Hydro-Economic Analysis of Flood Bypasses

By

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To my parents Francesco and Giacomina
who have always supported me in pursuing my dreams.

To my husband Angel
for putting up with my long nights studying
and "burning the midnight oil".

To my daughter Giulia,
for listening to all my presentations without prejudice.

Sapere Aude! - Horace

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ABSTRACT

Flood bypasses are used to reduce flood risk and damage. Flood bypasses also can reconnect rivers with floodplains for ecosystem and offer fertile land for agriculture and other benefits. Numerous economic and environmental interests can be involved in flood bypass management. This study integrates economic and hydraulic modeling to better inform and assist bypass system planning and management.

Design and operation of flood bypasses are usually not economically optimized. Modifications to bypasses are rarely analyzed with formal integration of economics, engineering and hydrology. This dissertation develops optimization modeling to explore flood bypass capacity in general. Hydrodynamic modeling and preliminary risk analysis are shown for the Yolo Bypass on the Sacramento River, California. The combined hydraulic and economic modeling can better inform policy makers and stakeholders on bypass design and structural modifications and long-term flood management strategy.

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CHAPTER 1: INTRODUCTION

Governments often neglect flood protection systems. Large floods are usually needed to mobilize federal, state, and local authorities for recovery of damaged areas and the implementation of flood protection. Yet the cost of implementing structural and nonstructural flood protection prior to large floods is often less than the costs of recovering from major flooding.

Large floods are common in California. The causes of floods are diverse and related to inadequate structural flood protection, local land use decisions, and to poor management decisions (Paulson et al., 1991), (USACE, 1999). California's alternation between droughts and floods makes it particularly difficult to maintain interest in flood management.

In the United States riverine floods are predominantly controlled by levees (Ludy et al., 2012). This practice has been criticized for over 100 years (Ludy et al., 2012). Additional actions, such as reservoirs and flood bypasses, and land use controls, have been proposed and used in the last century (Plate, 2002; Plate, 2004), (Apel et al., 2004).

Flood bypasses can be reliable for flood risk reduction, and simultaneously other benefits. Habitat restoration, recreation, and groundwater recharge depend on flood bypass capacity and management (Suddeth, 2014). While flood bypasses are used all over the world, the design of flood bypasses usually relies on hydraulic and hydrologic analysis, with less formal economic analysis. This study proposes a benefit-cost analysis of flood bypasses for flood risk management. The use of flood bypasses is limited by high costs and extensive amount of land needed. A bypass might be cost effective if in an area at high risk. Many other times levees are chosen over bypasses. A cost benefit analysis is usually conducted for the evaluation.

The first part of this chapter 1 describes flood bypasses all over the world. California's history of floods and flood management shows some general characteristic of floods and how the community addresses floods and flood risks.

The second part describes the need for better models to manage flood bypasses. Objectives of this research are presented. The end of the chapter explains the dissertation structure.

1.1 Floods

Flooding occurs from high river flows or water levels in lakes, reservoirs, aquifers and estuaries (Yevjevich, 1994). Floods are among the most common, destructive and life threatening natural disturbances globally (EM-DAT, 2009). In recent decades the number of floods and their economic damages have grown worldwide (EM-DAT, 2009) (figure 1.1 and figure 1.2).

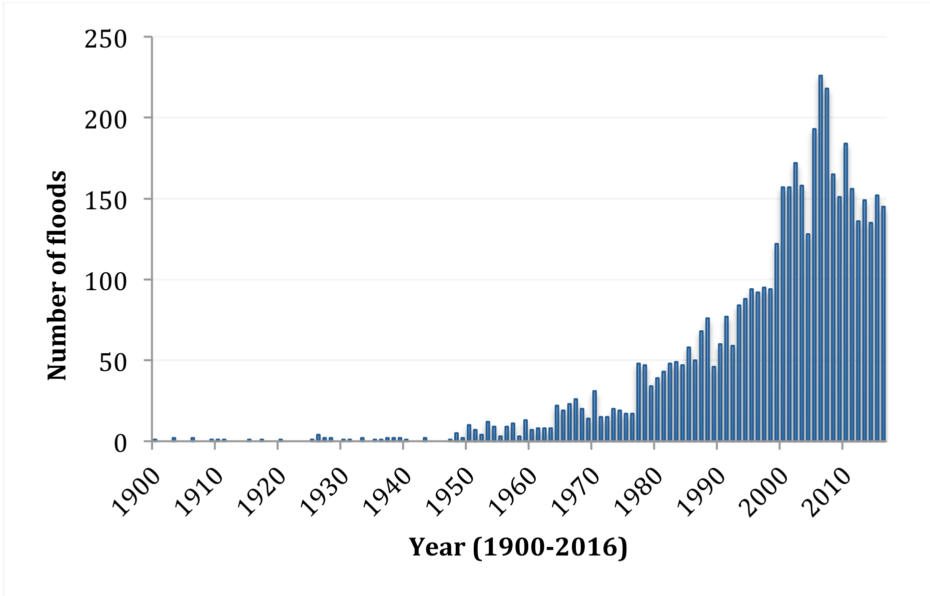


Figure 1.1 Worldwide floods for the years 1900 to 2016. Source: EM-DAT (2009)

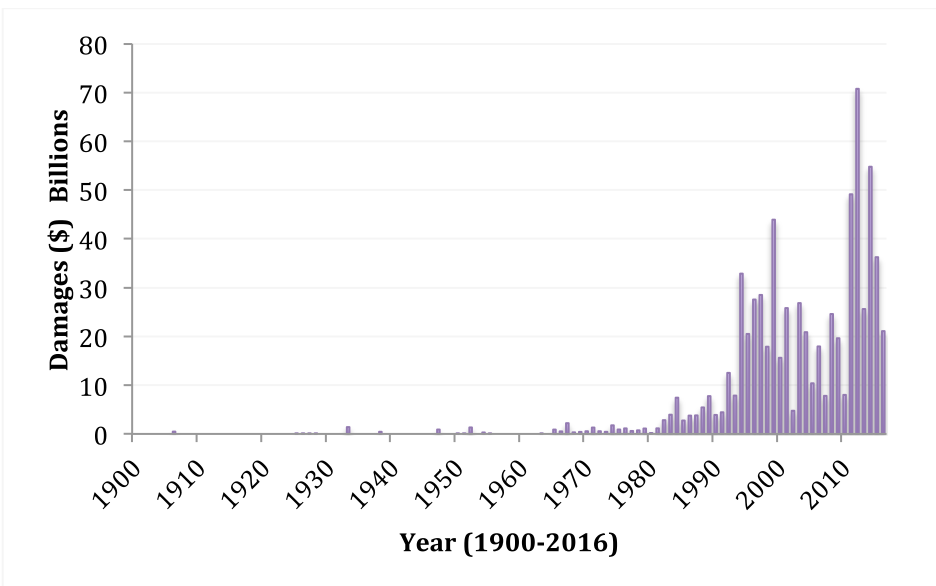


Figure 1.2 Worldwide damages for floods for the years 1900 to 2016. Source: EM-DAT (2009)

However, flood-related deaths peaked during the 1990s and continue to decrease. The reduction in deaths is due to better flood management, monitoring, forecasting, warnings, emergency response, and evacuation (EM-DAT, 2009).

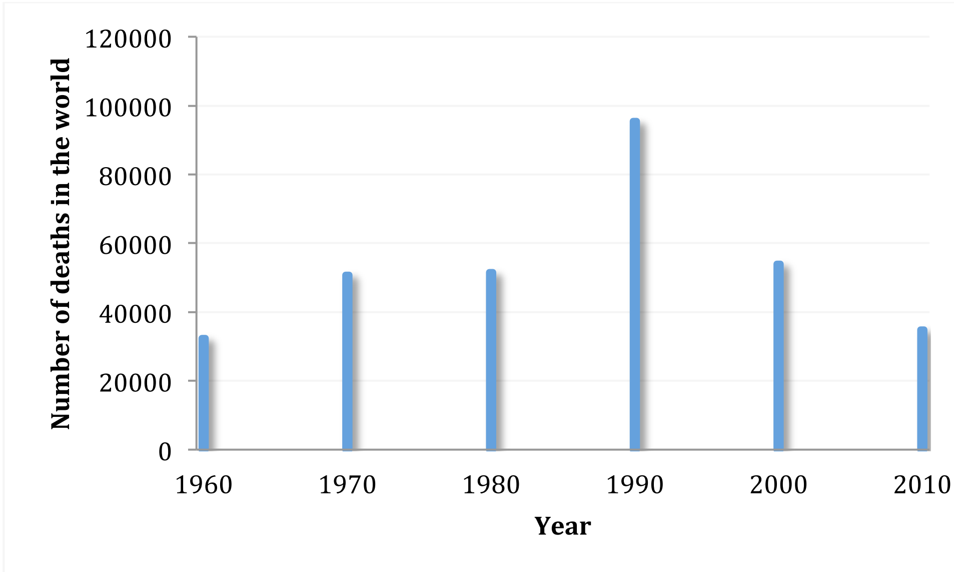


Figure 1.3 Worldwide number of deaths due to floods per decade. Source: EM-DAT (2009)

California has more than 7 million people and $580 billion in assets (crops, structures, and public infrastructure) exposed to flooding (DWR, 2013). California's Department of Water Resources (DWR) estimates that approximately 90 percent of all natural disasters (events which caused damages or deaths) in California are flood-related. California's recent large and extensive flood disaster was in January 1997, in Central Valley with damages exceeding $524 million and nine deaths (USACE, 1999).

1.2 History of flood management in the United States

Since ancient times, many civilizations settled and flourished along rivers, such as the Tigris and Euphrates in Mesopotamia, the Nile in Egypt, the Indus in what is today Pakistan, and the Yellow River in China. Egyptians understood as early as 3000 B.C. the benefits of flooding to replenish agricultural soils. With agriculture, irrigation and flood-control were developed together. In China around 2000 B.C. in the Yangze River area, flood control projects started with dredging the river and building dikes (Kagan, 2006). With the development of sophisticated irrigation, levees have been preferred to natural flooding. The result has been rivers confined by levees, and a strong disconnection from the floodplain, with periodic destructive floods due to overtopping or levee failures.

In the United States, federal involvement in flood control measures started in the early 19th century. The Constitution's Commerce Clause was intended to regulate commerce among the states (Stern, 1946). It was not directly focused on flood control but it has become commonly used to support federal flood control, and provided authority for the U.S. Army Corps of Engineers to remove navigation obstructions from the Ohio and Mississippi rivers. At that time flood protection was only by levees.

The Civil War left the Mississippi River with poor levees that needed improvements. The limitations of a "levees only" policy became apparent, while congressional focus was still on navigation (Wright, 2000). With the floods of the early 1900s, the Flood Control Act of 1917 was introduced. This was the first act of Congress to fund primarily flood control activities. In particular, $45 million for the lower Mississippi River and $5.6 million for the Sacramento River, which included the use of a flood bypass for the first time (Wright, 2000). The Great Flood of 1927 demonstrated further problems of the "levees only" policy. Since then, federal involvement in flood control grew. Between 1930 and 1960s the understanding of relation between land use and floods took place and floodplains and basins have been considered as the "right" scale to fight large floods.

Today American floodplain development projects are constrained by the National Flood Insurance Program (NFIP) guidelines, established in 1968. According to NFIP guidelines, development of floodplains is limited, while development is unlimited in areas above the level of 100-year flood (events with a 1% chance of occurring in any year) or protected by levees with at least 100-year protection. This criterion was adopted as a balance between protecting the public and overly stringent regulation (Holmes et al., 2010). With time, flood control by levees has been harshly criticized, especially since development in levee-enclosed areas promotes the belief that flood risk is eliminated. A National Academy of Science panel (National Research Council, 1982) stated: "it is short-sighted and foolish to regard even the most reliable levee system as fail-safe".

For this reason, and because levees disconnect floodplain habitat and affect ecosystem functioning, since the beginning of the twentieth century, other strategies have been preferred to levees. In particular, after evidence of the impossibility of 100% reliability for levee systems and substantial flood damages following the Great Flood on 1927, the Flood Control Act was approved, suggesting different strategies to give room to rivers, and some connectivity with floodplains: levee setback, channel improvements, and flood bypasses, which divert flows from the main channel. This strategy was in place in the Sacramento Valley by the 1920s (Kelley 1989).

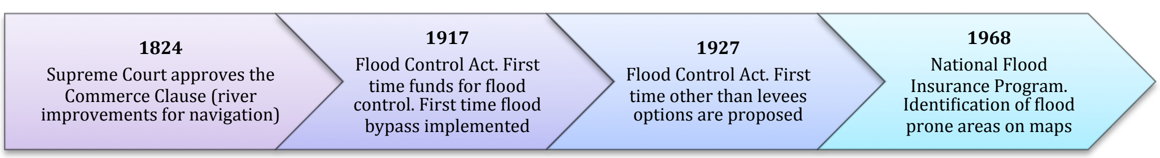


Figure 1.4 Major flood managment policies implemente in the United States

1.3 Floodplains

Recently, beneficial aspects of floods have been explored. Floodplain management faces potential conflicts and opportunities between reducing flood damage and achieving other floodplain benefits. Floods help restore riparian ecosystems, provide habitat for fish and wildlife, and help maintain plant and animal diversity. Floods also replenish agricultural soils with nutrients and water.

Flooding of historical floodplains and bypasses has two phases: an inundation phase with slower velocities which helps fishes, and a draining flood phase when water turbidity, depth, and velocity are low, and nutrients concentrated (Suddeth, 2014). Low flows enable fishes to move to feeding and spawning areas (Arthington, 2012). These conditions favor primary productivity (Suddeth, 2014), which supports a high invertebrate biomass that benefits floodplain fishes compared to fish in the river main stem (Bayley 1995). So, many species take advantage of floodplains.

1.4 Flood bypasses

A flood bypass or floodway permits excess water in a river or stream to be diverted to land that can better tolerate flooding and conveys excess flow downstream.
The first function of a flood bypass is to reduce regional flood risk. Flood bypasses also can help support ecosystems, provide land for agriculture, and provide other benefits.

Table 1.1 Flood bypasses around the world

Country	**River system**	**Bypass**	**Major Inflow Design capacity (m^3/s)**	**Principal references**
USA	Sacramento	Yolo bypass	9713 (Fremont Weir)	DWR, 2010
USA	Sacramento	Sutter bypass	1076 (Tisdale Weir)	DWR, 2012
USA	Mississippi	Bird's Point- New Madrid	15,574	USACE, 2008
USA	Mississippi	Morganza	42,475	USACE, 2008
USA	Mississippi	Bonnet Carre	7,079	USACE, 2008
Netherlands	Rhine	Kampen bypass	18,000	Sokolewicz et al., 2011
Austria	Danube	The New Danube	5,200	Chovanech et al., 2000
Spain	Turia	Plan Sur	Entire river diverted	López-Bermúdez et al.,2002
China	Yangtze	Lake Dongting & Poyiang	NA	Götz, 2006

The use of bypasses for flood management has short history. In 1920 a bypass was included as part of the Flood Control Project for the Sacramento River, after a series of major floods (Kelley, 1989). The technique was later used by the USACE for the Mississippi River. Today the technique is used in many places. The following is a brief description of the bypasses in the world and how different countries, such as the United States, China, and European countries, use flood bypasses (table 1.1).
Even if becoming common, the use of bypasses is still limited. Flood bypasses require extensive amount of land. Costs are high, and are mostly from acquisition of land, and structures construction. A bypass might be cost effective if in an area at high risk. Many other times levees are chosen over bypasses. A cost benefit analysis is usually conducted for the evaluation.

1.4.1 Bypasses in the United States

1.4.1.1 The Yolo and Sutter Bypasses, Sacramento River

Historically, California's Sacramento Valley has been prone to flooding because of its geographic position and weather. Floods from the Sacramento River are from a combination of rainfall, snowmelt, and soil moisture in the watershed. The surface runoff into the river can be quite large. Most comes from rain or snowmelt in the steep Sierra Nevada Mountains. The large and fast water, together with the shallow grade of the Sacramento River, often overtops riverbanks.

Flood management in California was created as a result of a series of inundations in the Sacramento Region, known as The Great Flood, covered much of the valley from December 1861, through the spring, and into the summer of 1862 (Bonta, 1973).
These main floods spanned 39 days, the first on December 9, 1861, the second December 23-28, the third January 9-12, and the fourth January 15-17

The Yolo Bypass

The earliest known origins of Sacramento River Flood Control system are in 1868, when Colusa Sun editor William S. Green called for a system of flood overflow basins for the Sacramento River. In 1894 consulting engineers Marsden Manson & C.E. Grunsky, working for State Commissioner of Public Works, issued Marsden & Grunsky Report for Sacramento Valley Flood Control, and presented it to California Governor. This was the first comprehensive report that advocated bypass channels (Marsden and Grunsky, 1984); (Kelley, 1989).

In 1907 the Sacramento River overtopped its banks north and south of Colusa, and similar intensity flood happened in 1909 (DWR, 2010). After these floods, the United States Army Corps of Engineers produced the foundation plan for the Sacramento Flood Control Project, "the Jackson Report" (Jackson, 1910), introducing the innovative idea of designing a flood flow of 600,000 cfs. By the 1920's, the Army Corps of Engineers completed the design of the bypass and implemented it. The Yolo Bypass has a design capacity of 343,000 cfs at the Fremont Weir and 500,000 cfs at Rio Vista. The major water sources are overflow from the Sacramento River and tributaries north of the Fremont Weir, the American River and its tributaries, Cache Creek, Willow Slough, and Putah Creek.

The floods of February 1986 and January 1997 severely tested the Sacramento Flood Control Project and the Yolo Bypass. In both floods, upstream flood control reservoirs prevented 1 million cfs from severely testing and inundating Sacramento Flood Control Project (DWR, 2010). Thus, the system design largely worked.

In addition to serving as an effective flood control facility, the Yolo Bypass acts as transitory storage and recharges groundwater. The Yolo Bypass serves as a wildlife refuge, grassland suitable for pasturage, and agricultural fields when not flooded.

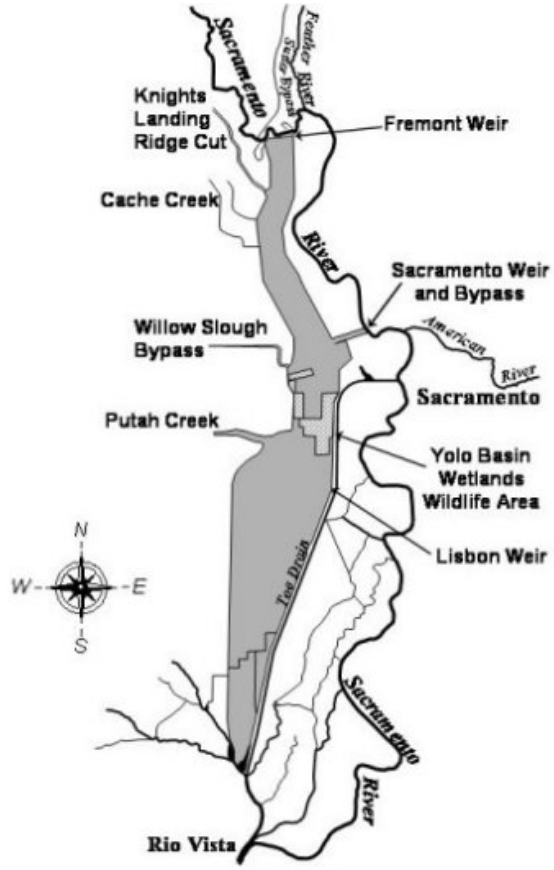


Figure 1.5 Yolo Bypass system in Sacramento Valley in California. Source: DWR, 2016.

The Sutter Bypass

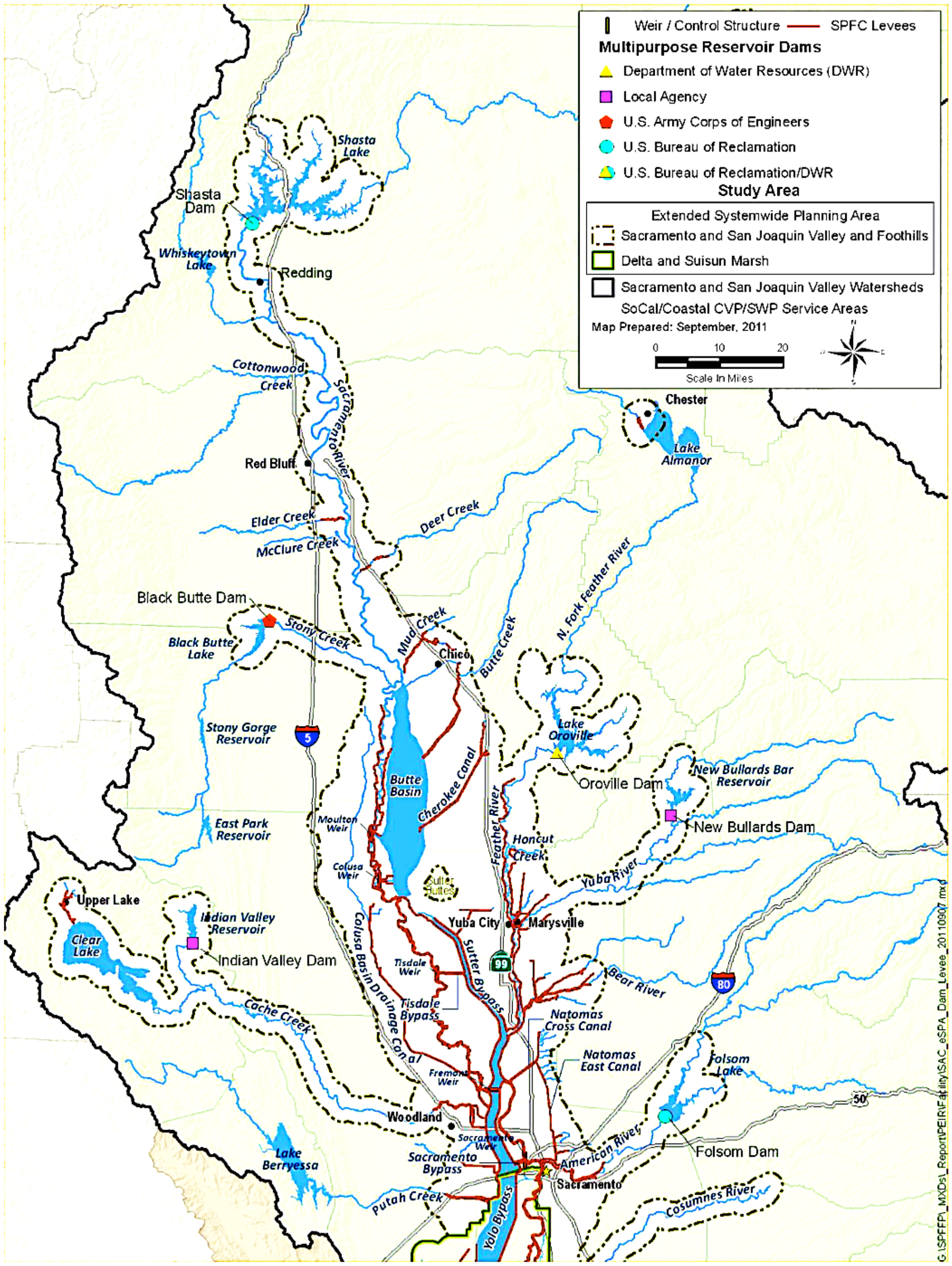


Figure 1.6 Location of Multipurpose Dams and Reservoirs and State Plan of Flood Control Levee in the Sacramento Valley and Foothills. Source: DWR, 2012.

The natural floodway in the Sutter Basin at its south part is leveed and is called Sutter Bypass. The Sutter Bypass began operating in 1930s. The bypass is south of the Sutter Buttes, between the Sacramento and Feather rivers.

Figure 1.6 shows the Sacramento Valley flood control dams, reservoirs, and flood bypasses (DWR, 2012). Water runs from the Butte Basin into the Sutter Bypass. Other inflows in the

Sutter Bypass include flows from pumping plants, the Wadsworth Canal, and the Sacramento River through the Tisdale Weir and Bypass.

Flows from the Sutter Bypass and the Feather River combine, and 7 miles downstream they further combine with the Sacramento River. Sutter Bypass design capacity upstream from the Fremont Weir is 380,000 cfs (DWR, 2012). During floods, much of this flow flows from the Sacramento River over Fremont Weir into the Yolo Bypass (Fig.1.6).

The Sutter Bypass is a route for floods, while providing other benefits. Much of land supports wildlife, with different species of birds, and terrestrial and riverine species. The area is also used for recreation, such as hunting, wildlife viewing, and fishing (California Department of Fish and Wildlife, 2016 (Fig. 1.7).

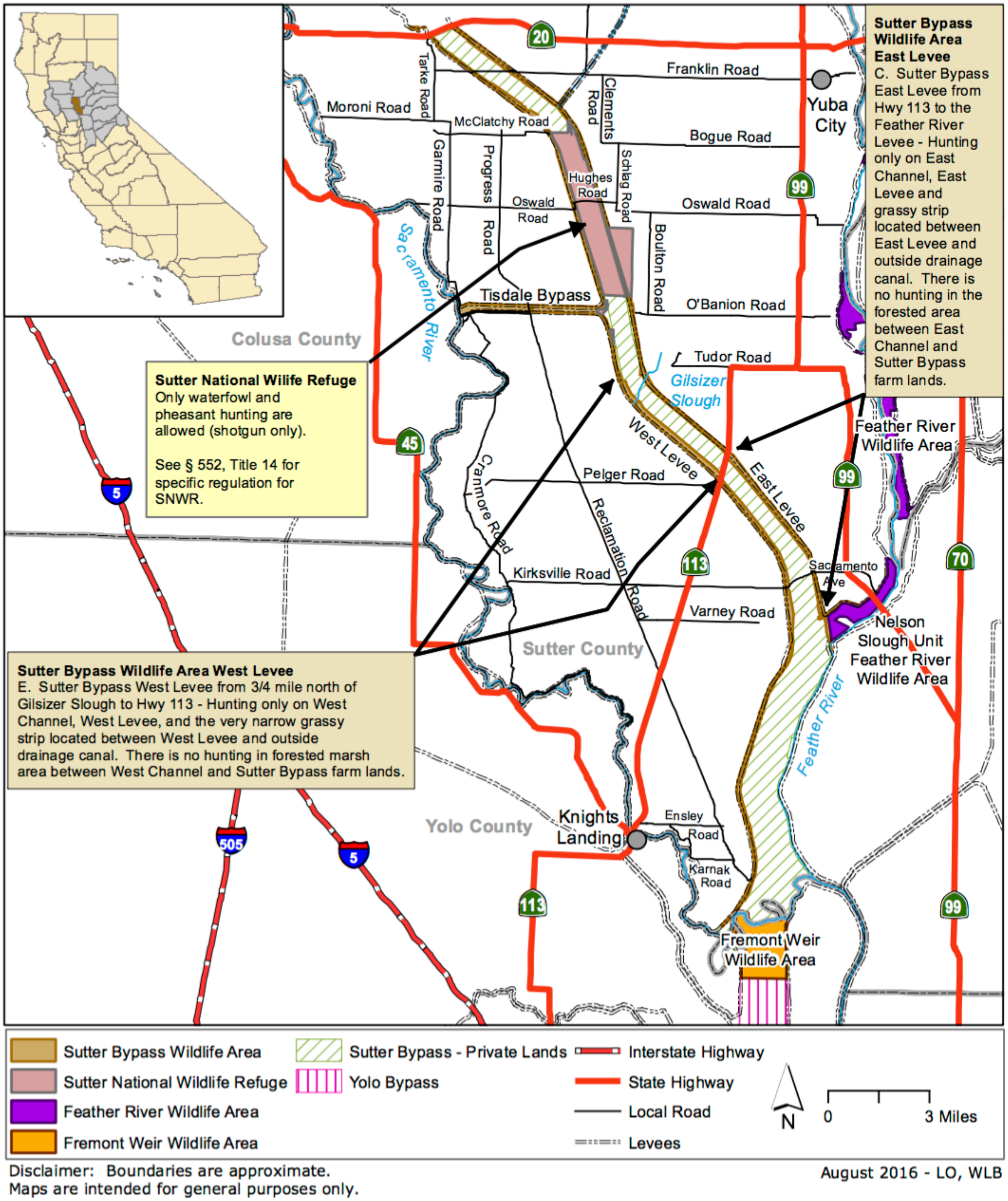


Figure 1.7 - Sutter Bypass map. Source: California Department of Fish and Wildlife, 2016.

1.4.1.2 Bird's Point-New Madrid, Morganza, Bonnet Carre, Mississippi River bypasses

The Yolo Bypass has been a highly effective part of the Sacramento basin federal flood management project. Learning from the experience on the Sacramento River, the U.S. Army Corps of Engineers designed and incorporated four floodways as part of the 1928 Mississippi River and Tributaries Project: Bird's Point-New Madrid, Morganza, Bonnet Carre, and the West Atchafalaya Floodway. The idea was to build a unified system of public works within the lower Mississippi Valley to enhance flood protection, and maintain an efficient channel for navigation (USACE, 2008).

The Mississippi River watershed is the third biggest watershed of the world, covering 41% of the United States (USACE, 2008). Before the tragic 1928 flood, flood control along the Mississippi river was by building levees "high enough" that could withstand the last greatest-recorded flood. For the first time in 1955 the Weather Bureau, the U.S. Army Corps of Engineers, and the Mississippi River Commission worked together to define the current project design flow. The sequence, severity, and distribution of past major storms have been analyzed together with 35 different hypothetical combinations of actual storms, with reasonable probability of occurring.

Upstream, floods are first regulated near Cairo. At a critical pre-defined level at Cairo, the **Birds Point-New Madrid Floodway** is opened. The floodway is 3 to 10 miles wide and approximately 36 miles long, with a diversion capacity of 550,000 cfs from the Mississippi River when open, producing about seven feet of stage lowering near Cairo (USACE, 2008). From the lower end of the Birds Point-New Madrid floodway to the Old River Control Complex, the design flood is confined by levees.
The Old River Control Complex was built in 1950 to prevent the Atchafalaya from capturing water from the Mississippi River. The system distributes flow between the Mississippi River and the Atchafalaya River as 70 and 30 percent respectively (USACE, 2008).

Thirty miles downstream, the **Morganza Floodway** diverts water from the Mississippi River to the Atchafalaya basin. Water is regulated by a 3,900-foot long and a 125-bay intake structure. The floodway was completed in 1953 with design capacity is 600,000 cfs during the design flood (USACE, 2008). The floodway is operated when the Mississippi River flows below Morganza exceed 1,500,000 cfs, to assure that flows between Morganza and Bonnet Carré remain at or below 1,500,000 cfs (USACE, 2008).

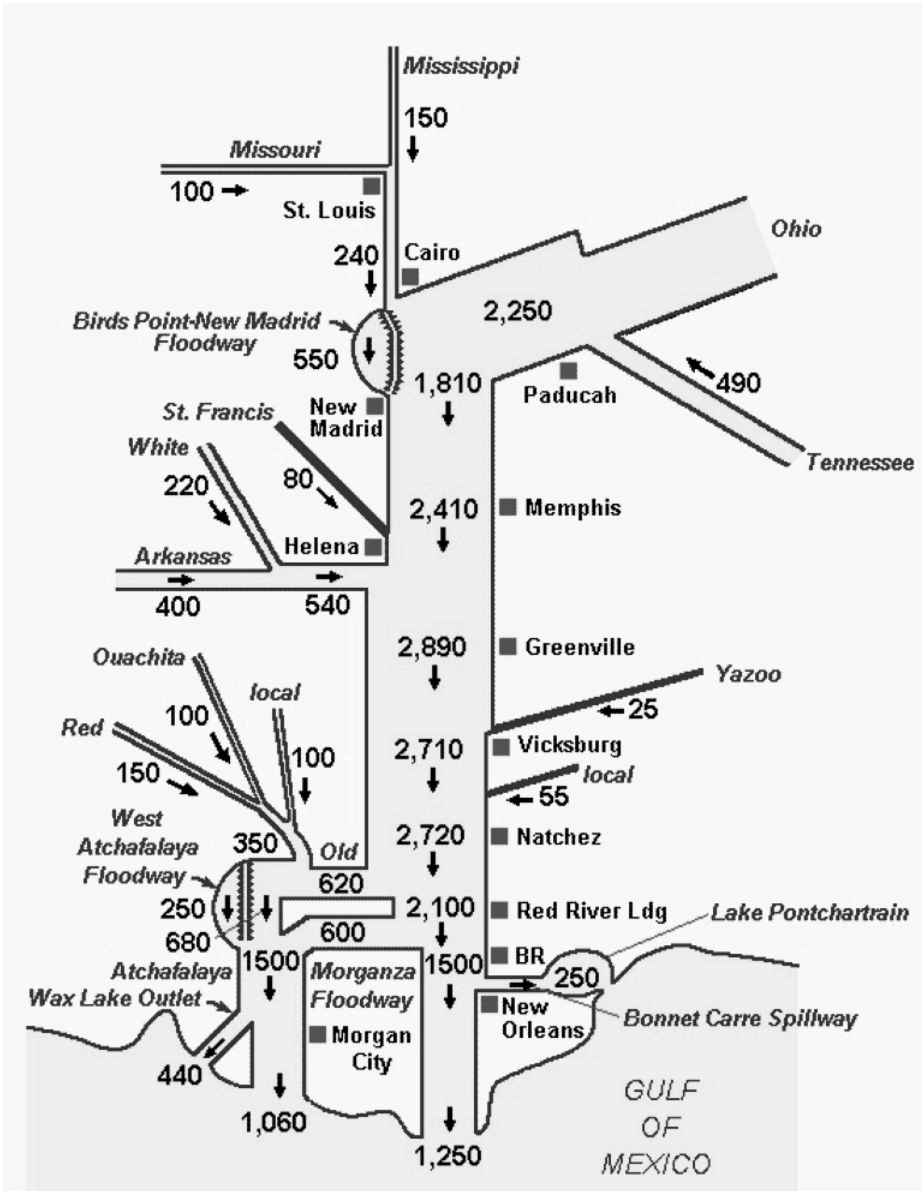


Figure 1.8 Mississippi River Project Design Flow (Flows in 1,000 cfs) Source: USACE (2008)

On the west side of the Atchafalaya River there is the West Atchafalaya Floodway. This floodway has a capacity of 250,000 cfs. The Atchafalaya River, the Morganza floodway, and the West Atchafalaya floodway converge to form the Atchafalaya basin floodway. This floodway can divert 1,500,000 cfs or nearly one-half of the project design flood discharge of 3,000,000 cfs at the latitude of Old River (USACE, 2008). At the latitude of Morgan City, Louisiana, 1,200,000 cfs are conveyed to the Gulf of Mexico by the Atchafalaya River and the remaining 300,000 cfs is passed to the Gulf through the Wax Lake outlet.

The **Bonnet Carré Floodway**, approximately 30 miles upstream of New Orleans, Louisiana, regulates the southeastern part of the system. The spillway structure is 7,200 foot long with 350 intake bays and a 5.7-mile long floodway that empties into Lake

Pontchartrain, which empties to the ocean. This floodway is designed to divert up to 250,000 cfs from the Mississippi River (USACE, 2008).

Table 1.2 Mississippi River Bypasses. Source: USACE, 2008

Mississippi's bypasses	Summary
Bird's Point-New Madrid Floodway, 1928, Missouri, US, Mississippi River	Operates in the Upper Mississippi River and protects Cairo, IL
Morganza Spillway, 1930-1954, Louisiana, US, Mississippi River	Diverts water from the Mississippi River during major floods and helps prevent the Mississippi from being captured by the Atchafalaya River
West Atchafalaya Floodway, 1937, Lousiana, US, Mississippi River	Together with the Morganza floodway and the Atchafalaya River is part of the Atchafalaya basin floodway. It diverts floodwater from the Mississippi River to the Gulf of Mexico by the Atchafalaya River and the Wax Lake outlet.
Bonnet Carre Spillway, 1931, St. Charles Parish (Louisiana, US), Mississippi River	Allows floodwaters from the Mississippi River to flow into Lake Pontchartrain and then to the Gulf of Mexico.

During the large Mississippi River flood of 2011, the Corps used of all three bypasses to reduce peak flows and protect urban populations in Cairo, Illinois and New Orleans, Louisiana. The decision to use all three bypasses was taken when the volume of Mississippi River flows reached 1.25 million cubic feet per second at New Orleans (USACE, 2008). The bypasses have been profitably farmed and inhabited for over 75 years, and provide important additional flood protection to major urban areas.

1.4.2 Bypasses in Europe

1.4.2.1 Kampen Bypass, Netherlands

The Netherlands are making floodplains a key part of their national flood management strategy, titled "Room for the River". This strategy seeks to reduce flood risks primarily from the Rhine River, which enters the Netherlands from Germany. Safety against flood does not rely only on building higher and stronger dikes but also increasing conveyance of the river system by creating more space for the flow (Sokolewicz et al., 2011). Among other measures, it incorporates a flood bypass around the Veessen-Wapenveld metropolitan area and dredging the Rhine's floodplain to increase flood conveyance capacity. The Dutch also identify the Room for the River strategy as the best means to manage the higher peak flows expected as climate changes, and to generate major environmental benefits with public safety improvements (Isoard and Winograd, 2013). The project's cost is € 2.3 billion (Sokolewicz et al., 2011), and will increased the maximum discharge capacity from 15,000

m^3/s to 16,000 m^3/s (Sokolewicz et al., 2011). Also, the environmental quality of the river area will be improved.

