Integrating Dutch Flood Policy Innovations into California Flood Policy

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Abstract: Flood control is such a part of daily life in the Netherlands that the dike system has developed historical and cultural value. The Dutch must continuously improve their flood defense system to prevent a disaster. As a result, several important flood management concepts have initiated in the Netherlands. This paper summarizes the implementation of these innovations in the Netherlands and the application in California of Dutch concepts of flood control structures, reliability and risk-based designs, "making room for the river," and financial management.

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Introduction

Flood risk management is an important part of life in the Netherlands. The Netherlands is formed by the deltas of three rivers- the Scheldt (rain-fed, originating in southern Belgium), the Meuse (rain-fed, originating in northern France), and the Rhine (glacier and rain-fed, originating in Switzerland). The country also sits along the North Sea, with the Scheldt River connecting the sea to Antwerp Harbor. The Rhine is the largest of the three rivers, splitting into three branches (the Ijssel, the Lek, and, the Waal) as it crosses the border into the Netherlands (Tol et al, 2003). Two-thirds of the country lies below mean sea level (Voortman, 2003).

Figure 1: Map of the Netherlands (greenwichmeantime.com, 2008)

The Dutch have a long history of attempting to control floods. As early as the ninth century, the Dutch started building dikes to protect reclaimed bog land (Kaijser, 2002). These dikes started as local, individually-owned structures, but communities soon realized that closed dike rings were necessary to protect all sides of the region. These dike rings eventually became *waterschaps*, or "waterships," regional districts charged with water management including drainage and dike building. These districts are still the administrative body for flood defense today (Voortman, 2003). The 14th century saw the first major recorded floods in 1313 and 1315, leading to the famine from 1314-1317 that killed 5-10% of the population. Periodic flooding continued through much of the Netherlands' history. As sediment settled between the dikes, dikes grew taller. During the 19th century, reorganization of the water districts occurred and a national body was formed. Military engineers took over the construction and maintenance of the dike system (Tol and Langen, 2000).

During the twentieth century, as trained engineers and the central government took over flood control efforts, the analysis of appropriate techniques and construction increased. Prior to 1953 dikes were built to the height of the previously known high-water level plus a margin of safety (Jonkman et al, 2004). Following the catastrophic flood of 1953, the

Delta Committee was formed to advise the government regarding flood control (Voortman, 2003). One recommendation of the Committee was to establish an optimal exceedance frequency of the design water level based on risk of flooding and cost of protection. van Dantzig's 1956 paper described this risk-based calculation. He proposed that flood management required integration of three areas with noted problems: statistics, hydrology, and economics. In the past 50 years, significant effort has been devoted to expanding on van Dantzig's work and working on solutions to the problems he noted and the assumptions he made. Increased computing power, additional rainfall and hydrologic data, and watershed models have all added to the understanding of flooding while increased emergency preparedness and response have enhanced protection of land, homes, farms, businesses, and lives.

Northern California has also experienced a history of devastating floods, although the history of floods and water management is much shorter than in the Netherlands. Throughout the past century and a half, winter rains have resulted in flood events that have caused billions of dollars in damage and multiple deaths. One of the largest floods in California history occurred in January, 1862, following four weeks of rain. No quantitative flows are known, but the banks of the Sacramento were breached and the water was, at minimum, three feet deep from Sutter's Fort to Davis (Harding, 1960).

This flood also brought significant mining debris, covering the land near Marysville with one to six feet of sediment. During the second half of the nineteenth century, mining techniques had developed from ditch and flume operations to high powered hydraulic techniques that discharged up to a million gallons an hour from a single nozzle (Kelley, 1989, Larson, 1996). It has been estimated that over 1.5 billion cubic yards of sediment was discharged into the Feather, Yuba, Bear and American River basins from hydraulic mines (Larson, 1996). Woodruff v. North Bloomfield Gravel Mining Company (1884) effectively stopped hydraulic mining by requiring complete containment of debris.

During the early period of settlement in California, flood control was typically very local and levees were built by individuals or local governments. Following this major flood in 1862 and the resulting litigation, the practice of hydraulic mining ended and levee management moved to larger regional agencies and the state government.
The largest recorded flows in the Sacramento River were reached during the flood of March 1907. Although some tributaries have since exceeded their 1907 flows, the Sacramento River has not exceeded its peak flow of about 600,000 second-feet (Harding, 1960). Thirty to forty inches of precipitation across Northern California during the week before Christmas in 1955 led to severe damages and levee failures. Seventy-four lives were lost and over $200 million in economic losses were contributed to the flood (Harding, 1960). Record rainfalls led to major flooding in 1986. Levee breaks in the Sacramento River Basin led to 13 deaths and over $400 million in damages. Two of the most expensive floods in California's history (1995 and 1997) occurred within two years of each other and together caused nearly $4 billion in damages (DWR website).

Figure 2: Map of Major California Rivers (www.mapsofworld.com, 2008)

In the early history of California, no state or federal agencies managed flood control; instead, flood control projects were managed locally. As settlement increased, however, state and federal funding and regional management became necessary. First, state and county agencies began acting to prevent flooding and then in 1917, federal authority for flood management was granted by Congress. Since then, there has been a fluctuating balance of power between regional and district, state, and federal flood control planning, funding, and management.

There are six types of actions considered for flood risk management (Hoojier et al, 2004):

- Actions to prevent flood generation: land use management in the upstream basin,
- Actions to modify flood flows and elevations: protection works; storage along channels,
- Actions to reduce flood damage reduction measures: adaptive land use, housing; awareness raising,
- Preparatory actions: flood forecasting, warning and emergency plans,
- Flood event actions: crisis management, evacuation, and
- Post-flooding actions: aftercare, financial compensation, insurance.

The Dutch concentrated mostly on preventive flood control measures, and many of the measures implemented in California were first tested by the Dutch in their attempt to control flood waters. Some more recent Dutch innovations might increase California's ability to reduce flood damage. This paper is organized into three subjects. First is a review of Dutch flood control innovations. Next, implementation of each measure is discussed in California's context. The final section wraps up the discussion with a summary of key points and conclusions. Supporting equations and references are presented in the Appendices.

Dutch Flood Management

Flood Control Structures

Dutch flood defenses consist of one or a combination of three components: dunes, dikes, and special structures. Natural sea dunes protect costal areas from tides and storm surges. The dunes are planted with helm grasses to hinder erosion. Where there are no dunes, the Dutch build dikes. As previously described, the dikes, initially constructed along the river, have become dike rings to ensure protection on all sides. The 1500 mile dike system in the Netherlands includes some massive engineering and construction accomplishments, as can be seen in the picture below of the Afsluitdijk. The dike prevents intrusion of the Zuiderzee (a North Sea inlet) and has created the IJsselmeer freshwater lake. The dike is over 90 m wide and 32 km long.

Figure 3 : Afsluitdijk in the Netherlands (Beenaker, 2008)

Cross dikes are used to protect against upstream dike bursts. An early example was constructed between the Lek and Linge rivers in 1284. Although this crossdike offered protection to those downstream, it increased the damage upstream (Tol and Langen, 2000).

