Climate Variability and Water Dependent Sectors

Impacts and Potential Adaptations

Edited by
Dannele E. Peck and Jeffrey M. Peterson

ROUTLEDGE

Climate Variability and Water Dependent Sectors

Demand for water in agricultural, municipal, industrial, and environmental uses is growing. More frequent and severe extreme weather conditions now exacerbate water shortages in many locations and existing infrastructure to store and release water rarely has the capacity to both prevent floods during wet periods *and* meet demand during drought periods. Competition among sectors adds pressure not only on water infrastructure, but also on management policies and allocation institutions.

This book of contributed chapters assesses the performance of existing infrastructure, institutions and policies under different climate variability scenarios. It also provides suggestions for minimizing conflict over scarce water resources. More flexible water-allocation institutions and management policies, and better tools for decision-making under uncertainty will be required to maximize society's net benefit from less reliable water resources. The chapters show how incentives for individuals to conserve water, and policies for helping vulnerable populations prepare for and recover from extreme events, will also need to be improved.

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Chapter 1

Introduction to the special issue on 'Climate Variability and Water-Dependent Sectors: Impacts and Potential Adaptations'
Dannele E. Peck and Jeffrey M. Peterson
Journal of Natural Resources Policy Research, volume 5, issue 2–3 (April–July 2013) pp. 73–78

Chapter 2

Cost of early snowmelt in terms of reduced irrigation deliveries
Aaron Benson and Ryan Williams
Journal of Natural Resources Policy Research, volume 5, issue 2–3 (April–July 2013) pp. 79–90

Chapter 3

Climate change opportunities for Idaho's irrigation supply and deliveries
Russell J. Qualls, R. Garth Taylor, Joel Hamilton and Ayodeji B. Arogundade
Journal of Natural Resources Policy Research, volume 5, issue 2–3 (April–July 2013) pp. 91–106

Chapter 4

Climate and choice of irrigation technology: implications for climate adaptation
George B. Frisvold and Shailaja Deva
Journal of Natural Resources Policy Research, volume 5, issue 2–3 (April–July 2013) pp. 107–128

Chapter 5

Potential economic impacts of water-use changes in Southwest Kansas
Bill Golden and Jeff Johnson
Journal of Natural Resources Policy Research, volume 5, issue 2–3 (April–July 2013) pp. 129–146

Chapter 6

Community adaptation to climate change: exploring drought and poverty traps in Gituamba location, Kenya
Amy Sherwood
Journal of Natural Resources Policy Research, volume 5, issue 2–3 (April–July 2013) pp. 147–162

Chapter 7

Medium-term electricity load forecasting and climate change in arid cities
Bhagyam Chandrasekharan and Bonnie Colby
Journal of Natural Resources Policy Research, volume 5, issue 2–3 (April–July 2013) pp. 163–182

Chapter 8

The joint impact of drought conditions and media coverage on the Colorado rafting industry
Karina Schoengold, Prabhakar Shrestha and Mark Eiswerth
Journal of Natural Resources Policy Research, volume 5, issue 2–3 (April–July 2013) pp. 183–198

Please direct any queries you may have about the citations to
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Contents

Introduction

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Water stress is an increasingly important challenge for the twenty-first century. Demand for water resources in agricultural, municipal, industrial, and environmental uses is rising due to population and income growth. Climate change is expected to exacerbate water stress by increasing the frequency and severity of extreme weather conditions. Although drought may not become more frequent or severe in all locations, growing demand for water will cause scarcity to become more pressing over larger geographic areas. In many locations, infrastructure to store and release water currently lacks the capacity to meet demand during drought periods and prevent floods during wet periods. Competition for scarce water resources, both within and among sectors, will place even greater pressure on existing infrastructure, as well as current water allocation institutions and management policies.

Reassessment of infrastructure capacity and management, including the timing of storage releases, will be necessary to minimize conflicts between competing uses. More flexible water-allocation institutions and management policies, as well as better tools for decision-making under uncertainty, will be required to maximize society's net benefit from scarce water. Effectiveness of incentives for individuals to conserve water, and policies for helping vulnerable populations and sectors prepare for and recover from extreme events, will also need to be improved.