The Rhine River is the Europe's 3rd largest river. The river Ijssel is a major branch of the Rhine River. Floods from both the IJssel River and Lake IJssel threaten the IJssel Delta. The Delta is protected from flooding by dikes with a high safety standard. The IJssel Delta is mainly agricultural, with the city of Kampen (50,000 inhabitants) in its center. To increase flood safety along the river Rhine branches, a bypass has been planned.

Kampen bypass project includes the creation of a new river branch that connects the river Ijssel to the lake Ijssel by the lake Dronten.

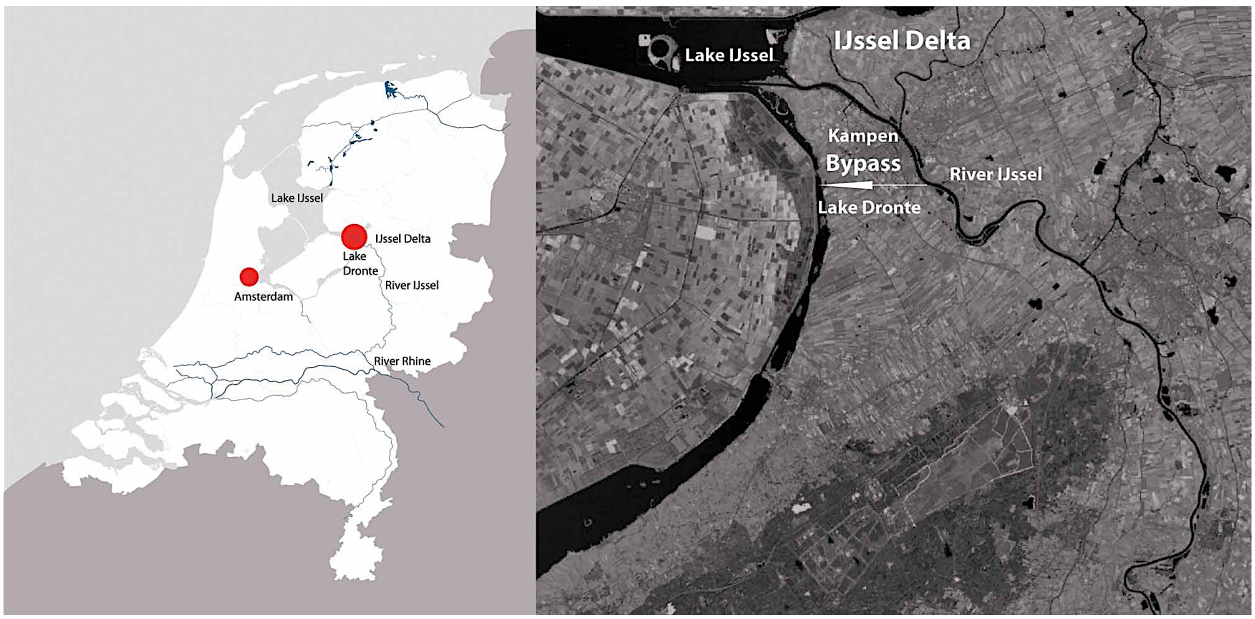


Figure 1.9 IJssel Delta in the Netherlands. Source: Sokolewicz et al., 2011

The bypass adds 350 hectares to the floodplains in the delta of the river IJssel. For excessive flow in the river IJssel 25% of the flow is diverted through the bypass to keep water in the river IJssel below the design level. Main purpose of the bypass is to increase river discharge capacity of the IJssel, anticipating on the expected river discharge of the river Rhine of 18.000 m^3/s at Lobith (Marlous van Herten & Steffen Neumann, 2013).

1.3.2.2 The New Danube, Austria

The Danube is Europe's second longest river, 2850 km long, flowing through 19 countries (ICPDR website). Its Austrian section is 350 km long (Chovanech et al., 2000). Recent damming and regulations have changed the geomorphology of the river.

River systems support dynamic and complex ecosystems. Over the last century, damming has disrupted these ecosystems. Hydraulic engineering has caused major environmental problems, such as habitat fragmentation, which threatens biological diversity (Chovanech et al., 2000). Many studies have examined returning an ecosystem closer to its condition prior to human development (Henry et al., 1995). Restoration ecology aims to improve the heterogeneity of ecosystems.

First major Danube River regulation was in the 19th century for navigation improvement and flood reduction. In its Austrian section the Danube has large hydroelectric power potential. In the second half of the 19th century, 10 hydroelectric plants were built.

The catchment area of the Danube in Vienna is 102000 km^2. High flows are common in May and June, and in the winter. The Danube has been largely channelized. Before it was a braided river with a tendency to change its bed away from Vienna, towards the northeast.

Flood risk management regulation started in the 17th century, with measures to increase navigability. In the 18th century embankments were built.

Large floods in 1830 and 1862 led to more regulation and actions. In1870 a straightened channel of 13 km was initiated, bringing together water from almost all the branches of the Danube, for navigation, flood control, and land development. The channel was divided into a main channel with a width of 300 m and an inundation plain with a width of 500 m (Chovanech et al., 2000).

Critics of this project led to improved flood protection for Vienna. A Bypass channel called the New Danube was built (1972-1980s). Danube Island separated the Danube from the New Danube. The New Danube has a capacity of 5200 m^3/s. The overall capacity of the system increased from 11700 m^3 to 14000 m^3, which is roughly a thousand-year flood (StaDt Wien, 2017). Three weirs control flow into the bypass.

The New Danube project started as a flood control project, but it also has recreation and restoration importance for the Vienna area.

1.3.2.3 Turia River, Spain

The Turia River is an extreme flood bypass case. The entire course of the river has been diverted far from the center of the city of Valencia, leaving a dry old river path. The old center-city river channel is now used for recreation, parks, and civic center development.

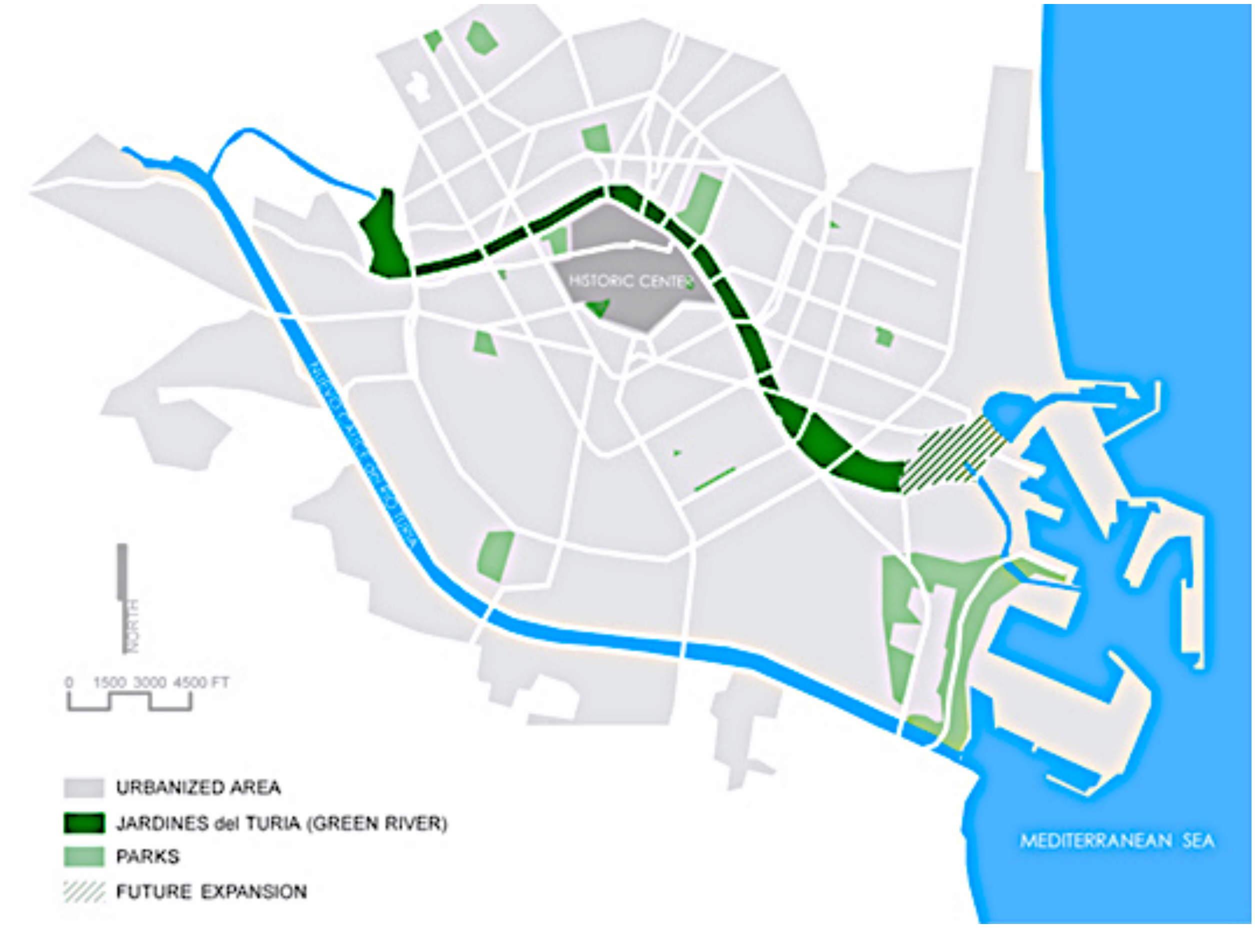


Figure 1.10 Map of Turia River re-routed in Spain. Source: Phelps, 2012

A flood in 1957 hit Valencia strongly (López-Bermúdez et al., 2002). From that catastrophic flood, the idea of diverting the river course was developed within the "Plan Sur". The project to reduce flood risk included creation of the Garden of the Turia in the dry riverbed, and was completed in 1969 (Visit Valencia, 2013) (Fig. 1.10).

The 120 hectares of dry riverbed were converted in a lush green garden split into twelve parts and full of native and non-native plants and Spanish wildlife, ponds and a zen garden (Visit Valencia, 2013).

1.3.3 Bypasses in China

1.3.3.1 Yangtze River

The Yangtze River is China's largest river and is subject to extreme flooding from summer monsoons. The Yangtze River basin also has a large population and economy. It runs from west to east into the East China Sea, with a drainage basin of more than 6300 km in length and a catchment area of 1.94×106 km^2 (Chen et al., 2001). The river is divided into the upper, middle and lower Yangtze reaches, based on geology and climate, and on geomorphology. The middle Yangtze is the most vulnerable region for flood hazard. Here flood control includes the Jingjiang dike, elevated to 12–16 m in different places above the ground surface, and the Three-Gorges Dam, in the Yichang. In the 1960s fluvial environment got managed to stabilize migration through cutoff, shortening the river by approximately 78 km (Chen et al., 2001) in the Jingjiang area.

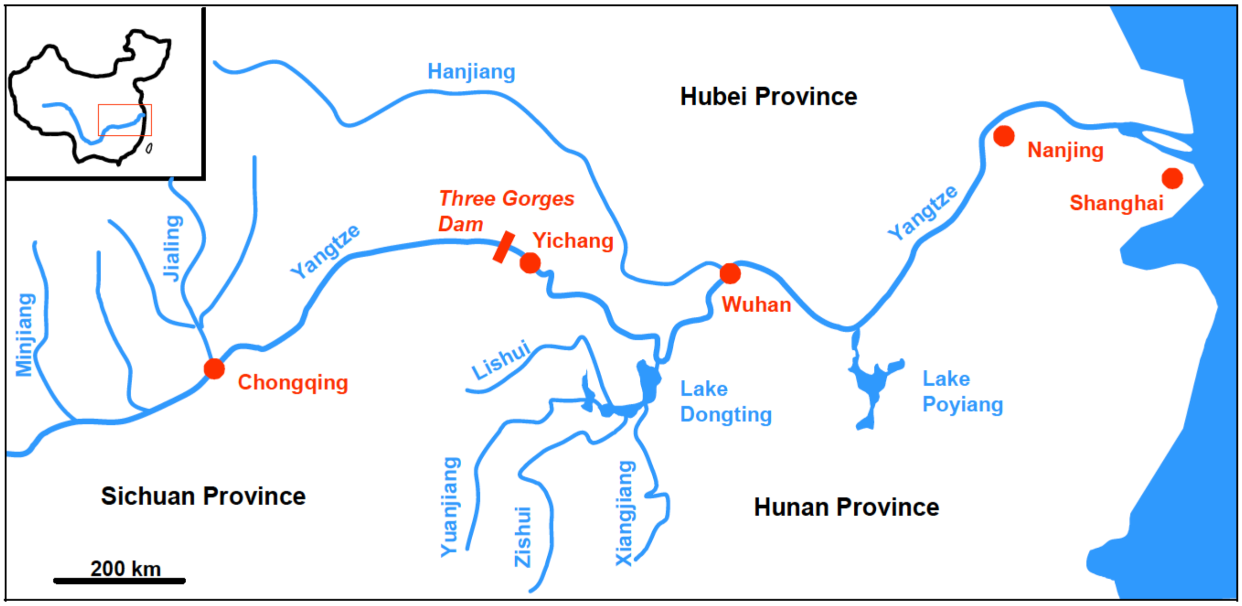


Figure 1.11Yangtze River. Source: Götz (2006)

The risk to people, ecosystems, and the economy from flooding in the central and lower Yangtze region is partly due to reclamation of floodplains for agriculture and increasing siltation from erosion in the watershed. Climate change may cause more frequent floods in the basin (Editorial Committee, 2007).

In 1998, severe flooding convinced the Chinese government to reevaluate flood management and adapt new policies focusing on environmental restoration. To increase floodwater retention capacity, agricultural polders and embankments were removed to restore 2,900 square kilometers of floodplains.

1.5 California's riverine systems

On average, 200 million acre-feet/year of precipitation fall on California (Hanak et al., 2011). Most of this water evaporates, leaving "unimpaired runoff" and flows downstream. California is a global anomaly in its spatial and temporal variability in annual and seasonal precipitation (Fig. 1.12).

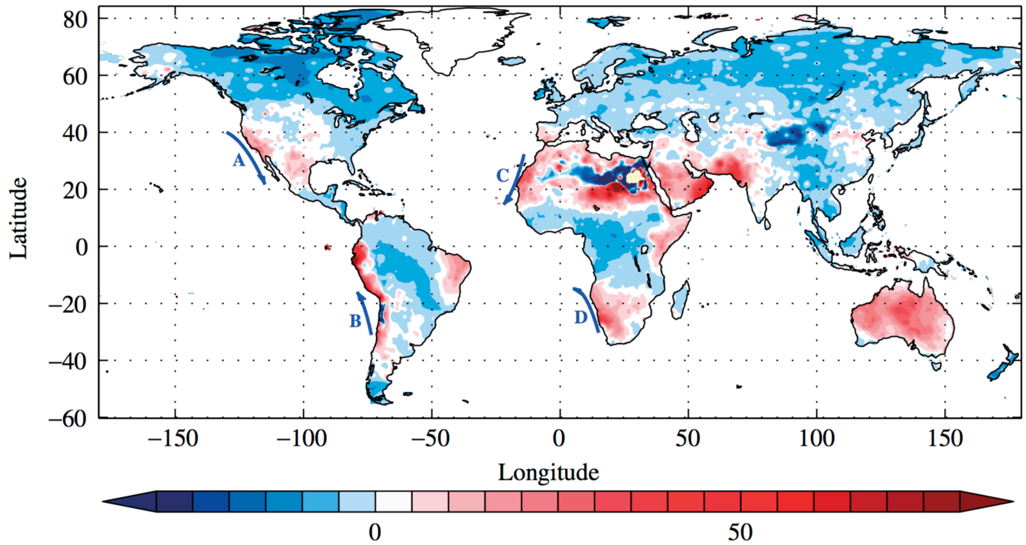


Figure 1.12 Spatial distribution of the anomaly of coefficient of variation calculated for the total annual precipitation during the period 1951–2000. The completely dry area where anomalies are not defined is marked yellow. A, B, C and D denote respectively the Californian, Humboldt, Canary and Benguela currents, respectively. Source: Sokol et al. (2016)

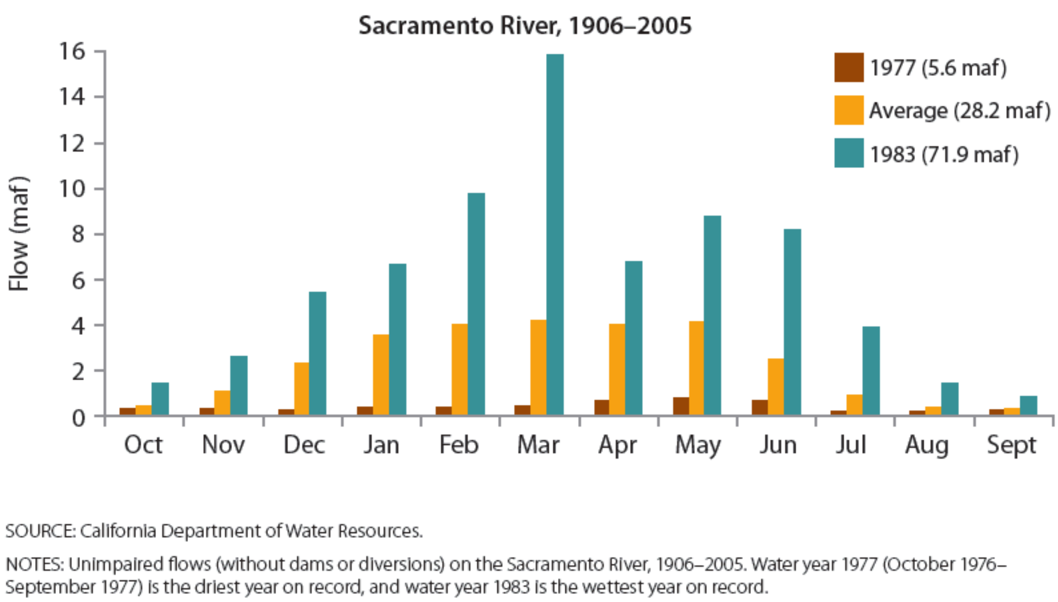
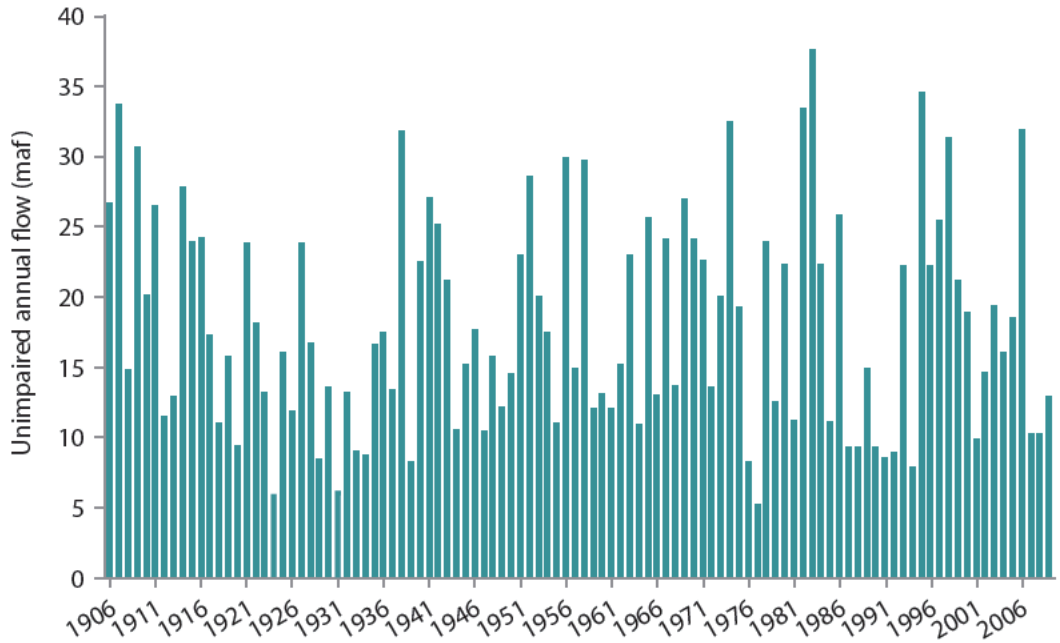


Figure 1.13 Sacramento River natural flow. Source: Hanak et al., 2011



SOURCE: California Department of Water Resources, California Data Exchange Center data.

NOTE: The figure shows unimpaired flows (the natural flows that would have occurred without dams or diversions) on the Sacramento River, 1906–2009.

Figure 1.14 Sacramento River natural stream flow year variability. Source: Hanak et al., 2011

California's north is wet with approximately two-thirds of all annual runoff, while the south is very dry, with much less water availability (Hanak et al., 2011). Extensive agriculture dominates the arid Tulare Basin and Imperial Valley. Most population also is in the more arid south. Variations are significant also during the years. The Sacramento River is the largest river in California with floods and multi-year droughts.

The current flood protection system includes reservoirs, levees, and flood bypasses (Figure 1.15), as well as land use controls and evacuation systems. Levees usually limit the area of flooding by containing water within banks. In the Sacramento Valley, flood bypasses augment levees and reservoirs for flood control. Flood bypasses create an additional route for the water of the Sacramento River to flow. Large areas of flood bypasses are also used for agriculture and habitat. The flow is also regulated upstream with reservoirs operations.

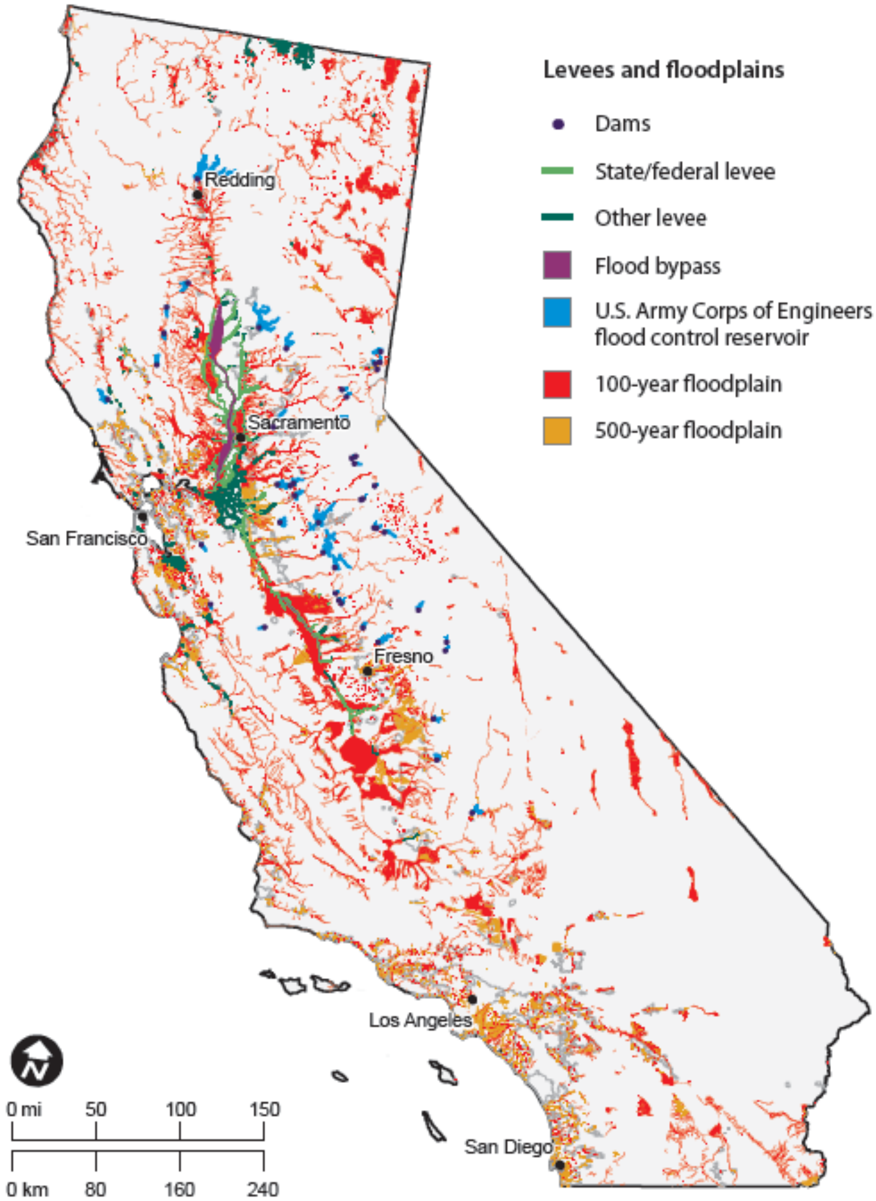


Figure 1.15 California flood protection system. Source: Hanak et al., 2011

Almost 5 percent of California's households live in the "100-year" floodplain, and approximately 12.5 percent in the "500-year" floodplain. During large floods the State faces challenges. In particular, the Sacramento area is the most hit (Hanak et al., 2011).

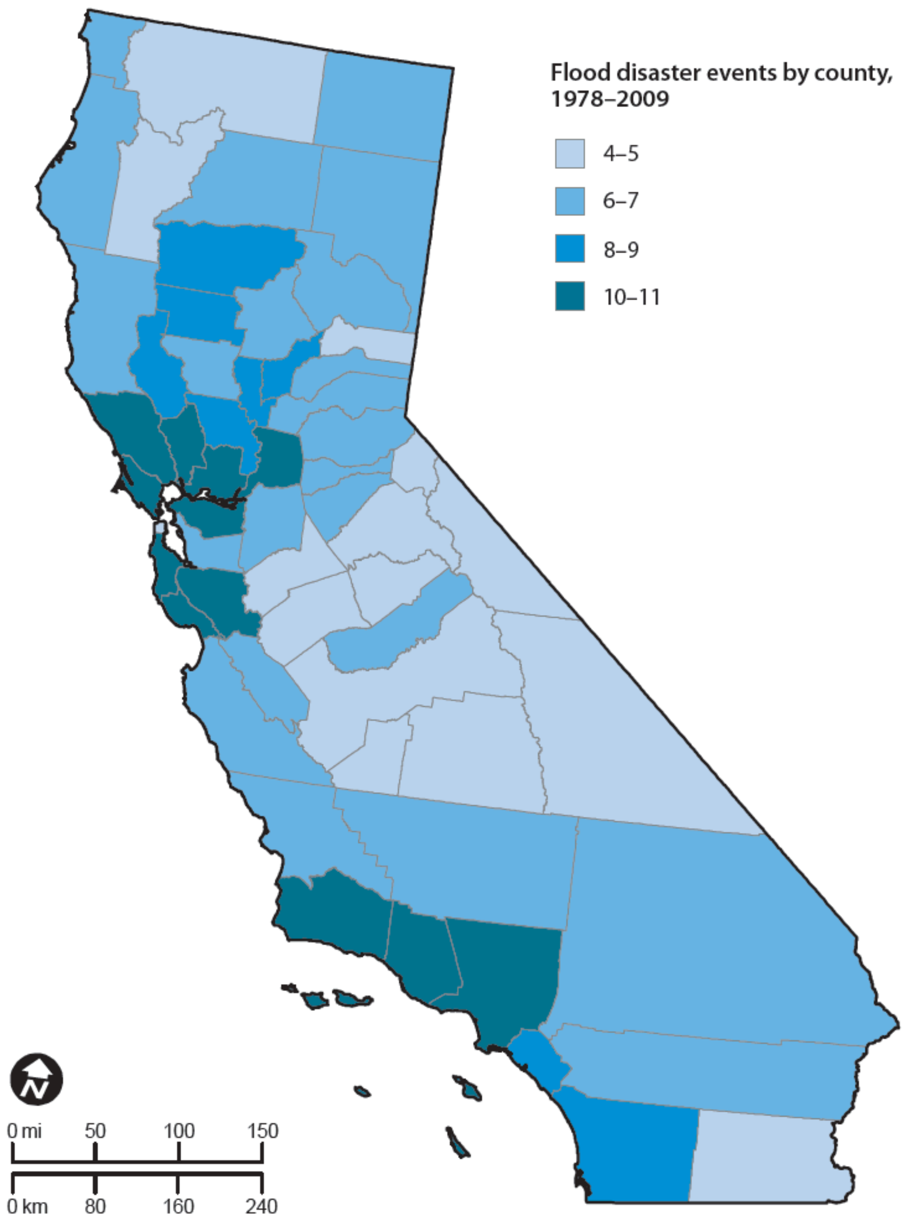


Figure 1.16 Flood disasters in California. Source: Hanak et al., 2011

1.6 California flood history

Despite the certainty of another severe flood, Californians often lack concern for flood risk, especially when major floods are not frequent. In California, with history of alternating floods and droughts, the general public's concern with flood risk notably decreases between one flood and the next. But significant floods can occur in any year. In the last 100 years all counties have suffered flooding with billions of dollars in damaged infrastructures and more than 300 deaths.

To assess flood response, floods from 1964, 1969, 1986 and 1997 are examined. Few efforts have been made to collect data on extreme floods, and even fewer efforts dedicated to collecting information on levee failures and flood response. The National Water Summary 1988-89 – Hydrologic Events and Floods and Droughts, reports floods with major impact in terms of magnitude and areal extent from 1827- 1987 (Paulson & al., U.S.G.S., 1991). Floods with the greatest loss of life or property were selected, but many significant floods were not included (Paulson & al., U.S.G.S., 1991). Two severe floods in 1995 and 1997 are added to this list.

Table 1.3 History of Major Floods in California (1827-1987), (SOURCE: USGS, 1988-1989) *

Date	**Area Affected**	**Recurrence Interval (in years)**	**Remarks**
Dec. 1861- Jan. 1862	Statewide	Probably >100	Record stages on major rivers from Oregon to Mexico
1863- 1936	Variable	Unknown	Major: Dec. 1867, Feb. 1884, Jan. 1895, Mar. 1906, Mar. 1907, Jan. 1909, Jan 1916.
Dec. 1937	Northern two-thirds of State.	5 to >100	Several peaks of record in northern and central Sierra Nevada. Damage $15 million.
Mar. 1938	Coastal basins from San Diego to San Luis Obispo, and parts of Mojave Desert.	50 to 90	Worst in 70 years. Deaths, 87; damage, $79 million.
Nov.- Dec. 1950	Kern River basin north to American River basin.	25 to 80	Deaths, 2; damage, $33 million.
Dec. 1955	Northern two-thirds of State.	10 to 100	Deaths, 76; widespread damage of $166 million. It lead to the creation of DWR in California
Dec. 1964	Northern one-half of State	10 to >100	Greatest known in the history of northern California. Deaths, 24; damage, $239 million.
Dec. 1966	Kern, Tule, and Kaweah River basins.	>100	Deaths, 3; damage, $18 million.
Jan.- Feb. 1969	Southern and central coastal California, parts of Mojave desert.	30 to 50	Deaths, 60; damage, $400 million.
Jan.- Feb. 1980	Central and southern coastal California.	10 to 50	Most severe in southern California. Deaths, 18; damage, $350 million.
Jan. 1982	San Francisco Bay area.	30	Severe, mudslides in mountains north of Santa Cruz. Deaths, 31; damage $75 million.
Feb. 1986	Northern one-half of State.	20 to 100	Peak discharge of record in Napa River and upper Feather River basins. Deaths, 14; damage, $379 million.

Table 1.4 History of Major Floods in California (years 1990-present), (SOURCE: USACE, 1999)

Date	**Area Affected**	**Recurrence Interval (in years)**	**Remarks**
1995	Statewide	Probably >100	Rainfall amounts were greatest in

			Humboldt, Lake, Mendocino, Napa, Sacramento, Shasta, Sonoma, and Trinity Counties. Damage $220 million, 18 deaths.
1997	Central Valley	>500	Major Flood in Central Valley; damage, $2 billion

Major Floods in California Modern History

December 1964

The floods of December 1964 resulted from an unusual arctic air stream on December 14 and rain from December 18th to 20th. Another storm arrived from Hawaii on December 20. A mix of warm and cold air produced strong rainfall that melted snow from the earlier storm. The heaviest rains were on December 22 and 23, but the nine-day totals (December 19-27) were also impressive (DWR, 1965). The Feather, Yuba, and American Rivers basins had the most precipitation and exceeded all previous records. The Mattole River basin recorded 15 inches rainfall in 24 hours, and rain from December 19 to 23 totaled 50 inches. Yet, again on December 23 large flow peaks were recorded on rivers in the coast of California, with recurrence intervals exceeding 100 years. Many bridges and roads along major rivers failed. Multiple towns along Eel and Klamath River were heavily damaged, and twenty-four deaths were reported. The U.S. Army Corps of Engineers estimated total damage for the State of $239 million (Paulson et al., 1991).

The flood occurred by levee failure. In the Sacramento River "Major and Minor Tributaries Project" the only levee breaks were on Deer Creek tributary to the Sacramento River near Vina. In the Sacramento Basin total damage was about $25 million (DWR, 1965). The "San Joaquin River Flood Control Project" suffered ten levee breaks, with damage in the San Joaquin Basin near $4 million (DWR, 1965).

January-February 1969

From January 18 to 27, 1969 multiple storms occurred in central and southern California, as warm air arrived from the southwest with large quantities of rain on the coast from Monterey Bay to Los Angeles and in the Sierra Nevada. In February a cold storm moved south, together with a low-pressure perturbation in the coastal area. During the 22nd to the 25th of February, 5 to 15 inches were recorded (the water year's precipitation exceeded 150% of normal). The same areas flooded in January were flooded again in February, with similar intensity. River levees failed in the Sacramento-San Joaquin Delta, on the San Joaquin River, and on the Stanislaus River. The most hit area was Southern California. Forty of California's 58 counties were declared as disaster areas. The 1969 flood injured 161 persons, hospitalized 40, and killed 47 (DWR, 1970), with damage totaling $ 400 million (Paulson et al., 1991). In May, heavy snowmelt in the San Joaquin River basin registered high flows. High releases were ordered at the major San Joaquin River basins reservoirs. Some releases caused damage, in particular along the Kings and San Joaquin Rivers. Over 89,000 acres of land in the lakebed were inundated.

The 1969 flood is an example of a flood caused by levees failure. Yet, ironically, it is an example of good cooperation among the Department of Water Resources, U. S. Weather Bureau, U.S. Bureau of Reclamation, U.S. Army Corps of Engineers, and local irrigation districts. Because of coordinated efforts during the critical snowmelt predicament, major snowmelt floods were prevented (DWR, 1970).

February 1986

In 1986 weather conditions generated flooding similar to the 1964 floods. During February it rained for 12 days, from the 11th to the 22nd. Santa Rosa, Yuba City, and the Yuba and American river basins were the most affected. Twenty to thirty inches of rainfall were recorded in the Feather River basin, and a record flood peak in the upper Feather River basin. Downtown Napa had major flood damage, multiple bridges were destroyed, and a damaged State Highway 70 was closed for several months.

Bypass weir operations, reservoirs releases, and overflow channels contributed in managing the flood. Despite the efforts, levees failures caused 14 deaths and the California Department of Water Resources estimated almost $380 million damages (Paulson et al., 1991). Prior to the floods, communities along Yuba and Feather Rivers appeared well prepared for a possible flood. As weather conditions worsened, evacuations were called for in hazardous areas. Heavy precipitation, high river levels, and several smaller levee breaks in the region alerted local residents and authorities. As a result, when levees did fail most people were already evacuated.

Reductions in property value were another consequence of the 1986 flood, particularly in Linda and Olivehurst. In some cases, the costs of the repairs greatly exceeded the market value of property (Montz and Tobin, 1986). Within a few months, houses were again on the market but with lower list prices than for comparable homes before the flood (Montz and Tobin, 1986).

The 1986 flooding showed flood control deficiencies in the state. The Department of Water Resources concluded that California's Central Valley flood control system had deteriorated, putting emphasis on the problems of population growth and new housing developments in flood risk areas. Underlining the decline was lack of funding to maintain and upgrade flood protection. Yet, as of 2003, the Third District Court of Appeal of the State of California ruled (the Paterno Decision) the state liable for flood-related damages caused by Flood Control Project levee failure. Under the theory of inverse condemnation, the court determined the failure of the levee was foreseeable. The state was responsible for damaged totaling $400 million in the unincorporated Yuba County Communities (Shigley, 2005). This ruling greatly increased state responsibility for flooding in areas with "state" levees.

1997 Flood

In late 1996 and early 1997, the states of California, Nevada, Washington, Oregon, Idaho and Montana experienced extreme weather. Extensive floods from snowmelt were generated when coming storms mixed with unexpected warm temperatures. Multiple locations registered over 30 inches of rainfall from December 26 until January 3. Total precipitation for December 20, 1996 and January 3, 1997 are listed in Table 1.5. Table 1.6 lists peak flows for stream gages that equaled or exceeded previous maximums during 1997.

