FAIR ALLOCATION AND TRADING OF SURFACE WATER RIGHTS UNDER THE RIPARIAN DOCTRINE

BY

XUETAO HU

DISSERTATION

Submitted in partial fulfillment of the requirements
for the degree of Doctor of Philosophy in Environmental Engineering in Civil Engineering
in the Graduate College of the
University of Illinois at Urbana-Champaign, 2009

Urbana, Illinois

Doctoral Committee:

Professor J. Wayland Eheart, Chair
Assistant Professor Nicholas Brozović
Assistant Professor Ximing Cai
Associate Professor Praveen Kumar

ABSTRACT

One key water resource challenge that faces the eastern United States today is how to regulate water withdrawals by offstream users, while preserving the fair sharing philosophy of the common-law Riparian Doctrine. Traditionally, this doctrine requires that riparians (users owning land adjacent to a stream) limit their withdrawals to what can be judged as "reasonable use." Water allocation regulations are currently being formed amid emerging water competition, due to rapidly growing water demand and increasingly frequent water shortages.

The study reported in the present dissertation develops a new type of water allocation scheme called the Proportionally Fair (ProFair) Program, which stresses on the fair sharing of water among withdrawers. The ProFair program is based on the Proportional Fairness Criterion, which is originally developed for bandwidth allocation in electronic communication networks. Three different methods are developed to attain the proportionally fair allocation, namely a log-linear programming model, a quadratic programming model, and a greedy procedure called the 'Bottleneck Algorithm'. The performance of the ProFair program, both in terms of equity and economic efficiency, is compared with four alternative hypothetical regulatory programs which are rooted in three different regulatory principles: the Benefit Maximizing (MaxBen) program, based on the principle of maximizing economic benefit, the Downstream Priority (DPrio) and the Upstream Priority with Municipal and Industrial User Privilege (UMIPrio) programs, based on the principle of prioritization according to type of use and/or geographical location, and the No-Rule (NR) program, which represents the status quo in many eastern states, and which is based on the principle of minimal regulation. Mathematical models are developed for each water allocation program. Economic efficiency and equity are measured by aggregate net benefit and a measurement called the Equity Index, respectively. Following the primary allocation programs, this study further develops a trading model to simulate a water rights market under each of the alternative programs.

Water allocation and water market simulations under the five allocation programs are performed for the Sangamon River system in Illinois under two economic scenarios and various reservoir capacities over a 30-year period. The simulation results show that the ProFair program dominates all other programs in fairness, generating the highest equity index in any year under any condition. Although the ProFair program results in lower net benefit than the MaxBen and UMIPrio programs, its economic efficiency can be improved through a properly instituted water rights market with complete information and minimum transaction costs. The results also demonstrate that changing supply and demand conditions have significant impacts on benefit, fairness, and market activities of all programs. Based on those findings, the dissertation recommends that policy makers give more consideration to the proportionally fair allocation due to its consistency with the Riparian Doctrine.

To Dad

ACKNOWLEDGEMENTS

This project would not have been possible without the support of many people. Many thanks to my adviser, Dr. J. Wayland Eheart, who read my numerous revisions and helped make some sense of the confusion. Many thanks to my committee members, Drs. Nicolas Brozovic, Ximing Cai, and Praveen Kumar, who offered guidance and support. Also thanks to Dr. Gregory Characklis who provided valuable insights to the thesis. Thanks to the University of Illinois Graduate College the Abbot Laboratory for awarding me research fellowships and, providing me with the financial means to complete this project. And finally, great thanks to my wife, parents, and numerous friends who endured this long process with me, with unconditional support and love.

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LIST OF SYMBOLS

α	A coefficient in the M&I water use benefit function.
β	A coefficient in the M&I water use benefit function.
$\phi_{\boldsymbol{i}}$	Degree of water supply satisfaction of user i.
$\phi^{(k)}$	Incremental degree of water supply satisfaction achieved at the kth iteration of the Bottleneck Algorithm.
Φ_k	The water supply satisfaction finally found for the users in $S^{(k)}$
λ_i	Lagrange multiplier for constraint i.
ω_i	Weight for user i, reflecting the priority of user i.
$\boldsymbol{A}$	Water availability matrix.
$\boldsymbol{A^{(k)}}$	Water availability matrix associated with the remaining subsystem at the kth iteration of the Bottleneck Algorithm.
$\boldsymbol{A}_i$	The ith row of the water availability matrix.
B	Water use benefit.
B	Marginal water use benefit.
C_f	Fixed cost of irrigation.
$c_{t,i}$	Transaction cost for user i.
c_v	Variable cost of irrigation.
c_w	Marginal cost of M&I water use.
EI	Equity index.
$\boldsymbol{e}$	Vector of in-stream flow requirements.
G	Aggregate gain in net benefit of a water market.
GDD	Growing degree days.
$\boldsymbol{g}$	Vector of water gains in all zones.
$\boldsymbol{l}$	Vector of water losses in all zones.
$\boldsymbol{m}$	Water rights entitlement vector, consisting of the water rights entitlements of all users.
m_i	Water rights entitlement of user i.
NB_i	Net benefit function of user i, a function of x_i.

$p_{t,i}$	Direct purchase price for user *i*.
p_c	Price of crop.
$\boldsymbol{Q}$	Vector of streamflows at all control points before withdrawals take place.
$\boldsymbol{Q_a}$	Vector of available streamflows at all control points before withdrawals take place.
$\boldsymbol{Q_a^{(k)}}$	Available streamflow vector associated with the *k*th iteration of the Bottleneck Algorithm.
$\boldsymbol{q}$	Vector of local water inputs.
R	Total rainfall in the allocation window.
S	Set of all zones.
$S^{(k)}$	Set of users whose allocation is cleared by the *k*th iteration of the Bottleneck Algorithm.
$\boldsymbol{t}$	Vector of water transfer, consisting of the amounts of water transferred to and from all users.
t_i	Water bought or sold by user *i*.
T	Total revenue of a water market.
T_{max}, T_{min}	Maximum and minimum temperature of the day.
$U(i)$	Subsystem of zone i, defined as the set of all zones upstream of and including zone *i*.
w	Water withdrawal rate.
$\boldsymbol{x}$	Vector of water allocation, consisting of amounts of water allocated to all individual users.
$\boldsymbol{x^*}$	Solution to a certain water allocation mechanism.
$\boldsymbol{x_0}$	Vector of pre-market water allocation.
$\boldsymbol{x_{MB}}$	The benefit maximizing allocation.
x_i	Amount of water allocated to user *i*.
$x_{i,opt}$	Optimal withdrawal of user *i* when water is unlimitedly available.
Y	Yield of crop.

CHAPTER 1. INTRODUCTION

Over the past decades, the eastern portion of the United States, which has generally been considered humid and water-rich, has been experiencing growing water consumption and increasingly frequent water shortages. Expanding municipal and industrial demand, along with increasing use of supplemental irrigation, rapidly escalates consumptive water use (see e.g. Dziegielewski, 2002 for documentation of this for Illinois). Water competition and conflict are emerging in many heavily developed regions in the eastern states (Sansonetti and Quest, 2003). The recent increase in popularity of biofuels has furthered the trend by creating large additional water demands from both the raw material and end production processes of biofuel production (IATP, 2006; Aden, 2007). Meanwhile, water availability conditions are also changing. More stringent streamflow protection regulations are making the development of new water supply sources more difficult (Ruhl, 2003). The erratic drought patterns that have been observed in recent years as a possible impact of the global climate change (Gaffen and Ross, 1998; Manuel, 2008) are raising serious concerns about the sustainability of water supply in the future.

Traditionally, the eastern states have followed the common-law Riparian Doctrine in the allocation of surface water. The Riparian Doctrine protects a vaguely defined ‘reasonable use’ right of all users along the same waterway and requires them to share water with and avoid unnecessary injury to each other. Because of the lack of accurate language in the doctrine, the sharing of water becomes largely voluntary, which leads inevitably to the problem known as ‘Tragedy of the Commons’ (Hardin, 1968) as water demands approach or exceed supplies. With the growing water conflicts in the eastern states, the traditional common-law systems are being widely criticized for their lack of specificity, allowing for too little administrative intervention, and relying too heavily on protracted court rulings for conflict resolution.

The growing needs for better water allocation management have pushed some eastern states to transform their traditional Riparian water laws toward a comprehensive body of more proactive and less ambiguous administrative statutes. At the core of these statutes is a permit system that requires qualified withdrawers to acquire a precisely defined water permit. While codifying the withdrawal regulations, most eastern states preserve the Riparian Doctrine as the legal foundation. The term ‘Regulated Riparianism’ has been given to these emerging new water law systems to emphasize their ties with both the common-law tradition and the recent statutory buildup.