This special issue contains seven research articles, which are purposely ordered to follow water's path through the sweep of the hydrologic cycle affecting human decisions and livelihoods: from its origin as snowpack in distant headwaters to its capture in multipurpose reservoirs, and its release for a diverse set of consumptive and non-consumptive uses by millions of downstream producers and consumers. Most of the contributed articles focus on the western United States, which is similar to a number of semi-arid regions in the world where water largely originates as mountain snowpack. Spring and summer snowmelt slowly seeps into ephemeral streams, which converge into roaring rivers that ultimately recharge aquifers and fill an intricate system of natural and constructed reservoirs. Society faces a complex set of decisions to manage the water in these storage basins, requiring difficult tradeoffs in allocating a scarce supply across the demands of numerous stakeholders.

Depending on its timing and intensity, water can be a productive asset or a destructive natural force. Constructed reservoirs help dampen the effects of too much water or too little water, along with the effects of water arriving too early or too late. It can be difficult, however, to manage reservoirs in a manner that achieves socially desirable outcomes, especially when multiple users have competing objectives.

Benson and Williams' opening contribution explores the circumstances in which flood-protection and irrigation water supply might be competing objectives. They model reservoir inflows and releases under historical versus future climate conditions. Climate change is expected to alter the timing of snowmelt, causing inflows to arrive earlier in the spring and over a shorter duration. To ensure that peak inflows will not lead to flood damage to downstream communities, reservoir managers must leave more excess storage capacity early in the runoff season. The authors show that the result can be far less runoff to be captured overall, leading to lower deliveries to farmers in the subsequent irrigation season. They also show that the tradeoff between flood protection and irrigation depends, in part, on a reservoir's storage capacity relative to downstream agriculture's water demand.

Qualls, Taylor, Hamilton and Arogundade continue the discussion of reservoir management under future climate conditions, but examine the strengths and weaknesses of an existing allocation mechanism. In the western US, the most prevalent legal institution to allocate water is the prior appropriation doctrine, which, in theory, concentrates water shortages on users holding the most junior water rights. In practice, water use is limited by the availability in a given location, and even senior users accessing water from a low-capacity reservoir may suffer shortages in times of drought. The authors find that although some users are likely to suffer occasional shortages in future drought years, the average shortages are relatively small. However, above-average precipitation might also occur under future climate conditions, and the authors' results also suggest that the current system is unable to store and allocate these above-average water supplies. Climate change could actually benefit water users in Idaho, but only if reservoir infrastructure management adapts appropriately.

Upon its release from natural or constructed storage basins, water's most likely user is irrigated agriculture, which consumes more water than any other user-group in the western US. Irrigated crop producers must be especially vigilant and responsive to changing climate because of their economic dependence on water quantity and timing, and other climatic variables during the growing season. As conditions evolve, so too will producers' production practices.

Frisvold and Deva explore the effects of temperature, growing season length, and irrigation costs on agricultural producers' adoption of sprinkler versus gravity-fed irrigation. Sprinkler irrigation may be a useful adaptation to changing climate conditions in some, but not all, regions of the western US. In many cooler regions, climate change is expected to increase the number of frost-free days while also raising the risk of frost during the growing season. In these locations, sprinkler irrigation may be beneficial to protect crops from early-season frost damage. In regions that already have high temperatures and long growing seasons, such as California and Arizona, sprinkler irrigation may not be a beneficial adaptation because warming conditions would increase evaporative losses during water delivery. The authors' regression analysis of past adoption in different states confirms that climatic variables, as well as farm size and farm input prices, are important determinants of sprinkler adoption rates.

Golden and Johnson continue the assessment of irrigated agriculture's vulnerability and adaptation to water shortages (current or future), but draw our attention to the Ogallala Aquifer in southwest Kansas, where decades of sprinkler-irrigated agriculture have significantly depleted the aquifer. In some areas, groundwater depletion is so severe that producers now face the difficult decision of whether to exhaust the aquifer, or reduce current consumption in an effort to extend its life for future generations. The authors estimate the potential benefits and costs of groundwater conservation, from the perspective of individual producers and the regional economies of three agriculture-dependent communities. Results suggest that groundwater conservation has the potential to generate net benefits for certain producers and regional economies, especially under drought conditions. For some regions, however, the short-term costs of groundwater conservation might exceed the long-term benefits. Conservation policies should therefore be tailored for each community's unique circumstances.