Table 1.5 Total Precipitation, December 20, 1996 - January 3, 1997, (Source: USACE, 1999)

Location	Precipitation (inches)	River Basin
Bakersfield	1.11	Kern River
Blue Canyon	39.34	American River
Brush Creek	37.04	American River
Fresno	3.08	San Joaquin River
Mc Cloud Ranger Station	14.83	Sacramento River
Mount Shasta	10.06	Sacramento River
Paradise Fire Station	22.66	Feather River
Sacramento	5.67	American River
Strawberry Valley	37.41	Feather River
Success Dam	3.36	Tule River

The U.S. Geological Survey reported 15 river floods in California, and with 3 rivers exceeding historical peaks: Consumnes River at Michigan Bar had a peak of over 90,000 cfs, exceeding the previous record by almost 50,000 cfs. The South Fork American River near Placerville recorded a flow volume of 71,000 cfs, exceeding the previous record by more than 20,000 cfs.

Table 1.6 Peak Flows For Stream Gages That Equaled Or Exceeded Previous Maximums During 1997, (Source: USACE, 1999)

Stream Gage	Drainage Area (sq mi)	Previous Date	Previous Maximum Flow (cfs)	1997 Maximum Flow (cfs)
Tuolumne River at Modesto	1884	1950	57,000	55,800
Cosumnes River at Michigan Bar	536	1986	45,000	93,000
South Fork American River near Placerville	598	1964	47,300	71,000
South Fork American River near Camino	493	1955	49,800	62,300
South Fork Mokelumne River near West Point	75.1	1986	7,300	7,600

In total, 43 of 58 counties in California were declared disaster areas. Approximately 16,000 residences were damaged or destroyed, more than 6,000 in Sacramento Valley, as shown in table 1.7.

Table 1.7 1997 Rain Flooding Of Residences, Mobile Homes, Businesses, Roads, And Bridges In The Sacramento Valley, (Source: USACE, 1999)

County	Residences Damaged[1]	Mobile Homes Damaged [1]	Businesses Damaged [1]	Roads Damaged? [2]	Bridges Damaged? [2]
Butte	250	73	320	yes	yes
Colusa	6	0	0	yes	-----
Glenn	55	9	1	yes	-----
Placer	137	0	22	yes	-----
Sacramento	2,495	172	29	yes	-----
Shasta	10	1	7	yes	-----
Solano	1,466	118	1	yes	-----
Sutter	1,280	30	600	yes	-----
Tehama	24	6	20	yes	yes
Yolo	0	0	0	yes	-----
Yuba	700	80	30	yes	-----
Totals	6,423	489	1,030	yes	yes

Notes:
1 California Governor's Office of Emergency Services, 1997. 2 Corps, 1997a.

Most flooding occurred in the Sacramento and San Joaquin River Basins from levee failures along the American, Feather, Tuolumne, San Joaquin, and Sacramento rivers. Property damages exceeded $2 billion (National Climatic Data Center, 1997). Authorities reported 8 flood-deaths. The 1997 flood was the most destructive of California's history economically. Table 1.8 lists the levee breaks and areas that flooded during the 1997 flood in the Sacramento and San Joaquin valleys.

Table 1.8 Areas Affected by Flooding During 1997 Rain Flood, (Source: USACE, 1999)

(RD = Reclamation District)

Stream	Area	Description
Sacramento Valley		
Butte Creek	State Maintenance Area 5	Both levees overtopped. West levee failed.
Deer Creek	Tehama County	Levee breaks on both levees
Elder Creek	Tehama County	Levee break on the south levee
Feather River	RD 784	East levee failed near town of Arboga
Bear River	RD 784	North levee failed in two places
Dry Creek (Yuba City)	RD 817	South bank overtopped
Sutter Bypass	RD 1660, RD 70, town of Meridian	West levee failed, flooding RDs 1660 and 70
San Joaquin Valley		
San Joaquin River	Lower San Joaquin Levee District	North levee failed in seven places in Madera County; south levee failed in four places in Fresno County; levee overtopped upstream from Chowchilla Canal Bypass

San Joaquin River/ Stanislaus River	RD 2064	East levee failed in two places
San Joaquin River	RD 2075	East levee failed in three places
San Joaquin River	RD 2094	East levee breached in four places; water from RD 2094 break flooded RD 2096
San Joaquin River	RD 2101	West levee failed in three places, inundating RD 2099, RD 2100, RD 2101, and RD 2102)
San Joaquin River	RD 2099	West levee failed (spur levee)
San Joaquin River	RD 2100	East levee failed in two locations
San Joaquin River	RD 2096	East levee failed, mouth of Walthall Slough
San Joaquin River	RD 2091	Spur levee failed
Tuolumne River	Modesto, Waterford, La Grange, & Roberts Ferry	Bank overtopped due to high flows from Don Pedro
Cosumnes River	Wilton	Four breaks; 1 overtopping - private levees
Cosumnes River	Sacramento and San Joaquin Counties	Numerous breaks and overtopping of private levees
San Joaquin River	RD 2031	East levee failed in two places
Finnegan Cut	RD 2031	East levee failed
Sacramento - San Joaquin River Delta		
Paradise Cut	RD 2107	East levee break floods RDs 2062 and 2107
Paradise Cut	RD 2095	Partially inundated when south levee failed
Tom Paine Slough	RD 2058	Partially flooded by overflow of unleveed Tom Paine Slough
Prospect Island	Prospect Island	Multiple levee breaks

Multiple problems emerged from the 1997 Northern California Floods: inadequate emergency response, uncoordinated information from officials, and late release of equipment for actions (California State University-Stanislaus, 1997). The irregular emergency response was because initial precipitation seemed controllable. But when a warm front arrived, snowmelt in Sierra Mountains occurred and the flow rate became uncontrollable. During moments of confusion, public officials released different declarations. For instance, an evacuation was ordered for the town of Marysville. During the evacuation, a person from DWR was interviewed and expressed no concerns of flood danger. This led to loss of credibility in public officials.

Problems continued to accumulate due to the State Office of Emergency Services (OES) failure to respond properly. A major problem was procurement of essential supply and equipment, and authorization for the equipment was handed down by the OES. Local agencies requested equipment from each other, without having official authorization. This lack of interagency coordination needs careful scrutiny; whereas some sort of accountability must be in place for state equipment, nature does not always wait for official authorization (California State University-Stanislaus, 1997).

Emergency professionals worsened the situation by being unable to answer questions from the public. Residents were terrified by not knowing how high the waters would go, if the dams and levees would hold, and what conditions would lead to imminent flood. Emergency professionals and public officials were unprepared.

1.7 California flood management

Flood management reduced flood damages through a portfolio of activities: prevention and preparedness prior to the flood, response, relief and mitigation actions during the event, and reconstruction, economic recovery, and efforts to prevent further flooding after the floods. The 2002 United Nations report on the Guidelines for reducing flood losses, written in collaboration with the National Oceanic and Atmosphere Administration (USA NOAA) suggests a multiple actions approach (UN & USA NOAA, 2002). In particular, the multiple approaches should consider restricting development in the floodplain, flood proofing of structures, control and maintenance of levees and other structural flood protection actions, a rational land use management, and a warning system using forecasting. The guidelines emphasize practical and sustainable solutions for areas at risk.

In the United States, flood management involves federal, state, local, and private decisions. These decisions encompass land use management, building standards, education, preparedness and the relationship between land use and conservation of resources. In 1968 the United States Congress introduced the National Flood Insurance Act, which lead to the National Flood Insurance Program (NFIP). Flood insurance is now required for properties in areas at high risk of flooding (25% chance of flooding during a 30-year mortgage, equivalent to 0.83% chance of flooding per year) (FEMA, 2014).
On April 1, 1979, the Federal Emergency Management Agency (FEMA) was created. Its role is to encourage citizens and first responders to improve their preparedness, protect against, respond to, recover from and mitigate all hazards (FEMA, 2014). The Federal Emergency Management Agency emphasizes the importance of hazard mitigation planning to reduce risk, damages and future losses.

Flood risk reduction actions

A risk analysis can lead to the production of risk maps based on surveys of vulnerability and topographic maps. The map helps identifying weak points. Risk management also includes maintenance practices and preparedness, response, relief and mitigation actions during the event, and reconstruction, economic recovery, and again efforts to prevent further flooding after the floods (figure 1.17).

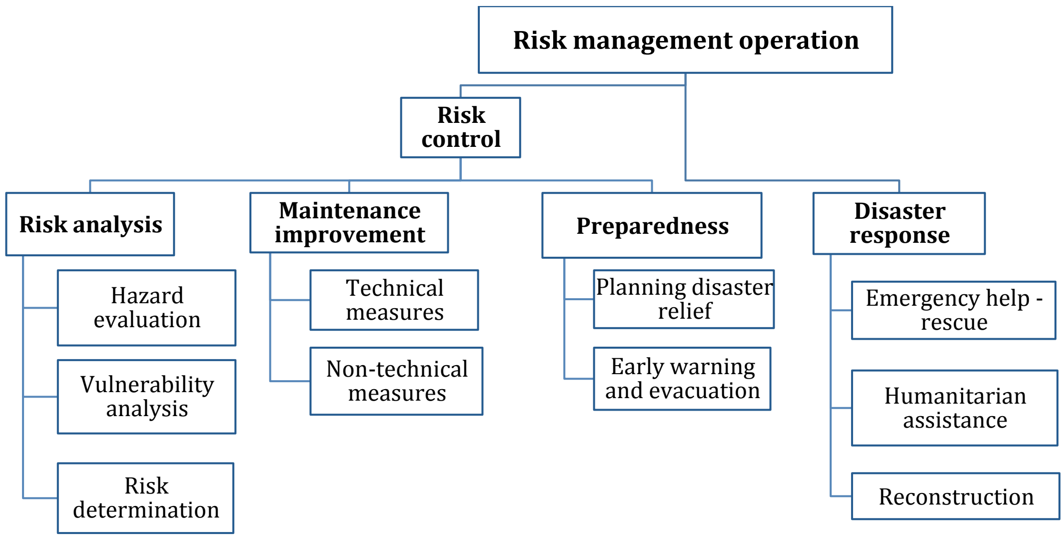


Figure 1.17 Risk Management Operations, adapted from Plate (2002)

Traditionally, actions to reduce flood risk were classified as structural, which modify the characteristics of flow, or non-structural, which usually reduce damages from a given flow. Structural actions can be direct, such as increasing stream conveyance capacity which reduces the frequency of flood, and levees which reduce the extent of areas flooded, or indirect actions, such as retarding and balancing basins, bypasses, floodways, detention basin or reservoir, which reduce the peak of flow. Non-structural actions encompass the use of flooding areas, mapping of area at risk, prevention of the flow peak, flood warning and evacuation of the areas, flood-proofing, flood insurance (Poggi, 2009). Flood fighting actions are listed in the 2002 State of California Emergency Flood Fighting Actions (DWR, 2002).

Another way to categorize these actions is to consider them over decision periods as preparatory, response, and recovery actions (Lund, 2012). Prevention actions reduce the probability of flooding by protecting or reducing potential flood damage to an area. The construction of levees, channel improvements, reservoirs, bypasses, drainages and pumps, together with regular inspections, assessment and maintenance are typical protection actions. Actions that reduce the flood vulnerability of an area reduce potential flood damage. These include: allocation of human activities far from the floodplain (land management), definition of flooding area through maps, and adapting construction standards for buildings such as flood proofing, raising structures etc.

Flood response actions include monitoring levees, flood fighting, reservoirs operations, warning, and evacuations during the flood. Recovery actions encompass reconstruction and repair of flooded infrastructures and structures, flood damage assessment, flood insurance (table 1.9) (Lund, 2012).

Flood damages depend on hydrologic, social, economic, and environmental conditions. Traditionally, large structural flood control structures (dams and reservoirs, bypass channels and levees) have modified the territory and hydrologic dynamics. Past structural solutions led to strong environmental concerns today. Moreover, flood protection structures are not completely reliable. They fail when events exceed a structure's design event, or when the design or its implementation are inadequate. With time, this has led to changes from classical flood control to broader flood management. Integrated Flood Management considers both flood risk control and sustainability (World Meteorological Organization, 2007).

Table 1.9 Major management portfolio options (Lund, 2012)

Protection	Vulnerability duction (Reduced damage and casualty potential)
PREPARATORY ACTIONS	
Levees	Relocation of vulnerable human activities
Flood walls and doors	Floodplain zoning and building codes
Closed conduits	Floodproofing–raising structures, sacrificial first floor, watertight doors, and flood vents
Channel improvements and flood corridors	Flood warning and evacuation systems
Reservoirs	Flood insurance and reinsurance
Bypasses	Flood risk disclosure
Sacrificial flooding	Public and policymaker education
Flood easements (bypasses and designated\ flood areas)	Flood preparation and training exercises
Local detention basins, drainage, and pumps	Floodplain mapping, gaging, data collection and availability
Regular inspections, assessments, and maintenance	Community engagement and multi-hazard planning
RESPONSE ACTIONS	
Levee and flood wall monitoring (structures and seepage)	Warnings, evacuation calls, and emergency mobilization
Flood fighting–sandbagging, sheet pile installation, wave wash protection, splash cap installation, ring levee construction, relief cut, pumping, and breach closure and capping	High water staking
Flood door closure and gate operation	
Reservoir operation–including coordinated operations, rule curve operations and encroachment, flash board installation, and spillway surcharging	
RECOVERY ACTIONS	
Reconstruction and repair of flood infrastructure	Flood damage assessment–flood infrastructure surveys, system performance, damage, response costs Flood insurance and reinsurance Reconstruction and repair Relocation or reconstruction to reduce future flood vulnerability

Many factors affect integrated flood management decisions: perception of risk, balance between protection of ecosystems and protection from floods, political and economic factors, and technical limitations. Poor flood risk management can increase loss of lives, economic losses, or excessive flood management costs. Flood risk management can be pursued through multiple actions to obtain an acceptable level of risk. In the United States the trend is to work for multiple lines of defense: flood prevention, land use planning and emergency management, in preparatory, response, and recovery time frames.

During all these phases, engineers and scientists help define risk. Yet, an acceptable risk is hard to compute. For politicians, making decisions based on acceptable risk is complex. Quantitative analysis of risk is needed. Policy makers can find an economic and rational approach useful (Kolen, 2013).

Flood risk management projects should be evaluated in terms of costs and benefits to better describe the value of structural and non-structural actions. Few evaluations of non-structural measures have been developed.

1.8 Flood bypass design with optimization

Given the importance of bypasses in flood management, as shown earlier, this dissertation focuses on methods for optimizing bypass capacity.

Formal bypass optimization is a new field not previously investigated. The next section describes literature available for flood bypass analysis. Each following chapter will include a more extensive literature review. This section instead summarizes literature divided into most relevant topic sections: flood risk analysis, multi-benefits of bypasses and multi-objective theory, climate change, and numerical hydraulic modeling of the Yolo Bypass.

Flood risk analysis has been analyzed since the end of the 1900. Flood management as practice to reduce risk is well explained in the literature, and well known practices in the United States are regulated by FEMA (FEMA, 2016). Flood risk and flood management have been subject of studies for decades (Plate, 2002). Flood risk assessment has been recently methodologically described (Pistrika et al., 2007).

Floodplains and flood bypasses have been the focus of several studies in California. Recently multi-objective analysis have been developed since when it came clear the other benefits related to floodplains other than flood risk reduction. Studies have focused on defining economic value for environment (Eisenstein et al., 2013) to use in examinations of expansion of the Sacramento River watershed bypass system (Jones, 2013) and multi-objective analysis of the Yolo Bypass (Suddeth, 2014).

Climate change effects on floodplain have been investigated (Zhu et al., 2009). In particular, economic optimality of levee height and setback with climate change has been analyzed (Zhu et al., 2009). In California, climate change is affecting the hydrology (Miller et al, 2003), and is requiring changes in water management (Hanak et al., 2011).

Flood bypasses literature presents some gaps. Flood bypasses capacity optimization has not been formally investigated. Multi-benefit analysis has not been investigated in terms of optimal bypass capacity. Also, long-term climate change effects on bypass have not been assessed. Effects of use of flood bypass in terms of reduction of levee failure probability have not been evaluated. This dissertation includes contributions in all of these just mentioned topics, as described more in detail in the following section.

1.8.1 Research objectives

This dissertation uses economic and hydraulic modeling to investigate how alternative structural solutions affect the relation among flood management, agriculture, environmental, and recreation activities for flood bypasses. The research has the following objectives:

1. To develop a theoretical analysis of economically optimal capacity for flood bypass design or expansion. A base bypass scheme is examined for a static case, and the optimal capacity found using optimization for the single-purpose of flood risk reduction. Flood economic risk reduction is evaluated with a probability analysis, and costs from levee setback, weir expansion, and land purchase.
2. To develop theoretical multiple benefit analysis for optimal bypass capacity, including agriculture, restoration, and recreation benefits. Results of these first two approaches are compared.
3. To investigate how long-term climate change affects static and dynamic optimal bypass plans. Given the variability of peak flow, a dynamic model will be developed. Effects of hydrologic and other parameters are explored.
4. Use a coupled 1D/2D hydrodynamic model of the Yolo Bypass, California to explore its optimal capacity. Simulations use HEC-RAS software. 1D tributaries channels are combined with 2D areas of the portion of the Sacramento River at Fremont Weir and the Yolo Bypass area. Capacity expansion can occur by widening the weir and setting back levees. Simulations are run for different expansion scenarios.

This work will include a theoretical approach for economic model development to create a more general framework for early-stage policy decisions for flood bypasses, applicable to any bypass, and a quantitative approach with more specific hydraulic modeling for the Yolo Bypass.

1.8.2 Organization of the dissertation

The **first chapter** of the dissertation is an introduction to flood management and flood bypasses. It describes successful flood bypasses around the world, overview of California flood management. It also includes a presentation of flood bypass design with an optimization approach. Research objectives and organization of the dissertation conclude chapter 1.

The second and third chapters focus on flood bypass optimization theory. **The second chapter** includes model development and preliminary application to California's Yolo Bypass, and other bypasses in the world. Two analyses include "only-flood risk reduction" and "additional-benefits" analyses. The **third chapter** includes model development for bypass capacity optimization for adaptation to uncertain climate change. Observed and projected climate, hydrology, and rivers runoff in California are employed as an example.

The **fourth chapter** focuses on development and use of mathematical hydraulic model to assist management of the Yolo Bypass in California. Structural modification such as a wider weir and setback of levees have the effect increase bypass capacity, and consequently further reduce river stage and flood risk. The model is used to evaluate different modifications to identify best solutions in terms of bypass capacity expansion and levees stability.

Chapter five presents general discussion of results and conclusions, and desirable future research.

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CHAPTER 2: FLOOD BYPASS OPTIMIZATION FOR STATIC CONDITIONS

Abstract

This study develops a model for flood bypass planning using economic risk analysis. Optimal capacity for flood bypasses is formulated and evaluated for static conditions. A preliminary analysis is developed for the adoption, use, and expansion of flood bypasses.

For this chapter, stream flow records are evaluated probabilistically, using a stationary lognormal distribution. The optimal bypass capacity is obtained using a benefit-cost analysis. A base case includes only flood risk reduction benefits. The model has been later developed to include the benefits of agriculture, restoration, recreation, and groundwater recharge. Costs include levee setback, weir widening, and land use cost. Bypass optimization for dynamic and uncertain future conditions are examined in Chapter 3.

Risk is quantified as the average annual damage. Risk reduction is evaluated as the residual risk after taking actions. To evaluate risk, damage has been quantified. Riverine flood damages could occur when peak river flood flow exceeds the base channel capacity. Large damages happen when river flow exceeds the overall base and channel capacity.

By maximizing expected total net benefits (the difference between flood damage reductions and flood control structures cost), the optimization suggests a preferred economic flood bypass capacity. The optimization model is applied preliminarily to the Yolo Bypass in California.

Model results suggest an optimal Yolo Bypass capacity of approximately 5,800 m^3/s. The expansion suggested is close to the Department of Water Resources' stated objective in their most recent Central Valley Flood Protection Plan and part of the Basin-Wide Feasibility Studies Sacramento River Basin, part of the Central Valley Flood Management Program of 2017. The department of Water Resources suggests t 1.5-mile expansion of Fremont Weir (approximately 6,000 m^3/s expansion) and expansion of Yolo Bypass in multiple locations with setback levees where feasible, including the use of Sacramento Deep Water Ship Channel to convey flood flows (DWR, 2017). This would add approximately 7,000 m^3/s of capacity, in total.

2.1 Introduction

The model is applied first to a simple case with benefits only from flood risk reduction and then to cases with multiple benefits. Costs depend on construction and land cost, which depend on location. Effects of geography and pricing are examined by analyzing bypasses along the Mississippi River.

Section 2 of this chapter presents the proposed method to assess optimal bypass capacity. Section 3 presents results, and section 4 presents the discussion of the results, and conclusions.

2.2 Methods

The model was built as shown in Figure 2.1. First, the peak stream flow analysis has been developed for the Sacramento River. A discharge-return period plot is created using 78 years of instantaneous peak stream flow values (1939-2016). The peak stream flow is analyzed statistically, following a Log-normal distribution.

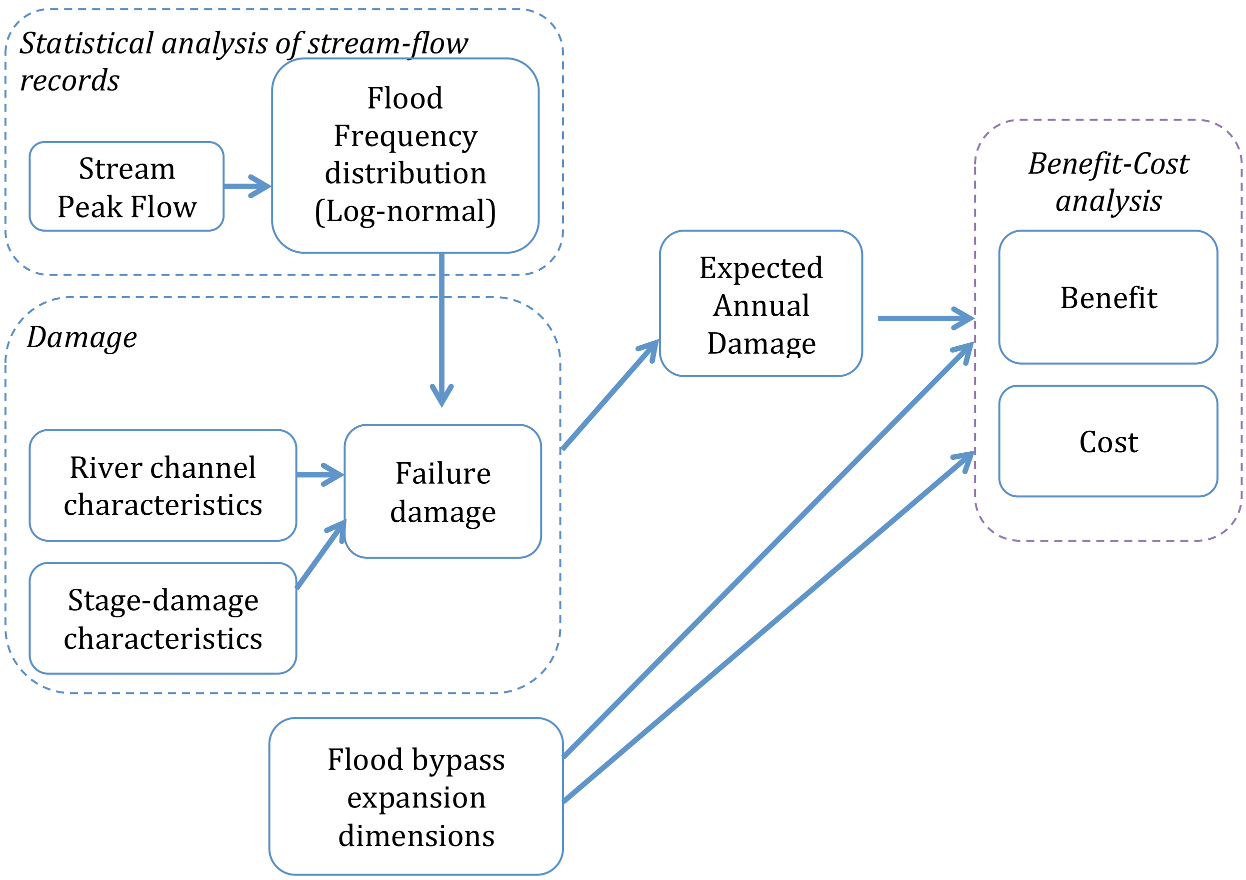

Figure 2.1 Flow diagram of the flood bypass capacity optimization model.

River channel characteristics and peak flow data, and stage-damage characteristics allow estimation of failure damage. Expected annual damage is computed with this information. Flood risk reduction benefit is a function of both the expected annual damage and expansion. Expansion costs depend on flood bypass expansion dimensions and land and construction costs. Details are explained below.

2.2.1 Statistical Analysis of Stream-flow Records

Common statistical analysis estimates probabilities on the future stream flows. It assumes the existence of a reliable representative sample of the population of stream flows (no watershed or climate changes). It also assumes the events are random and independent of each other. One of the bases for conventional hydrologic frequency analysis is the assumption of stationarity. This assumption would not hold with climate change.

In 1967 the U.S. Water Resources Council published "A Uniform Technique for Determining Flood Flow Frequencies" attempting to define a consistent approach to flood-flow frequency determination. In 1976 this was updated with "Guidelines for Determining Flood Flow Frequency", which is the currently acceptable methods of analyzing peak flow frequency data at gaging stations. Bulletin 17C published in 2015, defines flood potential in terms of peak discharge and exceedance probability. The annual flood series is recommended to be based on the Pearson Type III distribution with log transformation of the flood data (log-Pearson Type III), (Stedinger et al., 2008). Other common distributions suitable for flood frequency analysis are: normal, log-normal, and Gumbel distributions (Bobee et al., 1993).

Annual or partial duration series can be considered. The annual series is based on the maximum flood peak of each year, a partial duration series includes all flood peaks exceeding a predefined flood base, and is usually used when more than one flood per year occur (Water Resources Council (US). Hydrology Committee, 1981).

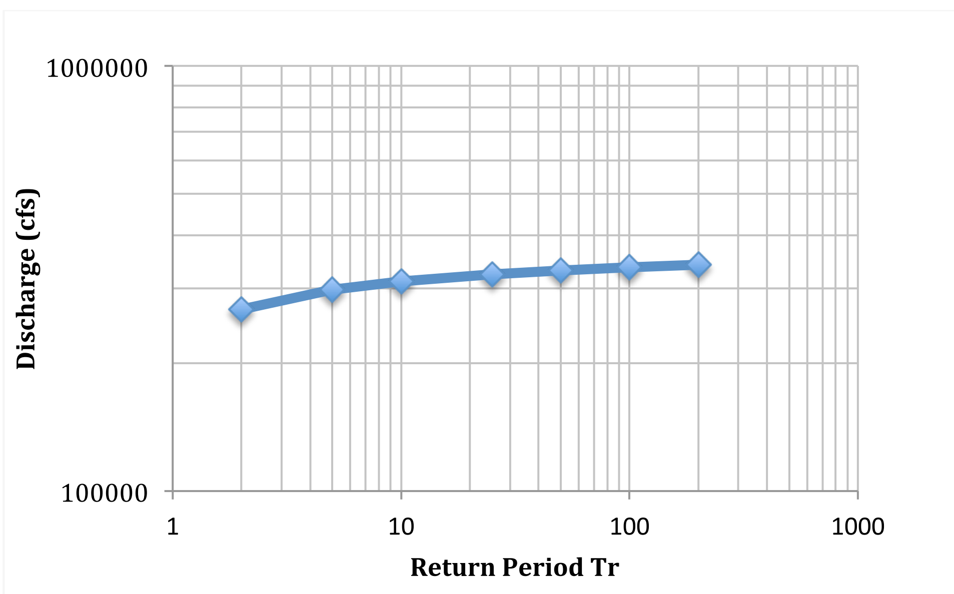

Figure 2.2 Flood frequency analysis for Sacramento River at Wilkins Slough Nr Grimes Ca, using Log-normal analysis, using instantaneous peak streamflow values (1939-2016)

It is possible to produce a flood discharge-probability relationship to provide stream flow data to calculate expected flood levels along the stream (Water Resources Council (US). Hydrology Committee. 1981). Water levels are converted to stream discharge utilizing relationships developed at the stream gaging site. Data series are plotted on log-normal paper. A curve is best fit to the data (Fig.2.2).

A drawback in using statistical analysis method is that flow records provide data only for several decades, never more than 100 years in the US. For this reason this method is not perfectly reliable, even under static conditions.

2.2.2 Flood Risk evaluation

Flood risk management has been extensively discussed (UNDRO, 1991; Plate, 1999; Plate, 2002) and occurs at three levels: 1) operating an existing system; 2) planning for a new system 3) revision of an existing one to adapt to changes in land use, increase in population, or climate change (Plate, 2002).

Risk management for an existing flood protection system mitigates flood damage by preparing for a flood and by minimizing its impact. It includes risk analysis, which might need to be reassessed with every system improvement.

Flood risk is the sum over all flood events of the probability of occurrence (hazard) and resulting flood damage event (vulnerability).

Hazard is defined as the probability of occurrence of potentially damaging flood events (Schanze et al., 2007). The area that can be affected by flood is called the *Vulnerable Area*. *Damage* by flood depends on the vulnerability of exposed elements, related both to the flood magnitude and to the characteristics of the element at risk. Four types of vulnerability can be defined: public safety, social and cultural, economic, and environmental vulnerability. Public safety vulnerability is determined by loss of life and health impacts. Economic vulnerability refers to potential for economic and financial losses. Environmental vulnerability refers to damages to ecosystems or water quality (Schanze et al., 2007).

Risk is defined as the summed product of the frequency of occurrence of flooding of a given intensity and the loss or damage that occurs from each possible flood event. Flood risk can be quantified as the expectation E(D) of flood damage (Begum at al., 2007):

$$R = E(D) = \int D * f_D(D)\,dD$$

This can be expressed in terms of Q flow as:

$$E(D(Q)) = \int_0^Q D(Q) * f_q(Q)\,dQ$$

where D as a random variable damage with density function f_D (D), usually expressed on an annual basis. Risk has the same unit as the annual damage (Begum at al., 2007). Probability is a numerical index of hazard, measuring the likelihood that the undesirable event will occur (FEMA website, 2016). Residual risk is the risk of floods exceeding the design capacity of levees (Ludy et al., 2012).

Flood damage reduction is the difference of risk without and with a risk reduction action. Given the uncertainties in flood risk analysis, the question is how much risk we are willing to accept and who absorbs that residual risk, because it is impossible to avoid flood damage entirely.

Flood flow rates (hydrology) and channel or floodplain characteristics (open channel hydraulics) are needed for mathematical models to calculate water levels for floods of various magnitudes and create maps to outline areas subject to floods for flood frequency and damage.

Flood probability can be defined using different methods: statistical analysis of stream-flow records, regional methods, transfer methods, empirical equations, and watershed modeling (Wright, 2007).

Statistical analysis is usually based on available data. Statistical analysis becomes complex when there is the need to predict large rare events with a small sample size. This is inevitable in flood risk analysis. Probability of flooding is only an estimate. Peak flow rate is a parameter of particular importance, and is used to design water conveyance and determine areas subject to floods.

2.2.3 Cost benefit analysis in a multi-criteria framework

Jonkman et al. (2004) explains benefit-cost analysis and flood damage mitigation in the Netherlands:

The basic principle of cost benefit analysis indicates whether a project results in an increase of economic welfare, i.e., whether the benefits generated by the project exceeds the costs of it. An economic optimization can be carried out to determine the optimal level of the system.

Jonkman et al. suggest considerations to include in benefit-cost analysis for flood management, such as costs of actions to decrease flood risk (investment, maintenance and management) and benefits from decreased flood damage (from direct costs of repairs to cost of disruptions of activities during the flood). Jonkman's work is based on the Dutch experience. He illustrates that even if the benefit-cost analysis has been strongly criticized because of the difficulty to accurately quantify in monetary terms some benefits and costs (particularly environment and social value), the benefit-cost analysis still should be considered as a base for a rational decision process. Benefit-cost analysis is imperfect, but is usually insightful.

2.3 Risk based flood bypass capacity optimization model

Bypasses divert water, usually over or through a weir, to protect urban and agricultural land and people from flooding. The planning analysis objective is to find the optimal (expected least-net cost) capacity for the bypass. The model here is based on benefit-cost analysis.

Figure 2.3 shows a bypass, in green. A weir, up north, in grey, protects a town from flooding by water diversion into the bypass. Some of the unregulated peak flow $Q_{unregRiver}$ is accommodated into the bypass, Q_{bypass}. Downstream in the river regulated peak flow $Q_{regRiver}$ flow.

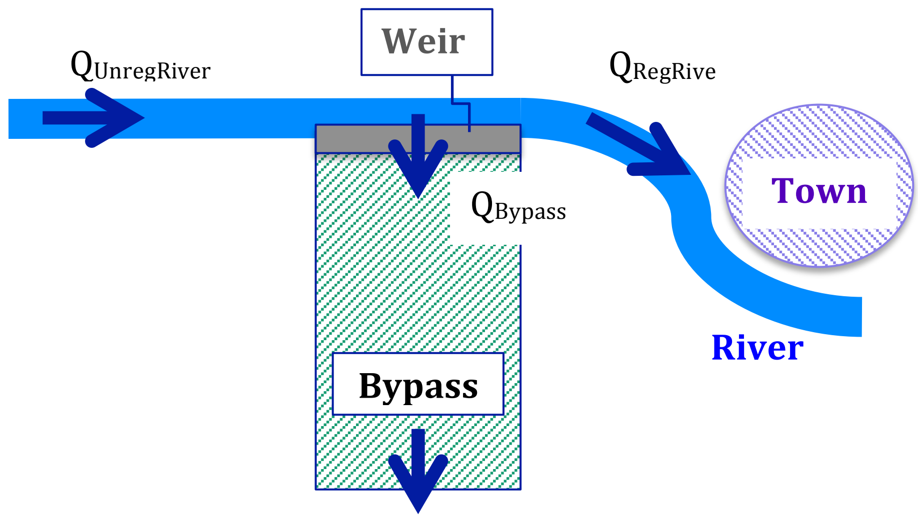

Figure 2.3 Basic Schematic of a bypass along a river

Data on the river channel are needed for the evaluation. In particular to define damage, the base channel capacity $Q_{basechannel}$ and the overtopping flow capacity $Q_{overtopping}$ are needed. River flood damage happens when the floodwater (peak flood flow Q) exceeds the base river flow, defined as running water during dry weather, while exceeding the overtopping channel capacity, defined as the total channel capacity, overflows adjacent flood-prone land and causes damage c_f. For simplification, damage cost is assumed to be a linear (or piece-wice linear) function of peak flood flow Q between base channel capacity and overtopping flow capacity (Fig. 2.4).

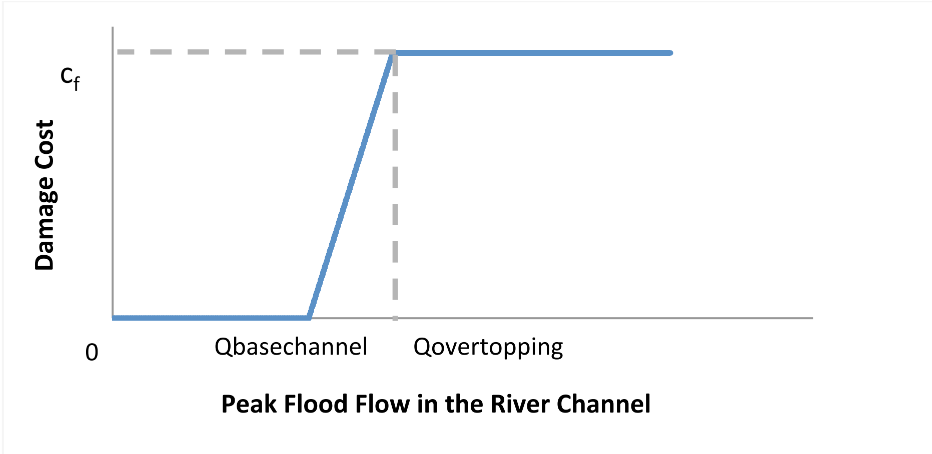

Figure 2.4 Damage function

Table 2.1 Risk based flood bypass capacity optimization model

(1) $\text{Max NETBenefit} = \text{Benefit}(\Delta K_{bypass}) - \text{Cost}(\Delta K_{bypass})$

(2) $\text{Benefit}(\Delta K_{bypass}) = \int p_i \times \left[D_i\left(Q_{UnregRiver_i}\right) - D_i\left(Q_{RegRiver_i}\right)\right] dQ \text{ , } i = 1{:}N$

(3) $\text{Cost}(\Delta K_{bypass}) = \text{Cost}_{LAND}(\Delta K_{bypass}) + \text{Cost}_{LEVEE}(\Delta K_{bypass}) + \text{Cost}_{WEIR}(\Delta K_{bypass})$

Constraints

(4) $Q_{RegRiver_i} = Q_{UnregRiver_i} - Q_{bypass_i} \text{ , } i = 1{:}N$

(5) $Q_{bypass_i} \leq K_{bypass} + \Delta K_{bypass}$

(6) $K_{bypass} + \Delta K_{bypass} \leq K_{weir}$

(7) $\Delta K_{bypass} \leq \Delta K_{bypass_{max}}$

(8) $\Delta K_{bypass} \geq 0$

The bypass conveys floodwater and reduces river peak flow and potential damage, with some costs (e.g. land use cost). The benefits and costs in the model compare the expanded bypass with the current bypass.