Special structures include the Maeslankering shown in Figure 4. This storm surge barrier located automatically closes to protect Rotterdam and surrounding towns from flooding in the case of an abnormally large storm surge. Each of the barrier "arms" is as tall as the Eiffel Tower if placed upright (Sayler, 2006). Other special structures include cofferdams, gates, and retaining walls. In general, these special structures are in place as temporary solutions in response to a flood event or storm surge.

Figure 4: Maeslantkering protects Rotterdam from storm surge (Sayler, 2006)

Risk-based versus Reliability-based Design

Flood management policies and system designs are established to minimize damage caused by flooding events. Engineers today use two strategies to evaluate flood management solutions- risk-based and reliability-based design. These design strategies are described below.

Risk-based design commonly focuses on minimizing the future costs of flooding by taking preventative measures today. Risk has two components- the chance that an event will occur and the consequences of that event (Sayers et al, 2002). A subset of cost-benefit analysis, the optimal risk-based design results in the minimum total cost by evaluating all costs of each alternative and choosing the least expensive. The risk-based design (cost-benefit analysis) equation used in this calculation is found in the appendix.

Risk-based design requires having a pre-established flood probability distribution, as well as reliable estimation of the damage caused by different flood levels. A discount rate is applied to future costs to give a net present value for evaluating different protection levels. A benefit of the risk-based approach is that it allows choices based on comparison of expected outcomes and costs of solution alternatives (Sayers et al, 2002, Hall et al, 2003, Vis et al, 2003).

Reliability-based design is based on a pre-established "acceptable" failure probability target. Legislation, insurance policies, or other parties may determine an acceptable failure probability based on different preferences regarding loss of life, infrastructure investment, or economic loss. Acceptable failure levels may be based on the previously discussed risk-based design using the failure rate with the best net present value for the flood protection system and probable damage during flood event. Reliability-based design allows engineers and planners to develop a solution set of alternatives that provide the target level of protection and then choose the lowest-cost alternative. The equation used to evaluate the solution set appears in the appendix.

Flood protection systems also can incorporate both methods. For example, risk-based design requires substantial data for a given floodplain. By evaluating just one section of that region with risk-based design, a target failure probability can be established and applied in a reliability-based approach to the entire region, provided other parts of the region have similar flood hydrologies, costs, flood damages and benefits. This integrated method has increasing application as evaluation of flood protection alternatives is extended to protection of existing landscape, natural environmental, and culturally-significant objects.

Currently the Dutch use a minimum acceptable flooding probability for flood protection. The reliability-based design standard is based on an economic optimal value, or risk-based evaluation. The safety standard for a dike ring protecting a heavily populated city and its suburbs is higher than the standard for a dike ring protecting agricultural land. This integrated method results in the reliability design standards summarized in Figure 5.

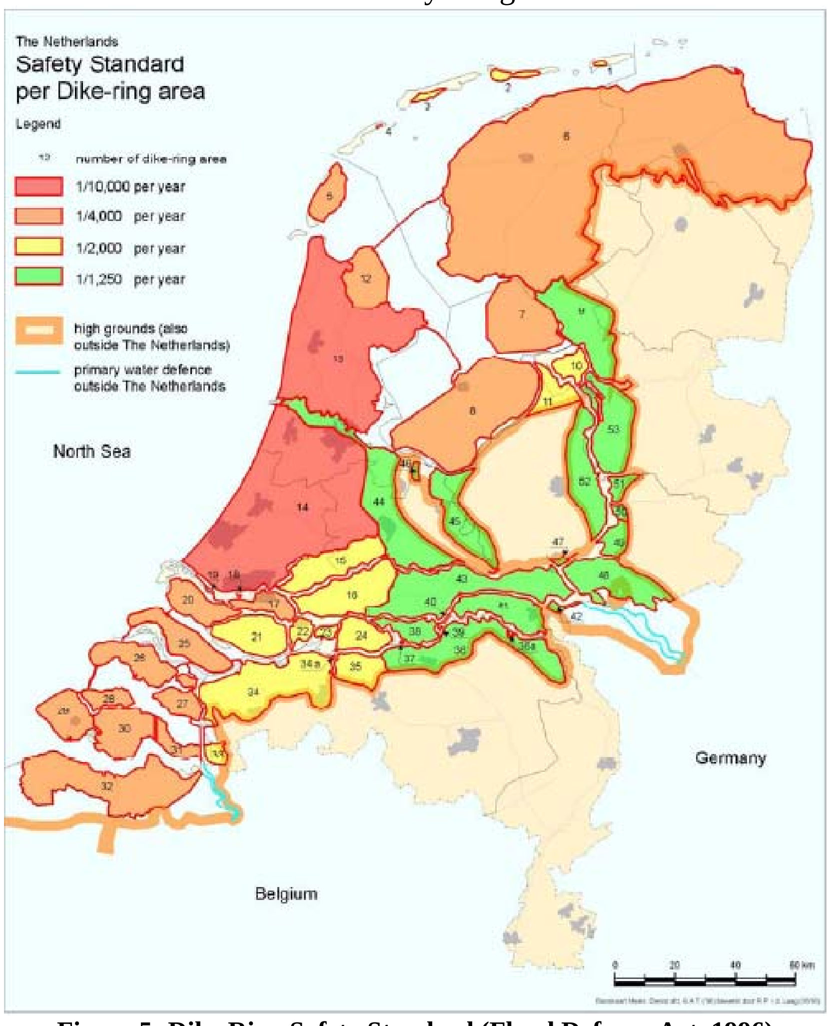


Figure 5: Dike Ring Safety Standard (Flood Defence Act, 1996)

Resistance versus Resilience Strategies

Evaluation of risk- and reliability-based designs considers the two factors of flood risk: the frequency of flooding and the consequences of flooding. Resistance strategies are designed to reduce flood risk by reducing the frequency and magnitude of flood events. Historically, these are the most common and include dike, or levee, systems, and reservoirs and dams. Vis et al, 2003, list the following disadvantages to resistance strategies:

- design discharge is constant, resulting in the assumption that all areas and land use types have equal probability of flooding,
- inaccurate projections of economic development occur when a resistance strategy was designed decades ago, and
- continual maintenance and improvements reduce environmental habitat and spoil landscape qualities.

Resilience strategies focus on minimizing the consequences of a flood. These strategies include allocating land as floodplains, developing better emergency response systems, and expediting flood clean-up and recovery. Often resilience strategies are described as ways of "living with the flood" instead of "fighting floods" (Vis et al, 2003). One disadvantage of resilience strategies is de-valuation of land due to rezoning for uses compatible with flooding.

Van Dantzig (1956)

van Dantzig and the Delta Committee focused on three areas of flood management: statistics, hydrology and hydraulics, and economics. van Dantzig's approach involved risk-based design for a (mostly) resistance strategy. He was the first to approach flood defense design from a quantitative cost-benefit analysis method (Voortman, 2003). The mathematics of this approach can be found in the appendix. In evaluating the economic decision, van Dantzig made several assumptions:

- Critical Dike height refers to height at which dike may break, but only describes the relationship between this height (H) and crown height (H_c) as $H <= H_c$,
- Dikes only fail by overtopping,
- Dike breaks are repaired immediately,
- Value of goods is stable in time relative to estimated national growth,
- Probability distribution of reaching critical dike height is stable in time once corrected for sinking dikes (no climate change),
- Value of ecological habitat (and other non-economic entities) is neglected, and
- Emergency response and evacuation capabilities are perfect with regards to human life.

