)

[75] Iowa Code § 6B.4 (West)

[76] *Id.*

[77] *Id.*

[78] Iowa Code § 6B.14 (West)

court, where the issue is heard in civil court to determine if the awarded compensation amount is sufficient.[79]

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[79] Iowa Code § 6B.18 (West)

CHAPTER 6: ENVIRONMENTAL LAW ISSUES ASSOCIATED WITH A DISTRIBUTED STORAGE SYSTEM

The distributed storage system will necessitate accumulating water on land that is typically used as farmland, and then releasing this stored water back into the rivers and streams. In holding the water on farmland, it is likely that the water will accumulate pollutants, such as nitrates and animal wastes, present on the farm land. Upon release, the pollutants accumulated by the stored flood water would travel downstream and could increase the pollutant concentrations of the larger waterways. This might trigger the need for a National Pollutant Discharge Elimination System ("NPDES") permit required by the Clean Water Act ("CWA").[80] The project could also require an Environmental Impact Statement ("EIS") under the National Environmental Policy Act ("NEPA").[81]

Clean Water Act

The Clean Water Act requires that a NPDES permit be obtained for any addition of a pollutant by a point source into navigable waters.[82] An NPDES permit is therefore required by the CWA when: (1) the discharge is made by a point source; (2) the discharge is into navigable waters; and (3) the discharge results in the "addition of a pollutant" to the navigable waters. [83]

Point Source

The Clean Water Act provides that a point source is "any discernible, confined and discrete, conveyance, including but not limited to any pipe, ditch, channel,

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[80] 33 U.S.C. § 1261 (West) *et. seq.*

[81] 42 U.S.C. § 4321 (West)

[82] 33 U.S.C. § 1311(a), 33 U.S.C. § 1342 (West) *et. seq.*

[83] 33 U.S.C. §1362(12) (West)

tunnel…"[84] However, it "does not include agricultural stormwater discharges and return flows from irrigated agriculture."[85] The definition of "point source" is intended to be broad and expansive, but not so broad as to read out the requirement of a point source from the Clean Water Act.[86] The reason for only regulating pollution from point sources is simple: point sources can be easily determined and regulated, whereas non point sources are difficult to measure and control.[87] The designation of "nonpoint source" under the Clean Water Act is limited to uncollected runoff water that is difficult to ascribe to single polluter[88] and that is not from a "confined, discrete conveyance."[89] The Clean Water Act leaves regulation of nonpoint sources to state or local agencies.[90]

Drainage from a distributed storage reservoir would likely qualify as a point source under the Clean Water Act. The discharge gates clearly fit under the definition of "any discernible, confined and discrete, conveyance." The discharge flows through a gate and pipe and then in to the stream or river from which it was withheld. The discharge of water from a dam through a spillway has been held to be a point source in terms of the Clean Water Act.[91] A distributed storage reservoir is essentially a miniature dam, and thus is analogous to a dam and spillway.

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[84] 33 U.S.C. § 1362(14) (West)

[85] *Id.*

[86] *Cordiano v. Metacon Gun Club, Inc.*, 575 F.3d 199, 219 (2d Cir. 2009)

[87] *United States v. Plaza Health Labs*, 3 F.3d 643, 653 (2d Cir 1993) (Oakes, J. dissenting).

[88] *Beartooth Alliance v. Crown Butte Mines*, 904 F.Supp. 1168, 1173 (D.Mont. 1995).

[89] *Trustees for Alaska v. E.P.A.*, 749 F.2d 549, 558 (9th Cir. 1984).

[90] *Plaza Health Labs*, 3 F.3d at 647 (*quoting* S.Rep. No. 92-414, reprinted in 1972 U.S.C.C.A.N. 3668, 3744)

[91] *National Wildlife Federation v. Gorsuch*, 693 F.2d 156 (D.C. Cir. 1982).