The decision variable of this problem is the bypass capacity expansion (ΔK_{bypass}), and the objective is to maximize net benefits (equation1).

The benefits of a hazard reduction project, such as a bypass, are reducing future damages and losses. Due to uncertainties in future floods, benefits are evaluated probabilistically and described by the difference between annualized damages with and without the action.

In equation 2, ΔK_{bypass} is the bypass capacity expansion, $K^B$is the original bypass capacity, K^W is the original weir capacity, $Q^R = Q^0 - Q^B$ is the operated peak flood flow by diverting flow Q^B into bypass, p_i is the probability that an unregulated peak flood flow Q_i^0 will occur.

Equation 3 represents the cost of expansion:

- Land use cost of purchasing or ease land occupied by expanded bypass, $Cost_{LAND}(\Delta K_{bypass})$;
- Construction cost of levee setbacks, $Cost_{LEVEE}(\Delta K_{bypass})$;
- Weir widening cost depending on the relative capacity of weir and bypass, $Cost_{WEIR}(\Delta K_{bypass})$.

Constraints include:

(4) The operated peak flood flow is the unregulated peak flood flow minus floodwater conveyed into the bypass

(5) Floodwater conveyed into the bypass cannot exceed the expanded bypass capacity

(6) Expanded bypass capacity cannot exceed the weir capacity, since weir capacity exceeding bypass capacity is useless

(7) Bypass expansion is no more than the maximum allowable expansion, which depends on the land availability, etc.

(8) Bypass expansion is non-negative.

Constraints 5 and 6 also require the flood conveyed into the bypass be less or equal to the weir capacity.

Analytically, when constraints are not binding, the solution is given by the first derivative of the objective function with respect to the decision variable equal to zero (necessary condition), and the second derivative negative (sufficient condition):

(9) $$\frac{d\text{NetBenefit}(\Delta K_{bypass})}{d\Delta K_{bypass}} = 0$$

(10) $$\frac{d^2\text{NetBenefit}(\Delta K_{bypass})}{d\Delta K_{bypass}{}^2} < 0$$

Equation (9) can be written in terms of marginal benefit and marginal cost:

(11) $$\frac{dB(\Delta K_{bypass})}{d\Delta K_{bypass}} = \frac{dC(\Delta K_{bypass})}{d\Delta K_{bypass}}$$

(12) $$\frac{d\int p_i \times \left[D_i\left(Q_{UnregRiver_i}\right) - D_i\left(Q_{RegRiver_i}\right)\right] dQ}{d\Delta K_{bypass}} =$$

$$\frac{d\left[Cost_{LAND}(\Delta K_{bypass}) + Cost_{LEVEE}(\Delta K_{bypass}) + Cost_{WEIR}(\Delta K_{bypass})\right]}{d\Delta K_{bypass}}$$

If the costs are linearly dependent on the bypass expansion, the term on the left in equation 12 is constant.

2.4 Yolo Bypass preliminary application

The model has been applied to a simplified representation of the Yolo Bypass, in California's Sacramento Valley. The Yolo Bypass has a weir capacity of 343,000 cfs (9,713 m^3/s) at the Fremont Weir. Major inflows are overflow from the Sacramento River and all tributaries north of the Fremont Weir, American River and all its tributaries south of the Fremont Weir, Cache Creek, Willow Slough, and Putah Creek. The Maximum design flow of 600,000 cfs (16,990 m^3/s) pours into the Sacramento-San Joaquin Delta via the Sacramento River and Yolo Bypass. In addition to flood control, the Yolo Bypass also provides wildlife refuge, grassland for pasture, and cropland. A

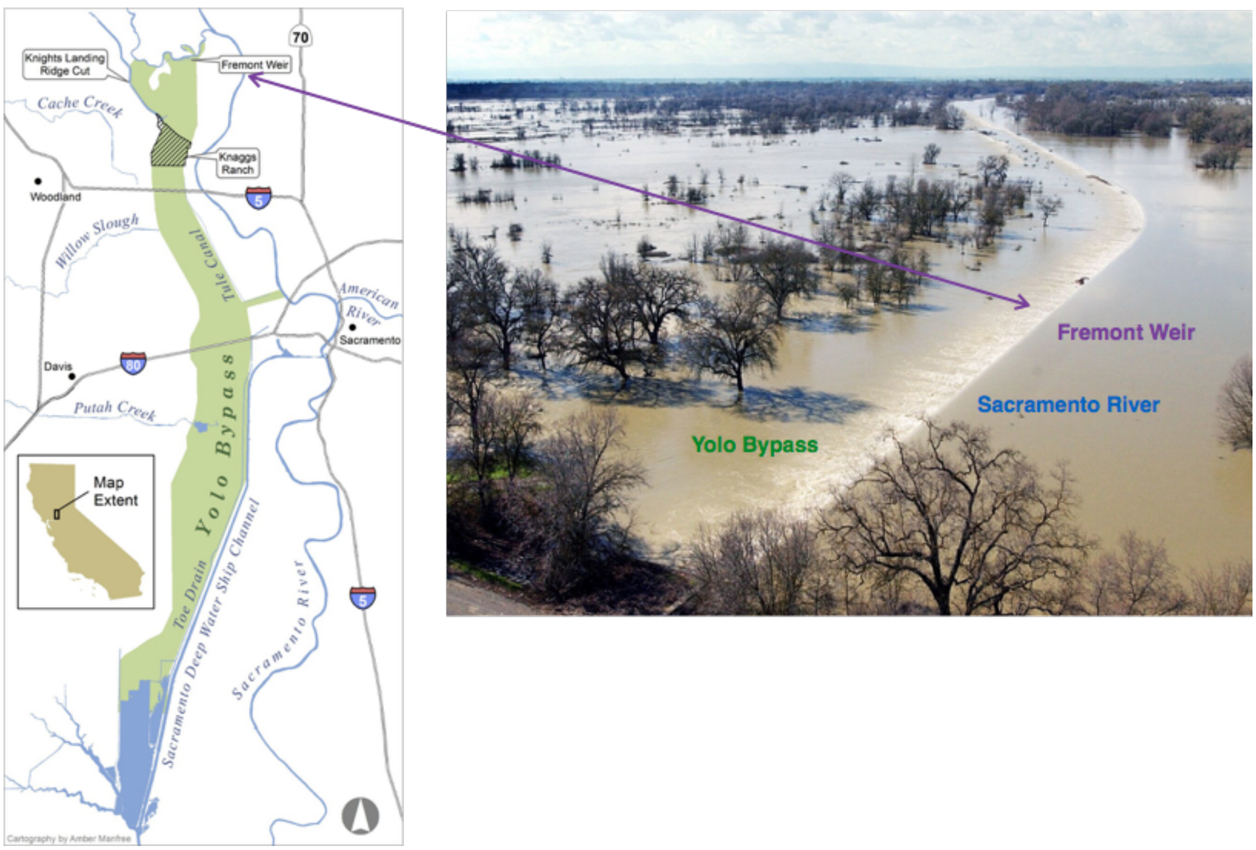

Figure 2.5 Map of the Yolo Bypass (left) and picture of Fremont Weir during the 2017 flood (right)

For this analysis, the Yolo Bypass is simplified to a rectangular area with a length of 10,000 m, and the water velocity in the bypass averaged to the value of 0.2 m/s. Sacramento River overflows over the two-mile wide Fremont Weir about 15 miles northwest of Sacramento, at the beginning of Yolo Bypass. The crest elevation is 10.21 m and the project design capacity of the weir is 9.71 m³/s (DWR, 2010). The only inflow considered initially is spill over Fremont Weir.

For this simplified application damage cost is assumed to be a linear (or piecewice linear) function of peak flood flow D(Q) between base channel capacity and overtopping flow capacity (Fig. 2.6).

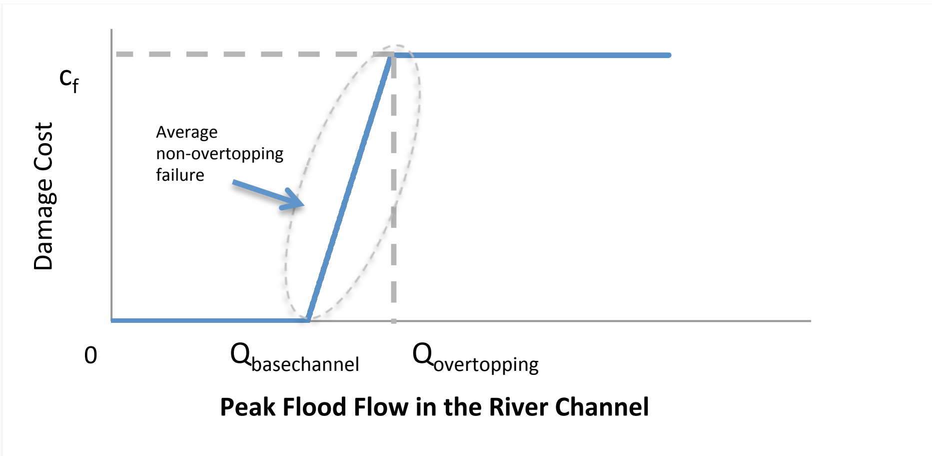

Figure 2.6 Flood damage cost as a function of peak flood flow, assuming linear.

To understand how the damage cost function would vary with a flood risk reduction action, damage cost has been evaluated for the pre-existent condition without a Yolo Bypass, with the actual conditions, and with hypothetical expansion of bypass capacity (Fig.2.7).

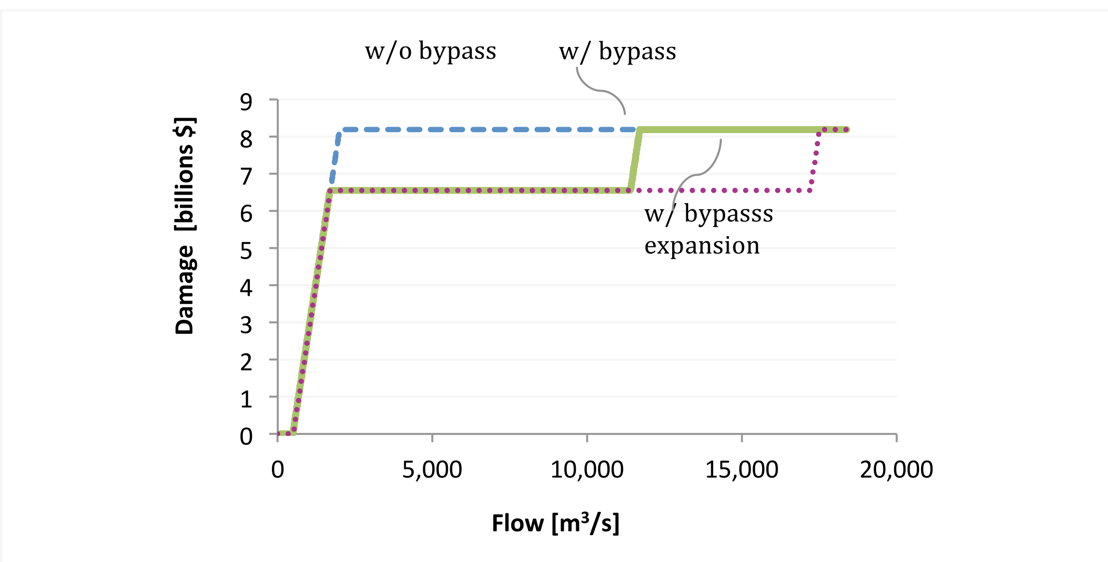

Figure 2.7 Damage occurring without a bypass, with the bypass, and with bypass expansion

Costs for bypass expansion are:

- Land use cost of purchasing or ease land occupied by expanded bypass, $\text{Cost}_{\text{LAND}}\left(\Delta K_{\text{bypass}}\right) = c_L(\Delta K_{\text{bypass}})$;
- Construction cost of levee setbacks, $\text{Cost}_{\text{LEVEE}}\left(\Delta K_{\text{bypass}}\right) = c_C\ (\Delta K_{\text{bypass}})$;
- Weir widening cost depending on the relative capacity of weir and bypass, $\text{Cost}_{\text{WEIR}}\left(\Delta K_{\text{bypass}}\right) = c_W * \Delta K_{\text{bypass}}$.

Costs associated with setting back levees along the Yolo Bypass include purchasing the land between an existing levee and a proposed setback levee, removing roads in the same area, removing existing levee, and building new ones. These costs depend on many variables. Costs in this analysis are only a rough estimate of actual costs.

For solution convenience, all costs are assumed to depend linearly on the bypass capacity expansion. Coefficients c_L, c_C and c_W are the unit cost per expanded bypass capacity for land purchase, construction and weir widening respectively. These coefficients can be estimated from collected data from the following sources:

Table 2.2 Land cost. Source: Bozkurt et al., 2000. Data reported by the United States Department of Agriculture (USDA) (National Agricultural Statistics Service, 1999)

Land cost of cropland	Removing vegetation cost
$5,300 per acre	$300 per acre

Table 2.3 Levee setback cost. Source: Bozkurt et al., 2000

Upper Elkhorn Levee setback cost (removing old and building ones)	To account for any changes	Planning and engineering design	Construction
$211 per foot	25%	15%	10%

Table 2.4 Weir expansion cost. Source: DWR, 2016

Fremont Weir expansion
$72 million per mile

2.4.1 Results

Fig. 2.7 shows estimated total costs and benefits for different levels of bypass expansion. The total benefit curve has a decreasing rate of increase (concave shape), representing flood damages avoided. In particular, expected avoided damage increases steeply, at a diminishing rate with expansion. For this case, an expansion of 5,000 m^3/s reduces flood risk by approximately $600 millions, while with further expansions reducing flood risk very slowly.

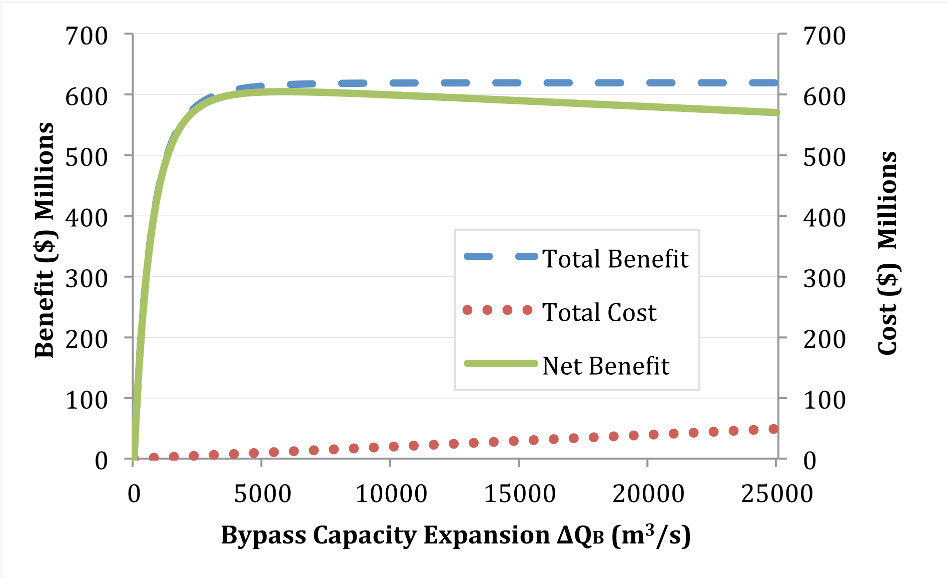

Figure 2.8 Economic Values for the Yolo Bypass

As shown in Fig. 2.9, without the land availability constraint, the optimization model results for the Yolo Bypass indicate an optimal expansion of 5,800 m^3/s. Actual capacity of the weir is 9,713 m^3/s. So the optimal capacity K_{bypass}* is approximately 15,500 m^3/s. The Yolo bypass has functioned well in the last century as flood relief for the city of Sacramento. But the Sacramento basin flood management system could be smaller than optimal for very large floods. Increasing the Yolo Bypass capacity would reduce pressure on the Sacramento flood protection system, while perhaps benefiting ecosystems.

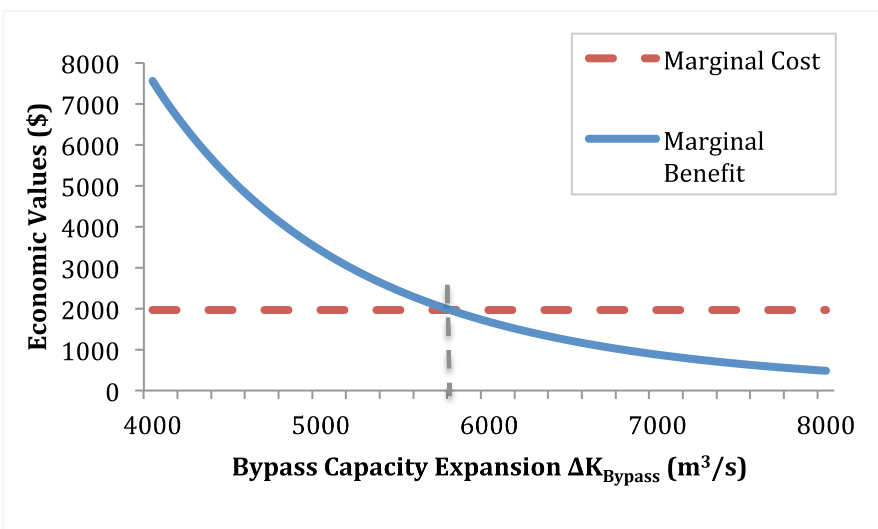

Figure 2.9 Marginal Values for the Yolo Bypass

2.4.2 Sensitivity analysis

Sensitivity analysis on the assumed and/or uncertain parameters has been performed. Sensitivity to hydrologic parameters of flood peak coefficient of variation (CV) and mean (μ) are explored. The optimized decision changes over these parameter ranges.

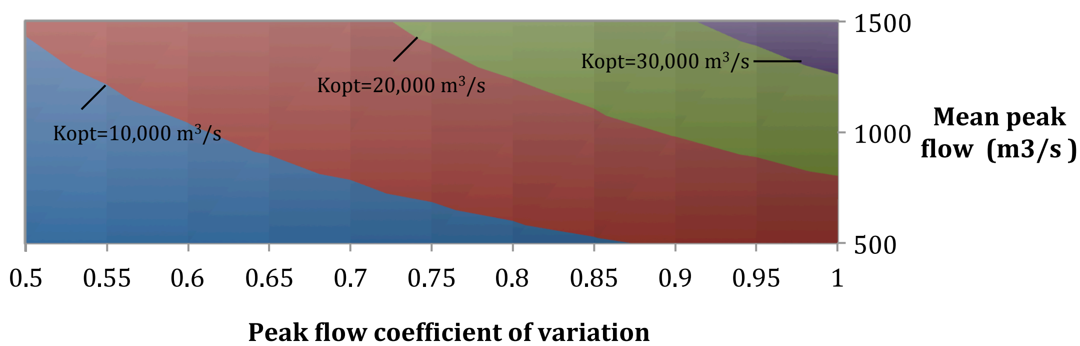

Figure 2.10 Yolo Bypass Optimal Capacity (Kopt) for different annual flood peak flow coefficient of variation CV and mean μ.

As the coefficient of variation and mean peak flow increase, optimal capacity also increases. The optimal capacity grows faster with the coefficient of variation for greater values of mean peak flow (Fig. 2.10 and Table 2.5).

Table 2.5 Sensitivity analysis on the optimal bypass capacity with respect to the coefficient of variation of the peak flow and the mean of the peak flow.

	Mean annual peak flow		
CV \ μ	**500 m^3/s**	**1000 m^3/s**	**2000 m^3/s**
0.5	3000	6800	10500
0.55	3700	8200	12400
0.6	4500	9600	14400
0.65	5400	11200	16600
0.7	6300	12800	18600
0.75	7300	14600	21400
0.8	8400	16400	23900
0.85	9500	18400	26000
0.9	10600	20400	29300
0.95	11800	22400	32200
1	13100	24500	35100

Other parameters include flood damage cost, land-use cost, construction-levees-setback cost, and weir-widening cost. The following is an analysis of the influence of land price for the bypass on the optimal bypass capacity, expressed in m^3/s.

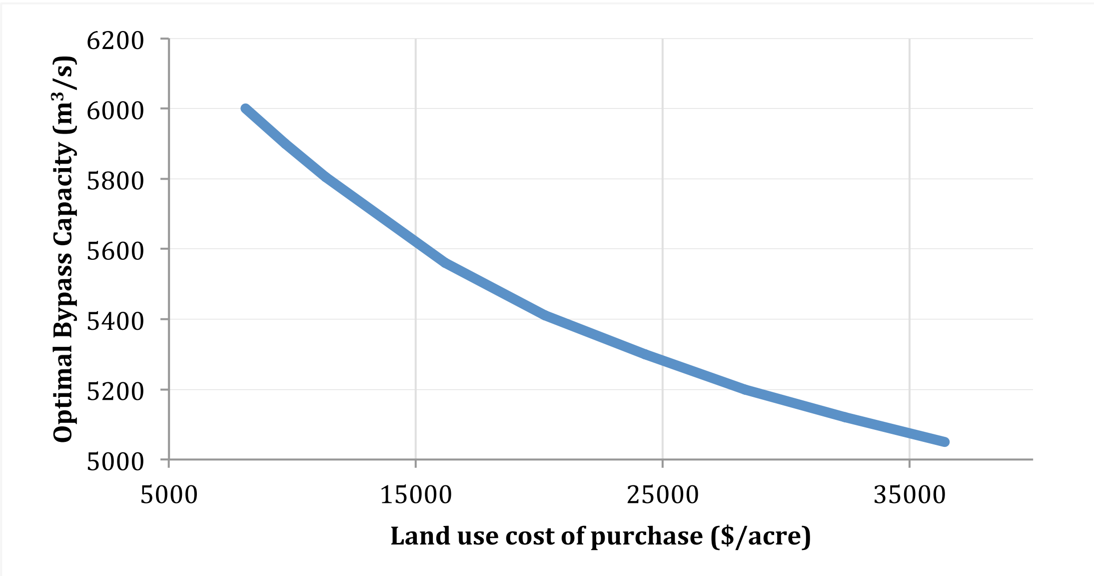

Figure 2.11 Sensitivity analysis on Land use purchase

A 50% increase of land cost from 10 to 15 thousand $ per acre leads to a 5% reduction in optimal bypass capacity. But, a 50% increase in land price from 20 to 30 thousands $/$m^3/s$ reduces optimal bypass capacity by about 3.8% (Fig. 2.11). Variability in optimal capacity is high for lower costs and low for higher costs.

Construction levee-setback can influence the choice of implementing a bypass. Further research is needed to define the importance of levee-setback fixed cost for this analysis, and in particular to define the limit fixed-cost that would prevent any expansion. Figure 2.12 shows an example of benefit-cost analysis with variable and fixed costs. The cost function is offset of the fixed costs. This results in immediate costs, which can defer action for a time.

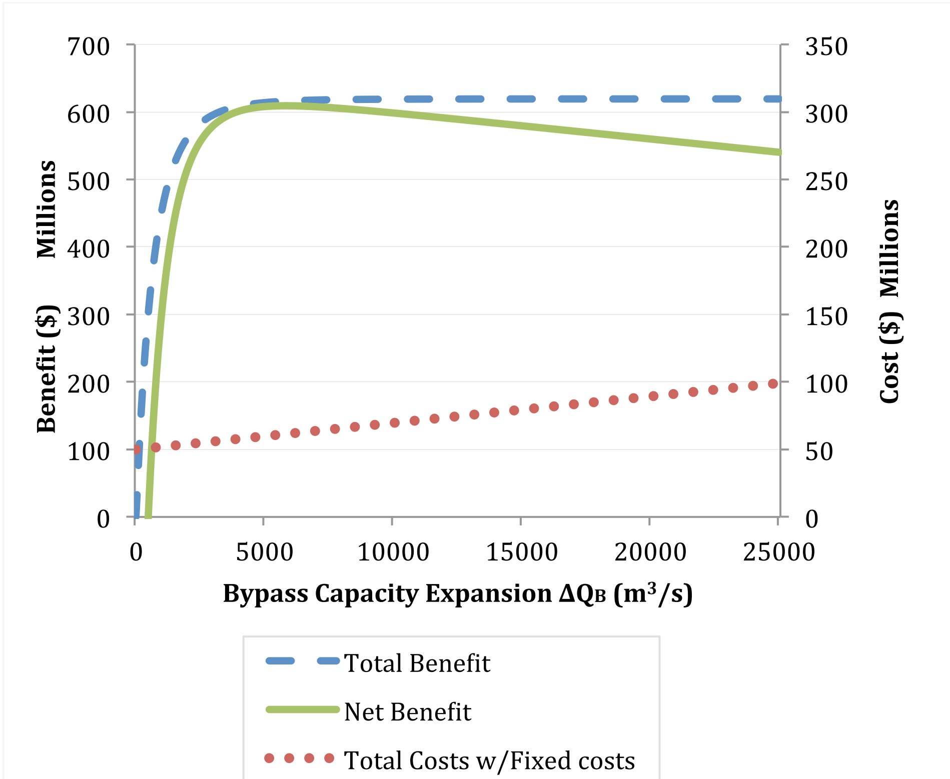

Figure 2.12 Economic values for the Yolo Bypass with variable and fixed costs

2.5 Application of the model to other bypasses

This optimization approach can be applied to other bypasses in the world. The model has been applied to Birds Point New Madrid and the Morganza floodway in the Mississippi river basin.

Sensitivity of the optimal capacity to different coefficients of variation in peak flow is evaluated for those bypasses. Fig. 2.13 shows a similar trend for these bypasses. As the coefficient of variation grows, the ratio of bypass capacity to mean peak flow grows.

This behavior seems fairly general for any bypass. Each curve represents physical characteristics of a type of bypass, and depends on economic parameters as well. In similar economic conditions, for rivers with the similar mean peak flow and economies represented with each curve, it is possible to evaluate the optimal capacity of a bypass. Values of optimal capacity in fig.13 were evaluated considering each bypass alone and not as part of a more complex basin flood protection system. Values have been evaluated without land availability constraints. Red squares in the graph represent the value for the actual coefficient of variation of the flow for each river upstream each bypass. For the Morganza floodway no expansion seems desirable.

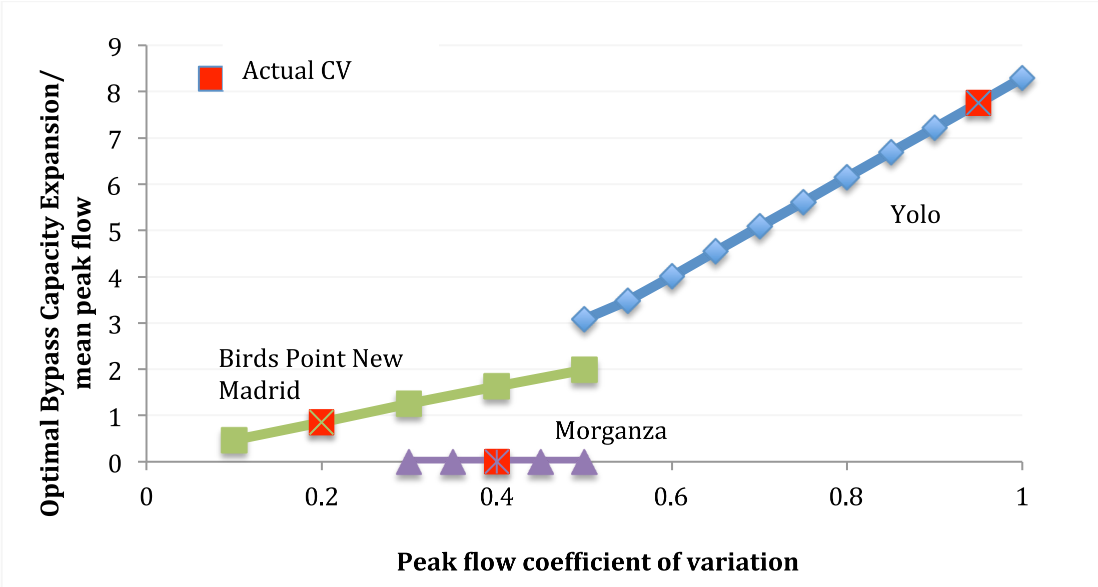

Figure 2.13 Optimal Bypass Capacity/ mean peak flow for different bypasses

2.6 Additional benefits

A bypass can benefit more than flood protection. When a bypass accommodates diverted water, it also often provides habitat capacity for fish and waterfowl. In addition, the bypass can provide benefits for agriculture, recreation and groundwater recharge (Suddeth, 2014).

A broader risk-based analysis and optimization are presented in this section, to estimate optimal capacity of flood bypasses considering benefits from agriculture, groundwater recharge, ecosystem habitat, and recreation. The objective is a preliminary analysis for decisions on adoption, use, and expansion of flood bypasses. By maximizing the expected total net benefits, the optimization model suggests optimal flood bypass capacity. The optimization model is preliminarily applied to California's Yolo Bypass.

California's Yolo Bypass is a good example of a multi-benefits bypass. Although flood control is the major function of Yolo Bypass, the floodplain also supports agriculture, fish wildlife, and recreation (DWR, Retrieved from: http://www.water.ca.gov/aes/yolo/). The Yolo Bypass floodplain is usually dominated by agriculture, with substantial "natural" habitats such as seasonal wetlands, and riparian and upland habitat. The largest contiguous area of non-agricultural floodplain habitat is the Yolo Basin Wildlife Area, managed by California Department of Fish and Game (DWR, Retrieved from: http://www.water.ca.gov/aes/yolo/).

Figure 2.14 Bypass operating during flood of 1997 (DWR)

Figure 2.15 Waterfowl wetland and agriculture in the Yolo Bypass (DWR)

Floodplain reconnection provides flood-risk reduction, an increase in various floodplain services, and potential adaptability to climate-change impacts. Land use within reconnected floodplains can be used for activities compatible with periodic inundation. Reconnection also increases the area available to store and convey floodwaters and reduces flood risk for nearby areas. Flood bypasses can allow floodplains to remain largely under private ownership, and generate revenue through agriculture.

Connected floodplains with vegetation can support high levels of biological productivity and diversity and provide numerous ecosystem services. While these benefits are achieved, large upfront costs for levee setbacks flow easements, land acquisition, and restoration, along with periodic compensation for flood damages need to be considered. An optimization framework allows such diverse concerns to be explicitly represented, integrated, and balanced.

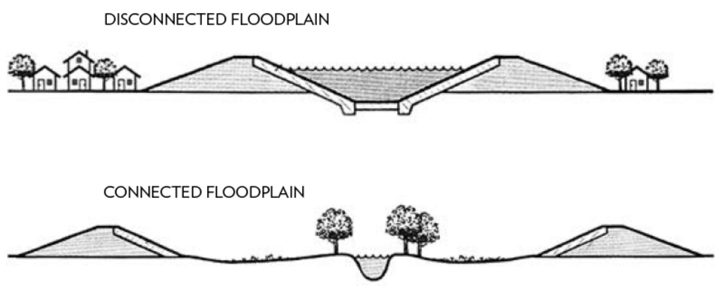

Figure 1. Levees built next to rivers disconnect floodplains. Image adapted from Water Education Foundation's *Layperson's Guide to Flood Management.*

Figure 2.16 Disconnected and reconnected floodplains (Eisenstein et al., 2013)

2.6.1 Valuing Central Valley Floodplains - A Framework for Floodplain Management

Hydrologically connected floodplains can host agriculture, recreation, and certain infrastructure land uses that produce benefit streams to the economy (Eisenstein et al., 2013). Floodplains provide flood protections, reducing pressure on levees and dams. They also reduce flood insurance and disaster recovery costs (The Nature Conservancy, 2018). Floodplains also improve water quality, by removing excess sediment and nutrients that can degrade water quality and increase treatment costs ((The Nature Conservancy, 2018). As the water runs very slowly in floodplains, they function as aquifers recharge sites. Floodplains include rich and diverse habitats (Allan et al., 2007), providing spawning areas for fishes and being used as migration routes for birds (Suddeth, 2014). They also function as recreational sites, in fact, the most common recreational uses include fishing, hunting, camping, hiking. Floodplains also enhance flood prone agriculture crops (FEMA, 2014).

To simplify the great list of benefits floodplains provide, four "accounts" can be used to more comprehensively assess the economic value of connected floodplains for both basin-wide and project-level planning (Eisenstein et al., 2013):

- Flood risk reduction value (including flood stage reductions and avoided residual risk)
- Ecosystem service value (including habitat, food web support, carbon sequestration, water management and sediment services)
- Land use value (including agriculture, recreation and aesthetic values)
- System operations value (including integrated water management, option values, climate change accommodation, and maintenance and liability management).

Table 2.6 Approximate Monetary Magnitudes of Services of Connected Central Valley Floodplains (From Eisenstein et al., 2013)

Flood plain value account	Examples	Annual Value per floodplain per acre
I. Flood risk reduction value		
Reduced flood stage	Yolo Bypass widening	$100s - $1,000s
Avoided residual risk	Various sites in Valley	$0 - $1,000s
II. Ecosystem service value		
Habitat	Central Valley salmon	$100s - $1,000s
Water quality maintenance	Valley-wide	<$0 - $100s
Groundwater recharge	Gravelly Ford, Yolo Bypass	$0 - $100s
Sediment deposition	Cosumnes	$0 - $100s
III. Land use value		
Agriculture (Net profits)	Yolo Bypass	$100s - $1,000s
Recreation	Delta	$100s
Visual and place value	Lower San Joaquin	$0 - $100s
IV. System operation value		
Integrated water management	Yolo Bypass	$100s

2.7 Risk based flood bypass capacity optimization model for multiple benefits

The decision variable of this problem remains the bypass capacity expansion (ΔK_{bypass}), and the objective is to maximize net benefits (equation1), now including additional bypass benefits. The model here allows comparing bypass expansion and the current condition without bypass expansion.

Table 2.7 Risk based flood bypass capacity optimization model with other benefits

$$(1)\ \text{Max NETBenefit} = \text{Benefit}(\Delta K_{bypass}) - \text{Cost}(\Delta K_{bypass})$$

$$(2)\ \text{Benefit}(\Delta K_{bypass}) = \text{Benefit}_{FLOOD}(\Delta K_{bypass}) + \text{Benefit}_{AG}(\Delta K_{bypass})$$

$$+\text{Benefit}_{GR}(\Delta K_{bypass}) + \text{Benefit}_{REST}(\Delta K_{bypass})$$

$$(3)\ \text{Benefit}_{FLOOD}(\Delta K_{bypass}) = \int p_i \times \left[D_i\left(Q_{UnregRiver_i}\right) - D_i\left(Q_{RegRiver_i}\right)\right] dQ\ ,\ i = 1{:}\,N$$

$$(4)\ \text{Cost}(\Delta C_{bypass}) = \text{Cost}_{LAND}(\Delta C_{bypass}) + \text{Cost}_{LEVEE}(\Delta C_{bypass}) + \text{Cost}_{WEIR}(\Delta C_{bypass})$$

Constraints

(5) $Q_{RegRiver_i} = Q_{UnregRiver_i} - Q_{bypass_i}$, $i = 1: N$

(6) $Q_{bypass_i} \leq K_{bypass} + \Delta K_{bypass}$

(7) $K_{bypass} + \Delta K_{bypass} \leq K_{weir}$

(8) $\Delta K_{bypass} \leq \Delta K_{bypass_{max}}$

(9) $\Delta K_{bypass} \geq 0$

The benefits of bypass expansion are reductions in future damages and losses. Due to uncertainties in future floods, benefits are evaluated probabilistically and described by the difference between expected annualized damages with and without expansion.

In equation 2, ΔK_{bypass} is the bypass capacity expansion, K^B is the original bypass capacity, K^W is the original weir capacity, $Q^R = Q^0 - Q^B$ is the operated peak flood flow by diverting flow Q^B into bypass, p_i is the probability of peak flood flow Q_i^0.
Equation 2 describes the benefits of expansion as the sum of benefit for flood risk reduction, agriculture, groundwater recharge, and environmental restoration.

Equation 3 represents the benefits of expansion as flood risk reduction.

Equation 4 represents the cost of expansion:

- Land use cost of purchasing or ease land occupied by expanded bypass, $Cost_{LAND}(\Delta K_{bypass})$;
- Construction cost of levee setbacks, $Cost_{LEVEE}(\Delta K_{bypass})$;
- Weir widening cost depending on the relative capacity of weir and bypass, $Cost_{WEIR}(\Delta K_{bypass})$.