An effectively functioning water permit system needs a sound approach to quantify each user’s withdrawal limit. For that purpose, two approaches have emerged, the fixed permits and the flexible permits. The fixed permit approach, which has so far gained some popularity in the eastern states (see e.g. Maryland Department of the Environment, 2008, Minnesota Department of Natural Resources, 2006, Northwest Florida Water Management District, 1998, etc.), defines for each user a fixed maximum withdrawal rate in a given period of the year. A permit may be subject to multiple withdrawal limits for different seasons. This approach takes little, if any, consideration of the fluctuation of water availability, and hence must be coupled with some sort of priority arrangement in order to mitigate possible water conflicts during times of drought. The priority system can be either time-based, like those established in the western states, or type-based, as have been favored by the majority of eastern states. But no matter which type of priority is chosen, the basic idea is to protect the benefit of those who rank high on the priority list at the cost of those who rank low. The time-based priority is apparently in contradiction with the reasonable use theory of the Riparian Doctrine, and, as a result, has not been successfully adopted by any eastern state. The type-based priority system, although seemingly consistent with the preference approach recognized by the Riparian Doctrine, finds its specifics a frequent matter of debate (see e.g. Butler, 1986). Moreover, the type-based priority cannot address the apportionment among users of the same type. Thus, the fixed permit approach leaves a number of legal uncertainties remaining to be addressed.

As its name suggests, the flexible permit approach allows each user's withdrawal limit to vary according to the current hydrologic conditions. One typical example of the flexible permit is the fractional flow permit (Eheart and Lyon, 1983; Eheart, 2002), which allows users along a common waterway to each withdrawal a predetermined portion of the streamflow. Thus, the users' allowable withdrawals all increase proportionally as the streamflow increases, and *vice versa*. This *pro rata* approach has a number of advantages. First, it does not need a coupled priority arrangement to resolve water conflicts, since the damage of water shortage is shared by all. Second, its emphasis on sharing is in perfect agreement with the Riparian Doctrine. Thus, there are fewer legal hurdles for the adoption of this approach in the Eastern States compared to the fixed permit approach.

However, this intuitively straightforward and legally justifiable approach has rarely been exercised on a large scale by regulators in the eastern states. Neither has it been seriously discussed in the water allocation literature, except for a small number of in-depth studies (Eheart and Lyon, 1983; Wong and Eheart, 1983; Harrison, 1991; An, 2004; An and Eheart, 2006). One important reason for the lack of interest in this approach is that the fractional flow permit program, which has so far been examined only in single-gage systems, does not appear to have the capability of determining the allocation in a more complicated real-world system, which often involves multiple gages, multiple tributaries, and scattered users. With the existing fractional flow equations, it is not clear which gage or combination of gages should be referenced to calculate the withdrawal of a particular user, and at what fraction.

It becomes clear that there needs to be a new type of fractional flow approach, which can be used to determine the allocation in a geometrically complicated water allocation system. Thus, to develop such an approach becomes one of the objectives, and a significant contribution, of this dissertation.

Recent research on bandwidth allocation in electronic communication network has shed some light on this task. Kelley and his colleagues (Kelley, 1997; Kelley et al., 1998) found a mathematical model that can achieve a so-called Proportionally Fair allocation for an electronic communication network with dynamic bandwidth. This study shows that, using several different models or algorithms, this Proportionally Fair allocation can also be produced in a distributed water allocation network, the structure of which can be viewed as a specific type of communication network. The fractional flow program is just a special case of the Proportionally Fair allocation when the system has only one reference gage.

The second objective of this dissertation is to examine how the Proportionally Fair allocation compares to four alternative allocation mechanisms. These alternative allocation mechanisms are selected based on three different water allocation principles. They are 1) the Benefit Maximizing allocation, based on the principle of economic maximization; 2) the Downstream Priority allocation and 3) the Upstream Priority allocation with municipal and industrial user privilege, based on the principle of prioritization; and 4) the No-Rule allocation, based on the principle of minimum regulation. A mathematical model will be developed to simulate each of these mechanisms.

All five allocation mechanisms will be evaluated based not only on their economic performance, but also on their fairness. Fairness is characterized quantitatively by an Equity Index, which is developed to measure the level of uniformity in the water supply satisfaction levels among users.

The third objective of this dissertation is to investigate the behavior and potential outcome of a water rights market when combined with the above primary water allocation programs. Water rights markets have been implemented and proved to be beneficial in many western states. In recent years, water markets have been increasingly discussed in the context of the eastern US. It is widely believed that a properly instituted water rights market can improve water use efficiency and create considerable economic benefit by allowing water to be transferred from low-value to high-value uses. For a flexible permit program, a water market can not only improve economic efficiency, but also help address another shortcoming of the flexible permit program: the lack of certainty. For users who are also water infrastructure investors and who may be concerned about whether the flexible permit program can sustain a profitable withdrawal, a water market can offer them a viable alternative means to secure their water supply in times of shortage.

This dissertation develops a mathematical model to simulate the water rights market under each of the selected programs. The form of water market that is of primary concern in the present dissertation is a ‘spot market’, where water rights are transferred on a short-term basis to meet immediate needs. Based on the model, this dissertation will further present an analytical framework that can be used to examine several characteristics of a spot market, such as the volumes of water transferred, prices at which water is transferred, transaction revenues, and net market gains.

The Sangamon River watershed in Illinois is chosen as a case study, to perform water allocation and water market simulations under the five allocation programs. The simulation will be performed based on two scenarios: the ‘Current’ scenario based on a mixture of real and hypothesized water demands and economic conditions in 2006, and the Future scenario based on projected water demands and economic conditions in 2030. Historical rainfall and streamflow data from 1977 through 2006 combined with a series of different reservoir storage conditions are used as hydrologic input for the analysis. The monetary results are all converted to the 2006 dollar.

The dissertation is organized as follows. Following this Introduction chapter, Chapter 2 gives a brief literature review of the water laws and relevant water allocation studies in the eastern US. Chapter 3 documents the efforts to develop mathematical models for the selected water allocation programs and the water market. Chapter 4 describes the setup for water allocation and market simulation in the Sangamon River watershed. Data utilized and assumptions adopted are presented and discussed. Chapter 5 presents the major results obtained from the simulation. Finally, chapter 6 concludes the dissertation, makes recommendations, and points out the possible directions for future studies.

CHAPTER 2. LITERATURE REVIEW

2.1 Emerging Water Shortages in Eastern US

Historically, the Eastern United States, often defined as the 31 states to the east of the 100th Meridian, has enjoyed abundant rainfall. People living in these states have considered water to be readily available at little or no cost. Over the past several decades, however, many eastern states have witnessed rapid growth in water consumption coupled with occasional water shortages and increase in water conflicts. Continuous population growth and economic development, enhanced legislation for in-stream flow protection, and emerging concerns with erratic drought patterns linked to climate change are combining to place increasing pressure on the already stressed water resources.

Analysis of water use trends in the US (Dziegielewski et al., 2002) shows that the water withdrawal for public supply and rural domestic use has been rising continuously in the eastern US from 1960 to 1995. This growth has coincided with the nationwide increase in total population and family income. A recent survey (US General Accounting Office, 2003) carried out in 47 states showed that due to population growth and insufficient water facilities, water managers in 36 of the states, many in the East, expect water shortages at state, regional, or local level even under average water conditions in the following decade.

The latest surge of ethanol production in the early 21st century has raised new water resource concerns, especially in the Midwestern States, such as Iowa, Illinois, Minnesota, and Indiana, which host more than half of the existing and potential ethanol plants in the US. In 2006, about 6.5 billion gallons (24.6×10^6 m^3) of ethanol were produced, nearly 3 times as much as in 2002 (RFA, 2008). As of 2008, the total ethanol production capacity in US has reached 13.6 billion gallons (51.5×10^6 m^3) per year, with another 3.8 billion gallons (14.3×10^6 m^3) under expansion (RFA, 2008). Given the US biofuel production goal of 36 billion gallon (136.3×10^6 m^3) by 2022 (Tyner, 2008) and estimated 3 to 6 units of water required for the production of per unit corn ethanol, it is predicted that water withdrawal by the ethanol industry will continue to increase substantially in the Midwest, enhancing the existing water competitions in the region (IATP, 2006).