However, the agricultural stormwater discharge exemption likely applies to some of the distributed storage reservoirs. The agricultural stormwater discharge exemption states that agricultural stormwater discharges are not considered point sources by the Clean Water Act.[92] In *Fishermen Against Destruction of Environment v. Closter Farms, Inc.*, the 11th Circuit decided a case involving a farm that was pumping collected runoff into a lake. [93] The court decided that it was reasonable to classify the water as "agricultural stormwater discharge" because it was the result of precipitation on agricultural land, and the fact that the water was pumped into a lake was irrelevant.[94] The Clean Water Act does not require that the discharge be made in the same place it would naturally flow.[95] Therefore, runoff as the result of precipitation on agricultural land, even if collected and discharged through a particular conveyance, still qualifies for the agricultural runoff exemption. However, if the agricultural runoff is mixed with runoff collected from lands other than agricultural lands, the agricultural stormwater discharge exemption only applies to that water collected from the agricultural runoff.[96] Therefore, any distributed storage reservoirs collecting water solely from agricultural land would not be considered a point source, and therefore would not require a NPDES permit. However, if the reservoir collected water from any non-agricultural land, that portion of the water collected would be considered a discharge from a point source.

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[92] 33 U.S.C. § 1362(14) (West)

[93] 300 F.3d 1294 (11th Cir. 2002)

[94] *Id*. at 1297.

[95] *Id.*

[96] *Id.*

Navigable Waters

The second condition that must be met for a NPDES permit to be necessary is that the discharge of a pollutant must be made into navigable waters.[97] "The term 'navigable waters' means the waters of the United States, including the territorial seas."[98] The waterway does not actually have to be navigable by barges, or even boats.[99] Congress intended to give the term the "broadest possible constitutional interpretation."[100] The only limitation that has thus far been placed on the term is that a body of water must be "relatively permanent, standing, or flowing bodies of water."[101] Therefore, under the Clean Water Act, a channel which only periodically flows to provide drainage is not considered a navigable waterway.[102] The Supreme Court declined to decide whether continuous flow was sufficient, in itself, for a determination of navigability, only holding that it is a requirement for navigability.[103] The Environmental Protection Agency ("EPA") has promulgated regulations attempting to define "waters of the United States," indicating that they include all waterways used in interstate commerce, all interstate waterways, intrastate waterways that would affect interstate commerce if destroyed or degraded, all tributaries of the above waterways, and any wetlands adjacent to a

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[97] 33 U.S.C. §1362(12) (West)

[98] 33 U.S.C. § 1362(7) (West)

[99] *United States v. Oxford Royal Mushroom Products, Inc.*, 487 F. Supp. 852 (E.D. Penn. 1980).

[100] *United States v. Byrd*, 609 F.2d 1204 (7th Cir. 1979), *quoting* Conference Report, S.Rep.No.236, 92d Cong., 2d Sess. 144.

[101] *Rapanos v. United States*, 547 U.S. 715, 739 (2006) (Scalia, J., plurality opinion)

[102] *Id.*

[103] *Id.*

navigable waterway.[104] This is an expansive definition, as it includes waters that *Rapanos* specifically discounted.

A distributed storage reservoir would undoubtedly be discharging into navigable waters according to the EPA's definition. The Iowa and Cedar Rivers are navigable in fact. Discharge into the tributaries upstream of these rivers is included in the EPA's definition of navigable waters. It is more difficult to determine whether the upstream tributaries would be considered navigable by the Supreme Court. Most or all of the reservoirs would discharge into permanent streams, as required by *Rapanos*, although there is no ultimate determination whether there are other requirements for a waterway to be navigable under the Clean Water Act. It is likely that at least some of the reservoirs would discharge into navigable waters under any definition.

Addition of a Pollutant

The Clean Water Act defines pollution as "the man-made or man-induced alteration of the chemical, physical, biological, and radiological integrity of water."[105] Water itself is not considered a pollutant for purposes of the NPDES permit requirement.[106] However, stormwater runoff contaminated only with sediment has been held to be a pollutant under the Clean Water Act, requiring an NPDES permit.[107] Furthermore, merely altering the flow of a stream can be considered pollution under the definition in the CWA.[108]

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[104] 40 C.F.R. § 122.2 (West)

[105] 33 U.S.C. § 1362(19) (West)

[106] *Bettis v. Town of Ontario, New York*, 800 F. Supp. 1113 (W.D.N.Y. 1992).