Constraints 5,6,7,8, and 9 are the same in the base model. For convenience of solution, all costs and benefits, other than flood risk reduction benefit, are annualized assumed to depend on bypass capacity expansion. The benefit and cost function become:

$$(10)\ \ B(\Delta K_{bypass}) = B_F(\Delta K_{bypass}) + B_A(\Delta K_{bypass}) + B_R(\Delta K_{bypass}) + B_G(\Delta K_{bypass}) = \int p_i \times [D_i(QP_i^0) - D_i(QP_i^R)]dQ + b_A * \Delta K_{bypass} + b_R * \Delta K_{bypass} + b_G * \Delta K_{bypass}$$

$$(11)\ \ C(\Delta K_{bypass}) = C_L(\Delta K_{bypass}) + C_C(\Delta K_{bypass}) + C_W(\Delta K_{bypass}) = c_L * \Delta K_{bypass} + c_C * \Delta K_{bypass} + c_W * \Delta K_{bypass}$$

Coefficients b_A, b_R and b_G are the unit benefit per expanded bypass capacity for agriculture, restoration and recreation, and groundwater respectively. Coefficients c_L, c_C

and c_W are the unit cost per expanded bypass capacity for land purchase, construction and weir widening respectively. These coefficients can be estimated from some collected data, or can be found from some reports or references.

Table 2.8 Approximate Monetary Magnitudes of Services (From Eisenstein et al., 2013)

Floodplain value account	Annual Value per floodplain per acre
Agriculture	\$500
Restoration	\$500
Groundwater recharge	\$100

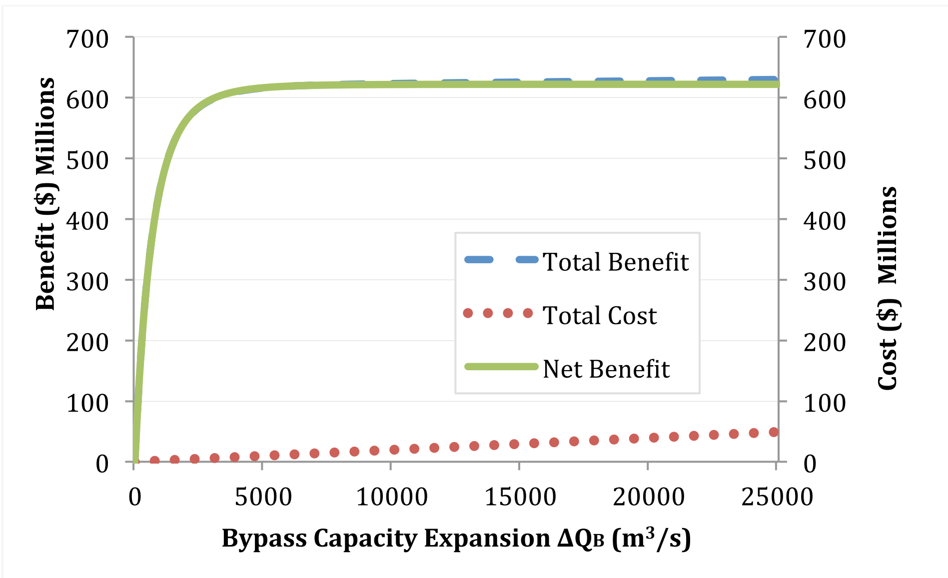

Figure 2.17 Economic Values for the Yolo Bypass

Optimal capacity solely for flood risk reduction is approximately 15,500 m^3/s. Considering other benefits than flood damage reduction expands the optimal capacity by another 400 m^3/s. Figure 2.17 - 2.18 shows changes in benefit and cost (in million of \$) with changes of bypass capacity (in cubic meter per second). The optimality condition is reached when the marginal benefit are equal to the marginal costs (figure 2.17).

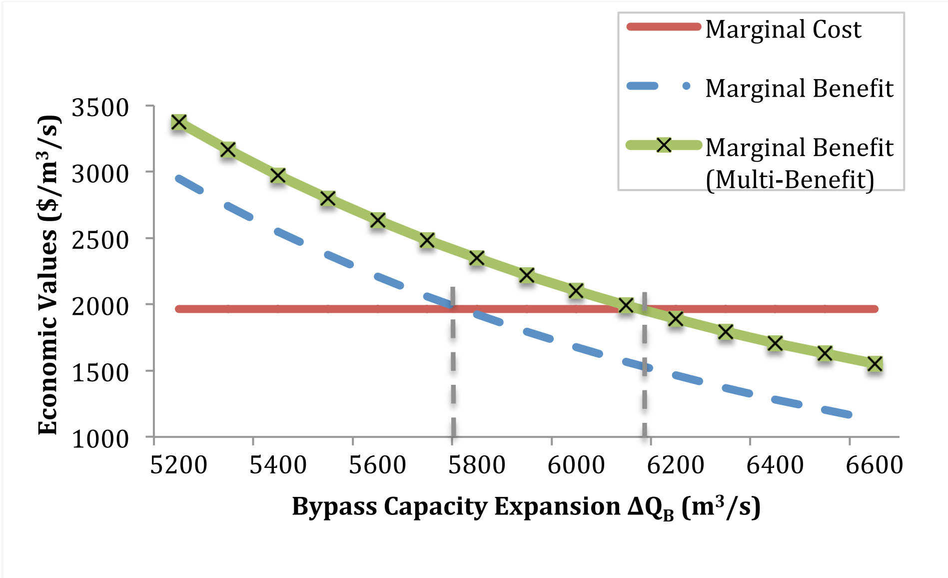

Figure 2.18 Comparison flood risk reduction only and multi benefit cases

Figure 2.19 shows difference in benefits of risk reduction only, and of agriculture, restoration and recreation, and groundwater recharge benefits. In monetary terms agriculture, restoration and recreation, and groundwater benefits are very small compared to flood risk reduction benefit (less than $10 million compared to more than $600 million for the optimal capacity evaluated).

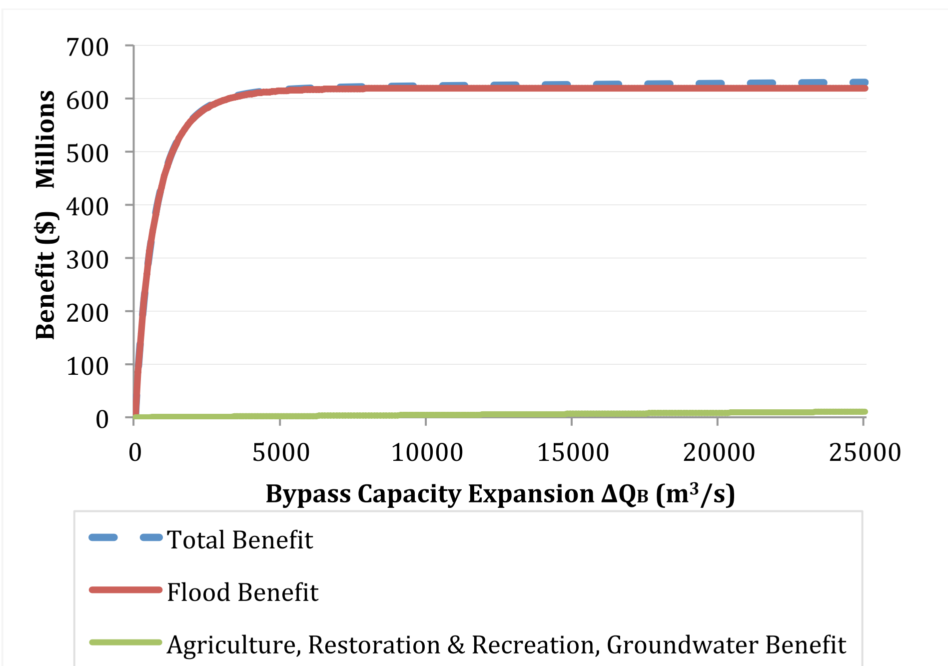

Figure 2.19 Comparison of benefits of flood risk reduction only and for agriculture, restoration and recreation, and groundwater recharge benefits

2.8 Conclusions and limitation of the model

Conventional flood control systems cannot completely protect urbanized areas from floods. Bypasses can be a supplemental component within flood management systems. Although flood bypasses are common, their economic analysis is rarely systematic. Formal bypass capacity optimization can help policy makers understand and select new or expanded capacities for a bypass. Linear modeling is good way to quantitatively account for benefit and costs for static optimization purposes. Linear modeling can deliver effective results in a simple way.

The Yolo Bypass in California has been studied for decades and recently the Department of Water Resources of California has proposed expanding the bypass. The linear model proposed in this chapter suggests an expansion of about 5,800 m^3/s could be economically justified, without implementing the land availability constraint. Actual capacity of Fremont weir is 9,713 m^3/s, so the optimal capacity K_{bypass}^* suggested is approximately 15,500 m^3/s.

The model has been applied to other bypasses, the Morganza floodway and the Birds Point-New Madrid to analyze sensitivity of optimal capacity to different coefficient of variation of peak flow. Results show that bypass capacity estimation follows a general behavior. As the coefficient of variation grows, the ratio of bypass capacity to mean peak flow grows.

Increasing the Yolo Bypass capacity would reduce pressure on the Sacramento flood protection system, while benefiting ecosystems and recreational activities, agriculture, and groundwater. Application to the Yolo Bypass, taking into account additional benefits, than solely the risk reduction, suggests an expansion of 6,200 m^3/s could be economically justified. Considering additional benefits than the flood risk reduction only increases optimal capacity by 400 m^3/s, adding approximately $10 million benefit to the $600 million benefit of flood risk reduction provided with optimal bypass expansion.

This analysis involves assumptions and uncertainties. Assumptions were made on the bypass shape, water velocity, stationarity of flood flow process, damage function, and levee failure. Further analysis should explore these uncertainties. In addition, the bypass is not put into the more complex system context of flood management in a larger basin system. Further studies should focus on changes in conditions of the floodplain due to human activities and to climate change.

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CHAPTER 3: BYPASS CAPACITY PLANNING WITH UNCERTAIN NON-STATIONARY HYDROLOGY

Abstract

Climate change, with warmer temperatures and changed in patterns of precipitation and runoff, will affect flood management in California and globally. Adaptation to climate change is a significant challenge, particularly because the exact future climate is uncertain. While climate change will likely worsen regional flooding (Andrew et al., 2017); (Miller et al., 2003), economic growth and urbanization of floodplains will increase potential damages. The long-term floodplain management challenge is to balance increasing flood damages and benefits from using floodplains adaptively over time. Based on these considerations, present planning for flood bypasses needs analysis for the range of likely evolving future conditions. The stochastic dynamic optimization presented in this chapter can explicitly take these changes into account.

Climate effects on hydrology have been investigated for decades (Gleick, 1988);(Lettenmaier and Sheer, 1991); (Lettenmaier et al., 1989). The Yolo Bypass in California has been the focus of many studies and modifications to the bypass have been recently explored and proposed by the California Department of Water Resources (DWR, 2017). A dynamic model presented in this chapter estimates future optimal flood bypass capacities with uncertain future climate and other changes. Stochastic dynamic optimization for flood bypasses has no precedent in the literature, although stochastic dynamic programming is widely used in water management. The model suggests promising structural modifications to the bypass. Results are driven by assumptions on the variability of trends in flood frequency.

3.1 Introduction

Probabilistic risk assessment is a traditional aid to flood policy, planning and management, which also can help assess future climate and socio-economic impacts and adaptations. This chapter provides a mathematical formulation to examine the effect of climate change on river hydrology and to propose economically optimal modifications to the existing Yolo flood bypass in California. A dynamic economically-driven optimization model is described and solved using stochastic dynamic programming. A dynamic model can help define optimal capacity over time, and can suggest when the expansions should occur. The scope is to analyze how flood management can and should economically adapt to probabilistic flood frequency changes, and how bypass capacity changes can help reduce damages over time. A preliminary application to the Sacramento River hydrology and possible modifications to the Yolo Bypass are explored. The research expands on previous work on levees height and setback analysis for climate change (Zhu et al., 2007) ;(Zhu and Lund, 2009) and more recent optimization analysis with uncertain non-stationary hydrology (Hui et al., 2017). Zhu et al. (2007) examined levee height and setback decisions over time. Zhu et al. (2007) examined levee-protected floodplains with climate and economic changes for the lower American River floodplain in Sacramento, California. Economically optimal choices of adaptations for the floodplain levee system were developed using a dynamic programming, considering several climate change and urbanization cases. Hui et al. (2017) formulated long-term levee plans given uncertainty in future flood climate using stochastic dynamic programming with Bayesian updating.

This chapter examines flood bypass capacity planning, and is expanded to include costs of land purchase or easement, weir expansion, and levees setback, and benefits of flood risk reduction. Changes in flood frequency parameters of the annual peak flow, such as mean and standard deviation, are treated as dynamic stochastic phenomena to represent uncertainty in climate change. Up to 10 climate scenarios are analyzed. Results are given for 3 cases: 1. Mean and standard deviation vary with the same rate for each year and each climate scenario, 2. Mean and standard deviation vary with different rates, and 3. Mean annual flood peak varies while standard deviation is constant.

Section 2 of this chapter introduces probabilistic sequential decision models and Markov decision process. Section 3 describes the model used to estimate optimal bypass capacity over time. Section 4 includes an analysis of the Sacramento River region climate. Section 5 describes global climate models and changes in flood frequency, with a description of the methods used by the California Department of Water Resources to evaluate effects of climate change on rivers for the Central Valley Flood Protection Plan update of 2017. Section 6 applies the stochastic optimization model to Yolo Bypass planning in California. Section 7 examines effects of bypass expansion on local agricultural production.

3.2 Probabilistic sequential decision models and Markov decision process

Likely climate changes should be considered in strategic water planning. A sequential decision making model integrates each time a decision maker makes a decision based on the state of the system into a strategy that includes future contingent decisions (Puterman, 2014)(Figure 3.1). By taking an action, the decision maker receives benefits or costs, and the system changes to a new state entering the next period with a probability distribution determined by the action (Puterman, 2014).

A probabilistic sequential decision model is a sequential decision model in which at each state the decision maker receives benefit or cost, and the system evolves to a possibly different state at the next time step (Puterman, 2014). Rewards and transitioning probability depends on the state and the choice.

The Markov decision process is a particular sequential decision model. In the Markov decision process, rewards and transitioning probabilities depend only on the current state and action and not on the state occupied in the deeper past or the actions taken in the deeper past (Puterman, 2014). Uncertainties in non-stationary hydrology can be represented with a Markov process.

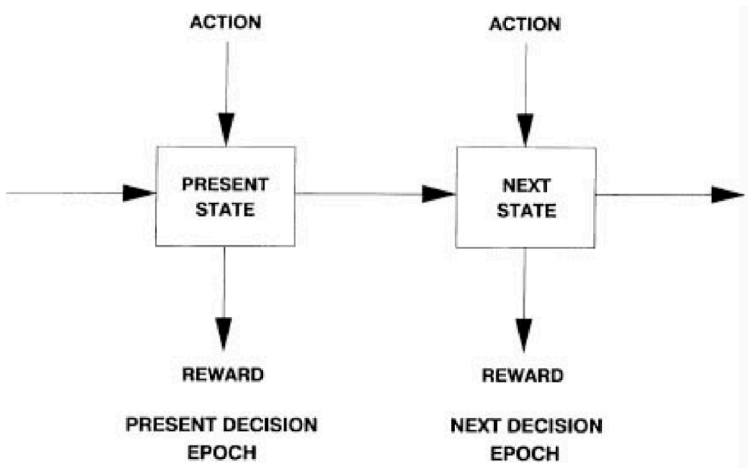


Figure 3.1 Sequential decision-making model. Source: Puterman, 2014

3.3 Dynamic modeling for flood bypass capacity with climate change

Including uncertain climate changes over time in formulating a policy rule for bypass capacity can be done with stochastic dynamic programming. The Markov decision process described above is used to include uncertainties in non-stationary hydrology.

The non-stationary annual flow distribution represented by mean μ_t^s and standard deviation σ_t^s of the annual flood flow varies with time for each of the climate scenarios (CS) considered. Hui et al. (2017) suggested the following representations to describe the mean and standard deviation at each climate scenario:

$\mu_t^s = \mu^{1s} * t + \mu^{0s}$, where μ^{0s} is the initial mean, t is time, and μ^{1s} is the annual rate of change of the mean.

$\sigma_t^s = \sigma^{1s} * t + \sigma^{0s}$, where σ^{0s} is the initial standard deviation, t is time, and σ^{1s} is the annual rate of change of the standard deviation.

The following formulation uses time t as the decision stage, flood bypass capacity at the beginning of current period as a state variable $K^B{}_t$, and the observed climate at the previous stage $\bar{A}_{t-1}(\bar{\mu}_{t-1}, \bar{\sigma}_{t-1})$ represented by observed mean $\bar{\mu}_{t-1}$ and standard deviation $\bar{\sigma}_{t-1}$ of annual flow distribution as additional state variable. The decision variable is the next period's flood bypass capacity $K^B{}_{t+1} = K^B{}_t + \Delta K^B{}_t$. The objective is to minimize total discounted costs over the planning period. All values are discounted to the present value at an inflation-corrected discount rate r.

The backward recursive function at each stage includes the direct cost function $C_t(\Delta K^B{}_t, K^B{}_t)$, which includes gain or loss of floodplain land value, construction, and damage costs (assuming that urbanization and real construction cost do not change over time), as well as the average future costs.

$$f_t(\Delta K_t^B, K_t^B, \bar{A}_{t-1}) = \begin{cases} C_n(\Delta K_t^B, K_t) * \frac{e^r}{e^r - 1}, \ t = n \\ C_t(\Delta K_t^B, K_t^B) + \sum_{s=1}^{m} P_t(A_t^s | \bar{A}_{t-1}) * f_{t+1}^*(\ K_{t+1}^B = K_t^B + \Delta K_t^B, \bar{A}_t), t = 1{:}\,n-1 \end{cases}$$

(Adapted from Hui et. al, 2017).

The future climate scenario probabilities in the present depend on the climate states observed in the immediate past. Wetter observations tend to make wetter futures more likely for example. All possible past climate states and their probabilities are included in the recursive function. The best decisions are carried forward for each state and stage.

$f_{t+1}^*(\ \vec{X}_{t+1} = \vec{X}_t + \overrightarrow{\Delta X}_t, \bar{A}_t) = \underbrace{min}_{\overrightarrow{\Delta X}_{t+1}} f_{t+1}(\overrightarrow{\Delta X}_{t+1}, \vec{X}_{t+1} = \vec{X}_t + \overrightarrow{\Delta X}_t, \bar{A}_t) * e^{-r}$ (adapted from Hui et al., 2017)

$f_t(\Delta K^B{}_t, K^B{}_t, \bar{A}_{t-1})$ is the benefit at each time t considered.

The stage benefit function is:

$$EAT_t(\Delta K_t^B, K_t^B) = EAD_t(\Delta K_t^B, K_t^B) + C_t(\Delta K_t^B, K_t^B)$$

where:

EAT_t is the expected annual cost

EAD_t is the expected annual damage at period t given the expansion of the bypass capacity from $K^B{}_t$ to $K^B{}_{t+1}$.

C_t is the cost function: $C_t(\Delta K_t^B, K_t^B) = \sum_{s=1}^{m} P_t(A_t^s | \bar{A}_{t-1}) * C_t(\Delta K_t^B, K_t^B, A_t^s), t - 1{:}\,n.$

$P_t(A_t^s | \bar{A}_{t-1})$ is the conditional probability that a climate scenario A_t^s is "true" at current stage given observed climate scenario $\bar{A}_{t-1}$ at previous stage (using Bayes' theorem):

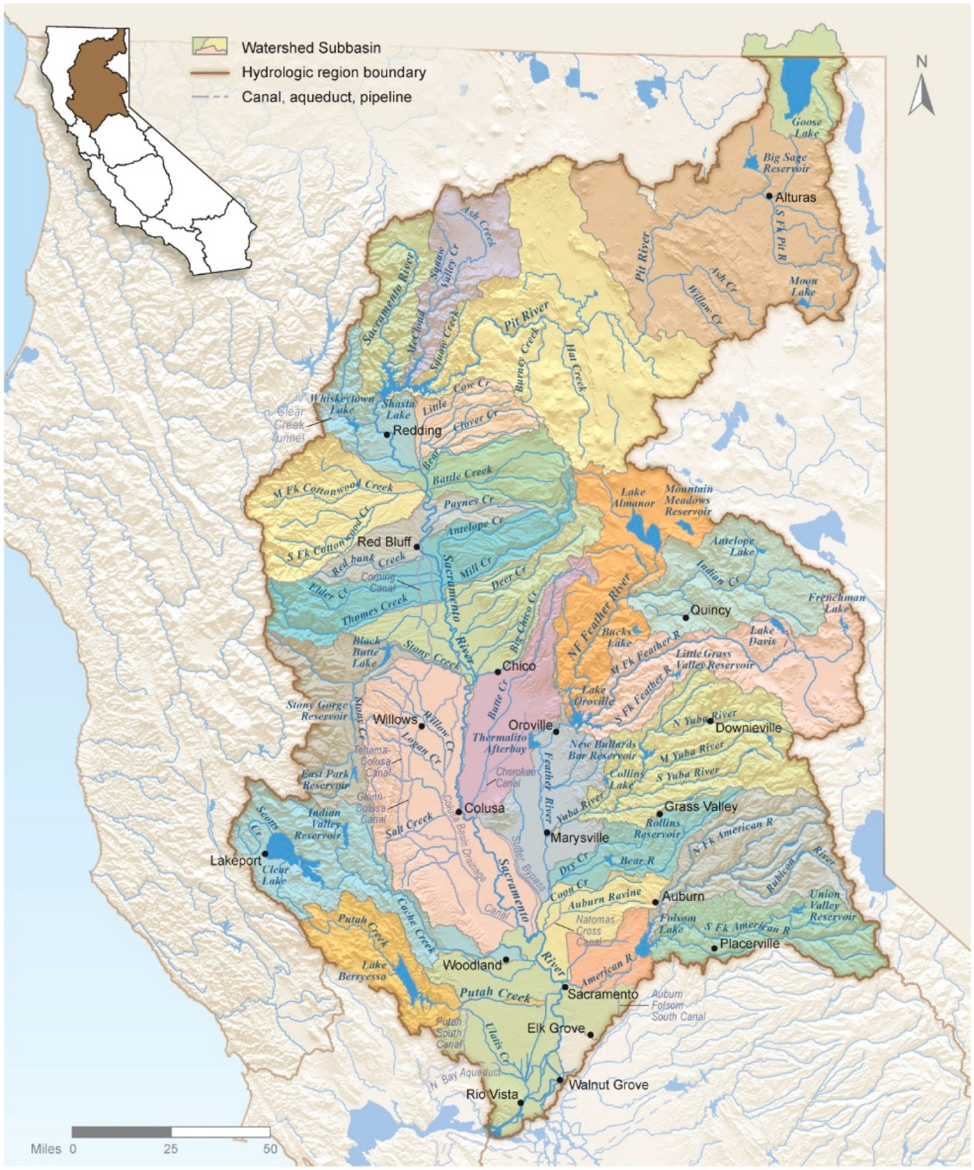
$$P_t(A_t^s | \bar{A}_{t-1}) = \frac{P(A^S) * P_{t-1}(\bar{A}_{t-1} | A_t^S)}{P(\bar{A}_{t-1})} = \frac{P(A^S) * P_{t-1}(\bar{A}_{t-1} | A_t^S)}{\sum_{s=1}^{m}[P(A^S) * P_{t-1}(\bar{A}_{t-1} | A_t^S)]}$$

Bypass improvements can only occur every T year interval and NT times over an infrastructure's lifetime, $n = T * NT$. The above-described model is applied to the Yolo Bypass in California. Construction costs considered are from the weir widening, land use, and fixed costs from the levee setback.

Expected annual damage has been evaluated by simplifying the damage function described in chapter 2. Damage cost is assumed to be a linear function of peak flood flow Q between base channel capacity and overtopping flow capacity (Figure 2.5). Expected annual damage is a function of the reduced flow in the river main stem downstream of the weir diversion (See scheme described in chapter 2).

3.4 The Sacramento River region climate

The Sacramento River begins near the California-Oregon border and runs over 700 km between the Klamath and Coast Mountain Ranges on the west, with the Cascade and Sierra Nevada Mountain Ranges to the east. The Sacramento River cuts the Sacramento metropolitan area, enters the Sacramento-San Joaquin delta in its southern part, and discharges to San Francisco Bay. The Sacramento River watershed covers more than 70,000 km^2 (Fig. 3.2).



Source: Department of Water Resources

Figure 3.2 Sacramento River basin. Source: Andrew et al., 2017

California has a Mediterranean climate, with frequent extremes, both floods and droughts. Natural variability of flow led to construction of several dams in California during the twentieth-century. The Sacramento River is regulated by Shasta Dam, which creates the largest reservoir of California (5.5 km^3) (Andrew et al., 2017). Temporal and spatial variability of demand and supply, together with the need for salinity control in the delta and flood protection, has led to a total reservoir capacity of 19 km^3 in the basin (Andrew et al., 2017).

As result of extensive dam construction and operation, flood peaks are smaller and less frequent, and summer base-flows higher and colder than natural conditions, resulting in a "flattening of the hydrograph" that has reduced habitat and its complexity (Grantham et al., 2010). In addition, the Sacramento basin has an extensive system of floodplain levees and flood bypasses, which altogether has fragmented riparian systems, blocked fish passage, and degraded floodplain habitat, modified water temperatures, and impaired sediment and nutrient transport (Andrew et al., 2017).

3.4.1 Temperature

In California, mean temperature increased by 0.4 to 1.3 °C during the 20th century (DWR, 2015). Temperatures will likely continue to increase, and even accelerate, in this century (Andrew et al., 2017). Projections show an increase in annual mean temperatures in the range of 2.2 to 2.6 °C by the mid-21st century (DWR, 2015).

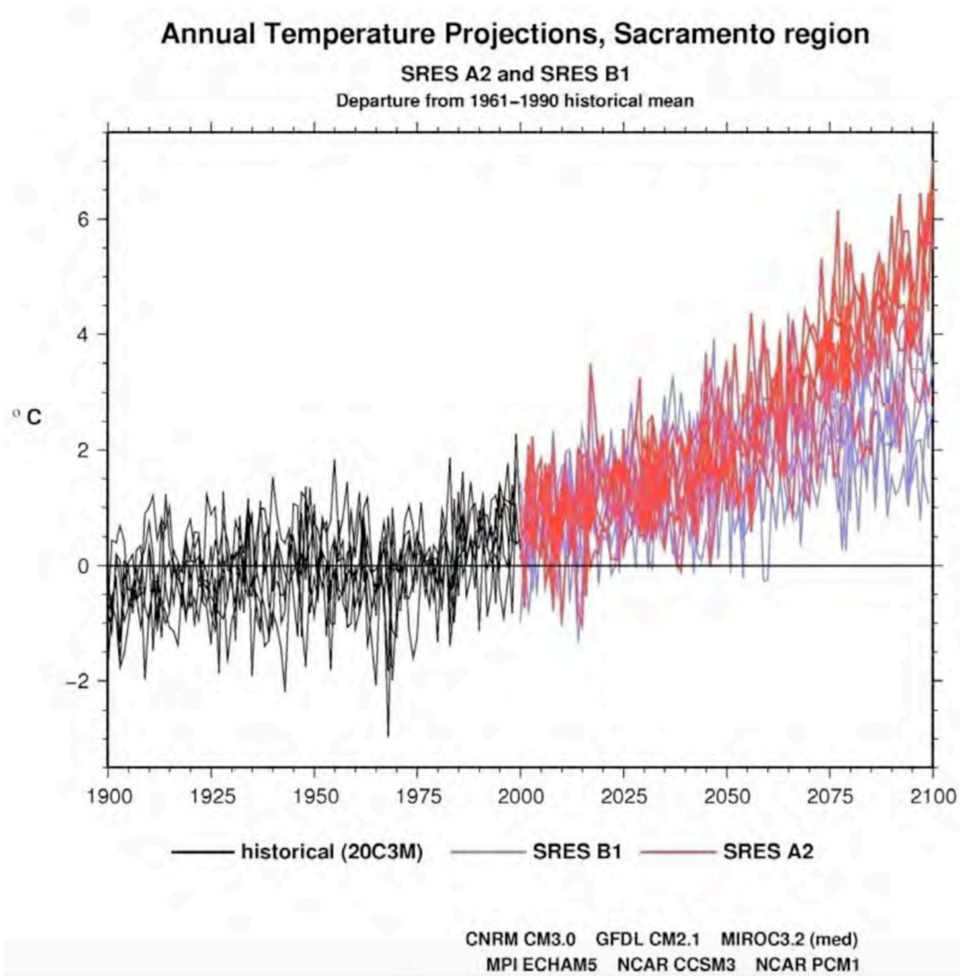


Figure 3.3 Annual temperatures for the Sacramento region. Simulated historical (for the six Global Climate Models (GCMs) for 203CM) (black) and projected 2000-20100 under Special Report on Emissions Scenarios (SRES) A2 (red) and B1 (blue) greenhouse gas (GHG). Source: Cayan et al., 2009

For the Sacramento San Joaquin basin, average mean annual temperature is projected to increase by 5 to 6 °F during this century. The duration of extreme warm temperature is expected to increase from 2 months (July and August) to 4 months (June through September) (Climate Commons, 2017).

The CalAdapt tool defines, during the next few decades, average temperature to rise between 1 and 2.3°F. The models used to predict temperature are based on greenhouse gases already emitted, and produce similar results for different scenarios. Results start to diverge around year 2050 and by the end of the century projected temperature increases in the higher emissions scenario (A2) approximately twice than those projected in the lower emissions scenario (B1) (Climate Commons, 2017).

3.4.2 Precipitation

Total precipitation projections are so variable that it is unknown if the climate will be wetter or dryer. Northern California is already undergoing a change towards more rain and less snow, with a seasonal shift of flows from spring to winter, due to higher temperatures, that is expected to continue (DWR, 2015).

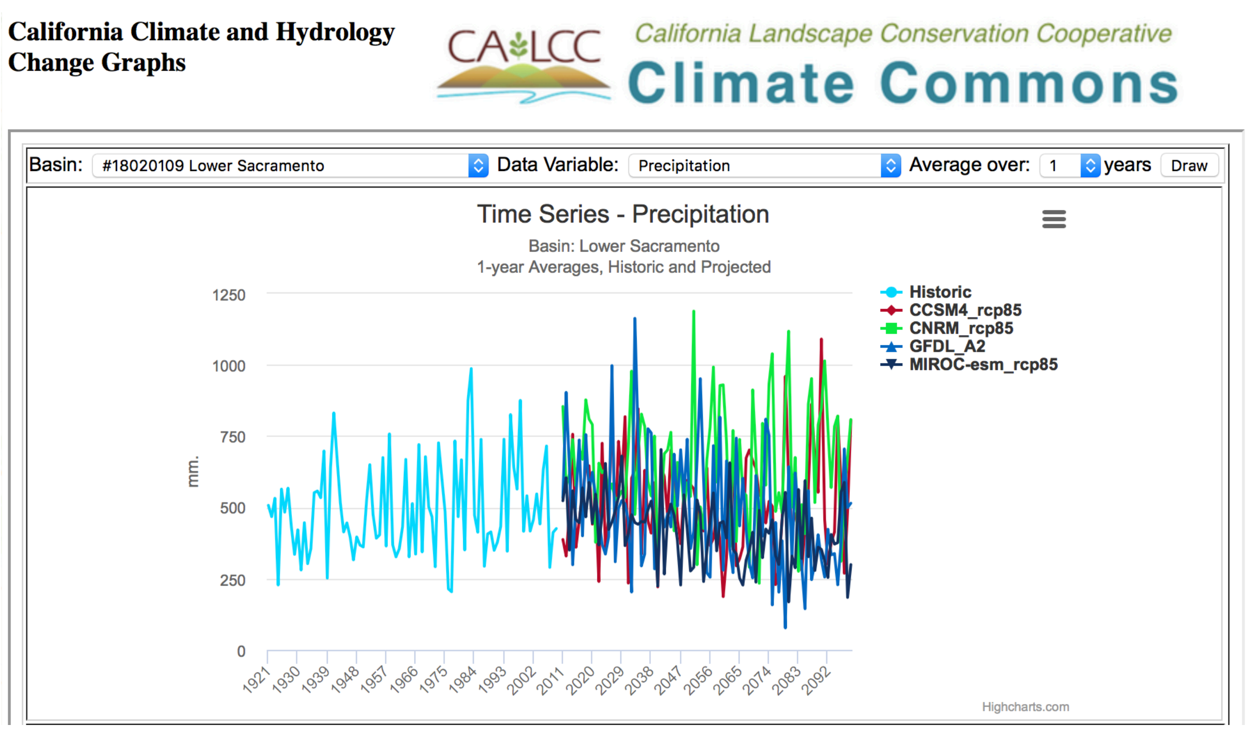


Figure 3.4 Historical and future projections of precipitation for the Lower Sacramento basin. Source: California Basin Characterization Model
http://climate.calcommons.org/aux/BCM_WS_graph/index.php?basin=18020109

To represent the uncertainty in future precipitation patterns, data from the California Basin Characterization Model (BCM) dataset are presented. The BCM offers data over time for 156 hydrologic basins. Figure 3.3 represents historical and four climate scenarios selected from the 18 used in the BCM dataset, for the Lower Sacramento basin.
The four scenarios used are:

- MIROC-esm_rcp85 (warmest, driest)
- GFDL_A2 (moderately warmer, drier future)
- CNRM_rcp85 (wettest and warm)
- CCSM4_rcp85 (midrange, closest to ensemble mean)

3.4.3 Runoff

Runoff will be influenced by changes in temperatures and precipitation. Extreme events will change in frequency, duration, and magnitude (Andrew et al., 2017). Warming will cause snowpack decline, reducing water storage (DWR, 2015). Winter flood flows will occur more frequently given the likely increase of late fall and winter runoff, while runoff will decrease in spring and summer (DWR, 2015). The Sacramento River has already experienced a shift of peak runoff by almost one month earlier due to earlier spring snowmelt (DWR, 2015) (Fig. 3.5).

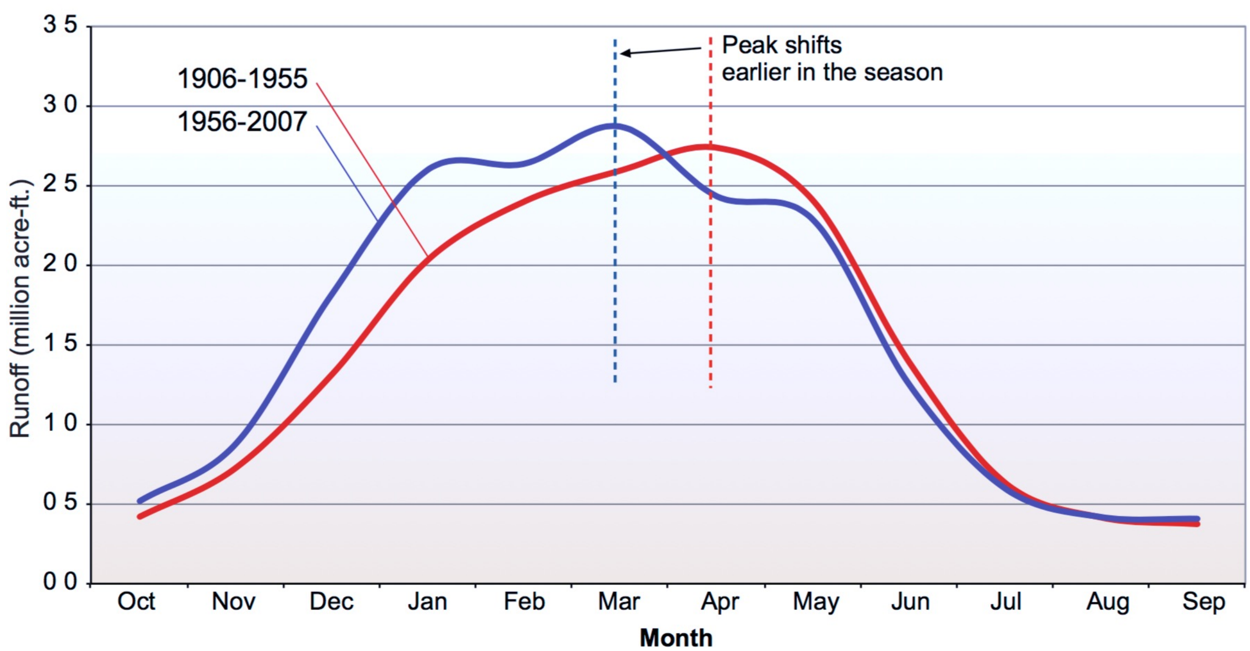


Figure 3.5 Monthly Average Runoff of Sacramento River system. Source: DWR, 2015.

Earlier runoff means reservoirs filled earlier in the season. With existing "flood rule curves" earlier releases from surface storage would be needed to reserve reservoir space for flood management (Andrew et. al, 2017).

Storm response to changes in temperature and precipitation has been analyzed for Shasta, Oroville, and New Bullards Bar reservoirs (Willis et al., 2011). The response has been seen to be similar for both temperature and precipitation changes. During warm storms changes in precipitation intensities affects discharge more than temperature changes. Warm storms contain little snowfall that would be affected by increased temperatures. For cold storms, both temperature and precipitation changes affect discharge strongly (Willis et al., 2011). Effects of climate change on reservoir operations has been also analyzed, with each basin reservoir managing floods differently and providing a full water- supply pool at the end of the flood season differently (Willis et al., 2011)..