Figure 6 graphically illustrates van Dantzig's basic approach. The horizontal axis is the project size, or level of protection, and the vertical axis is the annualized cost of the project. The dotted line is the annualized installation cost which is the sum of annualized construction and maintenance costs; as the level of protection increases, so do these costs. The dashed line is the annual expected damage cost- as the level of protection increases, these costs decrease. The solid line is the total cost line and which is the sum of the two types of costs. The optimal risk-based design is the level of protection corresponding to the least total cost, or the lowest point on the curve.

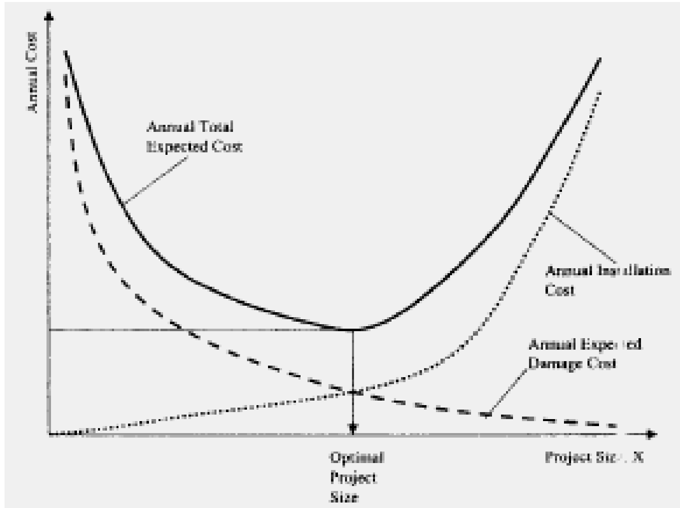


Figure 6: Schematic of Risk-Based Design (Tung, 2005)

Valuing Natural and Cultural Preservation

Within the Dutch river districts, the importance of preserving natural and cultural lands has historically received varying attention. In 1993, however, LNC (landscape, natural, and cultural-historical) values were incorporated into national Dutch policy on dike improvements (Walker et al, 1994, Lenders et al, 1999). Since then, each river district has varyingly integrated LNC values into their dike reinforcement plans. Environmental Impact Assessments are compulsory for projects that are not classified as immediate and urgent (Lenders et al, 1999). Participation by local citizens and environmental groups is also encouraged.

Extended Life Quality Index (ELQI): combining economics and life expectancy

van Dantzig ignored the value of human life in his calculations for economic optimization. Nathwani et al (1997) developed the Life Quality Index (LQI) as a measure of the economic benefits of life expectancy (see appendix). Voortman et al (2002) used the LQI to create the Extended Life Quality Index (ELQI) for evaluating flood protection decisions (equations are presented in appendix). The ELQI allows human life to be included in mathematical and economic calculations for flood defense systems. However, the ELQI may be less important to total flood damage estimates when emergency alert and evacuation systems are included in flood defense measures. Currently, flood forecasting along the Rhine allows 2 to 3 days for evacuation and along the Muese forecasting is between 12 to 36 hours ahead of the flood event (Hooijer et al, 2004).

Measuring and Managing Uncertainty

Uncertainty can contribute to flood management calculations in two ways- determining flood risk and estimating flood damages. Determination of flood risk requires knowing the probability and associated uncertainty of 1) hydraulic and hydrologic conditions, 2) failure modes of flood defense infrastructure, and 3) infrastructure failure and flood wave propagation (Kortenhaus and Oumeraci, 2001). Expected damage is a function of economic development and hazard warning and preparedness (Sayers et al, 2002). Figure

7 shows how various factors can affect flood risk and consequences, as well as the associated uncertainty.

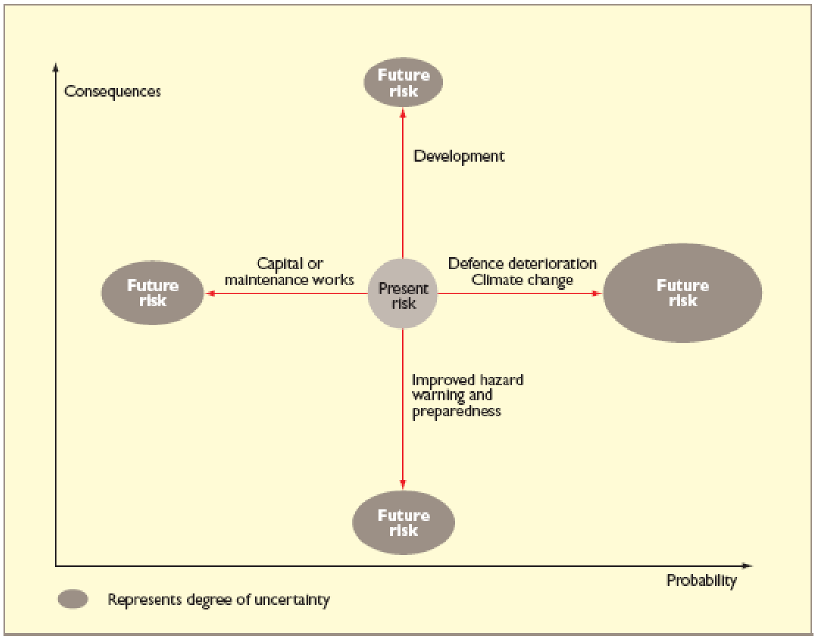


Figure 7: Factors affecting flood risk and consequences (Sayers et al, 2002)

Hydrologic uncertainty is often due to lack of sufficient data for estimating flood frequency curves. Five statistical distributions are commonly used for flood frequency analysis: Generalized Extreme Value, Gumbel, Lognormal, Weibull, and the Pearson-III (Singh and Strupczewski, 2002, Apel et al, 2004). Using 35 years of data from the Rhine and Cologne Rivers, Apel et al showed that the selection of distribution led to large variability (25% of maximum flood flow) in the estimate of the 150-year flood.

Failure of the dike system can be estimated based on failure mode. Voortman et al (2002) list failure modes as internal erosion, breaching through inner slope via wave overtopping, overflowing, or uplifting inner revetment, and breaching through outer slope via failure of pitched block revetment. Each failure mode can be described with a probability of failure. The combination of all failure modes can be used to estimate the overall probability of failure and by which mechanism (Voortman, 2003).

Once the defense system fails, flood wave propagation is important for estimating the extent of flood damage. Flood wave propagation can be a factor of the failure mechanism, the extent or length of original dike failure, and the characteristics of the flood itself (Kortenhaus and Oumeraci, 2001). Uncertainty can be reduced as better models for flood wave propagation are developed and the interactions of these factors are better understood.

As these different types of uncertainty are reduced through better models, more data, or further study, flood risk and damage calculations will become more certain. This will enable engineers and planner to more precisely evaluate flood protection systems and design alternatives.

Perception of Risk

Cost-benefit analysis requires economic quantification of all costs and consequences for a flood defense design. Because not all costs are easily defined in monetary terms, the bias of the decision-maker can be reflected in the analysis. Risk-prone decision making results in reported costs being lower than actual costs and benefits being valued more in the analysis. Risk-averse decision makers report higher costs and lower benefits than the flood defense system actually provides (Voortman, 2003). Such bias is often unintentional.