Individual producers in the US have access to numerous drought preparedness and mitigation tools, including private or government-sponsored safety nets, such as crop insurance and disaster assistance. In developing countries, however, these formal safety nets rarely exist, and individual producers have limited access to physical or financial resources necessary to adequately prepare for or mitigate the effects of drought.

Sherwood takes us to central Kenya, where a majority of households still engage directly in agricultural production. Few households can afford to drill groundwater wells or install advanced irrigation systems. Hand-watering is more common, but requires more labor than many households can afford to divert from other critical sources of income, such as off-farm employment. Drought is therefore more likely to lead to crop failure and life-threatening food insecurity. Sherwood uses participatory research methods to identify the consequences of a severe water shortage for women in a rural agricultural community, as well as their sources of vulnerability and resiliency. Agricultural households' preparedness for future droughts could be improved by reducing sources of vulnerability that erode their ability to build private or community-based safety nets during non-drought years. Despite being thousands of miles from the western US, these insights are relevant to any agricultural household whose livelihood depends on their ability to make the most of good growing conditions, and minimize losses during difficult times.

Few households in the US engage directly in agricultural production. These non-agrarian households tend to be more insulated from drought's negative effects on food production. They also have access to more resources for adapting to and mitigating the effects of drought and other features of climate change. Nonetheless, US households are not immune to the effects of water shortages. They rely, after all, on goods and services provided by water-dependent industries, such as agriculture, energy, and outdoor recreation. By understanding the effects of climate variables on consumer behavior and resulting demand, water-dependent businesses can minimize more-effectively the negative economic impacts of drought and climate change.

Chandrasekharan and Colby isolate the effects of weather conditions on consumers' use of electricity in a major metropolitan area of Arizona. They estimate the economic value to electric utilities of better-understanding and anticipating consumers' response to future climate conditions, especially changes in peak load during summer months when water for energy production is most scarce. Improved electricity load forecasts, based on medium-term weather expectations, should reduce electric utilities' cost of over or under-production.

Lastly, *Eiswerth, Schoengold and Shrestha* explore the sensitivity of commercial whitewater rafting customers to drought, air temperature, and wildfire. After controlling for the effects of drought and other relevant physical and economic variables, customer numbers along the Arkansas River in Colorado were lower than expected in 2002, a year in which wildfires ravaged the general region. The authors hypothesize that imprecise national media coverage of wildfires in Colorado had unintended negative consequences for recreation-dependent businesses in the region, even though the safety and quality of rafting in the study area was not adversely affected.

While tracing water's journey from its origin as mountain snowpack to its capture in reservoirs and aquifers, and its use in agriculture, electricity and outdoor recreation, the seven articles in this issue highlight the diverse, situation-specific effects of climate variability on different sectors. As the varied research problems require, these seven studies apply different methods and obtain distinct results. Common themes nevertheless emerge from this varied work, four of which we discuss below.

(1) Water's increasing scarcity and variability generate difficult tradeoffs that require individuals, and society as a whole, to make complex decisions, often under imperfect information. Reservoir managers must balance the needs of flood protection, agriculture, recreation and other potentially competing uses when planning the quantity and timing of reservoir releases. Agricultural producers must weigh short versus long-term tradeoffs when choosing irrigation technology and water application rates. Producers in the US have more options and resources available to them than smallholder farmers in Kenya, but both should anticipate the potential for higher opportunity costs of acquiring and consuming water under future climate conditions, and begin assessing their existing sources of vulnerability and resiliency.

(2) Although climate change, in many cases, will heighten the scarcity of water resources and raise the stakes of already difficult tradeoffs, it will generate some new opportunities. These opportunities are potentially beneficial to society, if we position ourselves to take advantage of them. Reservoirs in some regions, or with certain physical characteristics, may be able to capture earlier, faster, and above-average inflows in some years and store them for beneficial use in below-average years. Groundwater conservation, in some cases, could generate long-term benefits, such as buffering against future droughts, that outweigh short-term costs. Commercial rafting companies could mitigate some of the effects of drought by marketing their services to families and inexperienced rafters who seek low-risk rafting experiences.