3.4.4 Temperature and precipitation change effects

Effects of the changes described above include erosion of riverbanks, degradation of riparian habitat and changes in sediment transport, which can harm fishes and water quality. Ironically, climate change may restore some portion of the peak flows that were reduced by dam building (Andrew et. al, 2017).

Water demand will be affected by higher temperature raise, which will increase evapotranspiration. Less cold water from reservoirs means increase in river temperatures. Also recreational activities will be affected by reduced reservoir levels (DWR, 2014).

3.4.5 Sea level rise and Valley Flooding

Sea levels are expected to rise in the Sacramento-San Joaquin River Delta (Andrew et al., 2017). During the 20th century, sea levels at the Golden Gate (where San Francisco Bay meets the Pacific Ocean) rose 18 cm; another 12–61 cm of rise is expected by 2050 (Andrew et al., 2017). Propagation through San Francisco Bay, upstream into the delta, and into the lower reaches of the Sacramento River is uncertain.

3.5 Global climate models and changes in flood frequency

Given the difficulties in defining credible scenarios for change in large rainfall or snowmelt events that cause flooding, few studies have looked at possible changes in high flows (IPCC, 2014). Global climate models cannot accurately simulate short-duration, high-intensity, localized heavy rainfall, and a change in mean monthly rainfall may not be representative of a change in short-duration rainfall (IPCC, 2014). Some studies have tried to estimate changes in flood frequency assuming a correlation between changes in monthly rainfall and "flood-producing" rainfall. Some studies have analyzed the possible effect of climate changes on rainfall intensity. For example, Reynard et al. (1998) analyzed change of magnitude of different return period floods in the Thames and Severn catchments. Their study is based on the assumption that first all rainfall amounts change by the same proportion and then that only "heavy" rainfall increases (IPCC, 2014). According to their results, flood risk increases because winter rainfall increases, and in catchments of the size they analyzed the total volume of rainfall over several days is more relevant than the peak intensity of rainfall.

Schreider et al. (1997) in Australia assumed instead that all rainfall amounts change by the same proportion. Their results show greater floods under their wettest scenarios, while annual runoff totals did not increase, but lower flood frequency in their driest scenarios (IPCC, 2014).

The California Department of Water Resources in a technical memorandum for the Central Valley Flood Protection Plan provides an overview of climate change tools used in its 2016a update (DWR, 2017). Before this, evaluation of California Central Valley flood control improvements had been based solely on the past 100 years climate and hydrology.

Given future climate projections indicate possible increase of flood peak flows and flood volumes for the Central Valley, DWR started to assess potential implications. DWR defined a set of adjustments to historical flow volume-frequency curves to be used as a preliminary assessment of the effects of climate change in the Central Valley (DWR, 2017).

Climate scenarios based on climate model simulations from the Coupled Model Intercomparison Project Phase 3 (CMIP3) were used. Data from CMIP3 were the basis for the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4) released in 2007 (IPCC, 2007). The results were applied directly to the Basin Wide Feasibility Study (BWFS) technical evaluations (DWR, 2017).

Estimates of potential changes in unregulated flows throughout the Central Valley were updated based on climate model simulations from the Coupled Model Intercomparison Project Phase 5 (CMIP5) (DWR, 2017). The CMIP5 climate model data are the basis for the most recently released IPCC Fifth Assessment Report (AR5) (IPCC, 2013). Climate scenarios were applied to the historical variability in climate to estimate changes in unregulated flow volumes, and the hydrologic responses were simulated (DWR, 2017).

The California Department of Water Resources has included in the 2017 Central Valley Flood Protection Plan (CVFPP) Update a Scenario Technical Analyses Summary Report (DWR, 2017a). The Bay-Delta Water Surface Elevation (WSEL) for the future-conditions scenarios have been developed by using the two-dimensional (2-D) Resource Management Associates, Inc. (RMA) Delta Model to estimate Sacramento-San Joaquin Delta (Delta) stages under various flood events (DWR, 2017a). A range of events was used to develop flow-frequency and stage-frequency curves. This is the input for the flood risk analysis. To accelerate the modeling process DWR selected 10 CVHS flood events (Table 3.1) to estimate stages in the Bay-Delta. The selected CVHS flood events represent annual exceedance probability (AEP) ranging from 0.99 (AEP = 1/1.001) to 0.00025 (AEP = 1/4000). AEP was assigned to regulated flows for the Sacramento and San Joaquin River systems at given time (DWR, 2017a).

Table 3.1 CVHS Flood events for RMA Bay-Delta Model. Source: DWR, 2017a

Year	Event	Year	Event
1956	10% scaled event	1956	120% scaled event
1986	40% scaled event	1997	115% scaled event
1986	60% scaled event	1997	140% scaled event
1986	unscaled event	1997	160% scaled event
1956	unscaled event	1997	200% scaled event

Figure 3.6 shows the inverse of AEP for peak total Sacramento River flows at Sacramento, where AEP is shown for each scaled event under the current climate (blue bars) and for each scaled storm under the projected inland climate change (orange bars). The same scaled event represents drastically different AEPs in the two conditions. For example, 115 percent of the 1997 event represents a bit over 200-year return-interval (1/AEP) in the current climate and less than a 100-year return-interval taking into account projected inland climate change (DWR, 2017a).

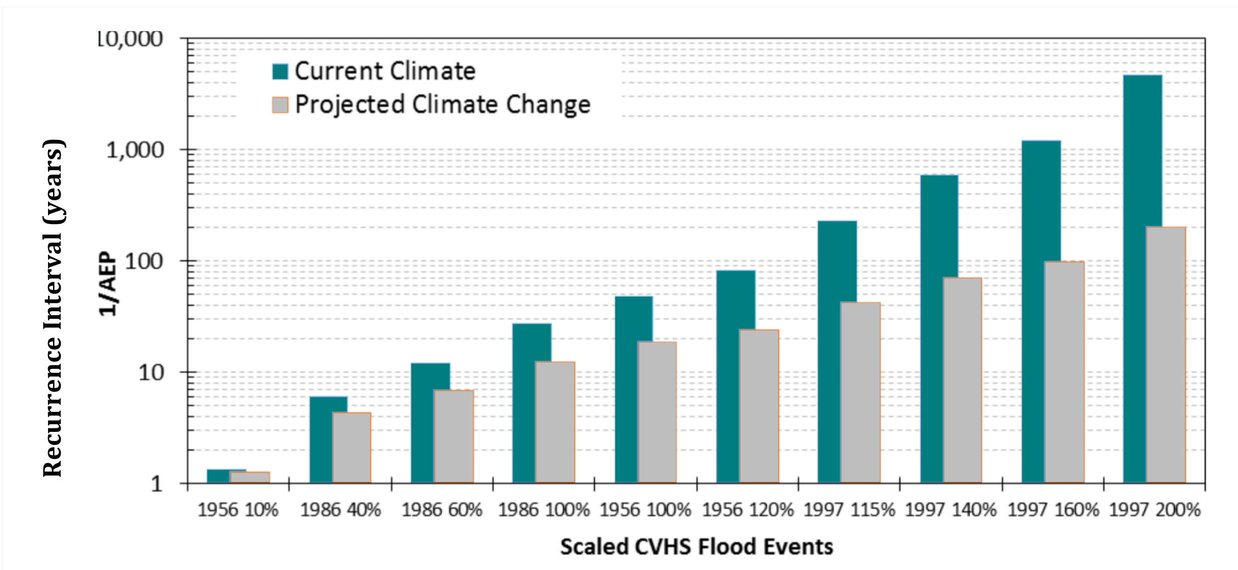


Figure 3.6 Inverse of annual exceedance probability for peak total Sacramento River flow rate at latitude of Sacramento for selected CVHS events Source: DWR, 2017a

3.6 Model application to the Yolo Bypass

The Sacramento region is expecting increased flooding problems due to climate change (Zhu et al. 2002), economic expansion, population, and increasing urban property values exposed to potential flooding. Population could increase in the greater Sacramento area by 2100 to four million (Landis and Reilly, 2002), doubling today's population of about 2

million. An analysis of bypass capacity expansion for long-term protection is needed, given changing climate, land use, construction costs, and flood damage costs.
Two long-term bypass strategies are analyzed:

1. one-time building planning
2. multiple improvements adapting over time.

One-time building assumes that any bypass modification will happen at the present time with no further modifications for the rest of the planning period. The adaptation strategy instead allows further modifications that can increase capacity over time.

Data on the system are the same used for the linear model application to the Yolo Bypass in chapter 2. Costs are assumed at the California Department of Water Resources cost list, in their 2016 Basin-Wide Feasibility studies on the Sacramento River Basin. In particular, DWR estimates \$72 million for 1 mile expansion of Fremont Weir, and \$280 million for the Upper Elkhorn Setback (based on a June 2014 unit cost) (DWR, 2016). From these costs, unit costs for weir expansion and levee setback have been calculated and used for this application. Land and vegetation removal costs are from the USDA (National Agricultural Statistics Service, 1999), equal to \$5,600 per acre.

Table 3.2 Cost of bypass expansion

Fremont Weir Expansion Cost	\$72 million / mile
Upper Elkhorn Setback	\$280 million
Land Cost of Cropland + Vegetation Removal	\$5,600 per acre

First, a case of mean and standard deviation of peak flow changing with the same rate (0.002 m^3/s/year) has been analyzed for 10 climate scenarios. Mean and standard deviation for each year and each climate scenario are reported in table 3.3 and 3.4.

Case 1: Mean and Standard deviation change at same rate

Table 3.3 Mean peak flow (m^3/s) for different years and different climate scenarios with rate of change of 0.002 m^3/s/year, defined according to section 3.3.

	Climate scenarios									
Year	1	2	3	4	5	6	7	8	9	10
1	748.0	749.5	751.0	752.5	754.0	755.5	757.0	758.5	760.0	761.5
2	748.0	751.0	754.0	757.0	760.0	763.0	766.0	768.9	771.9	774.9
3	748.0	752.5	757.0	761.5	766.0	770.4	774.9	779.4	783.9	788.4
4	748.0	754.0	760.0	766.0	771.9	777.9	783.9	789.9	795.9	801.9
.	.	.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.	.	.

197	748.0	1042.7	1337.4	1632.1	1926.8	2221.6	2516.3	2811.0	3105.7	3400.4
198	748.0	1044.2	1340.4	1636.6	1932.8	2229.0	2525.2	2821.5	3117.7	3413.9
199	748.0	1045.7	1343.4	1641.1	1938.8	2236.5	2534.2	2831.9	3129.6	3427.3
200	748.0	1047.2	1346.4	1645.6	1944.8	2244.0	2543.2	2842.4	3141.6	3440.8

Table 3.4 Standard deviation of peak flow (m3/s) for different years and different climate scenarios with rate of change of 0.002 m3/s/year.

Year	Climate scenarios									
1	1	2	3	4	5	6	7	8	9	10
2	710.6	712.0	713.4	714.9	716.3	717.7	719.1	720.5	722.0	723.4
3	710.6	713.4	716.3	719.1	722.0	724.8	727.7	730.5	733.3	736.2
4	710.6	714.9	719.1	723.4	727.7	731.9	736.2	740.4	744.7	749.0
.	.	.	.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.	.	.	.
197	710.6	990.6	1270.6	1550.5	1830.5	2110.5	2390.5	2670.4	2950.4	3230.4
198	710.6	992.0	1273.4	1554.8	1836.2	2117.6	2399.0	2680.4	2961.8	3243.2
199	710.6	993.4	1276.2	1559.1	1841.9	2124.7	2407.5	2690.3	2973.2	3256.0
200	710.6	994.8	1279.1	1563.3	1847.6	2131.8	2416.0	2700.3	2984.5	3268.8

Climate scenario 1 is stationary, with constant mean and standard deviation with time, as described by a constant probability density function. (Fig.3.7). The other scenarios have greater rates of increase in the mean and standard deviation of peak annual flood flows.

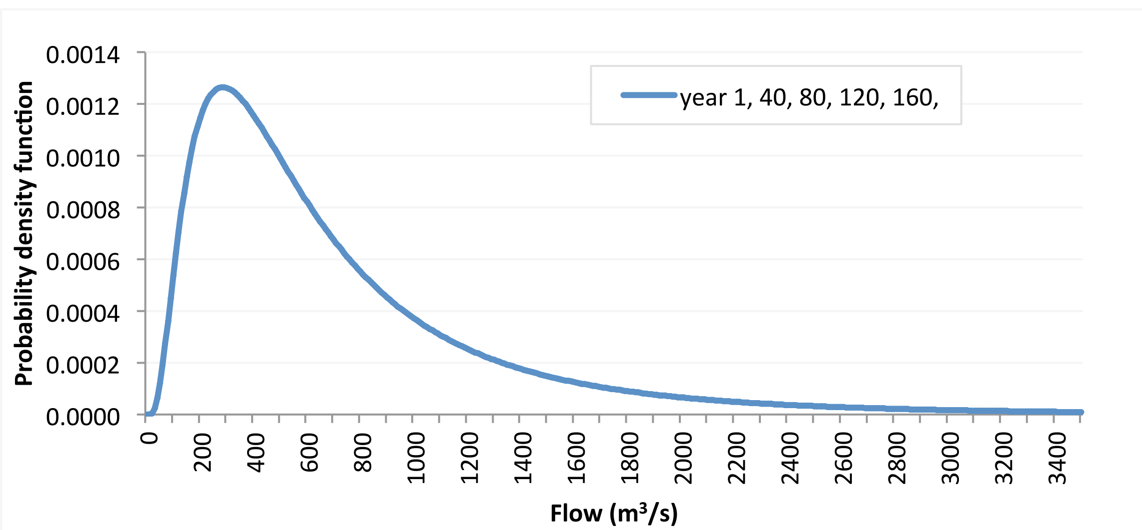


Figure 3.7 Probability density function with time for stationary hydrology (Climate scenario 1)

The probability density function for climate scenario 2 and climate scenario 10 follow the trends described in figure 3.8. Figure 3.9 shows probability density function at year 100 for all the 10 climate scenarios

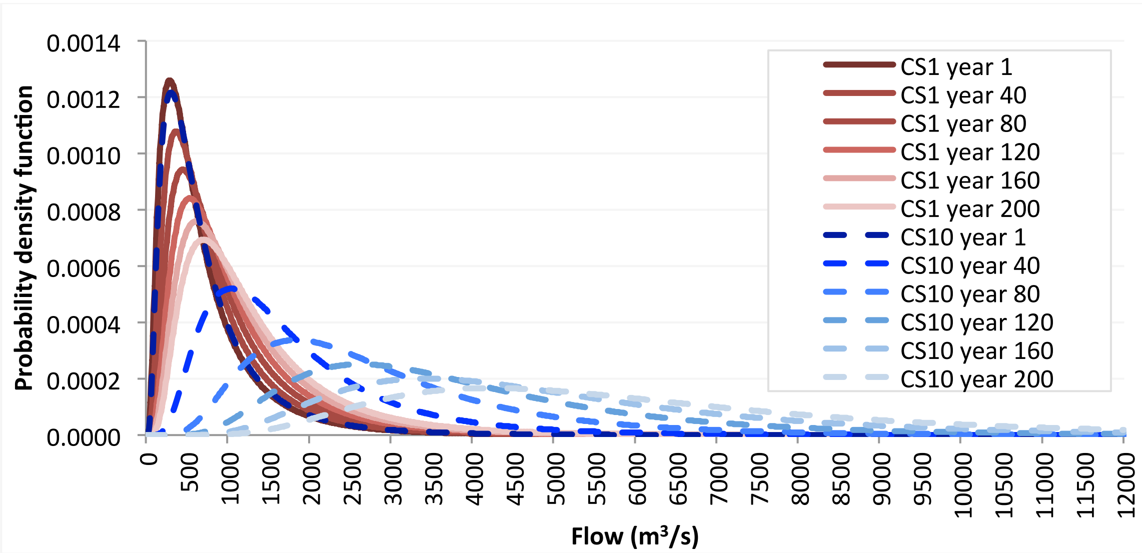


Figure 3.8 Probability density function with time for non-stationary hydrology (Climate scenario 2 CS2 (in red) and climate scenario 10 CS10 (in blue)

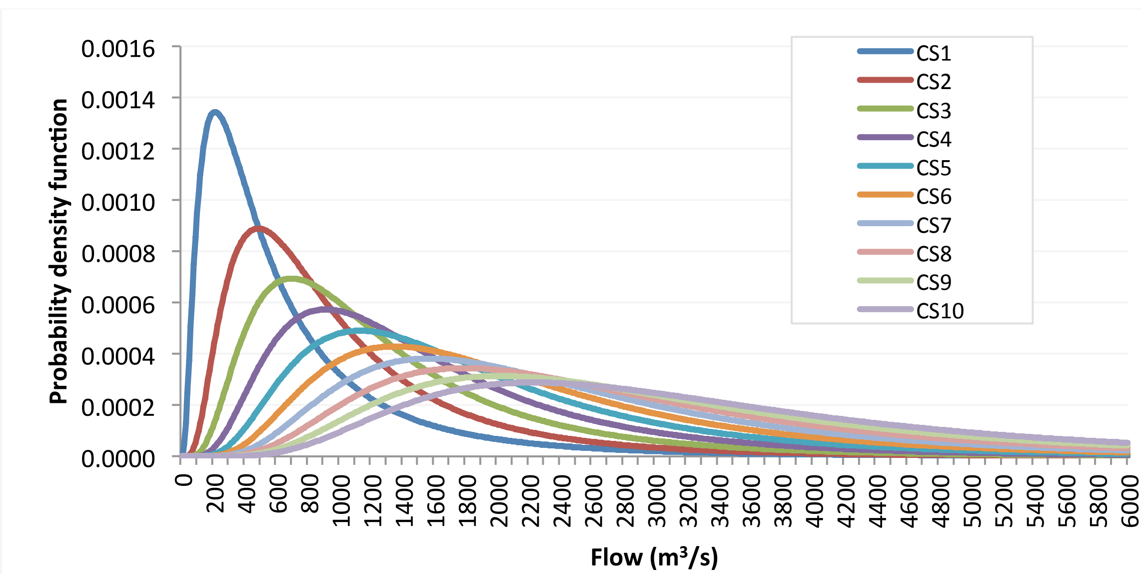


Figure 3.9 Probability density function at year 100 for the 10 climate scenarios (cs)

3.7 Yolo Bypass Model Results

Results of the optimization model suggest capacities for different cumulative climate scenarios and different decision time periods. Cumulative climate scenarios include the

current and all previous climate scenarios. So, for example, cumulative climate scenario 3 includes climate scenario 1, climate scenario 2, and climate scenario 3.
For this application scope the rate of change of the mean and standard deviation are equal to 0.002.

Table 3.5 Total average optimal initial bypass capacity (m^3/s) for different climate scenarios (changing mean and standard deviation at the same rate) (at the first stage, year 1), upgraded to capacity at the last stage (year 200)

		Initial optimal capacity		Average optimal final capacities
Climate uncertainty range	**Climate case scenarios**	**One-time expansions**	**Multiple expansions***	**Multiple expansions***
Stationary (Mean certain)	1	11,100	11,100	11,100
Climate change	1,2	11,400	11,300	13,000
Narrower uncertainty range	1,2,3	11,700	11,500	15,000
	1,2,3,4	12,100	11,700	16,900
	1,2,3,4,5	12,400	11,900	18,700
	1,2,3,4,5,6	12,800	12,100	20,500
	1,2,3,4,5,6,7	13,300	12,300	22,400
	1,2,3,4,5,6,7,8	13,700	12,500	24,100
	1,2,3,4,5,6,7,8,9	14,200	12,800	25,800
Broad range	1,2,3,4,5,6,7,8,9,10	14,600	13,000	26,100

*For expansions allowed over 200 years

Results for combinations of climate scenarios are in tables 3.5 and 3.6. Table 3.5 shows total optimal bypass capacity for the one-time building planning and the four-times building planning policy. Accounting for climate change could increase today's optimal capacity by up to 20% (average narrow uncertainty range, table 3.5).

Allowing only initial construction for 200 years, for 1 climate stationary scenario the optimal capacity is 11,100 m^3/s. Considering 2 climate scenarios the optimal capacity is 11,400 m^3/s. Considering 3 climate scenarios the optimal capacity is equal to 11,700 m^3/s. For 4 climate scenarios the optimal capacity 12,100 m^3/s, and so on. Adding wider ranges of uncertainty leads to greater optimal ultimate capacities.

Allowing possible improvement every 50 years, for the stationary climate scenario, optimal initial bypass capacity is 11,100 m^3/s with no future changes. Considering 2 climate scenarios the model suggests a greater capacity equal to 11,300 m^3/s, with improvements of 500 m^3/s, 600 m^3/s, and 600 m^3/s after each 50 years time step considered for a total of 13,000 m^3/s, as shown in table 3.6. Considering more extreme climate scenarios, the mean and standard deviation of the annual flood flow change more with each additional climate scenario. For this reason, in a particular year, optimal bypass capacity differs for group of scenarios considered.

Table 3.6 Total average present value construction cost, expected annual damage (EAD), Net Benefit = EAD – Costs ($Million) for different climate scenarios (changing mean and standard deviation at the same rate). Values are averages.

	One-time construction			Multiple-times construction		
Climate Scenarios	**COST ($M)**	**EAD reduction ($M)**	**NET BENEFIT ($M)**	**COST ($M)**	**EAD reduction ($M)**	**NET BENEFIT ($M)**
1	133	191	58	133	191	58
1,2	137	293	156	234	417	183
1,2,3	141	425	284	268	577	309
1,2,3,4	145	525	380	301	739	438
1,2,3,4,5	150	646	496	333	913	580
1,2,3,4,5,6	155	767	612	365	1078	713
1,2,3,4,5,6,7	161	886	725	396	1237	841
1,2,3,4,5,6,7,8	166	1003	837	427	1394	967
1,2,3,4,5,6,7,8,9	172	1114	942	457	1539	1082
1,2,3,4,5,6,7,8,9,10	178	1219	1041	491	1676	1185

In table 3.7, analyzing 7 climate scenarios, the model suggests a 12,300 m^3/s optimal capacity at year 1, 3,200 m^3/s improvement at year 51 for each of the 7 climate scenarios considered, 3,200 m^3/s improvement for scenario 1-2-3 and 3,300 m^3/s at year 101, and 3,600 m^3/s for scenarios 1-2-3-4-5 and 3,700 m^3/s for scenarios 6 and 7 at year 151. The model suggests improvement for scenarios 4-5-6-7 of 3,300 m^3/s at year 51, and improvements of 3,500 m^3/s for scenarios 1-2-3-4-5 and improvement of 3,600 m^3/s for scenarios 6 and 7 at year 101. Table 3.8 represents the optimal capacity at each time step for improvement for cumulative climate scenarios 7 just described.

Table 3.7 Optimal bypass capacity expansion (m^3/s) for different climate scenarios (CS) (changing mean and standard deviation at the same rate) with the multiple times expansion policy (every 50 years).

Cumulative climate scenarios	**Initial optimal capacity**	**Optimal expansion**			**Average final capacity**
	Year 1	**Year 51**	**Year 101**	**Year 151**	
1	11,100	-	-	-	11,100
2	11,300	500	600	600	13,000
3	11,500	1,000	1,100	1,400	15,000
4	11,700	1,500	1,700	1,900 (CS 1) 2,000 (CS 2-3-4)	16,900
5	11,900	2,100	2,200	2,500	18,700
6	12,100	2,600	2,800	3,000 (CS 1-2-3) 3,100 (CS 4-5-6)	20,500
7	12,300	3,200	3,200 (CS 1-2-3)	3,600 (CS 1-2-3-4-5) 3,700 (CS 6-7)	22,300
			3,300 (CS 4 to 7)	3,500 (CS 1-2-3-4-5) 3,600 (CS 6-7)	22,400
8	12,500	3,700	3,800	4,100	24,100
9	12,800	4,200	4,200	4,600 (CS 1 to 6) 4,700 (CS 7-8-9)	25,800
10	13,000	4,700	4,700 (CS 1 to 6)	3,600	26,000
			4,800 (CS 7-8-9)	3,500	26,000

Table 3.8 Optimal bypass capacity expansion (m³/s) for cumulative climate scenarios (CS) 7 (changing mean and standard deviation at the same rate) with the adaptive expansions policy (every 50 years)

In the hypothesis of observing scenario 1 for 150 years, the model suggests to still expand the bypass up to a total capacity of 22,300 m³/s. The model also shows in this case small differences in expansions for each climate scenarios.

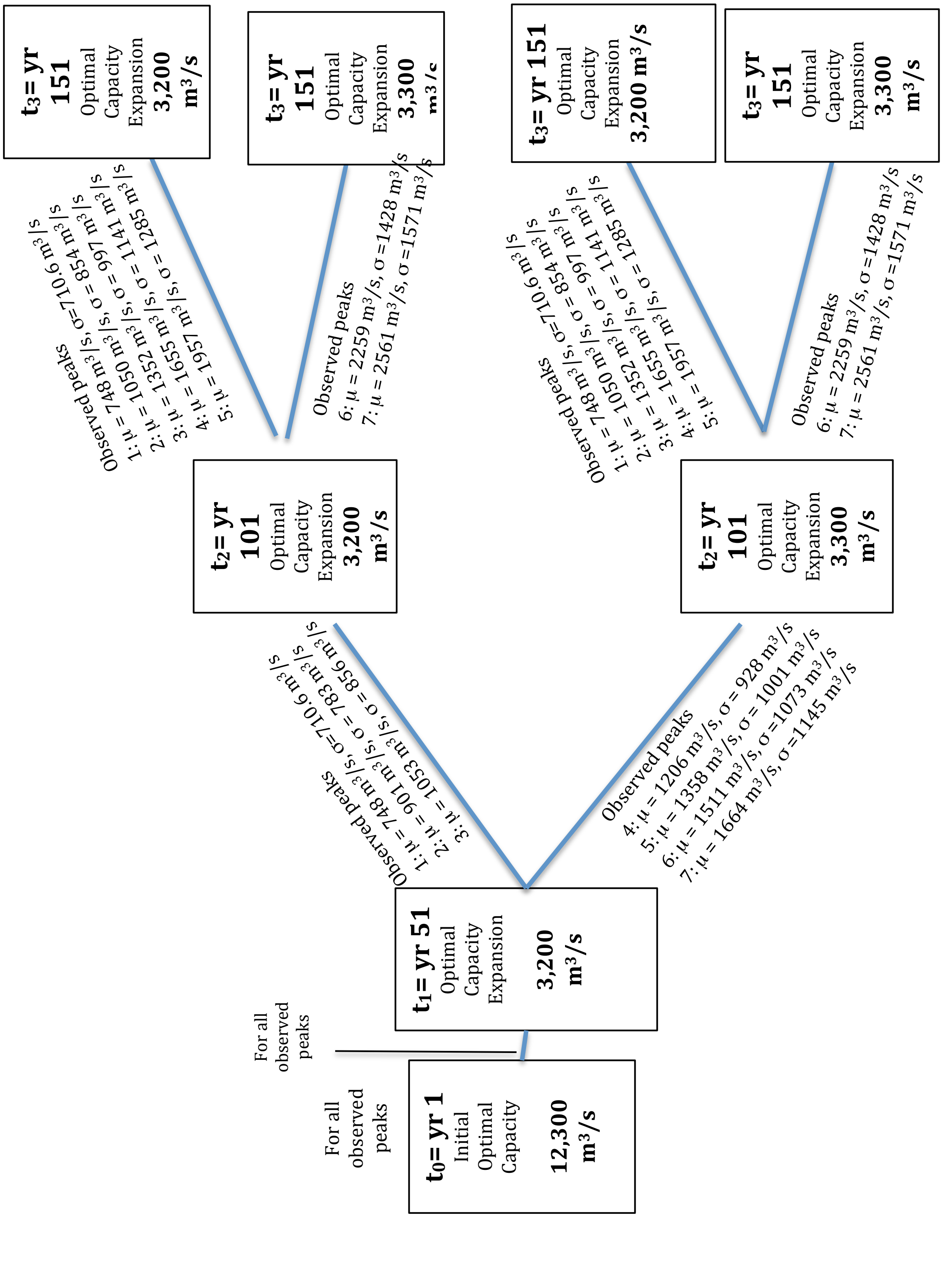


Figure 3.10 Optimal capacity (m³/s) for cumulative climate scenarios (CS) 7 (changing mean and standard deviation at the same rate) with the multiple times building planning policy (every 50 years).

Figure 3.10 explicitly reports the "split" decision parameter values of mean and standard deviation of peak flow. At year 1 it is advised to build a 12,300 m^3/s bypass for all observed peaks. At year 51 for all observed peaks the model suggests an expansion of 3,200 m^3/s. At year 101 and expansion of 3,200 m^3/s is suggested for the first 3 climate scenarios analyzed. For scenarios 4-5, 6 and 7, the model suggests an expansion of 3,300 m^3/s. At year 151, the model suggests other two splits of decisions. For the year 151 the model suggests other 2 decisions: 3,200 m^3/s expansion for the first 5 climate scenarios and 3,300 m^3/s for scenario 6 and 7.

Present value costs decrease with time because of the discount rate, and they increase as more extreme climate scenarios are considered. The additional uncertainty increases future flood damages to be accounted and prepared for (Table 3.9).

Table 3.9 Total present value construction cost ($ million) for different climate scenarios (changing mean and standard deviation at the same rate) with the multiple times building planning policy (every 50 years)

	YEAR				
Cumulative climate scenarios	**1**	**51**	**101**	**151**	**Total**
1	133	0	0	0	133
2	137	31	33	33	234
3	141	39	43	45	268
4	145	47	53	56	301
5	149	56	62	66	333
6	153	65	72	75	365
7	157	73	81	85	396
8	161	82	90	94	427
9	165	89	99	104	457
10	170	98	108	115	491

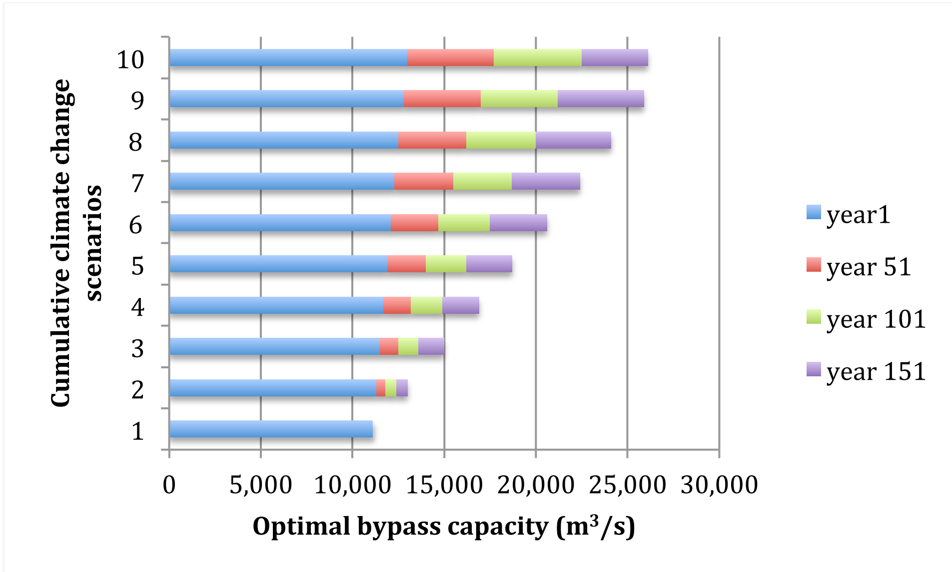


Figure 3.11 Optimal bypass capacity (m^3/s) for different cumulative climate scenarios with the multiple times building planning policy (every 50 years)

From fig. 3.11 the action at year 1 is similar for all combinations of climate scenarios considered, while the improvements at later times increase if more extreme climate scenarios become probable (fig. 3.11). Costs are showed in fig. 3.12.

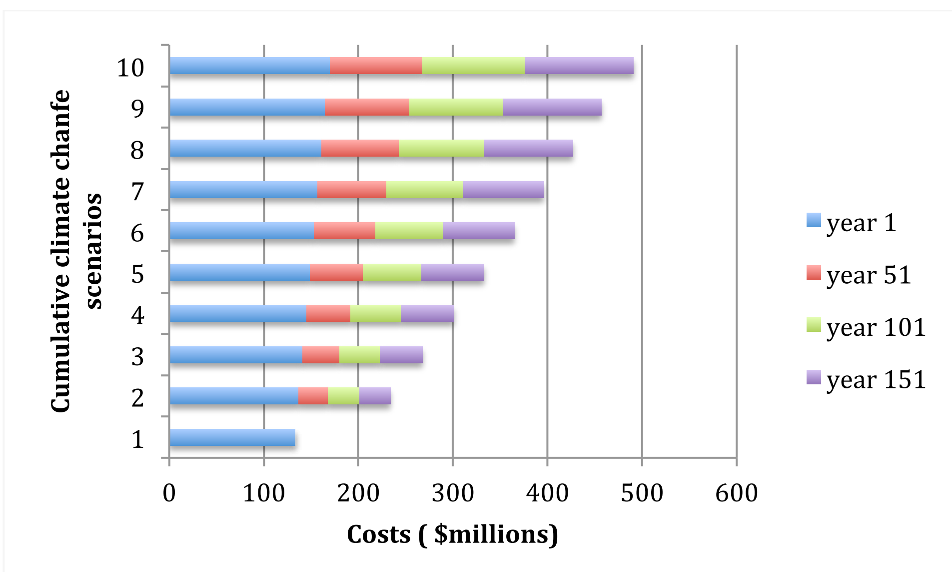


Figure 3.12 Expected present value costs ($ million) for different cumulative climate scenarios with the multiple times building planning policy (every 50 years)

Total optimal capacity differs notably between the one-time building policy and the adaptive improvements policy, especially when more extreme climate scenarios are included. The one-time policy suggests a lower optimal capacity than the total capacity suggested by the adaptive policy.

An additional 10,000 m^3/s is suggested considering all the 10 climate scenarios for the multiple-times improvement versus the one-time building policy. While the maximum difference for the 10 cases between one-time and multiple-times building policy is of approximately 10,000 m3/s of optimal capacity which is approximately 70% more than the one-time building solution (look at the cumulative climate scenario 10 in figure 3.13), costs differ even greater. The biggest difference of cost happens if considering the most extreme scenario (cumulative climate scenario 10 in figure 3.14) with a cost of approximately $180 million for the one-time building policy and an increase of approximately 170% up to $490 million.