An interesting aspect of flood management and risk assessment is how the public perceives risk and the importance of flood protection. Public perception of flood risk can affect budget, construction and maintenance of flood defense systems, and other aspects of flood risk management policy. There are three bases for public risk perception: dormant flood risk, immediate flood threat, and accidental/uncontrolled flooding (Baan and Klijn, 2004). Dormant flood risk has two components- crisis effect and levee effect. Crisis effect occurs immediately after a disaster and causes people to overestimate future flood risk. Levee effect starts once protection measures have been taken and causes people to rely too heavily of the protection of the system and then grossly underestimate future flood risk.

Immediate flood threat occurs during a flood event. As water height increases and comes close to the top of the dike, people feel various emotions ranging from fear to inconvenience to solidarity (Baan and Klijn, 2004). The degree of fear typically is inversely correlated to experience with flood events. People that live with frequent flooding typically experience less fear than those that are new to an area or live in an area that has not experienced flooding in several years. Past experience may be the single most important factor affecting people during high water levels. Those that have experienced minor flooding in the past with little or no damage will underestimate the risk of damage. Those that have experienced loss of life or extensive property damage in the past are most likely to experience helplessness and fear (Burn, 1999).

Evacuation is often perceived as more troublesome and threatening than the high water level (Baan and Klijn, 2004). Those that require assistance from others to evacuate (elderly, children, disabled) are the most susceptible to negative feelings during high water events. Interestingly, even the forecast of a high water event may be enough to trigger these feelings. As mentioned before, not all feelings are negative. Feelings of solidarity or togetherness can occur among people who band together during a high water event.

The third base for risk perception is uncontrolled flooding. A flood event is linked to several negative effects ranging from premature death to feelings of ill-health and mental distress. These feelings typically fade as time passes after the flood event (Baan and Klijn, 2004).

Public risk perception has been integrated into the Netherlands' flood strategy with specific regard to incorporating public involvement in decision-making. When the public is more involved and more educated in actual flood risk, negative feelings are reduced (Baan and Klijn, 2004). Recent research indicates that people in the Netherlands no longer perceive flooding as a natural disaster, but instead as a failure of the flood management system (Baan and Klijn, 2004). This has increased the likelihood that people overestimate the level of protection and place disproportionate trust in the man-made systems.

Financing Water and Flood Management

In the earliest days of dike building, landowners were responsible for protecting their property and making dike repairs. As cities formed, coordination among landowners was necessary, regional water authorities started to form. Maintenance costs were still distributed among land owners protected by the dikes and cities were mostly excepted from regular maintenance costs, but the *waterschappen* had authority to manage the construction, maintenance, and operation of dams, sluices, dikes and drainage canals (Tol and Langen, 2000, Kaijser, 2002). "Dike counts," *dijkgraaf*, were executives assigned the task of dike inspection three times a year (spring, summer, and fall). The spring inspection identified repairs to be made; the summer inspection made sure that the work had been completed; the fall inspection was a final opportunity to identify problems before the winter. If a land owner was unable to fund repair costs, the dike count would loan the money at interest rates in excess of 100% - 200% (Tol and Langen, 2000). In the event of excessive repairs or following flood damage, the dike count could raise money by imposing a tax on cities. However, most of the financial burden fell on landowners and frequently these repair costs led to bankruptcy. Often dike counts abused this privilege and were able to amass large amounts of land (Tol and Langen, 2000).

In 1798, a new constitution and more stable central government led to reorganization of a national budget and the formation of a national water authority (Tol and Langen, 2000). The funding for flood protection comes from a combination of inhabitant and property taxes at the state, provincial, and municipal levels of government. Provincial governments are responsible for implementing state water policies. Costs for flood protection may be covered by the national general budget, as long as they fit within the following activities:

- "Formulation of the national, strategic policy on flood protection and water management, supervision of its realization and enforcement,
- The realization of the operational tasks concerning the infrastructure shown in Figure 8,
- The flood protection works lacking hinterland or financial capacity; the Main Dike separating the Wadden Sea from the Lake IJssel, dams and barriers in the estuaries, dunes and dikes on the Wadden islands,
- The preservation of the coast by fighting the structural erosion,
- The operational management of the state waters. These waters concern the Rhine with its branches, the Meuse, the Scheldt, the Lake Ijssel, the estuaries, the principal canals and the territorial and international sea, and
- The promotion of the (inter)national shipping routes." (Huisman, 2002).

In 1998 (the most recent year with published information), The Netherlands spent 1% of its national income (US $ 3.14 billion) on water management- 15% of which was for flood protection (US $ 444 million). In the next ten years, the Dutch anticipate spending $2.9 billion on flood protection (Woorden, 2006). This investment will be discussed in further detail in the "Room for Rivers" section.

Figure 8: State managed waters and infrastructure (Huisman, 2002)

The Water Board Bank (*Nederlandse Waterschapsbank*) was formed in 1954 when funding for the substantial repair work caused by the 1953 floods was difficult. The local water boards were too small on their own and formed the collaborative to allow long-term borrowing at favorable rates (Huisman, 2002). The Water Board Bank is the fifth largest Dutch bank and it is owned by public authorities (81% is held by the water boards with state and provincial government holding the remaining 19%) (Huisman, 2002).

Flood damages place a large financial burden on the government as a result of requests for compensation. Previously, insurance policies excluded coverage for any flood damages, and the government was responsible for all claims. In 2000, a special committee convened by the Netherlands' government provided recommendations on the flood insurance policy (Kok et al, 2002). The committee recommended that the government work with insurance companies to designate flooding as a result of high rains (and no failure of flood defense systems) as part of property insurance. This reduced the governments' exposure to flood damage claims (Kok et al, 2002).

Public-private enterprises can help finance flood system improvements. Two recent partnerships include gravel and sand production and urban planning. The Grensmaas project combined private gravel and sand extraction with floodplain lowering (van Stokkom et al, 2005). Private enterprises have also presented plans for floating villages, which allow for river dikes to be moved further inland and maximize the public's willingness to pay for riverfront property. Although these partnerships have potential, so far implementation has been difficult and inefficient (van Stokkom et al, 2005).

Recent Developments in Dutch Flood Management: Room for the Rivers

The Dutch are increasingly incorporating resilience strategies into their flood management policies. This is an increasingly important alternative as the rate of economic value protected by the flood management system increases faster than dike heightening can occur. The economic value requiring protection has increased nationally by a factor of six in the past 40 years, and more in many local areas. Two strategies are receiving the most attention as potential resilience methods to minimize economic consequences of flooding: storing flood waters and increasing maximum flow capacity of channels (Vis et al, 2003, Silva et al, 2004, Hooijer et al, 2004). In the Netherlands, these two strategies are part of creating "room for rivers," an initiative led by the Dutch government to provide better flood protection and use spatial planning for long-term development (Woorden, 2006). The plan includes implementation of resilience measures in the four ways illustrated in Figure 9.