[107] *Nat'l Resources Defense Council v. U.S. E.P.A.*, 526 F.3d 591 (9th Cir. 2008)

[108] *State Dep't of Ecology v. Public Utility District 1 of Jefferson County*, 849 P.2d 646, (Wash. 1993), *aff'd by* 511 U.S. 700 (1994)

Discharge from a single gate within the distributed storage system would qualify as addition of a pollutant. Farmland in Iowa is particularly vulnerable to erosion, and sediment is sure to accumulate in water that is backed up onto farmland. In addition, the water will likely be contaminated with nitrogen and other pesticides and agricultural treatments. According to the definitions of addition of pollutants in the Clean Water Act, a distributed storage reservoir would add a pollutant to the water.

NPDES Permit

An NPDES permit would likely be necessary for those distributed storage reservoirs that collect water from non-agricultural land, and result in the addition of a pollutant into the stream. An NPDES permit requires that the applicant limit pollutants using the "best practical control technology currently available." The EPA has interpreted this to mean the "best available technology economically achievable," allowing for consideration of economic factors in determining whether the best practical technology has been implemented.[109] For a distributed storage reservoir structure, there is not likely to be significant control technologies. It would be economically infeasible to require every reservoir in a distributed reservoir system to have pollution control. One potential control technology to reduce sediment in the downstream river would be to require water held in the reservoir to remain there for a specified time. This would allow the sediment collected in the reservoir to settle to the bottom, thereby reducing the sediment in the downstream water. It would also have the added benefit of depositing a layer of fertile soil on farm lands inundated.

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[109] 40 C.F.R. § 125.3(2) (West)

The National Environmental Policy Act

The National Environmental Policy Act requires an Environmental Impact Statement ("EIS") for any major federal action "significantly affecting the quality of the human environment."[110] The "major federal action" requirement is only triggered when federal funds are used for a project, and that project requires "substantial planning, time, resources, or expenditure."[111] The EIS must disclose the "environmental impact of the proposed action," any unavoidable adverse environmental impacts, "alternatives to the proposed action," the relationship between short term adverse uses and long term productivity of the environment, and "any irreversible and irretrievable commitments of resources" that the project would entail.[112] The EIS also requires a cost-benefit analysis of the proposed action and suggested alternatives.

The EIS requirement is not likely to be a roadblock for the distributed storage project. An EIS would likely be required if federal money were apportioned to the project, although it is unclear at present if a distributed storage system would receive federal funding. However, even if an EIS were required, the EIS is merely a reporting requirement. There is no review of an agency decision to determine if the agency selected the appropriate action to minimize the environmental impacts.[113] The agency is only required to consider the environmental consequences and alternatives, but does not have to decide based on them.[114]

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[110] 42 U.S.C. § 4332(2)(C) (West)

[111] *Id.*

[112] *Id.*

[113] *Strycker's Bay v. Karlen*, 444 U.S. 223 (1980).

[114] *Id.*

SUMMARY

This paper presents a sketch of the feasibility and some of the considerations necessary for implementing a distributed storage system, focusing particularly on the Cedar River basin upstream of Cedar Rapids. The sketch of the Cedar Rapids basin was performed after analyzing of the much smaller Clear Creek Watershed, using the Clear Creek data to scale this small system to provide an estimate for the Cedar River basin.

First, this thesis demonstrated that there is an advantage to an active storage system over a passive storage system. Next, the advantages of accurate forecasting on a single reservoir system showed that accurate forecasting is invaluable to obtain the best flood protection from a reservoir or reservoir system. This is also true for a distributed storage system, where multiple reservoirs are scattered throughout a river basin and need reasonable forecasts to be able to predict the future flows resulting from releases throughout the basin. Accurate forecasting will allow the distributed storage system to be more efficient in reducing flooding downstream of the reservoirs.