Meanwhile, concerns have emerged that high food price, partly driven by rising energy cost and the growing demand for corn for ethanol production, may attract more and more farmers to adopt irrigation technology to ensure good yield. These farmers have relied traditionally on rain-fed land. Starting from early 2006, corn price went from an average of $87 per metric ton up to $217 per metric ton ($2.2 to $5.5 per bushel) in two years (Tyner, 2008), at times topping $300 per metric ton. Meanwhile, prices of other crops, such as soybeans and wheat, have been growing at a similar rate, according to the Chicago Board of Trade (www.cbot.com). Many eastern states have experienced a steady increase in irrigated farmland in the past decades. Some Midwestern states, such as Wisconsin, Indiana, Illinois, etc., have seen an increase in irrigation water use of more than 500% between 1960 and 1995 (Dziegielewski et al., 2002). In the Southeast, frequently occurring droughts in the past decades have intensified the interest in supplement irrigation, resulting in a steady growth of irrigated farmland (Cassel et al., 1985). A recent modeling study in Illinois (Eheart and Tornil, 1999) has shown that basin-wide irrigation practice may substantially diminish streamflow during drought periods.

Recent studies suggest that climate change is likely to stress water supply in the eastern US. It is observed that the eastern US has been under a significant upward trend in the frequency of extreme heat stress event in the past half century (Gaffen and Ross, 1998). This observation is consistent with a number of modeling studies (Delworth, et al., 1999; Gregory et al., 1997; Meehl et al., 2000), which predict that the combination of increased temperature and evaporation will likely raise temperature and the risk of drought in the southeastern US. Scientists from the US Climate Change Science Program also suggest that in a future climate there is an increased likelihood of more intense, longer-lasting and more frequent heat waves, which could aggravate the extremes of dry conditions in the Southeast, even though these events are interspersed with an increasing number of floods (CCSP, 2008). In recent years, that area has seen increasingly frequent severe droughts (Karl and Young, 1987; Manuel, 2008). The recent droughts in 2001, 2005, and 2007 have caused unprecedented drops in streamflow and levels of water supply reservoirs (see e.g. US Army Corps of Engineers, 2008), leaving several municipal areas, such as Atlanta, Georgia, Raleigh, North Carolina, and Southern Florida at times with only weeks or even days of water supply (Manuel, 2008; Fletcher, 2002).

Increasing legislation over in-stream flow protection and minimum water level has also posed additional limits on water supply in many eastern states. As of 1995, 23 eastern states have established minimum flow standard to ensure there is adequate water to protect the stream environment (Foran et al., 1995). Reservoirs in these states are mandated to comply with minimum release standards for aquatic habitat protection during a dry period. In order to protect the level of the Great Lakes, the eight Great Lake states are subject to firm restrictions under the Great Lakes Basin Compact on the amount of water each of them can divert from the lakes. As a result, heavily populated areas around the Great Lakes, such as Chicago, have to seek additional water supply sources from ground water and inland streams to meet their ever growing demands (Illinois Department of Natural Resources, 2004; Campaign for Sensible Growth, et al., 2005).

The interaction of growing demand and shrinking supply has sharpened the water conflict in the East over the past decades. There have been growing number of intra- and inter-state water disputes in the East on a scale that has traditionally only been seen in the western states (Dellapenna, 2007). Such conflicts widely occur between various interest groups, such as agriculture and municipalities (Gold et al., 1988; Norris, 2001; Thomas et al., 2003; MacDonnell and Rice, 1995), large cites and their neighboring communities (Chew et al., 2006; Schicht et al., 1976), as well as states sharing the same watercourse (Ruhl, 2005; Cox, 2007; Jordan, Jones and Goulding, Inc., 2003; Lipford, 2004; Sherk, 1994).

In her latest book, *Mirage: Florida and the Vanishing Water of the Eastern U.S.* (2007), Cynthia Barnett wrote:

> A century ago, Floridians thought their biggest problem was too much water where people wanted to settle. Now, our biggest problem is that we do not have enough water where people want to settle.

Florida is typical of many eastern states which have experienced heavy urbanization, fast economic boom, as well as emerging water crises in the 20th century. Today, the eastern states of the US are facing the water challenges that used to be seen only in the water-short West (Gould, 2002). Tackling the growing water shortages and water competitions will continue to be a challenging task that requires comprehensive and innovative efforts.

2.2 The Riparian Doctrine and Evolution of Eastern Water Laws in the 20th Century

2.2.1 The Common Law Riparian Doctrine

In terms of water rights, there are two distinctively different categories of legal doctrines being followed in the United States. The eastern portion of the country, consisting of the 31 states east of Kansas City, generally embraces the Riparian Doctrine, which traditionally treats natural water as a common property. The western portion of the US, consisting of the states west of Kansas City, generally follows the Prior Appropriation Doctrine, which recognizes private ownership of water rights.

It is believed that the Riparian Doctrine is rooted in English Common Law. The doctrine was first introduced to the US through the case *Tyler v. Wilkinson* (1827) (Tarlock, 2002; Tarlock et al., 2002). The core concept of the Riparian Doctrine is that every riparian land owner has an equal right to *reasonable use* of the water in the watercourse abutting his or her land. The right is tied to the land and can neither be transferred from riparian land owners to non-riparian land owners, nor be lost through non-use. The word riparian is derived from the Latin word "*ripa*", which means river bank (Tarlock, 2002).

The Riparian Doctrine is based on the premise that water is abundantly available, an assumption that was generally true throughout most of the history of the eastern US. Historically, the Riparian Doctrine used to require that no use should alter the natural flow of the watercourse (Sherk, 1990; Scott and Coustalin, 1995). Under the modern understanding of the doctrine, however, each riparian owner can make any use of water, regardless of the impacts the use has to streamflow, as long as each user does not injure other riparians' reasonable uses (Dellapenna, 1998).

In contrast, many parts of the water-short western US follow a distinctively different water rights approach. Although some western states recognize limited riparian rights (especially on streams whose watersheds lie entirely within a single state's borders), most western states rely on the Prior Appropriation Doctrine, which recognizes unequal water rights based on the principle of 'first in time, first in right'. Established in the Gold Rush era in the mid 19th century, this principle gives the highest withdrawal priority to the earliest permit registrants who claim their uses to be *beneficial*, regardless of their location and distance from watercourses. When drought occurs, water rights are curtailed in the order of their juniority and the most senior users receive the highest protection. Based on this basic principle, many western states have developed sophisticated regulatory systems, which, by clearly defining each user's withdrawal permit and priority, provide effective mechanisms for allocating water among competing users. As noted above, water rights administration in the western US relies on a mixture of the Riparian and appropriative doctrine. Some western states, such as California and Texas, have developed a 'dual system', which recognizes both prior appropriation and riparian rights.

For over a century following *Tyler*, the eastern states stuck closely to the reasonable-use version of the Riparian Doctrine and made little change to their common law water rights (Scott and Coustalin, 1995). It is simply uneconomical for a water-rich state to maintain a comprehensive water rights system (Butler, 1985; Foran et al., 1995). However, critics of the traditional Riparianism have emerged throughout the 20th century in the face of more frequently recurring water deficiency and growing demand for better water allocation management. The most frequently cited problem with the traditional common law system is that its poorly defined reasonable-use theory fails to provide the certainty that is needed for an effective water allocation management. The Riparian Doctrine allows riparian land owners along the same watercourse to share the water, but is not able clearly to specify the size of each owner’s share. Without such quantitative definition, the regulators have limited enforcement power to regulate water withdrawals, especially when water competition exists. In practice, users have to rely on costly and protracted legal procedures to settle water disputes arising from drought situations.

The uncertain nature of the riparian water rights encourages selfish behavior among water users, which, as pointed out by several commentators (Dellapenna, 1998; Foran, 1995; Sherk, 1990), leads inevitably to a problem known as the ‘Tragedy of the Commons’ (Hardin, 1968). Without a quantitative standard, the users are left to their individual judgments on how much water to use. Such a situation is unlikely to cause serious consequence as long as there is always excessive water running in the stream. As a shortage emerges, however, each user’s economic interest would be best served by maximizing his or her own withdrawal before everybody else behaves in the same way to deplete the shared resource. When numerous individuals follow the same greedy behavior, the resource will inevitably be exhausted, and to worse effect than if one entity owned all the water and the water-using facilities. Lacking an effective regulatory mechanism to control water withdrawals, the common law system can hardly prevent such a tragedy from happening. It can neither protect the stream from being destroyed, nor assure individuals’ water rights not to be injured by others.

As growing demand creates ever greater stress on water resources in the eastern states, there is a clearer need for a new Riparian system which can provide a more appropriate definition of individual water rights and a more effective mechanism for water allocation management than the traditional common law system.