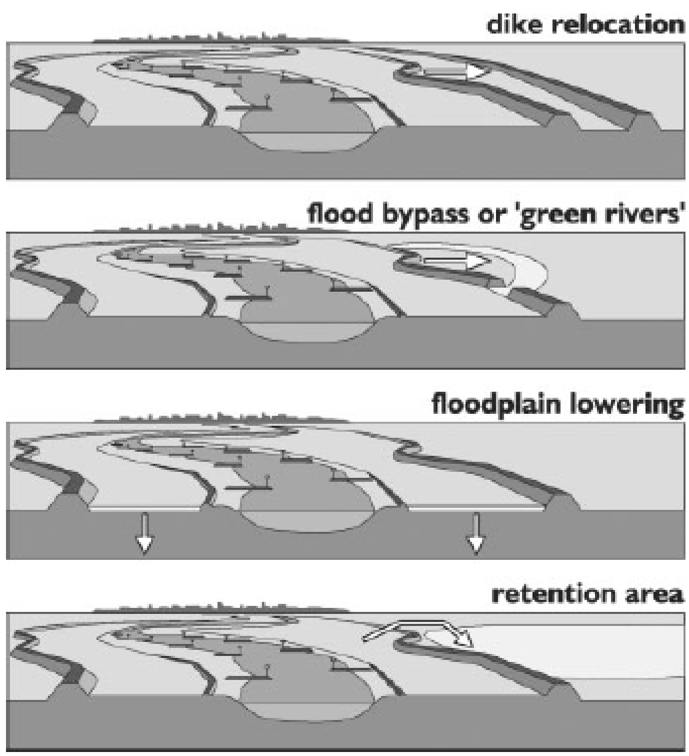


Figure 9: Implementation strategies for room for rivers (Hooijer et al, 2004)

The Dutch are currently building a flood bypass along the Ijssel branch of the Rhine that will protect the towns of Veessem and Hoenwaard from flood waters. This channel is being built in an area that is mostly agricultural (Woorden, 2006). As part of the same government measure to ensure flood protection objectives are met by 2015, the Dutch are also moving dikes along the Meuse between Geertruidenberg and Waalwik. By moving the dikes away from the river, the area known as the Overdiep Polder will be expanded and water levels in the area will drop up to 30 cm (Woorden, 2006). Although both of these measures do result in a loss of developable land, the goal is to maintain agricultural use while protecting more populated areas.

Detention of floods in compartments requires designating areas for temporary water storage and subdividing existing dike rings. The compartmentalized sections will have different flood probabilities resulting from a pre-determined order for rerouting flood waters to the compartments (Vis et al, 2003, Silva et al, 2004). Upstream compartments are filled first to reduce the flood peak's height and duration further downstream. Figure 10 provides a schematic of flood routing using detention in compartments. Typically, the compartments that are designated to receive flood waters first should be designated as natural or agricultural lands to minimize economic damage (Vis et al, 2003). These detention compartments can also be managed to help recharge groundwater supplies, reduce river bed erosion, and improve biodiversity (van Stokkom and Smits, 2002).

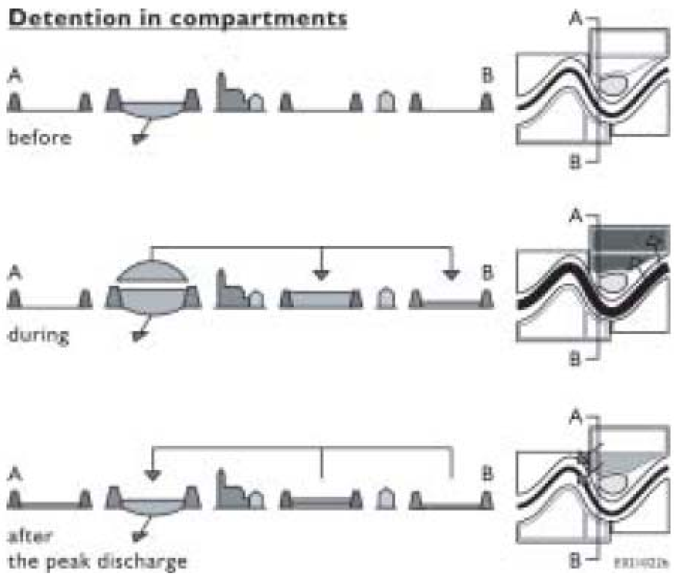


Figure 10: Schematic of detention in compartments (Vis et al, 2003)

Silva et al (2004) evaluated the potential for compartmental detention for Rhine flood waters. Because upstream storage is most desired, the Netherlands would have to focus on areas near the German border. To reduce flood water flow from an "average" flood hyetograph by 1000 m^3/s, 150 million m^3 of storage is required. This is equivalent to 3000 hectares (30 km^2) flooded to 5 meters (Silva et al, 2004). The increase of 1000 m^3/s from 15,000 m^3/s (current maximum flow capacity) to 16,000 m^3/s results in the probability of the detention area being used in a given year being approximately 1 in 500 (Silva et al, 2004). Such a low probability may lead to people forgetting the purpose of the detention area and begin to develop in ways that diminish its effectiveness at lessening flood damages.

Green rivers are one method to increase the maximum flow capacity of part of a channel. Green rivers are designated areas where water flows only during flood periods and maybe used for agriculture or ecological habitat at other times (Vis et al, 2003, Silva et al, 2004). These are similar to the flood bypasses in California's Central Valley. Figure 11 shows how green rivers aid in routing flood waters during peak events. Green rivers reduce water levels between their upstream and downstream ends (Silva et al, 2004). In the Netherlands, green rivers typically flood during the off-season for agriculture. This increases their economic benefit.

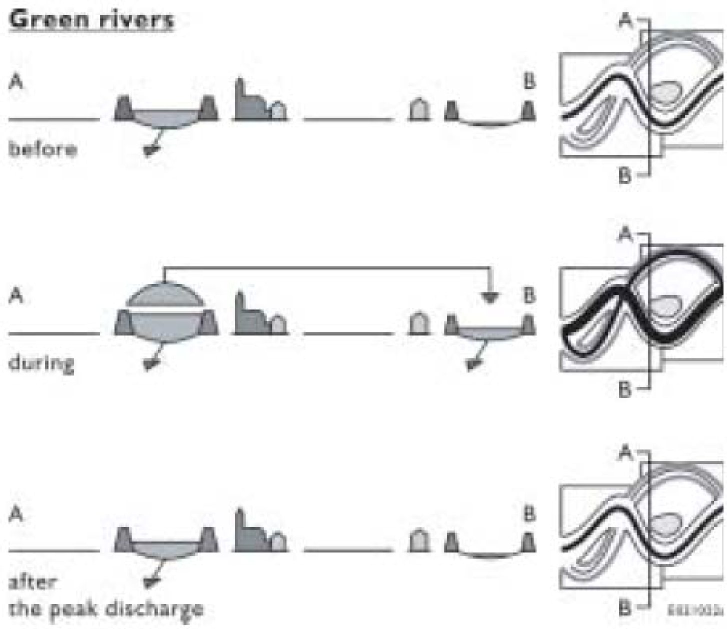


Figure 11: Schematic of green river flood routing (Vis et al, 2003)

Two final strategies for creating room for the rivers are relocating existing levees or lowering flood plain levels. These strategies require having enough undeveloped or minimally developed land available to adequately set back the levee or lower the floodplain. In the Netherlands, this is often difficult because flow capacity restrictions, or bottlenecks, most often occur in urban areas with little undeveloped land (Hooijer et al, 2004, Silva et al, 2004).