The research presented in this document used two algorithms to determine advantageous locations for 33 reservoirs throughout the Clear Creek Watershed in Eastern Iowa. The first algorithm placed the reservoirs according to the most efficient location, where the reservoir would store the most volume per unit of area inundated. The second algorithm located the reservoirs to maximize the storage of water falling in specific travel bands, areas where there is a risk of concentrations of rainfall reaching the outlet of the creek at the same time. Land use was considered to eliminate reservoirs flooding developed areas, leaving 29 efficient reservoirs and 28 travel band reservoirs. The 29 efficient reservoirs stored approximately 5.8 million cubic meters, inundating about 4.3 square kilometers, while the travel band reservoirs stored about 6.4 million cubic meters, flooding 5.2 square kilometers.

This paper extrapolated the data obtained from the analysis of Clear Creek to the Cedar River basin to attempt to estimate costs and requirements to stop a flood like the one that devastated Cedar Rapids in June of 2008. This estimate is subject to a number of assumptions, and can only be taken as a preliminary approximation, with further studies necessary for implementation of the system. The reservoirs in the Cedar River basin were assumed to be the same size as those in Clear Creek basin, storing 200,000 cubic meters and inundating 150,000 square meters. Stopping the flood of 2008 would have required approximately 8,530 of these reservoirs. The cost for constructing and flooding these reservoirs once is roughly estimated at approximately $1.1 billion, while the U.S. Army Corps of Engineers estimated the damage caused by the Flood of 2008 was approximately $2.4 billion, plus an additional $3.3 billion in economic losses. Therefore, even if the distributed storage system was used only once to prevent a disaster like the Flood of 2008, this research estimates that there is a substantial net benefit.

This research also examined the legal concerns with a distributed storage system with particular attention to Iowa law. Under current Iowa law, the best agency to control a large scale distributed storage system on the Cedar River basin is the Iowa Department of Natural Resources. A smaller system could be managed by a soil and conservation subdistrict created specifically for the purpose of running a distributed storage system. Iowa law also requires easements to flood the land in the reservoirs, while the land where the structures are located must be bought. The land and easements needed for the distributed storage system can be obtained through eminent domain, although it would be preferable to obtain the land and easements voluntarily. This paper also considered potential environmental concerns, finding that an NPDES permit may be required for storage reservoirs collecting water from non-agricultural land.

This preliminary analysis determined that a distributed storage system could be a feasible and cost-effective solution to protect Cedar Rapids from future flooding like the Flood of 2008. Furthermore, there are no significant legal impediments to implementing a distributed storage system in Iowa. More detailed studies will be needed before implementing a distributed storage system to find the ideal reservoir locations and to determine the costs and benefits of the system more accurately. Nonetheless, distributed storage is a promising alternative to traditional flood mitigation that could considerably reduce the flood risk in Cedar Rapids and other communities in Iowa.

APPENDIX A: DISTRIBUTED STORAGE TABLES FROM THE CLEAR CREEK SIMULATION

Table A-1: Listing of the 33 reservoirs on Horton level 4 tributaries of Clear Creek

Reservoir	Latitude	Longitude	Area Inundated	Volume Stored	Avg. Depth
			(m^2)	(m^3)	(m)
1	41.7182	-91.6232	111,600	207,900	1.86
2	41.7207	-91.5945	250,200	465,300	1.86
3	41.6799	-91.7937	32,400	57,600	1.78
4	41.6993	-91.8487	205,200	328,500	1.60
5	41.6963	-91.6898	71,100	113,400	1.59
6	41.7265	-91.9101	668,700	1,047,600	1.57
7	41.6990	-91.7098	92,700	141,300	1.52
8	41.6932	-91.8884	88,200	133,200	1.51
9	41.7315	-91.7248	49,500	74,700	1.51
10	41.6915	-91.8179	344,700	516,600	1.50
11	41.6935	-91.9915	164,700	244,800	1.49
12	41.7054	-91.6504	132,300	196,200	1.48
13	41.6877	-91.6623	229,500	335,700	1.46
14	41.7038	-91.7804	112,500	162,900	1.45
15	41.6935	-91.7495	277,200	396,900	1.43
16	41.7093	-91.6595	54,900	78,300	1.43
17	41.7257	-91.9037	108,000	153,900	1.43
18	41.6613	-91.9309	412,200	583,200	1.41
19	41.7043	-91.8809	61,200	85,500	1.40
20	41.6713	-91.8173	148,500	205,200	1.38
21	41.7004	-91.9468	101,700	137,700	1.35
22	41.7277	-91.7351	98,100	129,600	1.32
23	41.7052	-91.6257	77,400	100,800	1.30
24	41.6985	-91.7568	83,700	104,400	1.25
25	41.6768	-91.8934	40,500	50,400	1.24
26	41.6760	-91.9543	354,600	439,200	1.24