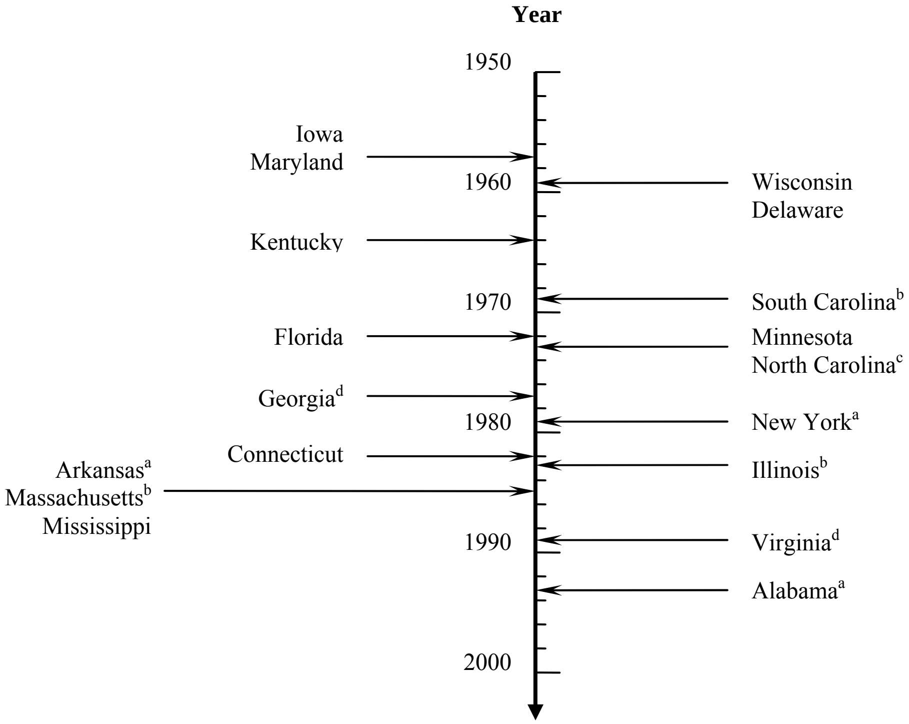
2.2.2 Riparian Water Laws in the 20th Century

In response to the inadequacies of the traditional Riparian Doctrine, the eastern states of the United States have taken different approaches to improve their water laws. Some earlier efforts attempted fully or partially to replace the common law system with the western-style appropriative water rights system. Due to the hardship in dealing with the existing ownership of riparian rights, the legislatures who want to establish appropriative rights in the traditional common-law states can at best develop a dual system, which inherits existing riparian rights as the earliest appropriative rights (ASCE, 2004). Such system has been created in some western states, such as California and Texas. Although favored by numerous scholars (e.g. Milliman, 1959; Trelease, 1977; Gould, 2002), this approach has however not been successful in the eastern states. Mississippi is the first and only eastern state that has formally introduced the prior-use doctrine to their existing riparian system, but the reform was unsuccessful. The state adopted a dual system in 1955, but repealed it later in 1985. During the 30 years, the appropriative doctrine was never cited by any court in the state, although numerous water disputes occurred in that period (Dellapenna, 1998; Dellapenna, 2002).

Dellapenna (2002) discusses the reasons for the failure of the western-style water rights in Mississippi. He reasons that under the dual system, where pre-existing riparian rights enjoy superiority over appropriative rights, users have little incentive to claim appropriative rights, because neither riparians nor non-riparians would benefit from doing so in terms of better securing their withdrawals. He further points out that the benefit-cost ineffectiveness of the approach reflected in the Mississippi experience is a strong reason for the eastern states to reject the appropriative doctrine as practiced in the West, even without considering the other shortcomings of the approach.

Instead of adopting the Prior Appropriation Doctrine, some eastern states have started to develop a new legal system for water allocation, which can be best described as a comprehensive statutory system of water administration. The new system borrows some features from western water rights, but preserves the basic principles of the Riparian Doctrine. Such a system is frequently referred to as ‘regulated riparianism’ (Dellapenna, 1998; ASCE, 1997; ASCE, 2004; Beck, 2000; Tarlock, 2006; Miano and Crane, 2003).

Dellapenna (1998 and 2002) views regulated riparianism as fundamentally different from the traditional common law riparianism. Regulated riparianism does not assume a vested water right attached to any land, riparian or non-riparian. Rather, with few exceptions, it allows no water to be withdrawn without a proved permit with clearly specified quantity (whether conditioned on current streamflows or not) and an effective period. In determining the permit, regulated riparianism inherited the reasonable use theory from the traditional Riparian Doctrine. But instead of using the reasonable use rules in judicial processes to review existing uses, as has been done traditionally under the common-law system, the regulated riparian system determines the reasonableness of a water use through an administrative agency prior to the start of the withdrawal. Moreover, the regulated riparian statutes abandon common law restrictions on the location of use and treat riparian and non-riparian permits equally. Furthermore, to enforce the permits, the statutes enable state administrations to use police power to enforce withdrawal rules. Based on the above characterization, Dellapenna (in ASCE, 2004) identified the states that have already established a regulated riparian system (Figure 2.1).



a. Less completely developed or implemented than for other regulated riparian states.
b. Permits required for the Lake Michigan basin and ground water only.
c. Applicable to critical management areas only.
d. Date refers to the adoption of regulation for surface water.

Figure 2.1 Timeline for the adoption of a regulated riparian system by eastern states of US (modified from Dellapenna, 2004).

Not all eastern states have developed a highly regulated water rights system. Some states, such as Louisiana, West Virginia and the part of Illinois outside the Lake Michigan basin, are still largely following the traditional common law system. Some others, such as Tennessee and Ohio, only require registration of use. Even in the states listed in Figure 2.1, the regulation may not be applicable state-wide or to all types of water. Nevertheless, studies on the modern history of eastern water laws have all concluded that the trend in the eastern water law is moving toward a more comprehensive, permit-based statutory legislation (Ausness, 1983; Foran et al., 1995; Sherk, 1990; Dellapenna, 2002; Abrams, 1989).

Recently, the American Society of Civil Engineers (ASCE) published the Regulated Riparian Model Water Code (ASCE, 1997; ASCE, 2004). The model code embodies the characteristics of regulated riparianism and provides legislative guidance for state legislatures who want to improve their water allocation regulations in order to meet the challenge of ever growing water competitions.

The regulated riparian water laws imbue the state administration with greater power to design and implement a wide variety of regulatory instruments, such as permitting systems, enforcement mechanisms, short- and long-term planning, drought emergency action plans, and so on. As a result, the system largely avoids the costly and time-consuming legal processes under the traditional common-law system and therefore provides substantially higher efficiency and certainty. It also creates opportunities for the emergence of new and innovative water allocation mechanisms.

2.3 Equitable Flow Sharing under the Provision of Regulated Riparianism

A permit system requires a quantitative approach to determine the upper limit of each user's withdrawal. For uses of surface water, two approaches have emerged: the fixed permit program and the flexible permit program. The fixed permit system, which has gained popularity in both eastern and western states, regulates withdrawals by issuing each user a permit of fixed maximum withdrawal rate (e.g., m^3/s) without considering the fluctuation of water availability. During its effective period, a fixed permit allows its owner to withdraw the water available to him or her up to a maximum of the amount specified by the permit. On the other hand, the flexible permit system, which has not been widely adopted but has a number of promising features, controls withdrawal based on a floating limit and allows users to increase and decrease their withdrawals according to *ad hoc* hydrological conditions. One typical example of the flexible permit is the fractional flow system (Eheart and Lyon, 1983; Eheart, 2002), which allows each user to withdraw a constant percentage of local streamflow. When streamflow fluctuates, the allowable withdrawals of the users sharing the same watercourse change accordingly.

Both fixed and flexible permit systems are faced with the issue of how to curtail withdrawals in times of drought when available water is insufficient to meet all permitted demands. To address this problem, the fixed permit program is often implemented in conjunction with a priority system. When a shortage occurs, permits with the lowest priority are suspended temporarily to protect permits with higher priority. As the shortage progresses more deeply, more and more permits are stopped in the reverse order of priority. In the western US, the temporal priority system based on the 'first in time, first in right' theory under the appropriative water rights has long existed. Such a system can protect the users with grandfathered water rights against junior permit holders. In the eastern US, on the other hand, the type-based priority system derived from the reasonable use theory of the Riparian Doctrine has been adopted by most of the regulated riparian states. Typically, domestic uses are protected with the highest priority, while luxury uses, such as recreational and aesthetic are often the first to be restricted in response to drought.

The type based priority system cannot fully address the problem of drought emergency allocation. It is not capable of apportioning the water when the competing users are of the same type, e.g. farmers counting on a shared river to irrigate their lands. In addition, it is argued that the type based priority system may cause political and economic controversy (Trelease, 1974). In that case, a flexible system which requires users to share equitably the burden of a shortage seems to constitute a better solution. When water is insufficient to meet total demand, all users are mandated to reduce individual withdrawals based on pre-specified rules. No one would have a privileged exemption, nor would any one be entirely deprived of water rights to protect others.