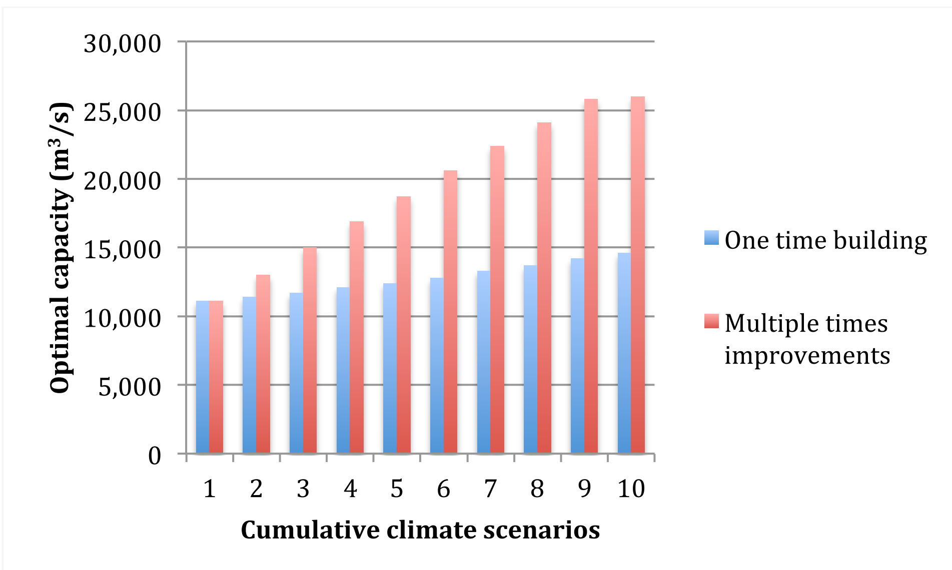


Figure 3.13 Average final optimal bypass capacity (m^3/s) for different cumulative climate scenarios with the one-time and the multiple-times building planning policy (every 50 years)

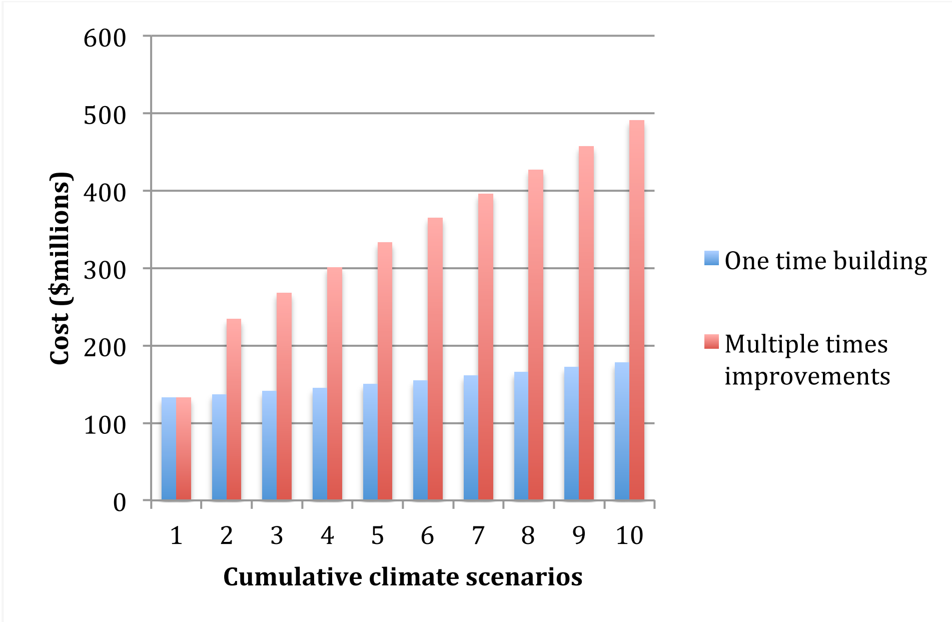
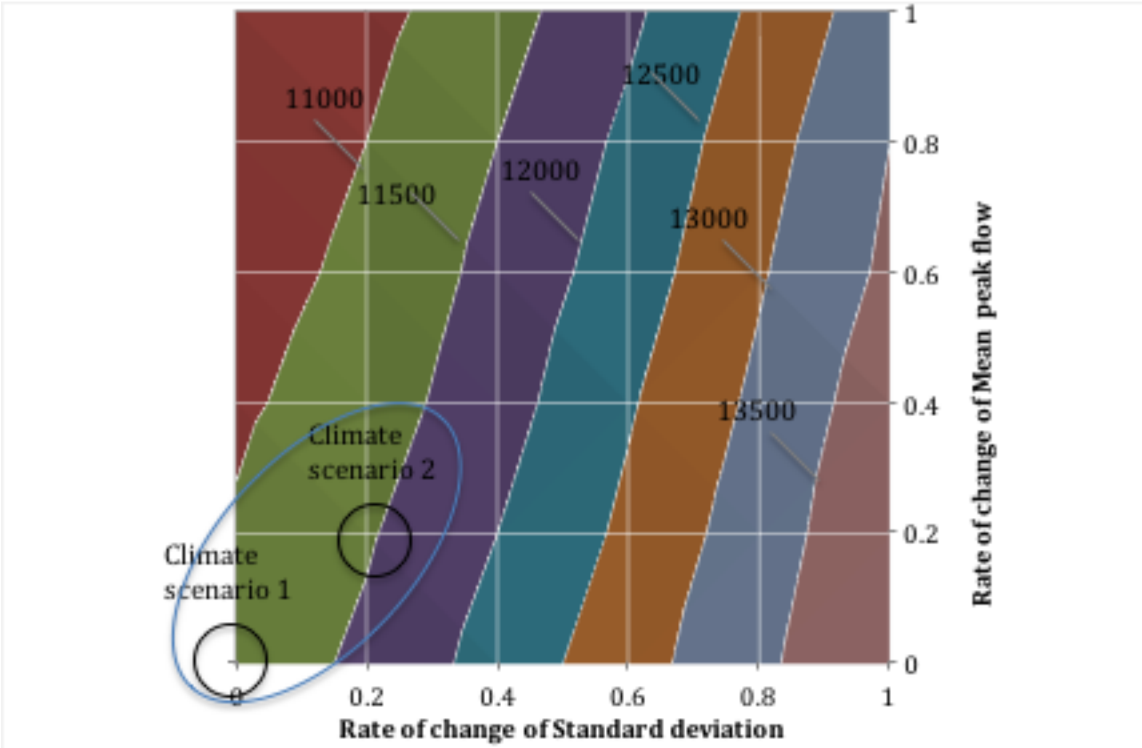


Figure 3.14 Costs ($ million) for different cumulative climate scenarios with one-time and the multiple times building planning policy (every 50 years)

Case 2: Changing mean and standard deviation with different rate of change

Figure 3.15 shows how the optimal capacity changes with rate of change for mean and standard deviation. Changes in mean affect the optimal capacity less than changes in standard deviation. For constant mean peak flow, rate of changes of standard deviation from zero to 1 produce altered optimal capacity from 11200 to 14000 m^3/s (25% increase). Constant standard deviation and rate of variation of mean peak flow from 0 to 1 reduce optimal capacity from 11200 to 10600 m^3/s (5% decrease).



3.15 Final optimal bypass capacity (m^3/s) for different for changing mean and standard deviation evaluated at year 100.

3.8 Conclusions

To analyze the effect of climate change on flood bypasses, optimal bypass capacity trajectories have been estimated for one-time building plans and for multiple-expansions plans.

A Bayesian stochastic dynamic programming approach can be used for dynamic capacity expansion problems, including climate change and potentially other uncertain changes in damage potential.

For a planning horizon of 200 years, a combination of different climate scenarios and capacity expansions has been explored. Effects of the range and probabilities of different climate change scenarios are examined. For the one-time building planning policy, the model shows that considering more climate scenarios means adding complexity and uncertainty, which translates in a "safer" (greater) optimal capacity.
The following policy and planning implications come from this analysis:

1) **Climate change can affect optimal bypass capacity today.**
For a lifetime of 200 years considered for the weir, with possible improvement every 50 years, the combination of different climate scenarios has been analyzed. The model shows that considering more extreme climate scenarios, the mean and standard deviation of the

annual flood flow change more in each projected climate scenario. For this reason, in a particular year, optimal bypass capacity is different for different climate scenarios considered. Costs increase with time because of the discount rate, and they increase as more extreme climate scenarios are considered, suggesting that the additional uncertainty has the effect of increasing flood damages to be accounted for.
Results also show that the action at year 1 is similar for each cumulative climate scenario considered, while the improvements at subsequent time steps increase more as more extreme climate scenarios are considered.

2) **Adaptability to climate change greatly lowers its costs.**
Total optimal capacity differs notably between the case of one-time building policy and the four-times improvements policy, and the difference increase accounting for further extreme climate scenarios. The one-time policy suggests a lower optimal capacity respect to the total capacity suggested by the adaptive policy. An additional 10,000 m^3/s is suggested considering all the 10 climate scenarios for the multiple-times improvement versus the one-time building policy. While the maximum difference for the 10 cases between one-time and multiple-times building policy is of approximately 10,000 m^3/s of optimal capacity which is approximately 70% more than the one-time building solution (look at the cumulative climate scenario 10 in figure 3.15), costs differ even greater. The biggest difference of cost happens if considering the most extreme scenario (cumulative climate scenario 10 in figure 3.16) with a cost of approximately $180 million for the one-time building policy and an increase of approximately 170% up to $490 million.

3) **For this case, uncertainty in future peak flow standard deviation is more important for optimization expansions than uncertainty in peak flow mean.**
Keeping constant the standard deviation while varying the mean results in a decreasing optimal bypass capacity and costs with more extreme climate scenarios considered with a significant difference from the same rate of change for mean and standard deviation case previously analyzed. The effect on optimal capacity given by the rate of change for mean and standard deviation has been analyzed. Changes in mean affect the optimal capacity less than changes in standard deviation. For constant mean peak flow, rate of changes of standard deviation from zero to 1 produce a 25% increase. Constant standard deviation and rate of variation of mean peak flow from 0 to 1 reduce optimal capacity of 5%.

4) **Further research should focus on analyzing the effect of other changes, such as discount rate and damage potential growth on initial adaptation and future adaptation.**

A more complete Bayesian formulation is needed to analyze cases when the mean and standard deviations are not included in the ranges defined in the climate scenarios considered.

Chapter 4 proposes promising expansions for the Yolo Bypass in California.

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CHAPTER 4: PRELIMINARY HYDRAULIC ANALYSIS OF EXPANSION OF THE YOLO BYPASS CAPACITY

Abstract

Possible modifications to California's Yolo Bypass are often suggested. The California Department of Water Resources has suggested some modifications to substantially increase the capacity of the Yolo Bypass (DWR, 2017). The Sacramento Area Flood Control Agency (SAFCA) proposed the implementation of flood control improvements to the Sacramento flood control system. The improvements included widening the Sacramento and Yolo Bypass, lengthening the Sacramento Weir and Fremont Weir, setting back the Sacramento Bypass North Levee and the Yolo Bypass East Levee (SAFCA, 2015).

This chapter develops a preliminary integrated hydraulic analysis of proposed modifications for multi-objective flood bypasses, applied to California's Yolo Bypass. A hydraulic model developed at the Center for Watershed Sciences at UC Davis is used to evaluate structural modifications to the Yolo Bypass. The model is an integrated 1D-2D model developed with the HEC-RAS software by the Army Corps of Engineers, representing the Lower Sacramento River. New model scenarios, representing capacity expansion by setting back levees in the Upper Elkhorn basin and expanding Fremont Weir, explore water levels and velocity changes.

Results show that expanding Fremont Weir of approximately half mile and one mile produces an average water surface elevation reduction for the 200-year flood (measured 1996-1997 flood) (unsteady flow simulation) along the Sacramento River at the Pocket Area of approximately 0.1 m and 0.2 m respectively. This study, through detailed 2D floodplain modeling, defines a relation between effects of diversion into bypasses and water levels in main stems during floods.

4.1 Introduction

The Yolo Bypass has been studied for over a century, given its importance for flood protection in the Sacramento region. Recently, the Department of Water Resources of California has explored its expansion, including two additional aspects:

- Aged infrastructure. Levees around the Yolo bypass were first built in the early 1930s (Sommer et al., 2001; DWR, 2016).
- Public expectations. The Yolo Bypass today is multi-purpose for flood control, wildlife protection (Suddeth, 2014) and enhancement (Fremont Weir Wildlife Area, Sacramento Weir Wildlife Area and Yolo Bypass Wildlife Area), recreation, and agriculture (DWR, 2016).

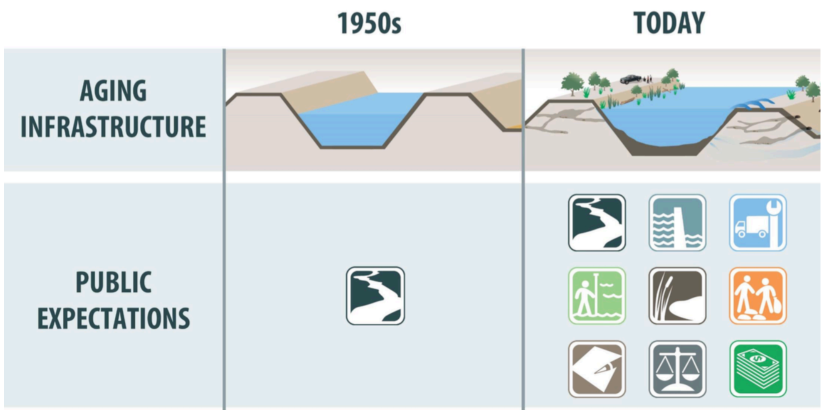


Figure 4.1 The Yolo Bypass in the past and today Source: DWR, Yolo Bypass Implementation Status & The Path Forward (May 20, 2016) Update to Central Valley Flood Protection Board

The problems summarized in figure 4.1 represent the situation of the Yolo Bypass, and also general trends for flood management in California. From 2007-2015, the State of California spent $1.315 billion on flood risk reduction projects, $698 million on Statewide Programs, $377 million on Delta Programs, and less than $600 million for flood emergency response, flood system operations and maintenance, floodplain risk management and flood management planning (DWR, 2016) (Figure 4.2).

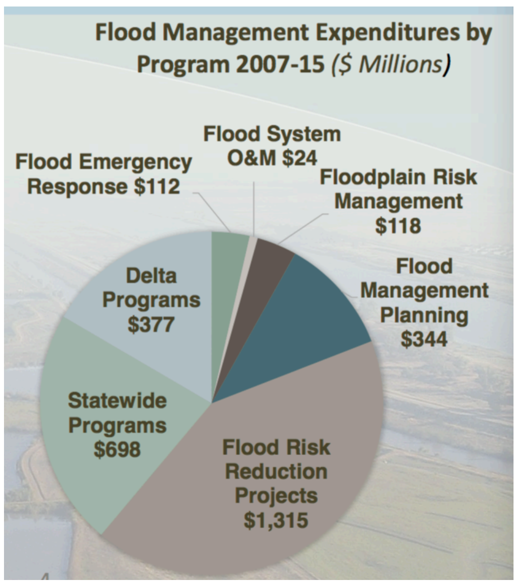


Figure 4.2 Flood management expenditures by program 2007-15 ($ Millions) Source: DWR, Yolo Bypass Implementation Status & The Path Forward (May 20, 2016) Update to Central Valley Flood Protection Board

A complex web of agencies is involved in managing the Yolo Bypass objectives for (DWR, 2016):

- Flood conveyance

- Fisheries and wildlife habitat
- Agriculture land preservation
- Economic stability

Proposed solutions include expanding hydraulic capacity, while aligning agency policies (DWR, 2016).

4.2 Proposed solutions

Potential solutions (Fig 4.3) include: Fremont Weir expansion, Upper Elkhorn basin expansion, Lower Elkhorn and Sacramento Bypass expansion, Sacramento Weir expansion, Westside Yolo Bypass expansions, and Tie-in to Deep Water Ship Channel.

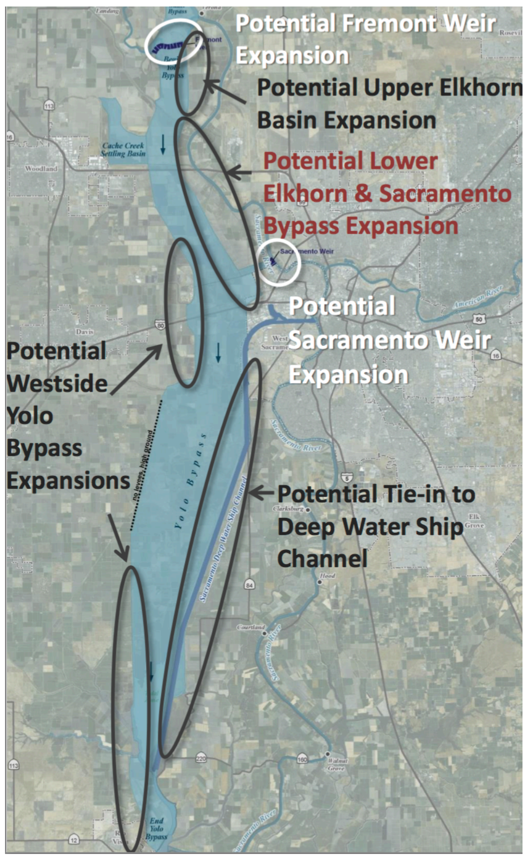


Figure 4.3 Potential flood and ecosystems improvement to the Yolo Bypass systemSource: DWR, Yolo Bypass Implementation Status & The Path Forward (May 20, 2016) Update to Central Valley Flood Protection Board

Table 4.1 Phases of expansion. Source: DWR, Yolo Bypass Implementation Status & The Path Forward (May 20, 2016) Update to Central Valley Flood Protection Board

Phase I (2015-2022)
1. Lower Elkhorn Setback
2. Sacramento Bypass Levee Setback
3. Bryte Landfill Remediation
4. Small community feasibility studies: Clarksburg, Knights Landing, Rio Vista, Yolo
5. Lower Elkhorn conservation strategy implementation
6. Deep Water Ship Channel design, permitting, and real estate
7. Sacramento River extension design, permitting, and real estate
8. Upper Elkhorn design, permitting, and real estate
9. Small actions in lower Yolo Bypass: degrade Prospect Island levees, build Prospect Island Cross levees, step levee modification, degrade lower Egbert levees.

Phase II (2023-2032)
10. Deep Water Ship Channel Construction
11. Sacramento Weir extension
12. Sacramento Bypass Conservation Strategy implementation
13. Upper Elkhorn setback
14. Upper Elkhorn Conservation Strategy implementation
15. Fremont Weir extension
16. Westside Yolo Bypass setback and levee raises
17. Lower Westside Yolo Bypass levee setback and fix-in-place improvements
18. Lower Westside Yolo Bypass Conservation Strategy implementation
19. Westside Yolo Bypass Conservation Strategy implementation

Short-term actions for agriculture and ecosystems
20. Agriculture crossing improvements
21. Wallace Weir improvements
22. Improve Fremont Weir adult fish passage
23. Lisbon Weir modifications
Mid-term actions for agriculture and ecosystems
24. Fish passage and floodplain inundation notch.

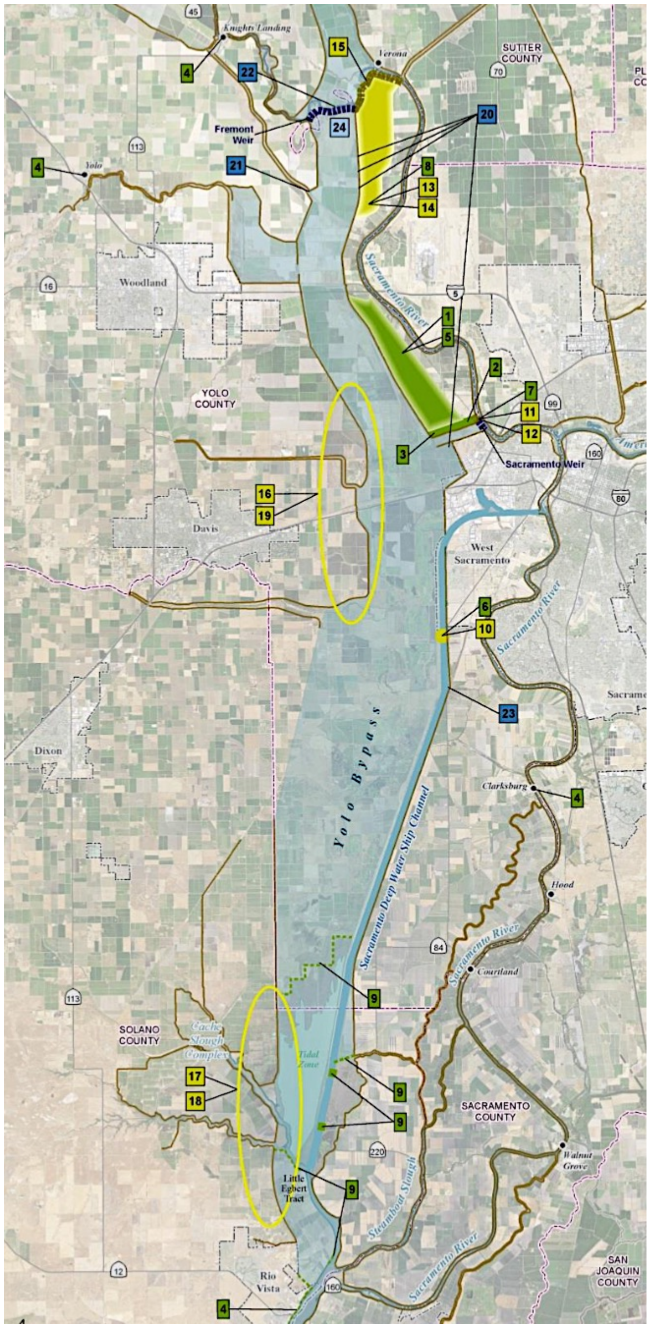


Figure 4.4 Timeline of potential flood and ecosystems improvement to the Yolo Bypass system. Source: DWR, Yolo Bypass Implementation Status & The Path Forward (May 20, 2016) Update to Central Valley Flood Protection Board

4.3 Previous mathematical hydraulic modeling of Yolo Bypass

The Yolo Bypass has been previously investigated with a UNET 1D model developed by the Army Corps of Engineering, part of the Army Corps Comprehensive Study for the Sacramento-San Joaquin River Basin (HEC, 1997). In 2006, the model was updated and used in a 1D version of HEC-RAS (USACE, 2007). An RMA2- 2D hydraulic model has been developed by the U.S. Army Corps of Engineers in 1995 and updated in 2007 (YCFCWC, 2002; USACE, 2006). Cbec eco-engineering developed a 2-D model, using MIKE-21, for Department of Water Resources (Northwest Hydraulic Consultants, 2012). The model simulated several flow alternatives past the Fremont Weir. More recently, Cbec eco-engineering developed a TUFLOW to analyze multiple alternatives aimed at increasing seasonal floodplain inundation in the lower Sacramento River Basin and improving fish passage throughout the Yolo Bypass (Campbell et al., 2014).

Table 4.2 Previous hydraulic models of the Yolo Bypass

Model Dimension	Software	Description	Agency	Year
1-D	HEC-1 and HEC-2	Willow Slough, Dry Slough, Covell Drain	Yolo County Flood Control & Water Conservation District	1992
1-D	UNET	Steady state, 1-D model for the Upper and Lower Sacramento Valley	USACE	1995
1-D	HEC-2	Putah Creek	USACE	1995
1-D	HEC-2	Cache Creek	USACE	1995
1-D	HEC-RAS	Updated model for the Sacramento River.	USACE	2006
2-D	MIKE 21	2-D unsteady flow model for the Yolo Bypass. Boundary conditions for western tributaries based on estimates.	MWD, DWR, cbec eco-engineering	2007
2-D	RMA2	2-D hydrodynamic model for the Yolo Bypass. Steady state. Designed for high flow scenarios.	USACE	1995 2007 (Updated)
1-D/2-D	HEC-RAS	Coarse-level HEC-RAS model of the Yolo Bypass from Fremont Weir to Liberty Island	CWS	2007
1-D/2-D	HEC-RAS 4.2	As part of the CVFED effort, an unsteady model was developed for the entire Sacramento Valley using the UNET model as the basis.	DWR	2010

2-D	RMA2	2-D unsteady flow model developed to examine low flow field-scale drainage	UC Davis	2012
1-D/2-D	TUFLOW	TUFLOW is a 1-D/2-D flood modeling software – it was used to develop flooding extents in Cache Creek, Willow Slough and Putah Creek. Breach hydrographs from the HEC-RAS model were used as inputs.	Yolo County	2012
1-D/2-D	HEC-RAS 4.2	Coupled 1-D/2D for the Yolo Bypass.	UC Davis	2012/2013
1-D/2-D	HEC-RAS 5.0	Coupled 1-D/2D for the Yolo Bypass and part of the Sutter Bypass south of Tisdale Weir.	UC Davis	2013-2015

4.4 Method

This study analyzes long-term flood-damage potential. Hydrodynamic impact on levees is evaluated along the Sacramento River, and within the Yolo Bypass. Levee failure is estimated probabilistically. Three scenarios were modeled in this study (Table 4.3): 1) current infrastructure, 2) expansion 1, which includes a half mile expansion of Fremont Weir and Upper Elkhorn levee setback, and 3) expansion 2, which includes one mile expansion of Fremont Weir and Upper Elkhorn levee setback. The model is a hybrid 1D/2D model, where 1D channel is coupled with 2D flow areas for floodplains and portions of the Sacramento River of particular interest. The study area includes the lower Sacramento River and its tributaries. The 1996-1997, which was estimated to be close to a 200 years event (annual exceedance probability of 0.005), modeled as an unsteady-flow simulation.

The 2D areas are built in HEC-RAS based on the topography map. Land cover for hydraulic roughness is mapped using the California Department of Water Resources geographic projections, and land use classification provided by cbec (cbec,2014b; cbec, 2013). The Digital Elevation Model used was developed at the Center for Watershed Sciences at UC Davis, using mostly LiDAR data provided by the Central Valley Floodplain Evaluation and Delineation Program (CVFED), together with a 10 meter DEM developed by the California Department of Water Resources (DWR) and the United States Geographic Survey (USGS), and a DEM developed by the National Oceanic and Atmospheric Administration (NOAA), DWR, and others. For the bypass modification cases, the DEM was modified to reflect the weir expansions and levee setbacks. Details on model development, and results are presented in this chapter.

4.5 Model development

The 1D-2D hydraulic model of the Lower Sacramento River developed at the Center for Watershed Sciences at University of California, Davis, focuses on the Yolo Bypass hydraulic dynamics and includes parts of the Lower Sacramento River and tributaries. The model uses “HEC-RAS Version 5.0.3” software. The model extent is shown in figure 4.5.

The Yolo Bypass, the southern portion of the Sutter Bypass, the Sacramento Bypass, and part of the Sacramento River between the Sutter and Yolo Bypasses are represented as 2 dimensional areas (Blue). The one-dimensional features are the southern portion of the Sacramento River, the Southern extent of the Feather River, the American River, tidally-influenced tributaries at the southern end of the bypass near Liberty Island, and western tributaries including Cache Creek settling basin, Willow Creek, and Putah Creek (green).

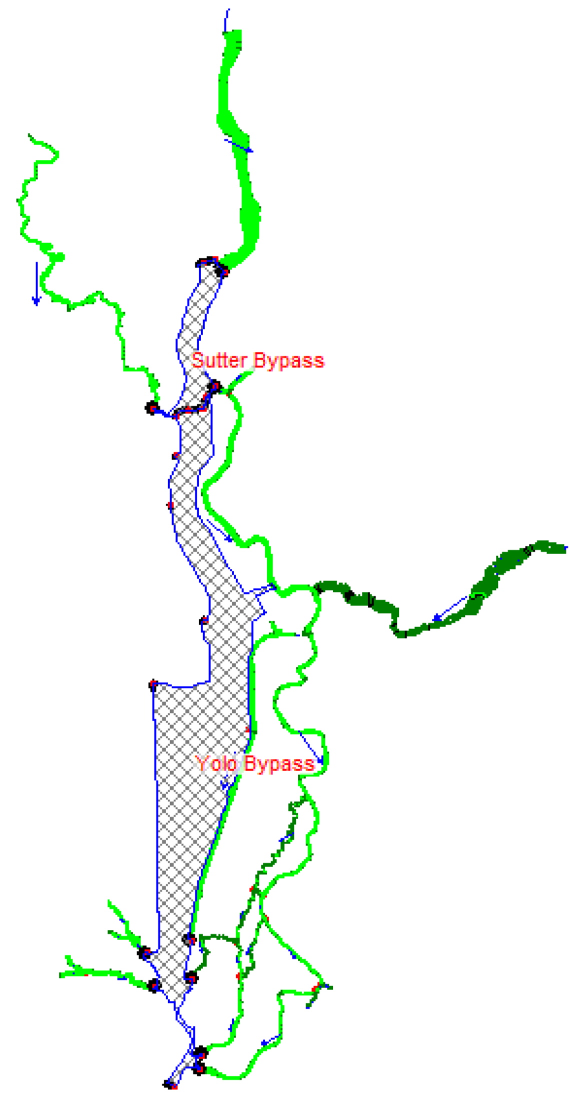


Figure 4.5 Extent of the HEC-RAS 5.0 model of Yolo bypass, California

One-dimensional models are usually suitable where flow has uni-directional pattern. One-dimensional models are commonly used for channels well bounded by steep slopes to prevent later flow, or cases when the flow moves mostly in one direction. Sometimes a 1D model is needed if data are lacking or data has poor quality. Two-dimensional models are preferable if the flow is expected to spread in more than one direction. Urbanized areas and large floodplains also benefit from a 2D model for local resolution and better representation of detailed processes. The model used for this analysis combines 1D and 2D representations to allow more detailed representation of water movement through Fremont Weir by representing the portion of river between Sutter and Yolo Bypass as a 2D area, and throughout the entire flood bypass.

Data are referenced to the horizontal North American Datum 1983 (NAD83) Universal Transverse Mercator (UTM) Zone 10. The input and output elevations are referenced to NAVD88.

In addition to the analysis developed for this dissertation to evaluate effects of bypass capacity expansion on flood risk, this model can help evaluate modifications suggested by the Conservation Measure 2 (CM2) of the Bay Delta Conservation Plan (BDCP). One goal of the CM2 Yolo Bypass Fisheries Enhancement is survival, migration, distribution and reproduction of covered fish species and to enhance natural ecological processes. Future research at the Center for Watershed Sciences (UC Davis) will analyze the effects of changes to model representation (*e.g*., inclusion of the current 1-D Toe Drain represented within the 2D area) and specific research investigations of floodplain benefits. The present model is suitable for future planning, current operations, and further studies of:

- Future hydraulic studies on the existing system
- Investigating possible structural or topographic modification of the Yolo Bypass
- Environmental restoration
- Flood management emergency operations in the Sacramento Basin
- Delta water supply analysis.

4.5.1 Boundary conditions

The boundary conditions used were developed by CBEC eco-engineering in its study "Yolo Bypass Salmonid Habitat Restoration and Fish Passage Hydrodynamic Modeling Draft Report". Westside tributary flow data were developed by Jones & Stokes (2001) for the Yolo Bypass Management Strategy (Management Strategy). Other data used include flow or stage data at gauges, from different sources: USGS, California DWR, BOR, County of Sacramento, and Solano County Water Agency (SCWA). Flows were estimated in places where data is not available. Table 4.3 describes boundary conditions and data sources used.

Table 4.3 Boundary conditions (Tomkovic, et al., Report for Yolo County, 2018)

Boundary Condition	**Source**	**Data Type**
Sacramento River flow below Wilkins Slough	USGS 11390500	Gaged flow
Knight's Landing Outfall Gates inflow	DWR A02945	Gaged flow

Feather River and Sutter Bypass flows	Based on USGS 11390500, 1142500; DWR A02930, A02945; Arcade Creek EMC02 gages	Calculated
Natomas Cross Canal flow	Based on Arcade Creek EMC02 gage	Calculated
Sacramento Weir flow	USGS 11426000	Gaged flow
Knight's Landing Ridge Cut flow	DWR A02930	Gaged and calculated from A02976, A02945, A02930 gages
Cache Creek Settling Basin	USGS 11452500	Gaged flow
Willow Slough Bypass flow	Yolo Bypass Management Study	Calculated
Putah Creek flow	Yolo Bypass Management Study	Calculated
American River flow	USGS 11446500	Gaged flow
Steelhead Creek flow (Natomas East Main Drainage Canal)	Based on Arcade Creek EMC02 gage	Calculated
Delta Cross Channel & Georgiana Slough flows	DWR's Dayflow program	From gages and estimates
North Bay Aqueduct	DWR's Dayflow program	From gages and estimates
Rio Vista tidal stage	DWR B91212	Gaged stage

4.5.2 Digital Elevation Model

The digital elevation model was developed at the Center for Watershed Sciences using mostly LiDAR data provided by the Central Valley Floodplain Evaluation and Delineation Program (CVFED), and several other sources. Areas not represented in the CVFED dataset used a 10 meter DEM developed by the California Department of Water Resources (DWR) and the United States Geographic Survey (USGS). Areas north of Interstate 80 used a DEM developed by the National Oceanic and Atmospheric Administration (NOAA), DWR, and others.

The dataset was manipulated into a non-continuous 1-meter raster. This included removal of bridges, highways, and vegetation included in airplane collected LiDAR data. Channel depth for small channels and agriculture ditches was added using ArcGis, including data from cbec's drainage reports. Depth of channels of larger streams was added from the 10 meter Sacramento-San Joaquin Delta DEM. More recent editing included improvement to the DEM with addition from a Real Time Kinematic survey for the Upper Tule Canal Pond near Fremont Weir (when dry in October 2014), and inclusion of parts of the Sacramento River previously represented as 1-Dimensional, and now included as a 2-Dimensional flow area.

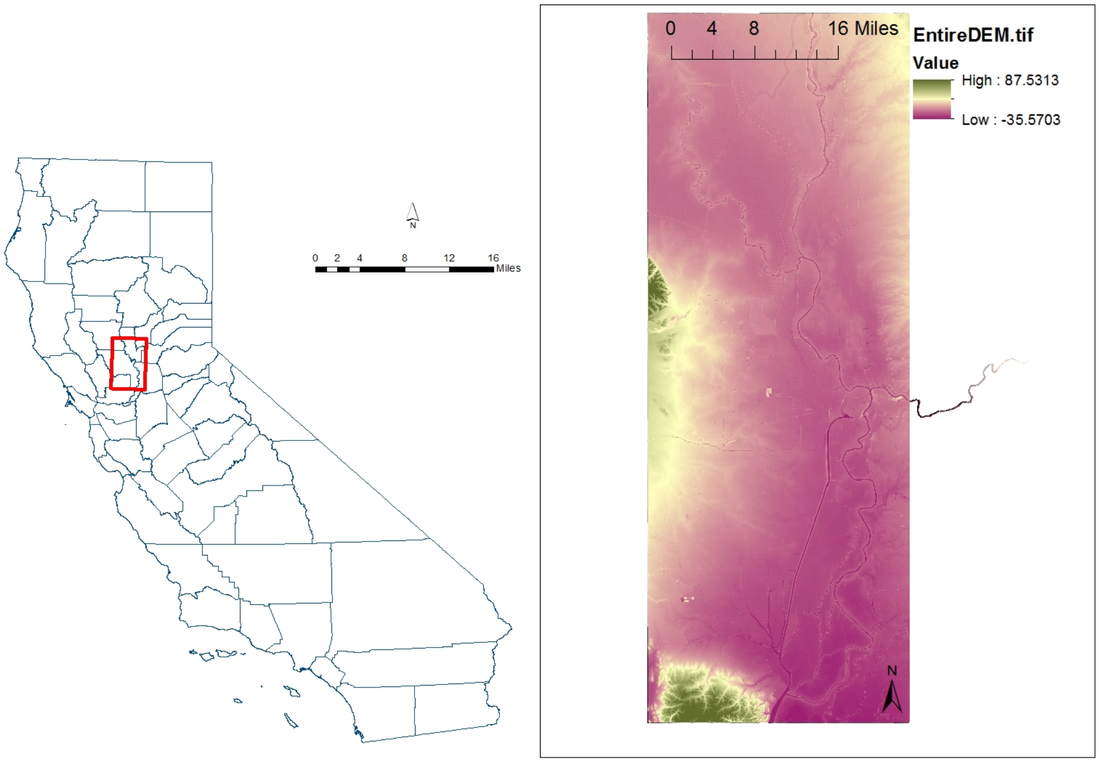


Figure 4.6 Final Terrain model for Yolo Bypass (Elevation values in meters)

More recently, part of the Sacramento River and part of the East Canal in the Sutter Bypass, previously represented as 1-Dimensional reaches, have been converted to a 2-Dimensional flow area using the channels' cross-sections, within the HEC-RAS model.

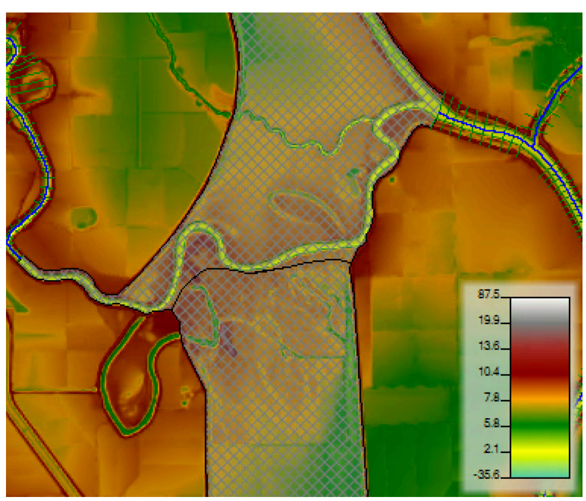


Figure 4.7 Two-dimensional representation of Sacramento River between Sutter and Yolo Bypass (elevations in meters)

4.5.3 Land Use

The California Department of Water Resources provides geographic projections for land use mapping. This model covers four counties: Yolo, Sutter, Sacramento, and Solano. All the projections were converted to NAD 1983 UTM Zone 10 (same geospatial reference used in HEC ras project geometry) (table 4.4).

Table 4.4 County Surveys listed with year collected and geographic projection (Source: DWR)

County	Year Collected	Projection
Yolo	2008	NAD 1983 UTM Zone 10
Sutter	2004	GCS North American 1927
Sacramento	2000	GCS North American 1927
Solano	2003	NAD 1983 UTM Zone 10

Manning's n values are based on two studies: Yolo Bypass Drainage & Water Infrastructure Improvement Study 2 by cbec (cbec 2014b), and Lower Feather River Corridor Management Plan Geomorphic & Ecological Modeling (cbec 2013) (table 4.5).

Table 4.5 Land use classification assignments (Sources: cbec,2014b; cbec, 2013)

	Class	Subclass	Description of Class	Description of Subclass	Manning's n
Agricultural Classes	G		Grain and Hay Crops		0.052
	R		Rice		0.03
	F		Field Crops		0.052
	P		Pasture		0.031
	T		Truck, Nursery and Berry Crops		0.052
	D	1-12,14,15	Deciduous Fruits and Nuts	Fruits, Nuts, Smaller trees	0.05
		13		Walnuts	0.075
	C		Citrus and Subtropical		0.05
	V		Vineyards		0.052
Semi-Ag	I		Idle		0.031
Urban Classes	S		Semiagricultural & Incidental to Agriculture		0.031
	U		Urban		0.03
	UR		Residential		0.03
	UC		Commercial		0.03
	UI		Industrial		0.03
	UL		Urban Landscape		0.03
Native Classes	UV		Vacant		0.03
	NC		Native Classes Unsegregated		0.03
	NV	1	Native Vegetation	Grass land	0.031
		2		Light brush	0.031
		3		Medium brush	0.036

		4		Heavy brush	0.036
		5		Brush and timber	0.036
		6		Forest	0.082
		7		Oak grass land	0.082
	NR	1	Riparian Vegetation	Marsh lands	0.052
		2		Natural high water table meadow	0.052
		3		Trees, shrubs or other larger stream side or watercourse vegetation	0.082
		4		Seasonal duck marsh, dry or only partially wet during summer	0.052
		5		Permanent duck marsh, flooded during summer	0.052
	NW		Water Surface		0.03
	NB		Barren and Wasteland		0.031

4.5.4 Model calibration and validation

Uncertainties lay in boundary conditions, measured and estimated data, and land use data. The model has been calibrated and validated at the Center for Watershed Sciences by Lily Tomkovic (for details look at: Tomkovic, et al., Report for Yolo County, 2018).