Table A-1: Continued

27	41.6932	-91.9598	180,000	221,400	1.23
28	41.7385	-91.6473	127,800	155,700	1.22
29	41.6724	-91.9540	73,800	87,300	1.18
30	41.7007	-91.9323	121,500	140,400	1.16
31	41.7160	-91.7262	259,200	293,400	1.13
32	41.6763	-91.8970	93,600	103,500	1.11
33	41.7018	-91.7104	210,600	95,400	0.45
Totals			5,437,800	7,587,900	

Table A-2: Listing of the 33 reservoirs on Horton level 4 tributaries of Clear Creek selected to maximize the storage in the travel bands.

Reservoir	Latitude	Longitude	Volume Stored	Area Inundated	10" Travel Band Volume	Storage from Travel Band
			(m^3)	(m^2)	(m^3)	(m^3)
1	41.6982	-91.9679	425,700	366,300	790,042	425,700
2	41.6613	-91.9309	583,200	412,200	1,450,924	583,200
3	41.7257	-91.9037	153,900	108,000	453,085	153,900
4	41.7265	-91.9101	1,047,600	668,700	3,172,739	1,047,600
5	41.6760	-91.9543	439,200	354,600	1,378,458	439,200
6	41.7160	-91.7262	293,400	259,200	933,602	293,400
7	41.6763	-91.8965	66,600	59,400	226,085	66,600
8	41.6832	-91.6498	487,800	419,400	1,807,312	487,800
9	41.7263	-91.7279	179,100	171,900	699,516	179,100
10	41.7290	-91.7234	76,500	69,300	341,986	76,500
11	41.6932	-91.9598	221,400	180,000	994,410	221,400
12	41.6760	-91.9540	99,000	94,500	467,258	99,000
13	41.6990	-91.7098	141,300	92,700	686,486	141,300
14	41.6990	-91.7782	225,000	191,700	1,113,282	225,000
15	41.7004	-91.9468	137,700	101,700	744,322	137,700
16	41.6935	-91.7495	396,900	277,200	2,244,852	396,900
17	41.6996	-91.7559	156,600	132,300	886,968	156,600
18	41.6749	-91.8968	131,400	128,700	792,099	131,400
19	41.7018	-91.7104	95,400	210,600	586,588	95,400
20	41.7007	-91.9323	140,400	121,500	1,001,039	140,400
21	41.6963	-91.6898	113,400	71,100	1,567,053	113,400
22	41.7385	-91.6473	155,700	127,800	0	0
23	41.7207	-91.5945	465,300	250,200	0	0
24	41.7190	-91.6240	234,000	161,100	0	0
25	41.7129	-91.6326	171,000	159,300	0	0
26	41.7118	-91.6573	139,500	119,700	0	0
27	41.7074	-91.6507	197,100	133,200	0	0
28	41.7043	-91.8762	112,500	108,900	0	0
29	41.6852	-91.8648	452,700	332,100	0	0

Table A-2: Continued

30	41.6915	-91.8179	516,600	344,700	0	0
31	41.6932	-91.8884	133,200	88,200	0	0
32	41.6871	-91.8009	187,200	163,800	35,890	35,890
33	41.6871	-91.8004	117,000	102,600	28,804	28,804
Totals			8,493,300	6,582,600	34,842,526*	5,676,194

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* The total ten inch travel band volume is calculated for the entire travel band, not merely the volume in the 33 reservoirs.