(3) To maximize society's net benefit from scarce water resources under future climate conditions, resource managers, businesses and policymakers need to understand how climate influences individual water-users' decisions and associated outcomes. This knowledge can help them prepare for, and adapt to, changing water availability and variability more effectively. Electric utilities, for example, can use medium-term weather information to improve peak load forecasts and reduce the cost of over or under-production. Outdoor recreation companies can coordinate with relevant media outlets to ensure potential customers are receiving accurate information about conditions in specific locales.

(4) Society's preparedness and adaptation activities should, ideally, be tailored to fit affected regions, communities, or water-user groups' unique characteristics, strengths and weaknesses. Local conditions will influence whether future climate conditions will exacerbate current water management challenges or create new opportunities, and whether proposed adaptation policies will increase or decrease society's net benefit from scarce water resources. A reservoir's resiliency to changing climate, for example, depends on its storage capacity relative to downstream demand and the value of properties within future floodplains. The appropriateness of adopting sprinkler irrigation or conserving groundwater

depends on individual farms and regions' physical and socio-economic characteristics, such as soil type, growing season length, and discount rate. For smallholder farmers in Kenya, the design of drought preparedness plans and climate change adaptation should be informed by existing sources of vulnerability and resiliency within the community and across households, including those that exist during non-drought years.

The seven articles in the pages that follow provide policy-relevant results for a number of sectors in the western US, which will be of direct interest to stakeholders and policymakers in the region. A number of the results and approaches are also applicable to numerous regions of the world that resemble the snowmelt-driven, semi-arid climates studied in this work. More broadly, these articles collectively bring out a set of tools and insights that can inform a range of management decisions as water-dependent and other resource sectors adapt to climate variability.

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Cost of early snowmelt in terms of reduced irrigation deliveries

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Climate change and windborne dust are expected to change snowmelt timing. Dust from agricultural activities is estimated to cause snow to melt two to four weeks earlier in some regions. Early snowmelt may decrease deliveries of irrigation water when reservoirs provide flood protection and irrigation water. To date, the quantity decrease has not been determined. We identify when early snowmelt causes earlier water release, and calculate the quantity decrease in water deliveries downstream. Irrigation reductions are negligible unless the dam capacity is less than twice the quantity of annual runoff, and unless snowmelt occurs more than four weeks early.

1. Introduction

Many irrigators and municipalities in western North America depend critically upon water that precipitates as snowfall and is temporarily stored as snowpack at high elevations. Reservoirs and water delivery systems in the region have been designed considering the timing and quantity of runoff as that snowpack melts. However, certain factors such as climate change and increased windborne dust and soot from human activities can cause snow to melt earlier than it would otherwise, or earlier than what was expected when the water delivery infrastructure was designed. In this paper, we investigate the economic effects of earlier runoff in the case of a small reservoir that is designed to provide flood control as well as water for irrigators downstream.

In the future, springtime snowmelt is expected to occur earlier in the year due to several factors, including climate change (Leung et al., 2004; Stewart, Cayan, & Dettinger, 2004;), and deposition of windborne dust and soot. Previous research has shown that most climate change scenarios increase the occurrence of extreme weather events and increase the variance of temperature and precipitation (Rowell, 2005; Seneviratne, Lüthi, Litschi, & Schär, 2006;), which can directly lead to snow melting earlier. Windborne dust and soot that settles on snowpack decreases the reflectivity of the snow, increasing the amount of solar radiation absorbed, and increasing the speed at which the snow melts (Painter et al., 2007; Qian, Gustafson, Leung, & Ghan, 2009). Much of the dust deposited on mountain snowpack in the western United States is from human activities, primarily cattle grazing (Neff et al., 2008). In simulations of snowmelt in the San Juan Mountains of southwest Colorado, windborne dust has been estimated to cause snow to melt 18 to 35 days earlier than in the absence of dust (Painter et al., 2007). Early snowmelt has been shown to have various biological and ecological effects (Steltzer, Landry, Painter, Anderson, & Ayres, 2009), and Stewart et al. (2004) recognized that, for reservoirs that provide flood protection in addition to other services, 'earlier flows would place more of the year's runoff into the category of hazard rather than resource' (p. 230), due to the facility needing to release more water earlier in the season than normal. The characteristics of snowmelt and storage facilities that might result in decreased irrigation deliveries later in the year were not identified, however, and the economic consequences of earlier snowmelt have, to our knowledge, not yet been determined.