4.6 Capacity expansion

Expanding Yolo Bypass would create additional capacity and flexibility for future flood management; potentially reducing conflicts between flood and environment management efforts; it would provide more floodplain habitat area for fishes, birds, and aquatic species (DWR, 2016). Yolo Bypass expansion also would reduce agriculture revenue by removing tree crops from the expanded bypass floodplain. This section explores consequences from widening Fremont Weir by 800 m (approximately half mile) and 1800 m (approximately 1 mile), at the first and second meander extremity of the Sacramento River east of Fremont Weir, while setting back levees in the Upper Elkhorn basin.

The digital elevation model was expanded to include the Upper Elkhorn setback and levees area. The manipulation modified elevations at the existing levees and new levee locations, and was done in parts. ArcGIS shapefiles were created with assigned projections, clipped into the DEM to create a raster file. The raster was converted into points, and through Spatial analyst, inverse distance weighted interpolation was performed. Point heights were changed with previously calculated elevations, before converting the file from point to raster again. At the end, a raster dataset was created including both the old DEM and the expanded bypass area with newer elevations.

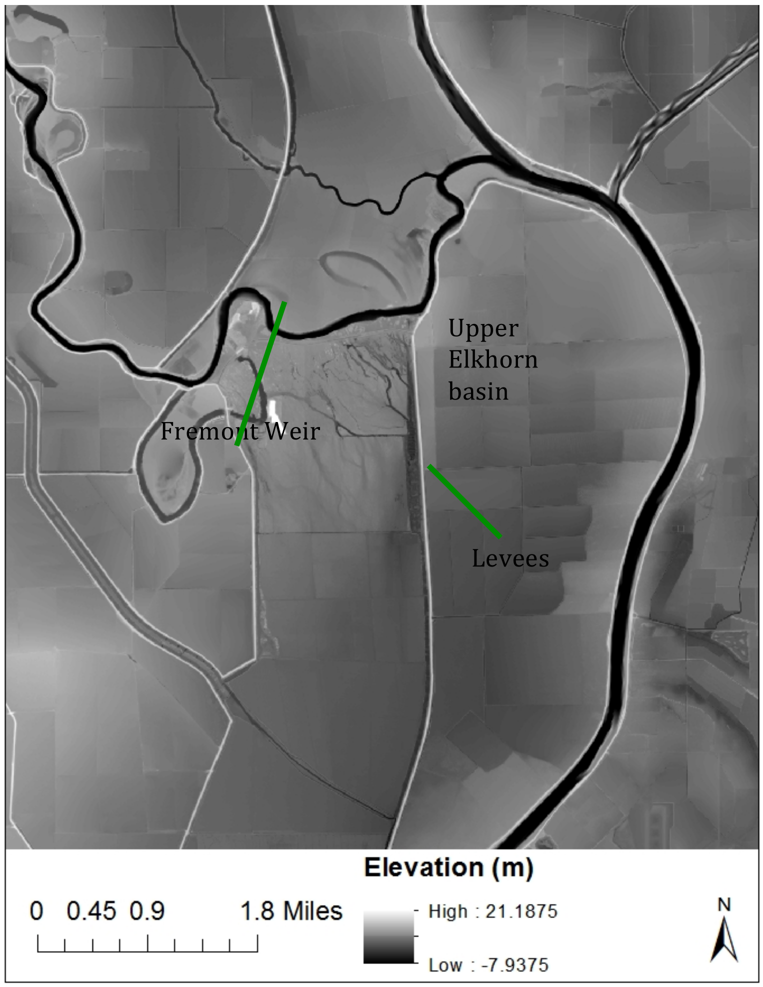


Figure 4.8 Digital elevation model of the portion of the study area representing Fremont Weir area and Upper Elkhorn basin

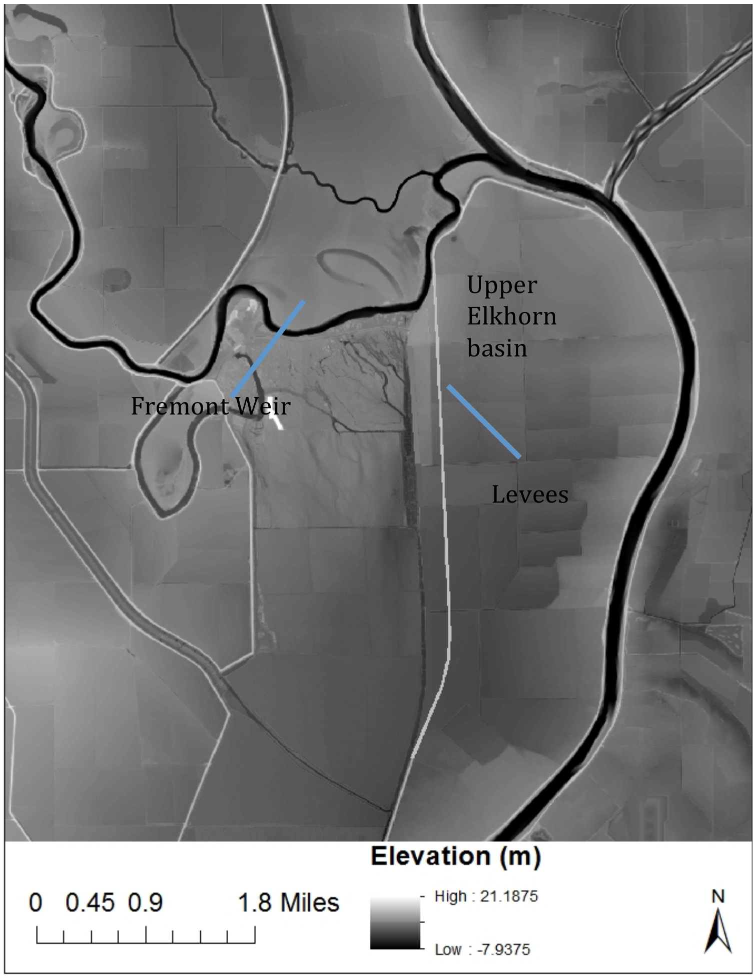


Figure 4.9 Digital elevation model of the portion of the study area representing Fremont Weir expansion of 800 m area and Upper Elkhorn basin levee setback

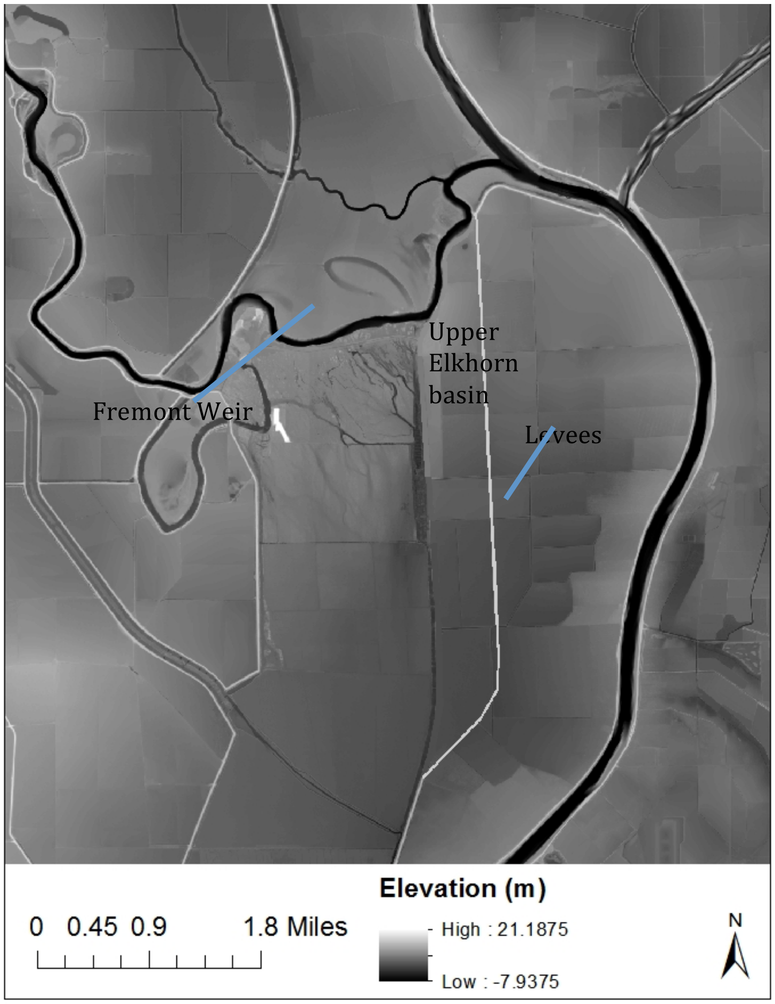


Figure 4.10 – Digital elevation model of the portion of the study area representing Fremont Weir expansion of 1900 m area and Upper Elkhorn basin levee setback

Geometry has been modified to represent the capacity expansion. In the first expansion, Fremont Weir was expanded by 800 meters east, providing an additional flow capacity of approximately 2400 m^3/s. The Yolo Bypass 2D area was expanded to accommodate the additional flow. The 2-Dimensional area of the Yolo Bypass has been recomputed in HEC-RAS. The second expansion includes Fremont Weir expansion of 1900 m east, providing approximately 4800 m^3/s of additional flow capacity. The Yolo Bypass 2D area was expanded to accommodate the additional flow. The 2-Dimensional area of the Yolo Bypass has been recomputed in HEC-RAS.

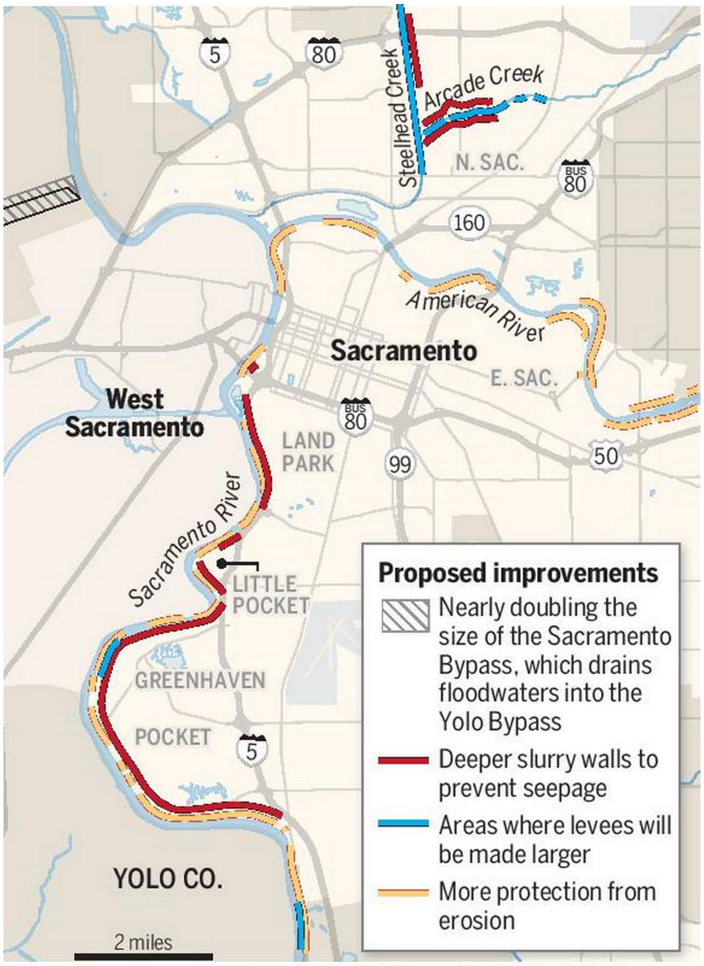
Table 4.6 Modeling scenarios used in this study

	Present condition	Expansion 1	Expansion 2
Fremont Weir Length (m)	2,780	3,580	4,680
Yolo bypass surface (acres)	4,047	4,491	5,328
Expansion capacity (m^3/s)	-	2,425	4,850
Bypass capacity (m^3/s)	9,700	12,125	14,550

4.6 Results

Results include water depths and velocities along the Sacramento River at the so-called Pocket Area, for the 3 scenarios.

The Sacramento River south of the confluence with the American River has been under study to boost flood protection. In particular, the U.S. Army Corps of Engineers in 2015 proposed improvements for the Pocket Area with deeper slurry walls to prevent seepage, larger levees, and more protection from erosion (Sacbee, 2015).



Sources: Army Corps, SAFCA Sharon Okada sokada@sacbee.com

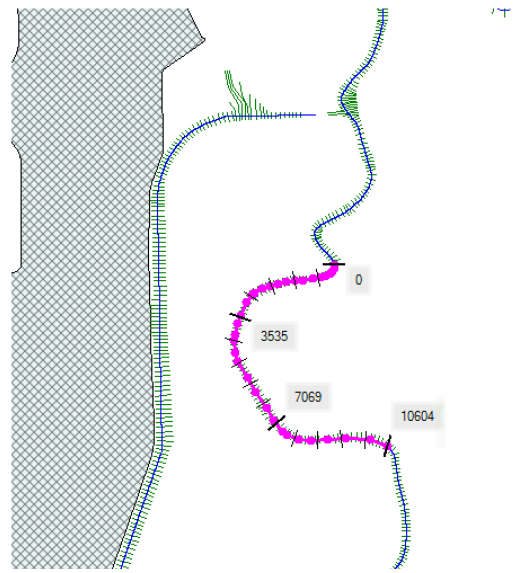


Figure 4.11 – (Left) Levee work planned along Sacramento River. (Source: Sacbee, 2015)

The average water level for the 200-year flood (measured 1996-1997 flood) (unsteady flow simulation) along the Sacramento River is approximately 0.1 m lower when modeled with expansion 1 than with current conditions, and it is approximately 0.2 m lower for expansion 2 (Fig. 4.12). Table 4.7 shows the average and maximum difference between base case and expansion 1, and base case and expansion 2.

Water surface elevation decreases due to additional bypass capacity (Figure 4.12).

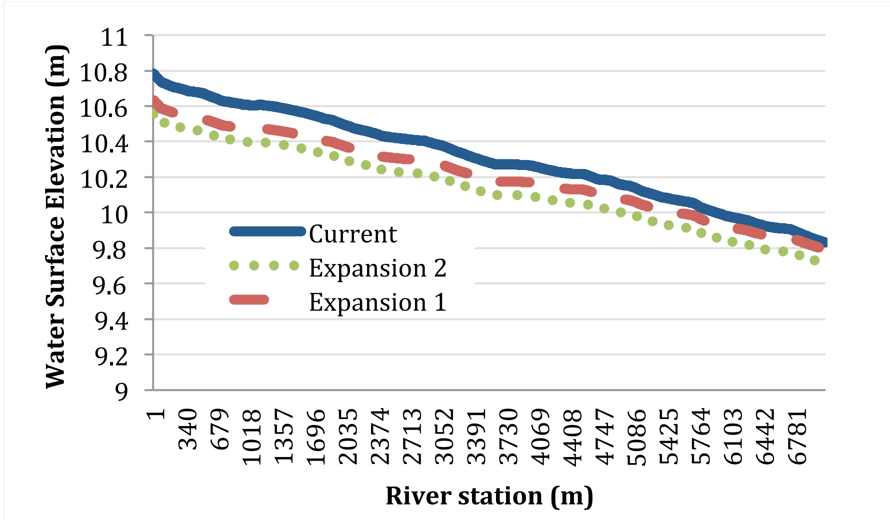


Figure 4.12 Water surface elevation along the Sacramento River in the Pocket Area, for current conditions, expansion 1, and expansion 2 (on the 4th of Jan 1996)

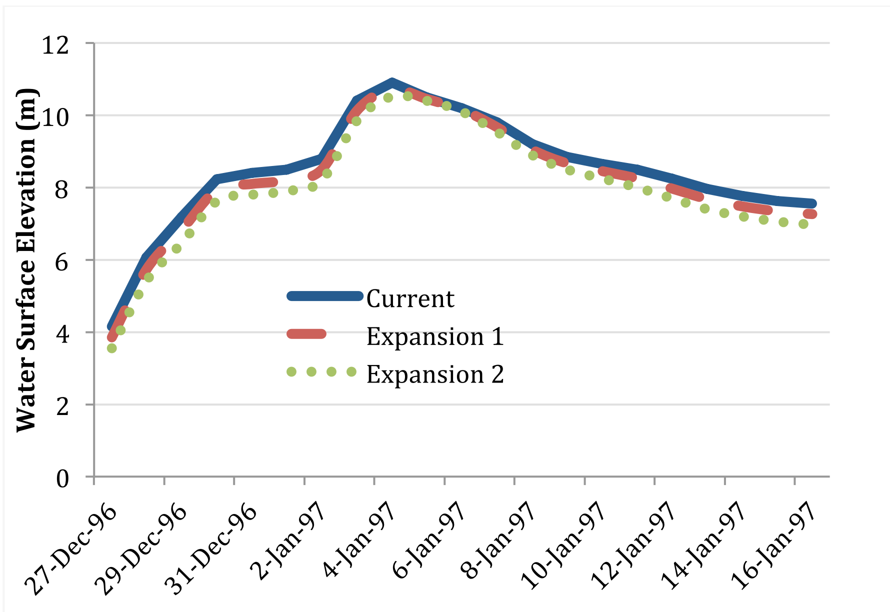


Figure 4.13 Water surface elevation at first cross section north (river station 0 m) at the Pocket Area, for current conditions, expansion 1, and expansion 2

Table 4.7 Average and maximum water level reduction due to bypass expansion on 04 Jan 1996

	Current to expansion 1	Current to expansion 2
Average reduction (m)	0.105	0.213
Maximum reduction (m)	0.133	0.235

Figure 4.14 shows reduction of maximum velocities. Variability of velocity reduction is higher than variability of water surface elevation reduction. Average velocity is reduced by 0.026 m/s and 0.036 m/s from the current conditions to expansion 1 and expansion 2. Maximum velocity reductions are 0.079 m/s and 0.087 m/s respectively.

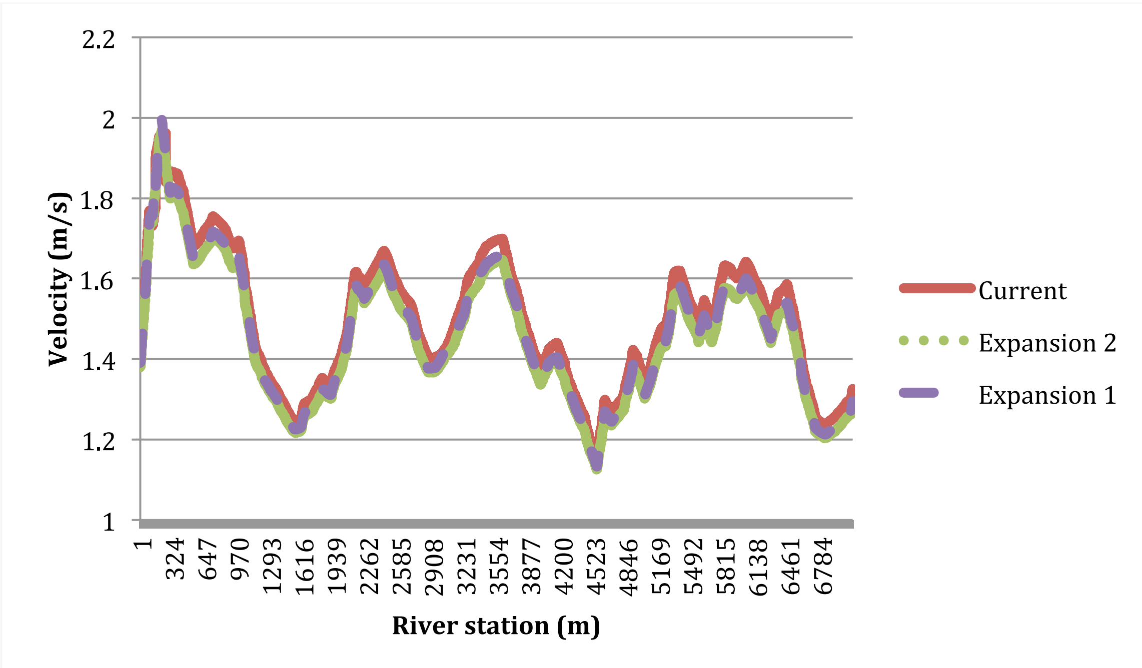


Figure 4.14 Average flow velocities along the Sacramento River in the Pocket Area, for current conditions, expansion 1, and expansion 2

Table 4.8 Average and maximum velocity reduction due to bypass expansion

	Current to expansion 1	Current to expansion 2
Average velocity reduction (m/s)	0.026	0.036
Maximum velocity reduction (m/s)	0.079	0.087

This results indicate the significance of bypass conveyance in terms of water surface elevation reduction and velocity reduction.
Velocity is an important parameter. This analysis of velocity can help assess potential erosion and sedimentation.

Levee failure probability

Increasing the Yolo Bypass capacity would reduce residual risk of levees overtopping or failure. At the same time, expansion would reduce agriculture land use and crop revenues.

Levees can fail by overtopping or geotechnical causes such as erosion, under-seepage, or through-sepage (Rogers et al., 2008). Long-term flood-damage potential can be evaluated using the hydraulic model. It is possible to evaluate detailed hydrodynamic impacts to levees, to estimate probabilistic levee failure for flood events.

Levee failure probability for a flood exceeding the design height of a levee has been defined by the US Army Corps of Engineers (USACE) model for planning studies for a levee of "average reliability" (USACE, 1999):

$$P_f = 0.36 * \tan^{-1}\left(10.3 * \frac{WSEL - h_{\min}}{h_{max} - h_{min}} - 7.2\right) + 0.52$$

The probability of failure (Pf) varies from 0 to 1 for water surface from the levee toe (hmin) to the levee crest (hmax). This approach has been used to evaluate levee failure probability for the Upper Mississippi River with or without levees (Pinter et al., 2016).

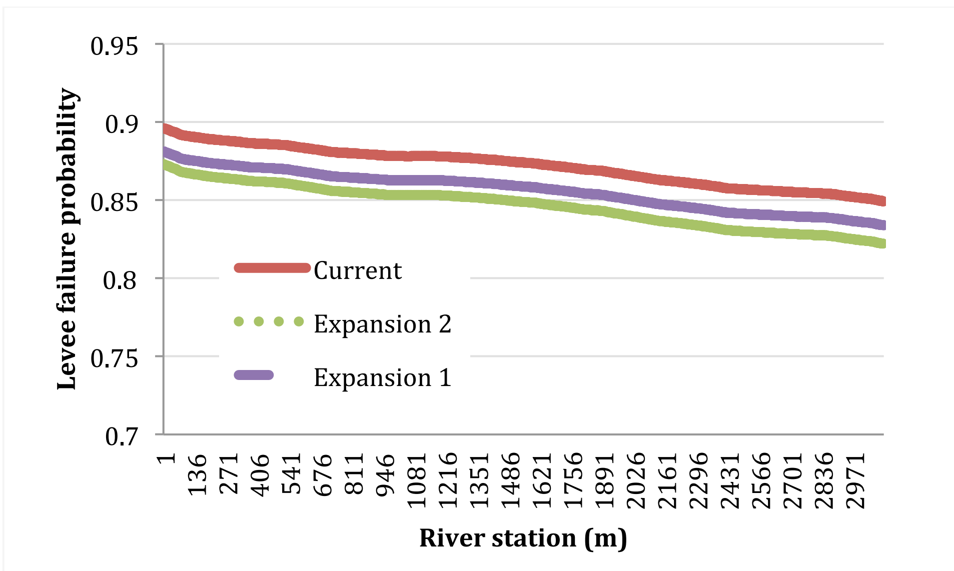


Figure 4.15 Levee failure probability along the Sacramento River at the Pocket Area, at max WSE

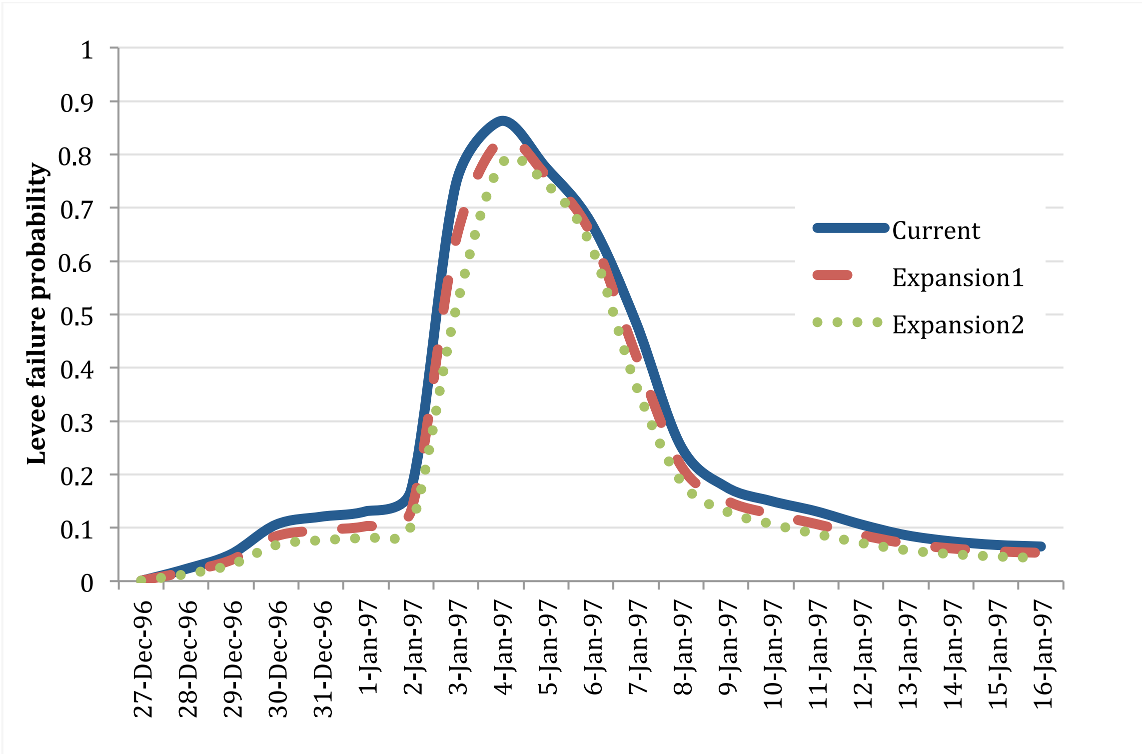


Figure 4.16 Levee failure probability at the first cross section north (river station 0 m) at the Pocket Area (Sacramento River) from the 27 Dec 1996 to the 16 Jan 1997

Table 4.9 shows results for the first cross section north (river station 0 m) of the area analyzed, part of the Pocket Area, along the Sacramento River. The probability of failure would be reduced by 4% and 8% implementing the expansion 1 and the expansion 2.

Table 4.9 Levee failure probability of a 200 years return flood exceeding the design height of levees at the Pocket Area (Sacramento River) at the Max WSE, at first cross section north (river station 0m)

Current	Expansion1	Expansion2
0.84	0.81	0.78

Probability of levee failure at the Pocket Area for a 200 year return period flood is very high. The bypass expansion alone would not significantly reduce the probability of levee failure. The bypass expansion should be supplementary to a more effective set of actions to reduce such levee failure probability.

This analysis can be expanded to include the probability of levee failure for all the Pocket area, and the other areas affected by the bypass expansion, to evaluate the economic value of the expansion. The probabilistic analysis should include the 200 year flood event here analyzed and every other possible event. The expected annual damage can be evaluated as:

$$EAD = \int_0^{\infty} \int_i \; P_{f_i} * \; D_i \, dx \, dQ$$

Where the Expected Annual Damage (EAD) is calculated as the product of the levee probability failure P_{f_i}times the damage D_i over all the possible flood events at all locations i affected by the bypass expansion.

The benefit of expansion is the expected annual damage reduction. This can be calculated as the EAD without bypass expansion minus the EAD with bypass expansion.

4.8 Conclusions

Modifications to the Yolo Bypass in California have been investigated in this chapter using an integrated 1D-2D hydraulic model developed with HEC-RAS software. Three scenarios have been analyzed: current conditions, expansion of Fremont Weir of half mile and correspondent Upper Elkhorn levee setback, expansion of Fremont Weir of one mile and correspondent Upper Elkhorn levee setback. Water surface level and velocity reduction hydraulic benefits were examined.

Expanding Fremont Weir approximately half mile and one mile produces an average water surface elevation reduction for the 200-year flood (measured 1996-1997 flood) (unsteady flow simulation) along the Sacramento River at the Pocket Area of approximately 0.1 m and 0.2 m respectively.

Velocities decrease in average of 0.036 m/s and 0.026 m/s from current conditions to expansion 1 and expansion 2 respectively. These results stress the significance of bypass conveyance in terms of water surface elevation reduction and velocity reduction.

Long-term flood-damage potential can be evaluated using hydraulic models. It is possible to evaluate in detail hydrodynamic impacts to levees, to estimate probabilistic levee failure.

Levee failure probability of a the 1996-1997 flood exceeding the design height of levees in the Pocket Area, west of Sacramento, has been evaluated. The probability of failure would be reduced of 4% and 8% implementing the expansion 1 and the expansion 2.

The model developed can be used for other analysis and studies: further hydraulic studies on the existing system, investigating other possible structural or topographic modification of the Yolo Bypass, environmental restoration, and flood management emergency operations in the Sacramento Basin..

This study, through detailed 2D floodplain modeling, defines a relation between effects of diversion into bypasses and water levels in main stems during floods. Quantifying benefit of flood risk reduction and cost of expansion, it would be possible to assess the economic value of Yolo bypass expansion for levee stability.

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CHAPTER 5: CONCLUSIONS

This chapter presents the goals and conclusions of this dissertation. Potential future research is suggested.

5.1. Objectives

This dissertation focuses on the development of a hydro-economic analysis of flood bypasses. The combined hydraulic and economic modeling can provide insight to policy makers and stakeholders on bypass design and structural modifications and long-term flood management strategy.

The objectives of this research are:

5. To develop a theoretical analysis of economically optimal capacity for flood bypass design or expansion.
6. To develop theoretical multiple benefit analysis for optimal bypass capacity, including agriculture, restoration, and recreation benefits.
7. To investigate how long-term climate change affects static and dynamic optimal bypass plans.
8. Use a coupled 1D/2D hydrodynamic model of the Yolo Bypass, California to explore its optimal capacity.

5.2 Conclusions

In the United States riverine flood protection is predominantly by levees (Ludy et al., 2012). Conventional flood control systems cannot completely protect urbanized areas from floods. Flood bypasses have been proposed as supplemental component within flood management system in the last century (Plate, 2002, 2004; Apel et al., 2004). Flood bypasses help reduce flood risk, and simultaneously provide other benefits. Habitat restoration, recreation, and groundwater recharge depend on flood bypass capacity and management (Suddeth, 2014).

Bypass capacity optimization can help policy makers select new or expanded capacities for a bypass. Optimization modeling can quantitatively account for benefit and costs for static optimization purposes. Linear programming model can deliver effective results in a simple way.

A linear programming model developed in Chapter 2 has been applied to the Yolo Bypass in California. Results suggest an expansion of about 5,800 m^3/s could be economically justified. Actual capacity of Fremont weir is 9,713 m^3/s. The preliminary model suggests an optimal capacity $K_{bypass}*$ of approximately 15,500 m^3/s. The model was also applied to other bypasses, the Morganza floodway and the Birds Point-New Madrid bypass to analyze sensitivity of optimal capacity to different coefficient of variation of peak annual flow.

Results show that optimal bypass capacity follows a general behavior. As the coefficient of variation grows, the ratio of bypass capacity to mean peak flow grows.

Increasing the Yolo Bypass' capacity would reduce pressure on the Sacramento flood protection system, while benefiting ecosystems and recreational activities, and potentially benefitting agriculture and groundwater recharge. Application to the Yolo Bypass, taking into account also these additional benefits suggests an expansion of 6,200 m^3/s could be economically justified. Considering additional benefits than flood risk reduction only increases optimal capacity by 400 m^3/s, adding approximately $10 million expected annual benefit to the $600 million expected annual benefit of flood risk reduction provided with optimal bypass expansion (fig. 2.19).

In Chapter 3, a Bayesian stochastic dynamic programming approach was used to dynamically optimize bypass capacity expansion with uncertain climate change. Optimal bypass capacity policies were defined for one-time building plans and for multiple-expansions plans. For a planning horizon of 200 years, a combination of different climate scenarios and capacity expansions was explored. Effects of the range and probabilities of different climate change scenarios are examined. For the one-time building policy, the model shows that considering more wide-ranging climate scenarios adds complexity and uncertainty, which translates in a "safer" (greater) initial optimal capacity. Results from this analysis show that climate change can affect optimal bypass capacity today, in this case increasing initial bypass capacities by about 20% for the average narrow uncertainty range and by about 30% for the broad uncertainty range (table 3.5).

Costs increase with time because of the discount rate, and they increase as more extreme climate scenarios are considered, suggesting that additional uncertainty increases flood damages. For the multiple-times expansion policy climate change can affect optimal bypass capacity today, increasing initial bypass capacities for the broad uncertainty range by about 10% and increasing final average capacity expansions for the broad uncertainty range by about 130% (table 3.7). Results show that adaptability to climate change greatly lowers its costs. Total optimal capacity differs notably between the case of one-time building policy and allowing multiple expansions over the 200-year planning period, with differences increasing with inclusion of more divergent and extreme climate scenarios. The multiple-expansion policy suggests an average optimal final capacity approximately 70% more than the capacity suggested by the one-time policy. Costs differ even more. The biggest difference of cost occurs with the widest range of climates considered (10). The present value construction cost of initial expansion is approximately $180 million for the one-time building policy, and increases by 170% up to $490 million for the multiple-times building policy (table 3.6). For this case, uncertainty in future peak flow mean is more important for optimization expansions than uncertainty in peak flow standard deviation.

In Chapter 4, promising expansions for the Yolo Bypass in California have been investigated, using an integrated 1D-2D hydraulic model developed with HEC-RAS software. Three scenarios have been analyzed: current conditions, expanding Fremont Weir by a half mile with corresponding Upper Elkhorn levee setback, expanding of Fremont Weir by one mile with corresponding Upper Elkhorn levee setback. Water surface level and velocity reduction have been analyzed.

Results show that expanding Fremont Weir by approximately half mile and one mile produces an average water surface elevation reduction for the 200-year flood (measured 1996-1997 flood) (unsteady flow simulation) along the Sacramento River at the Pocket Area of approximately 0.1 m and 0.2 m respectively. Velocities at the Pocket Area decrease in average of 0.036 m/s and 0.026 m/s from current conditions to expansion 1 and expansion 2 respectively. These two effects reduce the probability of failure for main stem levees.

The following planning implications come from this analysis:

1. Increased flood bypass conveyance capacity decreases water-surface elevations and velocities in quantifiable ways.
2. Long-term flood-damage potential can be evaluated using hydraulic models.
3. Increasing bypass conveyance capacity reduced the probability of levee failure.

5.3 Further research

Several research gaps remain.

The use of bypasses is limited because they require extensive land and high costs. A bypass might be cost effective to protect an area at high risk, but more frequent flooding of an area with much lower damage potential. Many other times levees are chosen over bypasses. Further studies should compare net benefits of bypasses to those of levees, to assess the most effective method and combination, since bypasses are usually placed within levee sytems.

The linear model developed for optimal bypass capacity analysis involves assumptions and uncertainties. Assumptions were made on the bypass shape, water velocity, stationarity of flood flow process, damage function, discount rate, and levee failure. Further analysis should explore effects of these uncertainties on optimized bypass capacities. In addition, the bypass is not put into the more complex system context of flood management in a larger basin system, with levees, reservoirs, and non-structural flood damage potential reduction actions. Further studies should focus on changes in conditions of the floodplain due to human activities and to climate change.

Chapter 3 focuses on dynamic capacity expansion with climate change. Further research should focus on analyzing the effect of other changes, such as discount rate and damage potential growth on initial adaptation and future adaptation. The analysis is based on pre-defined climate change scenarios with ranges of mean and standard deviations. A more complete Bayesian formulation is needed to analyze cases when the mean and standard deviations are not included in the ranges defined in the climate scenarios considered.

Developing Chapter 4, with hydraulic modeling to explore bypass structural modifications, some research gaps were identified. Further hydraulic studies should focus on the existing system, investigating other possible structural or topographic modification of the Yolo Bypass, environmental restoration, and flood management emergency operations in the Sacramento Basin. More complete risk analysis would expand from the changes in levee failure probabilities at one location to the many flood-vulnerable locations in the system over the entire range of possible floods, with economic valuations of flood damages and expansion costs.

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