Implications for California Flood Mitigation

Flood Control Structures

The history of flood control structures in California is similar to that of the Netherlands, although on a different time scale. Initially, flood-control efforts were undertaken by local interests- typically nineteenth century settlers building their own rudimentary defense system with a lack of knowledge about flood periods and water heights (Harding, 1960, Kelley, 1989). In the twentieth century, local, state and federal agencies began to cooperate to build flood control systems. One of the earliest cooperative governmental projects was in 1916 to construct flood by-passes that are still in operation today (Harding, 1960).

The US Army Corps of Engineers, in cooperation with state and local agencies, constructed 1600 miles of federal levees in the Sacramento and San Joaquin River basins, also known as the Central Valley. Following construction, the federal government turned over maintenance of the levee system to the state. An additional 700 miles of non-federal levees have been constructed by landowners and local reclamation districts. These levees mostly protect agricultural land with the exception of Sacramento and its growing suburbs. Today, California's levees are regulated by the state Reclamation Board. Approximately 1300 miles of floodways have been designated by the Reclamation Board for flood discharge. The state, along with local reclamation and water districts, operates and maintains the extensive system of dams, levees, weirs, channels and bypasses along the Sacramento and San Joaquin Rivers. Figure 12 depicts this extensive this levee and channel system.

Much like the Netherlands, the flood protection system is under increased pressure as development and demand for housing and land increase. Today, these levees protect over $47 billion in Central Valley infrastructure (www.water.ca.gov/levees). One example of this increased pressure is the Natomas neighborhood near Sacramento. The 53,000 acre Natomas area and its 70,000 residents contribute upwards of $4 billion to the local economy each year (Lamb, 2008). A recent reclassification of the 43 miles of levees that protect Natomas from flooding on all four sides has resulted in a construction permit moratorium and increased required flood insurance by three times (Lamb, 2008). According to FEMA and the Army Corps of Engineers, the levee system would not meet the safety standards during a storm that has a 3 percent chance of occurring, which equals a 60 percent chance of occurring during a 30-year mortgage (Lamb, 2008). The construction moratorium has halted growth in an area that accounts for 47% of development in the greater Sacramento area. The Sacramento Area Flood Control Agency has pushed the levee improvements in Natomas to its top priority, and has a plan to allow the area to meet FEMA standards (described below) by 2010. This work is funded in part with $49 million from a state bond measure passed in 2006.[1]

Reliability-based Design

The Flood Insurance Administration of the Federal Emergency Management Agency (FEMA) uses the 100-year flood as a "base flood." The agency uses this flood to determine floodplains and flood insurance requirements and premiums under the National Flood Insurance Program, NFIP (FEMA website). These floodplain maps often lead citizens to believe that they are more protected and "safer" from flood damage than they actually are (Moser, 1997).

The state of California has used a standard project flood (SPF) to evaluate flood protection systems. This standard project flood is meteorologically based and is a derived discharge from a storm with a set return period. The Central Valley level of protection standard is a rain event with a return period ranging from a 200 to 500 years (Galloway et al, 2007).

Much like engineers in the Netherlands, the USACE historically used a design flood plus a freeboard when constructing flood defense systems (typically called flood reduction measures by the Corps). Often the design flood was the 100-year flood, or 1% exceedance flood (CGER, 2000) in accordance with the FEMA NFIP standards. The freeboard is included to account for uncertainties in the discharge, stage, and damage of a flood (Moser, 1997). Recently the USACE has shifted to a risk-based approach that is discussed in the next section.

[1] Proposition 1E is further discussed in the "Financing Flood Protection" section on page 32

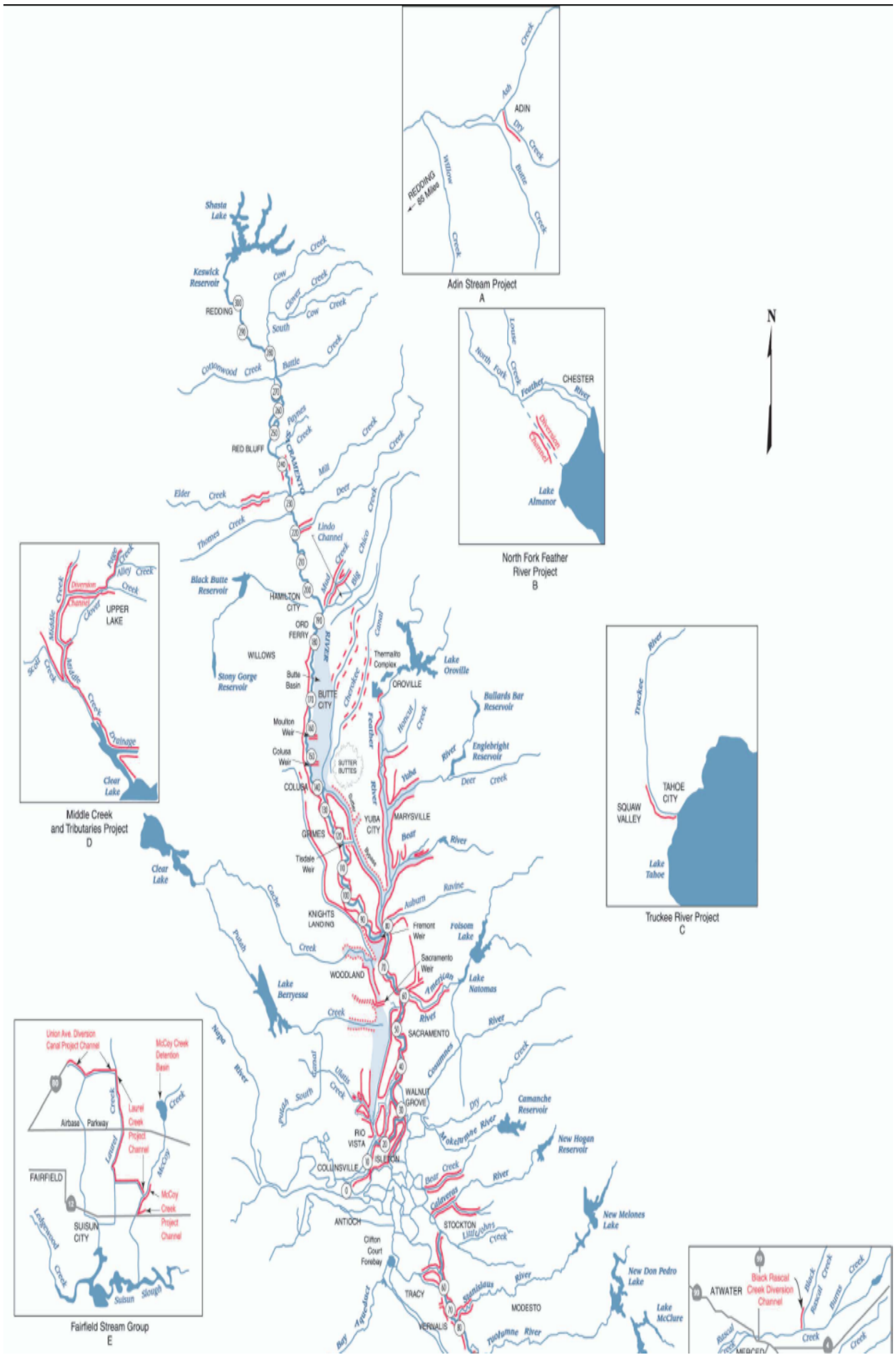
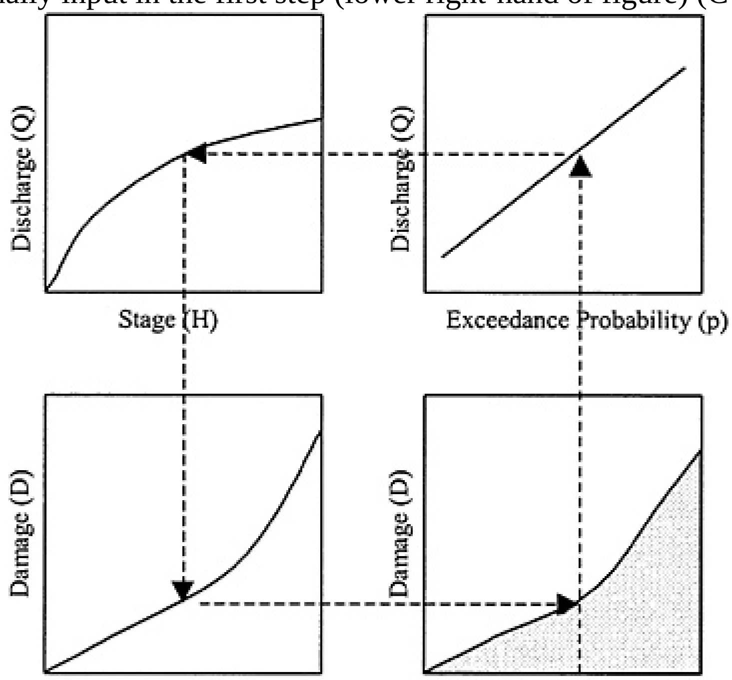