Regardless of the cause of early snowmelt, it is necessary to first identify the cost of accelerated snowmelt runoff before designing policies to mitigate those costs. Once an estimate of costs of early snowmelt is available, it will be possible to identify the optimal investment in strategies (to adjust infrastructure, for example) to adapt to early snowmelt from climate change. Likewise, if early snowmelt is caused by dust deposition, an accurate estimate of costs is necessary to determine the optimal abatement of dust from ranchers and farmers, similar to a classic nonpoint source pollution problem. This scenario differs from many of the common examples of nonpoint source pollution, however, in that at least some of the agricultural producers will directly bear some of the 'externality' cost caused by windborne dust. This characteristic opens the door to policy instruments that are more common in provision of public goods, rather than just pollution reduction, since the reduction that results will benefit those who choose whether or not to participate in abatement. So, policies to reduce dust that causes early snowmelt will potentially need to include provisions to handle free-riders who allow others to adjust management to reduce dust and then benefit without bearing any abatement costs themselves. Again, however, damage costs need to be estimated before reduction policies can be considered.

To determine those costs, we create a simplified model of a small reservoir that stores spring runoff water for irrigation later in the year and also provides flood protection for a municipality downstream. We choose a small reservoir to simplify the model by avoiding the multi-year decisions that would be made by a manager of a large reservoir. Given the dual objectives of the dam, the dam manager must choose the quantity of water to release during spring runoff to both maximize the benefits of water stored for irrigation and minimize the expected monetary damages of releasing a flood-level quantity of water, which would be necessary if the reservoir is at capacity when a flood-level quantity of runoff enters the reservoir (a flood-level quantity of water is defined here as a flow rate greater than the capacity of the river/stream system below the dam).

Previous work has investigated the interaction of different objectives of reservoir management. Dudley (1988) examined the potentially conflicting short-, intermediate- and long-run irrigation objectives of a reservoir, when irrigation requirements and water availability are both stochastic. Vedula and Mujumdar (1992) and Vedula and Kumar (1996) considered reservoirs that provide only irrigation water, but that provide water for different crops with different water requirements, and built stochastic dynamic programming models to determine optimal water allocation to the different crops. Chatterjee, Howitt, and Sexton (1998) created a dynamic optimization model to determine the optimal allocation of water for irrigation and hydropower, recognizing that peak irrigation demand does not occur concurrently with peak hydropower demand, and find that actual water allocation in California deviates from the optimum. Lee, Yoon, and Shah (2011) modeled an entire watershed that includes a reservoir in order to determine optimal soil conservation upstream of the dam, reservoir sediment removal, water deliveries to downstream farmers and pollution control downstream of the dam, and find that an integrated watershed management plan can substantially increase the value of the watershed compared to a scenario in which the goals are considered individually.

In addition to modeling a dam with multiple, competing objectives, we also model a significant change in the characteristics of the runoff water the dam is meant to hold, which may require an adjustment from the dam manager, somewhat similar to Palmieri, Shah, and Dinar (2001) who studied the possibility of changing dam management strategies to address unsustainable sedimentation and increase the life of the reservoir. Other studies of streamflow timing and irrigation include Heidecke and Heckelei (2010), who investigated the effects on irrigation and farm income of decreasing water inflow to a single-use reservoir in Morocco, and found that the probability of the farmers receiving revenues below the subsistence level increases sharply under different climate change scenarios.

2. Model

We model the decisions made by a dam manager during a single runoff season to hold or release water, assuming that the releases after the runoff season are predetermined. We assume that the manager knows only the quantity of water currently held in the reservoir and the probability of a flood, which is determined by fraction of the reservoir's capacity currently filled and the number of days until the irrigation season begins. During runoff, the dam manager holds and releases water to satisfy the dual objectives of maximizing the benefits of water available for the later irrigation season and of minimizing the expected costs of having to release a flood-level quantity of water.[1] These two objectives will lead the manager to impounding water during spring runoff until the marginal benefit of stored water equals the marginal cost of using additional storage capacity. The marginal benefit of additional stored water is simply the additional revenue received by farmers when that water can be used to irrigate crops. The marginal cost of using additional storage capacity is the increase in the expected damage cost of having to release a flood quantity of water. Throughout this paper, we consider the effects of early snowmelt on irrigation deliveries in a year with average snowfall.