Table A-3: Land cover inundated for 33 efficient reservoirs, in square meters.

		Developed								
Reservoir	Open Water	Open Space	Low Intensity	Medium Intensity	High Intensity	Deciduous Forest	Grassland/ Herbaceous	Pasture/ Hay	Cultivated Crops	Woody Wetlands
1	900	45900	29700	11700	17100	0	6300	0	0	0
2	0	122400	80100	36000	1800	5400	4500	0	0	0
3	0	0	0	0	0	20700	0	11700	0	0
4	0	1800	0	0	0	0	4500	115200	83700	0
5	0	0	0	0	0	5400	0	45000	20700	0
6	0	123300	55800	82800	18900	12600	23400	0	351900	0
7	0	900	13500	0	0	7200	9900	0	57600	3600
8	0	0	0	0	0	0	0	55800	32400	0
9	0	0	0	0	0	0	0	0	49500	0
10	0	1800	0	0	0	19800	44100	179100	94500	5400
11	0	0	0	0	0	0	0	0	164700	0
12	0	2700	0	0	0	0	0	0	129600	0
13	0	0	0	0	0	45000	0	143100	41400	0
14	0	5400	0	0	0	0	0	14400	91800	900
15	0	24300	16200	6300	0	0	131400	0	90900	8100
16	0	11700	21600	18900	0	0	2700	0	0	0

Table A-3: Continued

17	0	900	0	16200	0	0	0	0	90900	0
18	0	0	0	0	0	0	35100	0	377100	0
19	0	0	0	0	0	0	0	0	61200	0
20	0	0	0	0	0	4500	33300	44100	66600	0
21	0	4500	0	0	0	0	0	0	97200	0
22	0	0	4500	0	0	0	0	86400	7200	0
23	0	0	0	0	0	67500	3600	0	6300	0
24	0	1800	0	0	0	0	4500	0	77400	0
25	0	900	0	0	0	0	0	0	39600	0
26	0	4500	0	0	0	0	0	0	350100	0
27	0	0	0	0	0	0	0	0	180000	0
28	0	19800	0	0	0	900	35100	23400	48600	0
29	0	0	0	0	0	0	0	0	73800	0
30	0	900	0	0	0	0	15300	0	105300	0
31	0	0	0	0	0	0	0	110700	148500	0
32	0	0	0	0	0	0	0	0	93600	0
33	0	16200	1800	0	0	7200	9900	0	174600	900
Totals	900	389700	223200	171900	37800	196200	363600	828900	3206700	18900

Table A-4: Land cover inundated for 33 efficient reservoirs selected by travel band, in square meters.

	Developed									
Reservoir	Open Space	Low Intensity	Medium Intensity	High Intensity	Deciduous Forest	Grassland/ Herbaceous	Pasture/Hay	Cultivated Crops	Woody Wetlands	Emergent Herbaceous Wetlands
	21	22	23	24	41	71	81	82	90	95
1	9000	2700	0	0	0	0	0	354600	0	0
2	0	0	0	0	0	35100	0	377100	0	0
3	900	0	16200	0	0	0	0	90900	0	0
4	123300	55800	82800	18900	12600	23400	0	351900	0	0
5	4500	0	0	0	0	0	0	350100	0	0
6	0	0	0	0	0	0	110700	148500	0	0
7	0	0	0	0	0	0	0	59400	0	0
8	34200	35100	0	0	0	0	3600	344700	1800	0
9	15300	2700	0	0	0	0	27900	126000	0	0
10	0	0	0	0	0	0	900	68400	0	0
11	0	0	0	0	0	0	0	180000	0	0
12	0	0	0	0	0	0	0	94500	0	0
13	900	13500	0	0	7200	9900	0	57600	3600	0
14	18000	0	0	0	0	33300	3600	136800	0	0