Figure 12: Levees and Channels along Sacramento and San Joaquin Rivers (California State Dept. of Water Resources, 2008)

Risk-based Design

When the United States Congress passed the Flood Control Act of 1936, it required consideration of the consequences following flood control structure failure. However, it was not until after van Dantzig's work that the economic costs were explicitly considered. The earliest application of risk-based design in the United States was by H.D. Pritchett in 1964 and looked at the hydraulic design of highway drainage culverts (Tung, 2005).

Although early USACE flood design was reliability-based, in the 1990's, there was a push within the Army Corps to transition to a risk-based analysis. This resulted in the current USACE approach illustrated in the figure below. First, the USACE determines the discharge associated with a standard set of exceedance probabilities (p = 0.5, 0.2, 0.1, 0.04, 0.02, 0.01, 0.004, and 0.002) (upper right-hand of figure). Then the discharge-stage relationship is determined (upper left-hand of figure). The stage (H), is then related to a damage function (lower left-hand of figure), which is then related back to the exceedance probabilities originally input in the first step (lower right-hand of figure) (CGER, 2000).



$$EAD = \int_0^1 D(p)dp$$

Figure 13: USACE Risk-Based Analysis Schematic (Moser, 1997)

Following this analysis, the USACE makes its funding decision based on national economic development (NED). The NED decision rule requires the USACE to invest funds in projects that have a risk-reward tradeoff at a national level (Yoe, 1993). This may mean that local interests would increase the level of protection based on the economic trade-offs, but at the federal level, the additional spending can achieve greater reward elsewhere (Yoe, 1993). This does not exclude local governments from providing additional funding to reach the increased level of protection (Moser, 1997).

Financing Flood Protection

Federal policies and responsibilities for flood control were first established in 1917 with the Flood Control Act. Although this act was mostly related to flood control along the Mississippi River, a Sacramento River flood-control project was included with the federal obligations being limited to navigation (Harding, 1960).

Over time, the role of the federal government in flood-control was broadened. The 1936 Flood Control Act included the construction of dam and reservoir projects as a federal responsibility. Gradually, by the mid-twentieth century, the federal government had assumed responsibility for most of the costs of flood control construction with the exception of payments for local right-of-way, which states typically cover. Local costs for flood control were limited to some maintenance (Harding, 1960).

Today, the state of California has assumed much of the financial burden for levee maintenance. In 2006, voters passed a bond measure (Proposition 1E) that provides $4.09 billion for levee repairs and flood control system maintenance. Of that bond, $3 billion is set aside for levee improvements. The repayment of these bonds will cost the state government approximately $8 billion over 30 years.

Local reclamation district funding ranges from slightly more than $50,000 in Yuba City to more than $2.1 million in Natomas (suttertaxpayers.com). In Sutter County, homeowners pay approximately $25 per year in Reclamation District taxes. In Yuba City, this funding goes to mostly administrative costs, and levee inspections and repairs are done by volunteers.

The California State Water Code Section 8400, Flood Hazard, requires that relevant local governments participate in the National Flood Insurance Program (NFIP), as supplemented with state provisions (May, 1993). To receive federal disaster aid following flooding, FEMA requires participation in the NFIP (FEMA, 2002). In turn, the California state requirement ensures that local areas will receive aid in the event of a flood.

Insurance covers much of flood losses in the United States. For the period of 1985-1999, although North America sustained only one-third of economic losses due to natural disasters, it accounted for over two-thirds of the insurance-protected losses sustained worldwide (Linnerooth-Bayer and Amendola, 2003). In the US, there are approximately 4.3 million flood insurance policies covering over $606 billion in property (FEMA, 2002).

The NFIP has been one of the most effective measures at reducing economic loss during a flood because of the safety standards that insured properties are required to meet. Analysis done by FEMA estimates that $1 billion in flood damages are avoided each year for new construction meeting NFIP regulations, and that the new structures suffer 80 percent less loss during a flood event (FEMA, 2002).

However, there is a need for more consistent maintenance of the levee systems. Army Corps estimates place the cost of levee improvements in the Natomas area at more than $1 million per levee mile. With 43 miles of levees in this area, even one of the largest reclamation districts' operating budgets is not sufficient to meet minimum safety requirements. Emergency bond measures and disaster relief funding become overly expensive as interest rates and payback periods double the cost of the levee improvements, as in the case of Proposition 1E.

It seems as if California shares a flood protection funding crunch with the Netherlands; however, two financial resources used in the Netherlands may aid California. Public-private partnerships might aid areas of high development like Natomas. By requiring land developers to provide flood protection funding as part of the permitting process, levee improvements can be made. Although places a premium on the real estate being developed (theoretically equal to the cost of the flood protection provided), the results can be positive. One example of a developer funded levee project is the 1.3 mile set-back levee along Bear River near Plumas Lake (Dickey, 2007). A $29,345 fee was assessed for each home built in the new development. Initially, limited development was authorized before the levee was completed to help raise the nearly $70 million required to build the levee. Builders were also required to fund each homeowner's first year of flood insurance to ensure that homeowners were aware of the risk associated with living in the Plumas Lake area.

Making Room for the River: Bear River and Yolo Bypass
The levee built along Bear River near the Plumas Lake developments also provides an example of the Dutch technique of "making room for the river." The set-back levee has provided an additional 600 acres of habitat that will ease pressure on the river during floods (Dickey, 2007).