We assume D is the (constant) damage cost of a flood, and O is the probability of having to release a flood quantity of water, given t days until the irrigation season begins and ε percentage of the reservoir filled, so that the expected damage cost is $D^{*}O(t,\varepsilon)$, and the marginal cost of impounding additional water is $D^{*}\partial O(t,\varepsilon)/\partial\varepsilon$. The dam manager satisfies the dual objectives of the dam by choosing a threshold value of ε to maximize $B(\varepsilon) - D^{*}O(t,\varepsilon)$. As runoff flows into the reservoir on a given day, the dam manager will allow the water level to rise up to point where $MB = D^{*}\partial O/\partial\varepsilon$, or until $MB/D = \partial O/\partial\varepsilon$, that is, until the ratio of the value of one additional unit of water for irrigation to the damage costs of a flood just equals the increase in the probability of flood due to filling 1% of capacity. Once the optimal threshold is reached, the manager will immediately release additional inflows to keep the water level constant.

We assume that the probability of flooding, O, increases with ε (at an increasing rate) and that the marginal increase in probability of flooding, $\partial O/\partial\varepsilon$, decreases with t. These assumptions, along with an assumption of constant or diminishing marginal benefits of stored water, imply that the dam manager's threshold level increases as the season progresses. Depending on the timing of runoff, it is possible that this effect (of storing less water earlier in the season) could lead to less water available when the irrigation season begins under early runoff than under normal runoff.

The size of total storage capacity of the reservoir compared to annual irrigation obligations critically determines whether early snowmelt decreases irrigation deliveries in a single year. Consider a reservoir that has total storage capacity substantially greater than irrigation obligations, which is the case in our example referenced below. If there is a small amount of water stored when runoff begins, even if runoff occurs early, the optimal storage threshold would not be reached before irrigation started, and all of the runoff water could be used for later-season irrigation. If, instead, the reservoir was closer to capacity when runoff begins early, the manager would release much of the snowmelt runoff, but since the reservoir was close to capacity, which is greater than planned irrigation deliveries, irrigation obligations could be easily met.

If the total reservoir storage capacity is closer to total irrigation obligations, then early snowmelt would reach the optimal storage threshold early in the runoff season. Even if the quantity of water in the reservoir is relatively low when runoff begins, the manager would optimally hold a lower maximum quantity of water, meaning that something less than reservoir capacity would be held over for irrigation. If peak runoff occurs early in the runoff season, well before irrigation normally begins, and the manager is unable to hold much of that water, then it may not be possible to fulfill irrigation obligations in this case, depending on the relative size of those obligations to the runoff quantity. We assume that farmers are unable to adjust their growing seasons earlier to capture some of the released runoff water, although such an action may be possible if warmer temperatures allow farmers to anticipate early snowmelt. These adjustments would mitigate the costs of early snowmelt we estimate below.

In addition to the size of obligations relative to snowmelt quantity, early snowmelt may or may not result in reduced irrigation deliveries depending on the nature of the snowmelt and runoff. Reservoirs and watershed basins have different average runoff profiles that occur at different times in the year and over different periods of time, all of which affects the shape of the probability of flood function, O. As the decision rule for holding water in the reservoir depends on how the probability of flooding changes as the number of days to the irrigation season decreases and also depends on how the probability of flood changes as more water is stored, different flood probability functions will result in different quantities of water released with early snowmelt at different reservoirs. So, aside from the assumptions (stated above) that lead to the implication that the optimal threshold increases with time, t, we make no additional general assumptions about the shape of the function O.

2.1. Simulation model

Because the decisions to release and hold water under early snowmelt will be reservoir-specific, we create a simulation model of Ririe Reservoir, a small reservoir in southeastern Idaho that primarily provides flood control for the city of Idaho Falls. Ririe also stores irrigation water in a 'joint use' conservation storage and flood control pool for the greater Snake River project (recreation is not considered in our model, but Ririe is also used extensively for fishing and boating). The purpose of our simulation model is to determine the conditions, if any, under which early snowmelt leads to lowered irrigation deliveries. Ririe Reservoir impounds water from Willow Creek, a minor tributary of the Snake River. Willow Creek drains an area roughly 1500 km^2, 50% of which is at an elevation exceeding 1900 m above sea level. The reservoir has a total capacity of 99,300,000 m^3 available for flood control and irrigation, and the floodway system below the dam can carry flows up to 57 m^3/sec without causing flooding conditions downstream (US Bureau of Reclamation, 2012). Data for the period 1986 to 2011 from the US Geological Survey (USGS) suggest that snowmelt runoff exceeds this rate about once every 2.5 years. The same data also show that, while total capacity of Ririe Reservoir is just under 100 million m^3, average irrigation season deliveries are only 43 million m^3 – even in the heavier-than-average snow year of 2009, irrigation season deliveries only amounted to 55 million m^3 – putting Ririe in the category of reservoirs with irrigation obligations that represent only a fraction of total capacity.