Table A-4: Continued

15	4500	0	0	0	0	0	0	97200	0	0
16	24300	16200	6300	0	0	131400	0	90900	8100	0
17	12600	0	0	0	0	33300	0	86400	0	0
18	0	0	0	0	0	0	1800	126900	0	0
19	16200	1800	0	0	7200	9900	0	174600	900	0
20	900	0	0	0	0	15300	0	105300	0	0
21	0	0	0	0	5400	0	45000	20700	0	0
22	19800	0	0	0	900	35100	23400	48600	0	0
23	122400	80100	36000	1800	5400	4500	0	0	0	0
24	36900	47700	7200	18000	0	51300	0	0	0	0
25	3600	16200	43200	16200	11700	15300	0	50400	2700	0
26	8100	19800	44100	0	0	39600	0	3600	4500	0
27	20700	6300	0	0	0	0	0	105300	900	0
28	0	0	0	0	0	0	0	108000	0	900
29	9900	0	0	0	0	9000	78300	234900	0	0
30	1800	0	0	0	19800	44100	179100	94500	5400	0
31	0	0	0	0	0	0	55800	32400	0	0
32	0	0	0	0	0	141300	16200	6300	0	0
33	0	2700	0	0	3600	0	83700	12600	0	0
Totals	487800	300600	235800	54900	73800	631800	630000	4139100	27900	900

APPENDIX B: LAND COVER DEFINITIONS

Included is a listing of the definitions for the relevant 2001 NLCD land cover classes used in the distributed storage analysis, obtained from http://www.epa.gov/mrlc/definitions.html:

11. Open Water - All areas of open water, generally with less than 25% cover of vegetation or soil.

21. Developed, Open Space - Includes areas with a mixture of some constructed materials, but mostly vegetation in the form of lawn grasses. Impervious surfaces account for less than 20 percent of total cover. These areas most commonly include large-lot single-family housing units, parks, golf courses, and vegetation planted in developed settings for recreation, erosion control, or aesthetic purposes.

22. Developed, Low Intensity - Includes areas with a mixture of constructed materials and vegetation. Impervious surfaces account for 20-49 percent of total cover. These areas most commonly include single-family housing units.

23. Developed, Medium Intensity - Includes areas with a mixture of constructed materials and vegetation. Impervious surfaces account for 50-79 percent of the total cover. These areas most commonly include single-family housing units.

24. Developed, High Intensity - Includes highly developed areas where people reside or work in high numbers. Examples include apartment complexes, row houses and commercial/industrial. Impervious surfaces account for 80 to100 percent of the total cover.

31. Barren Land (Rock/Sand/Clay) - Barren areas of bedrock, desert pavement, scarps, talus, slides, volcanic material, glacial debris, sand dunes, strip mines, gravel pits and other accumulations of earthen material. Generally, vegetation accounts for less than 15% of total cover.

41. Deciduous Forest - Areas dominated by trees generally greater than 5 meters tall, and greater than 20% of total vegetation cover. More than 75 percent of the tree species shed foliage simultaneously in response to seasonal change.

42. Evergreen Forest - Areas dominated by trees generally greater than 5 meters tall, and greater than 20% of total vegetation cover. More than 75 percent of the tree species maintain their leaves all year. Canopy is never without green foliage.

71. Grassland/Herbaceous - Areas dominated by grammanoid or herbaceous vegetation, generally greater than 80% of total vegetation. These areas are not subject to intensive management such as tilling, but can be utilized for grazing.

81. Pasture/Hay - Areas of grasses, legumes, or grass-legume mixtures planted for livestock grazing or the production of seed or hay crops, typically on a perennial cycle. Pasture/hay vegetation accounts for greater than 20 percent of total vegetation.

82. Cultivated Crops - Areas used for the production of annual crops, such as corn, soybeans, vegetables, tobacco, and cotton, and also perennial woody crops such as orchards and vineyards. Crop vegetation accounts for greater than 20 percent of total vegetation. This class also includes all land being actively tilled.

90. Woody Wetlands - Areas where forest or shrubland vegetation accounts for greater than 20 percent of vegetative cover and the soil or substrate is periodically saturated with or covered with water.

95. Emergent Herbaceous Wetlands - Areas where forest or shrubland vegetation accounts for greater than 20 percent of vegetative cover and the soil or substrate is periodically saturated with or covered with water.

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