The idea of equitable flow sharing has been long rooted in the history of the common law Riparian Doctrine, which emphasizes equal rights and demands sharing among users when damage is present. Based on the reasonable use theory, a riparian must be conscious of the common right of other riparians located above and below his property and should avoid interfering with their water rights in exercising his own (Butler, 1985). In *Harris v. Brooks*, which took place in 1955 in Arkansas, the court found that all lawful uses of water other than strictly domestic use are equal. When one lawful use of water interferes with another equally lawful use, a solution requiring both parties to make a reasonable and equitable adjustment to their withdrawals should be considered (Gould, 2002).

A logically sound and technically simple approach, *pro rata* sharing has been favored by the court in numerous historical cases. For example, in the landmark-setting case, *Evans v. Merriweather* (1842), the Illinois Supreme Court established the concept of *just proportion* (see Mann and Krausz, 1964; Clark, 1985). In that case, two mills located along the same stream disputed over water use during a dry summer. The court held that all riparian proprietors have a right to participate in the benefits of the water not needed to supply natural wants, but none has a right to use all of it. The court further ruled that:

> "Where all have a right to participate in a common benefit (artificial wants), and none can have an exclusive enjoyment, no rule, from the very nature of the case, can be laid down, as to how much each may use without infringing upon the right of others. In such cases, the question must be left to the judgment of the jury, whether the party complained of has used, under all circumstances, more than his just proportion."

Note that by use of the phrase "just proportion, " rather than "equal proportion," the court left the door open to proportional allocations prioritized by type of use. In a later case in Illinois, *Bliss v. Kennedy* (1867), the court exercised the principles from *Evans* and ruled that the flow shall be divided between the two parties in proportion to their respective requirements (Mann and Krausz, 1964; Clark et al., 1976; Clark, 1985).

Even in the Appropriative western states, proportional sharing among irrigators has been widely practiced, especially within irrigation districts. According to Gould and Grant (2002), some western irrigation districts which take water wholesale and retail water to irrigators require their customers to share shortage on *pro rata* basis when stream flow or storage is insufficient to supply in full the districts appropriation. In several water rights law suits, the courts allocated fixed proportions of water to each of the affected riparian irrigators, although the basis for determining the proportions varied from case to case.

The new era of the regulated riparianism creates opportunities for the invention of a variety of flexible permit mechanisms under the statutory provisions. Dellapenna (2004) suggested that a well-designed regulated riparian system would bring within its scope all significant water users and it will treat them all equally in terms of the criteria within the statute. Grigg (1996) pointed out the needs by the eastern states relying on administrative permitting to develop a system of curtailing uses when water is short so that the loss could be fairly shared.

Lipford (2004) proposed a *pro rata* approach involving the oversight of the Army Corps of Engineers to solving the drought-introduced conflicts. Based on his design, the Army Corps of Engineers could first establish a daily “water budget,” consisting of the total net withdrawals allowed from the basin, based on average daily withdrawals from some past period of consumption. After this global budget is established, the Army Corps of Engineers could grant water allocations to each user based on average daily use, again from some period of past consumption. When the supply of rainfall was abundant, so that water in the basin exceeded the global daily budget, all users could be satisfied without the need to limit anyone’s withdrawal. However, in the case of drought, the Army Corps of Engineers could cut daily permit allowances by an equal percentage for all users.

In 2002, ASCE published *Riparian Water Regulation* (Eheart, 2002), which provides a useful guide to developing a flexible permit system under the provision of regulated riparian statutes. Specifically, the document elaborates the algorithm for the fractional permitting system and comments that the system is more consistent with the

Riparian Doctrine’s fundamental concept of sharing water than a priority based permit system. Further, the system saves the administrative efforts of determining the priority for each individual user. No user is ever entirely deprived of water as long as the flow in the river does not go below the minimum flow standard.

Several studies have demonstrated the advantages of the fractional flow approach in terms of economic benefit, administrative convenience and protection of stream ecosystems. Burness and Quirk (1979) and Wong and Eheart (1983) show, using economic models, that an equal sharing system produces a higher value of output than an appropriative system under every possible streamflow condition. Their mathematical deduction further suggests that a free market built upon an appropriative system would ultimately produce an equilibrium that resembles the equal sharing allocation. Recent studies (An and Eheart, 2006; An et al., 2004; An, 2004) conducted based on a Illinois watershed show that the fractional flow permit program that controls withdrawal based on flows measured at a downstream gage would require less regulatory operation and cause less ecologically damaging flow interruption than a fixed-flow permit program.

To date, most publications envisioning the fractional flow permit program, especially those involving quantitative modeling, tie the allowable withdrawals to readings at a single gage. Even most of the irrigation districts using proportional sharing under the Appropriative doctrine draw water from a single point of the river, thus tying the amount of water they have to distribute to that single point, whether gauged or not. This program needs to be modified to deal with a multiple gage system. Eheart and Lyon (1983) introduced an algorithm to extend the fractional flow permit to a multi-gage system. The algorithm, demonstrated by the authors through a single hypothetical case, determines the users' allowable withdrawals based on pre-defined individual fractional permits, the flow measured at the outlet of the stream, and the spatial distribution of water availability within the watershed. The authors, however, did not give a generalized procedure for the algorithm to be applied under any condition. Mathematical formulations for the algorithm were also not provided.

Harrison (1991) proposed a so-called New Riparian program, which can achieve equitable flow sharing among users in a lotic system (which here means one in which, in contrast to a lentic system, water cannot naturally flow in an upstream direction to meet allocations). The core of the program is an algorithm which determines the allocation through a series of proportional dividing operations. The program does not explicitly define a fraction for each user. Instead, the program uses a feature of all users (optimal economic benefit in his case) as the common ground for the proportional dividing operations. Hence, the actual fraction each user can take from the local stream is not a constant, but rather a function of the spatial distribution of both water supply and demand. Harrison's program is a more generalized flexible water rights system than the single-gage fractional flow permitting. It is equivalent to the single-gage fractional flow sharing only when the system is constrained only by the most downstream gage.

Another approach to flexible permit programs for a lotic system is to tie the allowable withdrawals to the local flow measurements at one or more upstream and/or downstream points. Harrison (1991) introduced a program called 'Function of Local Streamflow', which calculates users' allowable withdrawals as a prescrbed function of the streamflows measured just upstream of their withdrawal points. The study shows the feasibility of the program based on economic, fairness, and practical criteria. In a water allocation study conducted of an agricultural watershed in Illinois, Wollmuth and Eheart (2000) also showed that a program tying withdrawals to streamflow measured at a downstream gauge could provide higher economic efficiency than that achieved in the absence of any withdrawal regulation.

2.4 Market for Tradable Withdrawal Permit under Regulated Riparianism

As a theoretically attractive and practically sound mechanism for water allocation, market-based transfer of water rights has been widely studied for decades (see, e.g., Anderson and Hill, 1997). Many believe that water markets can provide opportunities to transfer water from low-value to high-value uses, creating a win-win outcome for both the sellers and buyers. As a result, water rights transfer will increase the aggregate social net benefit. At the same time, however, existing discussions also point out that the establishment of water markets is often hindered by issues associated with high transaction costs and externalities (often referred to as third-party impacts). The strengths and weaknesses of water markets have been extensively discussed in the existing literature (Dinar et al., 1997; Lund and Israel, 1995; Brajer et al., 1989; Howe et al., 1986; Dellapenna, 2000).

The Riparian Doctrine has long been criticized for obstructing the transfer of water rights (Milliman, 1959). The common law system and the restriction thereof on the location of water uses create a major legal barrier to such transfers. Even without such restriction, the poorly defined water rights under the reasonable use theory would make it extremely difficult, if not impossible, to form a water market and a pricing mechanism. Historically, water transfers from riparian land to nonriparian land have happened occasionally in the traditional common-law states as a result of the balance of interests by the courts (Butler, 1985; Tarlock, 2002). However, it is unclear how much the buyers can actually benefit in such transactions. Some courts have concluded that the buyer obtains no rights against riparians other than the seller (Dellapenna, 2002). In other words, the transaction creates for the buyer a privilege only against the seller, but not any other riparian right holder.

Market transfer of water rights has been widely practiced in the western states of the United States for decades. In the East, the rapid growth of new water demands and emergence of regulated riparianism have created opportunities for institutional reforms in favor of market transfer of water rights. Regulated riparianism provides clear definition to a withdrawal permit, which makes it possible to reallocate the permit if a better use exists, and thus, to define a marketable commodity. This approach also imposes no restrictions on the location of permits, and therefore reduces barriers confronting nonriparian uses under the traditional Riparian Doctrine, thus providing greater security than traditional riparianism (Gould, 1998).

To reflect the emerging needs for water rights transfers, the Regulated Riparian Model Water Code charges the administering agency to encourage permit transfers (Dellapenna, 1997; ASCE, 2004) among permit holders. The publication *Riparian Water Regulation* (Eheart, 2002) further provides detailed guidance on the regulatory procedures for the management of water transfer activities. As of 1998, 18 of the 31 eastern states had known regulations to manage intra- and inter-basin water transfers (Flood and Wright, 1998).