The Yolo Bypass is also an example of making room for rivers; it is an example of a "green river." At 59,000 acres, the Yolo Bypass is the largest bypass in the Sacramento Valley, and during flood events can discharge to the estuary much more than the main channel of the Sacramento River (up to 14 to 15 thousand m^3s^{-1}) (Schemel et al, 2002). During the winter and spring, the Yolo bypass is flooded, offering shallow-water habitat to aquatic species. Then, during the late spring and summer, when the bypass is not flooded, the land is used for irrigated agriculture (Schemel et al, 2002). Bypass construction started in 1917 after federal funding was approved to help the state government coordinate reclamation, navigation, and flood control projects in the (Kelley, 1989). Since its completion in 1963, the bypass has been used as the main storage for floodwater drainage from the Sacramento River Valley (Jones and Stokes, 2001).

Summary and Conclusions
Flood control is a problem of too much and not enough- too much water and not enough money or space. The Dutch have centuries of experience trying to maintain the balance

between flood damage and control. Advancements in risk-analysis of flood defence systems and the accuracy of the valuations used in making economic decisions have been applied by the US Army Corps of Engineers in the last decade. The NED decision-rule directs federal funding to projects with the greatest economic value to the United States. Reliability- based standards (using a predetermined failure probability) fails to account for the value of the land and lives being protected. Applying the same level of protection to agricultural land as well as heavily populated cities is economically inefficient. The inadequacies of reliability-based design have been exposed, but continue to be used for flood insurance (and thus, many design) purposes in California.

Public-private partnerships, which are in the early stages in both the Netherlands and California, have shown more potential in California. The Plumas Lake example shows that when developers assume some of the risk and cost of flood management, the economic benefits to the local government can be great. Not only was the local government able to save on the cost of the levee construction, but it also has established a tax base for future levee maintenance.

Flood insurance in the United States and California goes far beyond insurance in the Netherlands. In the Netherlands, much of the burden for flood damage is on the government, including all damage caused by a failure of the flood defense systems to adequately protect homes. The increase in national and local economic values occurs faster than the government can develop adequate flood protection infrastructure.

In the United States, the NFIP has provided an economic stimulus for more responsible construction and development that local and state governments would otherwise ignore. Additional state and federal funding from bond measures aids local governments in maintaining adequate flood protection and lowering insurance premiums for residents. The Natomas area provided an example of local and state failure to insure levees were adequately constructed to safely protect new development.

Finally, “making room for the river,” has been used for decades in the example of the Yolo bypass and then was revisited to ensure that Plumas Lake had adequate flood protection. The bypass solution also incorporates the environmental value that Californians place on wildlife habitat and open, green space. However, it will not work in all locations. Much like congested areas of the Netherlands, making room for the river will not work in California’s populous areas or areas were development along the river already exists (i.e. Natomas).

This review of flood protection methods in the Netherlands and California has reestablished the importance of land-use planning and risk-based analysis. It is expensive to build haphazardly in floodplains. The costs of flood protection (a levee the size of the 90 m x 32 km Afsluitdijk) and the loss following a flood disaster (especially one that does not meet FEMA and NFIP criteria for federal disaster relief) both have the potential to drain the economic resources of the state of California.

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Appendix

Risk-based design (Cost-benefit analysis)

Van Dantzig introduced risk-based design in his 1956 paper evaluating the optimal dike height, H_0, "taking account of the cost of dike-building, of the material losses when a dike-break occurs, and of the frequency distribution of different sea levels." van Dantzig assumed that the probability distribution of the high-tide sea level is known and is constant. He also initially assumed that the material value protected by the dike, V, is also constant in time. Overtopping was considered the only failure mechanism; dike breaks were not considered. So,

$$X = H - H_0$$

H = current dike height
X = increase in dike height to reach optimal dike height

$$p(h) = p_0 e^{-\alpha(h-H_0)}$$

p(h) = the probability that the height of the flood, h, will exceed the height of the dike, H

Two costs were evaluated: a) the cost of the dike heightening, I, and b) the "insurance investment, L," required to cover the expected value of all future losses.

$$I = I_0 + kX$$

I_0 = the initial decision investment, i.e. survey and design costs, mobilization costs
k = additional cost per unit dike is heightened, i.e. materials, labor

$$L = p(H)V\sum_{t=0}^{\infty}(1+0.01\delta)^{-t}$$

V = the economic loss when the height of the flood exceeds the height of the dike
δ = the interest rate on the initial investment
To determine the optimal height increase, X, minimize the costs, I(X) + L(X):

$$\frac{dI}{dX} + \frac{dL}{dX} = 0$$

This results in the following solution equation:

$$X = \frac{1}{\alpha}\ln\frac{100 p_0 V\alpha}{\delta k}$$

Voortman et al (2002) simplified the risk-based equation into one step. It can be read: During T period of time, the total economic benefit is equal to the total economic value of land minus economic value of land and property lost during floods minus cost of flood protection system. The total economic benefit is optimized for a given flood frequency distribution.

$$B_{ref}(P_{flood}, T) = -I_{sys}(P_{flood}) + \sum_{t=0}^{T}\frac{b(1+r_e+i)^t}{(1+r)^t} - \sum_{t=0}^{T}\frac{P_{flood}(b+d)(1+r_e+i)^t}{(1+r)^t}$$

P_{flood} = Flood frequency distribution
T = reference period
I_{sys} = cost of protection
b = yearly economic benefits in undisturbed conditions
r_e = rate of economic growth
d = direct damage in case of flood

i = inflation rate
r = interest rate

Reliability-based design
Voortman et al (2002) described the reliability-based design process for a flood defense structure using the following equations:

$$D = \{\mathbf{z} |\ P_{flood}\ (\mathbf{z}) <= P_{flood;max}\}$$

D = set of acceptable design alternatives
z = design variable vector
P_{flood} = flood probability
$P_{flood;max}$ = maximum acceptable probability of flooding

Once the set of design alternatives is determined, the goal of reliability-based design is to minimize the cost of the structure.

$$\min_{p} I(z)$$

$$\text{s.t. } P_{flood}\ (z,x) <= P_{flood;max}$$

I = direct cost of structure

Extended Life Quality Index (ELQI)
Nathwani et al (1997) developed the Life Quality Index (LQI) as a measure of the economic benefits of life expectancy:

$$LQI = g^{w} e^{(1-w)}$$

g = Personal income
e = Life expectancy
w = model parameter derived from the amount of time spent working.

Voortman et al (2002) used the LQI to create the Extended Life Quality Index (ELQI) for evaluating flood protection decisions:

$$LQI_{life}(P_{flood},T) = G_{life}(P_{flood},T)^{w}\, E_{life}(P_{flood},T)^{1-w}$$

$$G_{life}(P_{flood}) = DF\left(\frac{Ng_0 + B_0 - (B_0 + S)P_{flood}}{N}\right) - \frac{I(P_{flood})}{N}$$

$$DF = \frac{\left(\frac{1+r_e}{(1+r-i)(1+r_p)}\right)^\wedge T - 1}{\ln\left(\frac{1+r_e}{(1+r-i)(1+r_p)}\right)}$$

N = population at the beginning of the plan period
g_o = personal income at t=0
B_0 = yearly turn-over when no flooding occurs
$I(P_{flood})$ = investment as a function of flooding probability
$E_{life}(P_{flood},T) = e_o T$
e_0 = Life expectancy at birth without flooding.