We use streamflow data from USGS (from the stream gage on Willow Creek, just above Ririe Reservoir) to estimate the probability of flooding equation, O, for Ririe Reservoir. The probability of a flood is a function of two variables: the percentage of reservoir capacity filled and the number of days until the irrigation season begins (assuming that flood-level runoff always occurs before the start of irrigation). For a given percentage of capacity filled and a number of days until irrigation starts, the probability of a flood is the product[2] of the probability of the reservoir filling sometime before irrigation starts and the probability that a flood-quantity of water (i.e., more than 57 m^3/sec) enters the reservoir after that time. We estimate the probability of the reservoir filling a given amount of excess capacity in a given number of days by simulating 1600 10-day, 20-day, 30-day, 40-day and 50-day runoff scenarios, with initial capacity filled values between 85% and 99% of total available capacity. We use 10-day increments to simplify the calculation. The simulations are conducted by drawing N-day sequences randomly from the 25-year record of average daily streamflows during the runoff season (from March through May).

From these simulations, to determine the probability of flood in say, a 60-day period, with (100-ε)% of capacity remaining, we multiply the probability of the reservoir filling in 10 days (which is the number of observed simulations in which 10-day inflow exceeded [100-ε]% of capacity divided by 1600) by the probability that one flood would occur in the next 50 days, and add to that the product of the probability of filling in 20 days (but not 10 days, since the 10-day case is included in the 20-day case calculation) and the probability of a flood in the next 40 days and so on. Mathematically, we calculate

$$O(N,\varepsilon) = pr\left(\sum_{i=1}^{10} f_i \geq \frac{(100-\varepsilon)}{100} S_{\max}\right). pr(f_i \geq 57m^3/\sec).(N-10)$$

$$+\left[pr\left(\sum_{i=1}^{20} f_i \geq \frac{(100-\varepsilon)}{100} S_{\max}\right) - pr\left(\sum_{i=1}^{10} f_i \geq \frac{(100-\varepsilon)}{100} S_{\max}\right)\right]. pr(f_i \geq 57m^3/\sec).(N-20)$$

$$+\ldots+\left[pr\left(\sum_{i=1}^{N-10} f_i \geq \frac{(100-\varepsilon)}{100} S_{\max}\right) - pr\left(\sum_{i=1}^{N-20} f_i \geq \frac{(100-\varepsilon)}{100} S_{\max}\right)\right]. pr(f_i \geq 57m^3/\sec).10$$

for $N = 60, 50, \ldots, 10$ and $\varepsilon = 83, 84, \ldots, 100$; and where $S_{max} = 99{,}300{,}000$ m^3, and f_i is flow rate of incoming water on a given day (the probability of inflow being greater than 57 m^3 is 0.0038) – as stated above, the f_i are simulated by drawing randomly from the daily average streamflow history for this stream gage. This gives 108 combinations of days and capacities with their associated simulated probabilities of flood, O. From those simulated probabilities, we estimate the following function (in log form) using Ordinary Least Squares (OLS): $O(\varepsilon, t) = b_1(T-t)^{b_2}\,\varepsilon^{b_3}$ we adjust notation slightly here, so that t is now the day of the year, and T is the day of the year when irrigation starts, so that T-t is the number of days until the irrigation season begins.[3] Note that the assumptions we make in section 2 regarding the probability of flood function hold for any positive values for the parameters b_2 and b_3. Thus, the dam manager's decision rule to hold water, $MB/D = \partial O/\partial\varepsilon$, becomes

$$MB/D = b_3 b_1 (T-t)^{b_2}\,\varepsilon^{b_3-1} \quad (1)$$