It should, however, be noted that although regulated riparianism appears to provide great opportunities for water market development, it is not without problem.

Gould (1998) points out that the bureaucracies involved in and the temporal limitations imposed on the permits under regulated riparianism may create barriers to the development of an effective water market. Dellapenna (2000, 2004) even argues that the 'public good' property of water makes it very difficult, if not impossible, to create a true water rights market under a regulated riparian system.

As the academic community is still debating the feasibility of water rights market in the traditionally riparian states, a water rights market as a practical means of water reallocation has taken place in several eastern states. In Georgia, for example, there now exist both wholesale and retail water markets (Isley and Middleton, 2003). Both interbasin and intrabasin water transfers have been considered in Georgia's future water resource planning (Georgia State Water Council, 2007). In North Carolina and Florida, water transactions through informal markets between small agricultural users or land developers have been observed (See *http://sogweb.sog.unc.edu/Water/index.php/Water_market*).

The benefit of a water market in the context of the eastern states has been illustrated by a small number of modeling studies. Wong and Eheart (1983) show, through a case study in an agricultural watershed in Illinois, that a system with marketable water rights permits can capture about 95% of the optimal economic value of the water allocation system, while two alternative systems with non-marketable permits captured only 84% and 53% of the optimal value, respectively. An (2004) simulated water transfer through a perfect market for single-gage, multiple-user agricultural water allocation system. The study shows that whether the initial allocation is made by the fixed-flow permit system or the fractional-flow permit system, the free market based reallocation would make small but consistent improvement in the aggregate net benefit. Saleth et al. (1991) discover that the choice of bargaining rules is important in a thin (less than 20 players) spot water market under a riparian rights permit system. Their simulation suggests that appropriate design of bargaining rules can affect players' bargaining strategy and reduce social efficiency loss due to the thinness of the water market. In general Saleth et al. (1991) confirm the findings of many of the other investigators cited above, which is that centralized markets, with good communication among potential buyers and sellers, result in greater efficiency of allocation of water rights than do isolated two-party trades.

Nowadays, economic development in the eastern states keeps creating spatial and temporal disparity between water demand and supply. There needs to be a system that allows for the reasonable transfer of water rights to bridge the gaps between supply and demand in order to maintain a sustainable economic growth. Despite the philosophical, practical, and legal obstacles to water marketing, water rights markets are expected to grow in the traditionally water-rich states in the 21st Century (Huffman, 2004; Neuman, 2004).

CHAPTER 3. WATER ALLOCATION MECHANISMS AND THE MODELS THAT SIMULATE THEM

A water allocation mechanism is a set of rules that determines how water from all available sources is distributed among withdrawers in order to achieve one or more economic, social, and/or environmental goals. A water allocation mechanism can be implemented through certain policy program executed by a water authority. Throughout this thesis, the terms ‘mechanism’ and ‘program’ are used interchangeably.

In this chapter, I first introduce five alternative water allocation mechanisms based on different underlying regulatory philosophies. These allocation mechanisms are : 1) the Benefit Maximizing (MaxBen) program, based on the principle of maximizing economic benefit, 2) the Proportionally Fair (ProFair) program, based on the principle of equitable sharing, 3) the Downstream Priority (DPrio) and 4) the Upstream Priority with Municipal and Industrial User Privilege (UMIPrio) programs, both based on the principle of prioritization according to type of use and/or geographical location, and 5) the No-Rule (NR) program, based on the principle of minimal regulation.. Two criteria, the total aggregate net benefit and the Equity Index are introduced as the measurements to evaluate the performance of the programs. Optimization models are developed to simulate the five withdrawal rules in terms of allocations to the users. An additional model is developed that incorporates a water market, using the results of the allocation model as the initial allocation.

3.1 Conceptualization of Water Allocation Systems

In surface water allocation studies, water sources, sinks, and channels are often conceptualized into a simplified network system. In this study, a water allocation system is seen as a dendritic, unidirectional network consisting of zones and control points. Control points are river cross-sections where streamflows are measured or regulated, such as gages, reservoir inlets and outlets, divisions of administrative districts, etc. Zones are river segments or water storages confined by immediate upstream and downstream control points. Each zone receives water from its upstream neighboring zone(s), interacts with local hydrologic processes (runoff, groundwater, ET, etc.), distributes water to local users, and then passes the remaining water to downstream zones. For the analysis in this thesis, no return flow (water returned to the stream by users) is considered. This assumption is tantamount to defining the withdrawal rights as consumption rights, thus giving users full credit for any return flows. The complication introduced by return flow is discussed quantitatively later in this Chapter.

Shown in Figure 3.1 is an example of the conceptualized water allocation network described above. This is a simple allocation network consisting of 3 zones divided by 3 gages. Each zone serves only one user and the local water budgets are consolidated into one water input per zone.

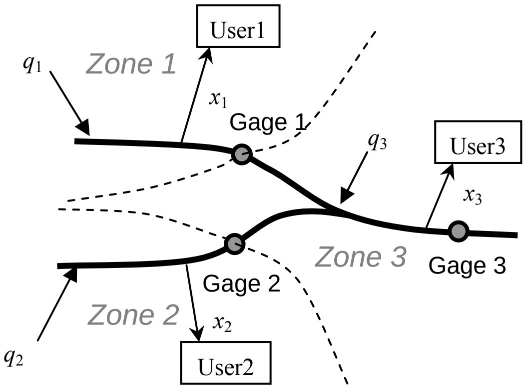


Figure 3.1 A three-zone, three-user water allocation system, with local water input $\boldsymbol{q}$ and withdrawal $\boldsymbol{x}$.

3.2 Benefit Maximizing Allocation

The Benefit Maximizing (MaxBen) mechanism assumes that there exists a water authority, which has perfect knowledge about the benefit function for every user and the capability of coordinating and regulating all withdrawal activities. As its name suggests, the mechanism seeks to maximize the aggregate economic net benefit of all users within the allocation system. The MaxBen allocation can be determined by the following optimization model:

$$\text{Max. } \sum_i NB_i(x_i) \tag{3.1.a}$$

Subject to

$$\boldsymbol{Ax} \le \boldsymbol{Q} - \boldsymbol{e} \tag{3.1.b}$$

$$x_i \ge 0 \qquad \text{for all } i$$

where ***x*** is the vector of water withdrawals to be determined by the model, x_i is an element of ***x*** and denotes the amount of water allocated to user *i*, $NB_i(x_i)$ is the net benefit function of user *i*, ***A*** is called water availability matrix, and ***Q*** is the vector of streamflows at all control points before any withdrawal takes place, and ***e*** is the vector of in-stream flow requirements for environmental protection at all control points. Representation (3.1.b) is called the *water availability constraint*, which is essentially a water balance constraint that limits the total withdrawal upstream of any control point to be less than the total available streamflow at that point. For conciseness, the right-hand side of the constraint can be replaced by a single vector $\boldsymbol{Q_a}$, which represents the streamflows that are available for allocation at the control points.

For an allocation network without return flow, the water availability matrix ***A*** is a 0-1 matrix. If the system is also dendritic with unidirectional flow, then ***A*** is a triangular 0-1 matrix, in which the upper right elements are always zero, the main diagonal elements are all 1, and the lower left elements may be zero or 1, depending on the spatial relationships of withdrawal points to gauges. For instance, the water availability matrix for the system in Figure 3.1 is $\begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 1 & 1 & 1 \end{bmatrix}$. For a retrospective analysis using existing streamflow data, constraint (3.1.b) for this system is written as:

$$\begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 1 & 1 & 1 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} \le \begin{bmatrix} Q_1 - e_1 \\ Q_2 - e_2 \\ Q_3 - e_3 \end{bmatrix} \text{ or } \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 1 & 1 & 1 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} \le \begin{bmatrix} Q_{a1} \\ Q_{a2} \\ Q_{a3} \end{bmatrix}.$$

which in effect consists of 3 separate constraints. For a predictive analysis where streamflows are yet unknown, one can predict local water budgets for every zone using hydrologic models, and then calculate $\boldsymbol{Q}$ as:

$$\boldsymbol{Q} = \boldsymbol{A}(\boldsymbol{g} - \boldsymbol{l})$$

where $\boldsymbol{g}$ and $\boldsymbol{l}$ are the vectors consisting of water gains and losses in all individual zones, respectively.

For cases where return flow is considered, the water availability constraint takes a more complicated form. $\boldsymbol{A}$ will still be a triangular matrix, but its elements are no longer 0-1 binary. Instead, the values of the elements would be fractions between zero and one, depending on the fractions of withdrawals the users return to the river.

Since economic efficiency is the only consideration in the MaxBen program, its allocation result sets a bench mark as the greatest economic value an allocation program can possibly achieve. This benchmark serves as a basis for evaluating the economic efficiency of the other programs.

3.3 Proportionally Fair Allocation

The Proportionally Fair (ProFair) mechanism is grounded on the notion that under the Common Law framework, river flow should be shared among riparian users in proportion to their reasonable demands, regardless of their purposes of use. Different from MaxBen, the ProFair mechanism stresses on equity among withdrawers, leaving economic outcome a secondary consideration. Economic efficiency is maximized subject to the realization of fair allocation, which, in this case, incorporates a notion of proportional sharing.

3.3.1 The Proportional Fairness Criterion

For users having equal access to a single water body, it is easy to calculate each user's share by a proportional division. However, for multi-tributary river system with spatially distributed water inputs and outputs, it is not so straightforward to decide each user's share based on a simple proportional rule. For example, suppose the users in Figure 3.1 have the same water demand of 5 m^3/s, and the available flows are 1, 5, and 9 m^3/s at gages 1, 2, and 3, respectively. If we calculate the allowable share for the three users according to a simple proportional rule with respect to the outlet flow, then each user is allowed to withdrawal 3 m^3/s. However, this allocation is infeasible because it is impossible for user 1 to get 3 m^3/s since the locally available flow in zone 1 is only 1 m^3/s. The allocation can be made feasible by reducing user 1's withdrawal to 1 m^3/s and maintaining the 3 m^3/s withdrawal by users 2 and 3. However, the system would in that case produce 2 m^3/s of unused water, which was accessible, but not granted to user 2 and 3. Obviously, a more reasonable solution in this case would be to keep user 1 with 1 m^3/s and allot 4 m^3/s each to users 2 and 3. In this way, the allocation is still fair, because the allocation is proportional insofar as the supply in the stream allows, and the increase in user 2 and 3's shares does not cause any damage to user 1. At the same time, the overall economic efficiency is also improved, since no water is wasted.

The 3-gage system is simple, but the more important question here is whether the solution to this simple system can be extended to a general system. In other words, given a water allocation network as described in Section 3.1, does there exist a general solution that can maximize the proportional sharing among competing users, while making sure that no water is wasted? Further, if such solution exists, how do we find it?

Now consider a system with multiple gages and users. Assume that any user i in this system has an initial water entitlement of m_i, which is the maximum allowable withdrawal initially granted by the water authority, and an allocated withdrawal of x_i, which is the actual amount of water the user receives under a given water availability condition. The values of m_i could be determined by the user's optimal demand or on some other basis dependent on the user's characteristics.

Here, it is assumed that streamflows don't change with time, so that allocations may be made on a static basis, without considering channel lag times. While factually incorrect, this assumption is justified if changes in streamflow are slow in comparison to the residence time of the channel system, which, by and large, is the case here.

It is discovered by this study that under a water availability condition given by (3.1.b) there exists a unique allocation that satisfies the *Proportional Fairness Criterion*, which is defined as follows:

> *An allocation* ***x**** *is called proportionally fair if for any other feasible allocation* ***x****, the following relationship holds:*

$$\sum_i m_i \frac{x_i - x_i^*}{x_i^*} \leq 0 \tag{3.2}$$

If we define the ratio

$$\phi_i \equiv \frac{x_i}{m_i} \tag{3.3}$$

to be the *degree of water supply satisfaction* received by user *i*, then the Proportional Fairness Criterion can be written as

$$\sum_i \frac{x_i - x_i^*}{\phi_i^*} \leq 0 \qquad (3.4)$$

where $\phi_i^* = \frac{x_i^*}{m_i}$ represents the water supply satisfaction of user *i* resulting from the proportionally fair allocation. This criterion implies that any change made to the proportionally fair allocation will incur a loss from some user whose degree of satisfaction is equal or already smaller than that of those who benefit from the change. In other words, at the proportionally fair allocation no user can be better off without damaging some one else who is equally or already less well off.

The Proportional Fairness Criterion was first discovered by electrical engineers. Over the past few decades, extensive research has been conducted in the field of design and control of electronic communication networks. One of the key issues in this field is the allocation of limited bandwidth among competing data transfer requests. The *Proportional Fairness Criterion* was first introduced by Frank Kelley and his colleagues (Kelley, 1997; Kelley et al., 1998) in the late 1990s. In their research, they tried to develop a scheme that can perform fair and robust allocation of data transferring capacity among competing users in a network, subject to dynamic bandwidth availability. They discovered that a system optimum is achieved when the users' choices of payment and the network's choice of bandwidth allocation are in equilibrium with each other. This particular equilibrium is captured precisely by the Proportional Fairness Criterion. The present study finds that a proportionally fair allocation can also be found in an allocation network with dentritic, unidirectional and loop-free water geometry.

Although governed by very different physical principles, electronic communication networks are similar to water allocation networks in many ways. For example, bandwidth follows the same ‘mass balance’ rule as water – the total bandwidth is equal to the sum of fractions occupied by individual users in the network at any moment. For another example, bandwidth, often greater than 10^6 bytes per second in capacity, can be largely considered as continuous substance like water, assuming one byte per second to be the smallest discrete unit. Besides, the dentritic, unidirectional, loop-free networks of water allocation systems discussed in this study can be viewed as a subset of the more complicated electronic communication networks. There is, however, a noted difference between the two types of networks in that there can be return flow (water that is not consumed by users and hence returned to the system) presented in a water allocation system while there is no such thing as ‘return bandwidth’ in a communication network – there cannot be a user requesting and releasing bandwidth at the same time. Whether the Proportional Fairness Criterion still applies when return flows are present is a question subject to further investigation and is not addressed in the current study.

The proportionally fair allocation has another important property – given a qualified network, it is unique (see proof in Appendix 3A). This property is useful from a regulatory point of view, but more importantly, it is critical in developing the methods to find this allocation.

The following sections introduce two approaches for locating the proportionally fair solution for a given water allocation system: 1) the concave optimization approach and 2) the 'Bottleneck' Algorithm. It is proved in Appendix A that the two approaches are equivalent to each other.

3.3.2 Convex Optimization Approach

With slight modification of the work of Kelley (1996) and Kelley et al. (1998), the following log-linear-programming model is used to obtain the proportionally fair allocation for a raw water supply system:

$$\max \sum_{i} m_i \ln x_i \qquad (3.5.a)$$

Subject to

$$\boldsymbol{Ax} \leq \boldsymbol{Q_a} \qquad (3.5.b)$$

Over $\qquad x_i \geq 0$

where m_i is user i's entitled water right, which is initially granted by a water authority and x_i is the actually amount of withdrawal the user is allowed to take under a given set of water availability conditions. The notations $\boldsymbol{A}$ and $\boldsymbol{Q_a}$ are defined the same as in the MaxBen model (3.1). Given the strict convexity of the objective function and the linear nature of the constraints, model (3.5) is guaranteed to have a convex decision space and a unique solution.

In an electronic communication network setting, model (3.5) requires that the network is congested (total supply less than total demand) in order to find the proportionally fair solution. A similar requirement holds for water allocation systems: there should be a shortage of water supply in order for model (3.5) to produce the true proportionally fair allocation among competing withdrawers. For a system where supply may exceed demand, one more set of constraints should be added:

$$x_i \le x_{i,\,opt} \qquad \text{for all } i \tag{3.5.c}$$

where $x_{i,\,opt}$ represents the optimal amount of water user i would take if streamflow were unlimitedly available. When constraint (3.5.c) is binding for some i, we call the solution a *practical allocation*, since the allocation has in practice satisfied a subset of users and therefore it is no longer necessary to pursue the Proportional Fair Allocation for the entire system.

A general proof of the proportional fairness of the solution by model (3.5) is given in Appendix A. Here we demonstrate the model effectiveness using the simple numerical example shown in Figure 3.1.

Again, we suppose that the three users have a common water demand (or water rights entitlement) of 5 units each. The locally produced runoff of the 3 zones is $\boldsymbol{r} = (1, 4, 4)$, implying the available streamflows at the 3 control points to be $\boldsymbol{Q_a} = (1, 5, 9)$. Model (3.5) for this simple system is then written as

$$\max.\ 5\ln(x_1) + 5\ln(x_2) + 5\ln(x_3)$$

Subject to:
$$\begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 1 & 1 & 1 \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} \le \begin{bmatrix} 1 \\ 5 \\ 9 \end{bmatrix}$$

$$x_1 \le 5,\ x_2 \le 5,\ x_3 \le 5$$

Over
$$x_1, x_2, x_3 \ge 0$$

Using the Karush-Kuhn-Tucker conditions we find the solution to be $\boldsymbol{x} = (1, 4, 4)$, i.e. user 1 withdraws the entire 1 unit local flow, user 2 takes 4 units and passes down 1 unit, and user 3 receives 4 units with 3 from local runoff and 1 from upstream input. It is easy to demonstrate numerically that this solution satisfies the Proportional Fairness Criterion given by (3.2). In this case, the constraints associated with control points 1 and 3 are binding.

If, for another example, the local runoff is $\boldsymbol{r} = (3.5, 4, 1.5)$ and corresponding available flow $\boldsymbol{Q_a} = (3.5, 4, 9)$, then the solution becomes $\boldsymbol{x} = (3, 3, 3)$, which also satisfies the Proportional Fairness Criterion. The new proportionally fair solution is different from the one in the previous example, because the feasible space has changed due to the change in flow availability. In this case, only the water availability constraint associated with control point 3 is binding.

The form of the objective function for the convex optimization model is not unique. For example, the current study finds that the following quadratic objective function is equally able to elicit the Proportionally Fair solution to the water allocation network as the Kelly's logarithmic objective function:

$$\max. \sum_i \left(x_i - \frac{1}{2m_i} x_i^2 \right) \tag{3.6}$$

It is easy to verify that objective function (3.6) yields the same results for the examples above.

3.3.3 Bottle Neck Algorithm

Neither the convex programming model nor the Proportional Fairness Criterion is very intuitive to understand, because from a water resource manager's standpoint, neither of them provides any allocation rules. It would be helpful if there is a set of explanatory and operable rules that can lead to the Proportionally Fair Allocation.

In his master's thesis, Harrison (1990) proposed a so-called 'New Riparian Program' as a potential water allocation mechanism for the Eastern U.S. Under that program, water allotments for users along a waterway system are determined using an algorithm consisting of a series of iterative steps. With modification, the algorithm is reintroduced in this study as follows:

1) Starting from natural flow conditions, increasingly allocate water in the entire system in proportion to the users' initial entitlement until a constraining point, where available flow becomes zero, is encountered.
2) Maintain all the withdrawals upstream of the constraining point at their present level.
3) Continue the proportional allocation process for the remaining unconstrained system until the next constraining point is encountered.
4) Repeat steps 2) and 3) until all available water in the system has been allocated, or until all the remaining users are fully satisfied.

Because the algorithm progresses as if it is looking for a series of bottlenecks in a water supply system, it is named in this dissertation the *Bottleneck Algorithm*. The Bottleneck Algorithm is in its nature a greedy algorithm, which seeks to reach a global solution by a series of short-sighted sub-optimization actions at each iterative step. It minimizes “waste” (unused release through the watershed outlet) under a proportional sharing restriction.

The Bottleneck Algorithm breaks down the allocation problem into a series of successive sub-problems. At the very first iteration, the solution is obtained by solving the following linear optimization problem:

$$\max \sum_{i \in S} x_i \tag{3.7.a}$$

s.t.

$$\boldsymbol{Ax} \leq \boldsymbol{Q_a} \tag{3.7.b}$$

$$\frac{x_i}{m_i} = \phi \qquad \text{for all } i \tag{3.7.c}$$

$$0 \leq \phi \leq 1 \tag{3.7.d}$$

$$x_i \geq 0 \qquad \text{for all } i,$$

where S represents the set of all users within the allocation system, m_i is the pre-defined water entitlement for user i, ϕ is the common proportion, i.e. degree of water supply satisfaction, to be achieved in this iteration.

By substituting (3.7.c) into (3.7.a) and (3.7.b), we can eliminate $\boldsymbol{x}$ from the problem:

$$\text{Max } \phi \tag{3.8.a}$$

s.t.

$$\phi \boldsymbol{Am} \leq \boldsymbol{Q_a} \tag{3.8.b}$$

$$0 \leq \phi \leq 1 \tag{3.8.c}$$

where $\boldsymbol{m}$ is the water entitlement vector, consisting of all m_i's. The new problem has only one decision variable, ϕ. The goal becomes to find the maximal water satisfaction that can be achieved by every user without violating the water balance constraints. By the Karush-Kuhn-Tucker conditions, we know that under general situations there should be one and only one binding constraint in a feasible one-variable linear programming problem. In this case, if (3.8.c) is not binding, then the binding constraint must be the one associated with the bottleneck point, where the streamflow is most limiting. Thus, the solution to the first iteration is

$$\phi^* = \min\left[\min_{j \in S}\left(\frac{Q_{a,j}}{\sum_{i \in U(j)} m_i}\right), 1\right] \tag{3.9}$$

where $U(j)$ is called *subsystem j*, defined as the set of users that are upstream of and including user j, and $Q_{a,j}$ is the available flow at gage j if no withdrawal were to take place.

After the initial iteration, the following iterations can be written in a similar mathematical form for the remaining unconstrained part of the system. In general, at the kth iteration the problem is written as

$$\text{Max } \phi^{(k)} \tag{3.10.a}$$

s.t.

$$\phi^{(k)} \boldsymbol{A}^{(k)} \boldsymbol{m} \le \boldsymbol{Q}_{\boldsymbol{a}}^{(k)} \tag{3.10.b}$$

$$0 \le \phi^{(k)} \le 1 - \phi^{(k-1)} - \phi^{(k-2)} - \ldots - \phi^{(1)} \tag{3.10.c}$$

where $\boldsymbol{A}^{(k)}$ is the water availability matrix associated with the remaining subsystem at the kth iteration, $\boldsymbol{Q}_{\boldsymbol{a}}^{(k)}$ is the vector of the remaining available flow associated with the remaining system at the kth iteration, ***m*** is still the water rights entitlement vector, and $\phi^{(k)}$ is the **incremental** water supply satisfaction obtained by the remaining users at the kth iteration. For the users cleared in the kth round, the final water satisfaction ratio they receive, denoted as Φ_k, is calculated as

$$\Phi_k = \phi^{(1)} + \phi^{(2)} + \ldots + \phi^{(k)} \qquad (3.11)$$

and the corresponding volumes of water they are allowed to withdraw are the products of their individual water entitlements and the above summation.

The mathematical representations above will help in the proof for the equivalence between the Bottleneck Algorithm and the Proportionally Fair Allocation (See Appendix 3A).

Figures 3.2 and 3.3 illustrate a hypothetical 10-gage free-flowing allocation system and how the Bottleneck Algorithm is applied to achieve a proportionally fair allocation in the system. In this case, allocation is completed in 6 iterations. Each plot of figure 3.2 represents the ending status of one iteration. The numbers in the arrow boxes are the remaining available flows that have not been allocated by end of the current step. In the rectangular boxes, the first number is the cumulative volume of water that has been allotted to the users by end of the current step, and the second number is the associated degree of water supply satisfaction defined by (3.3). The gage that presents the bottleneck (where available streamflow becomes zero) found in the current step is indicated by a hatched arrow.

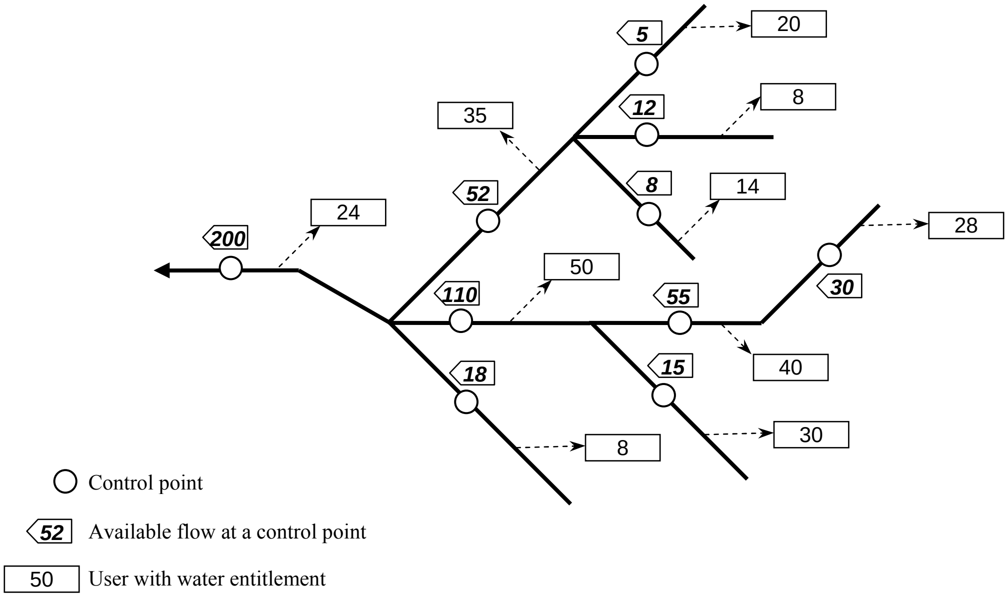


Figure 3.2 A 10-gage dendritic water allocation network

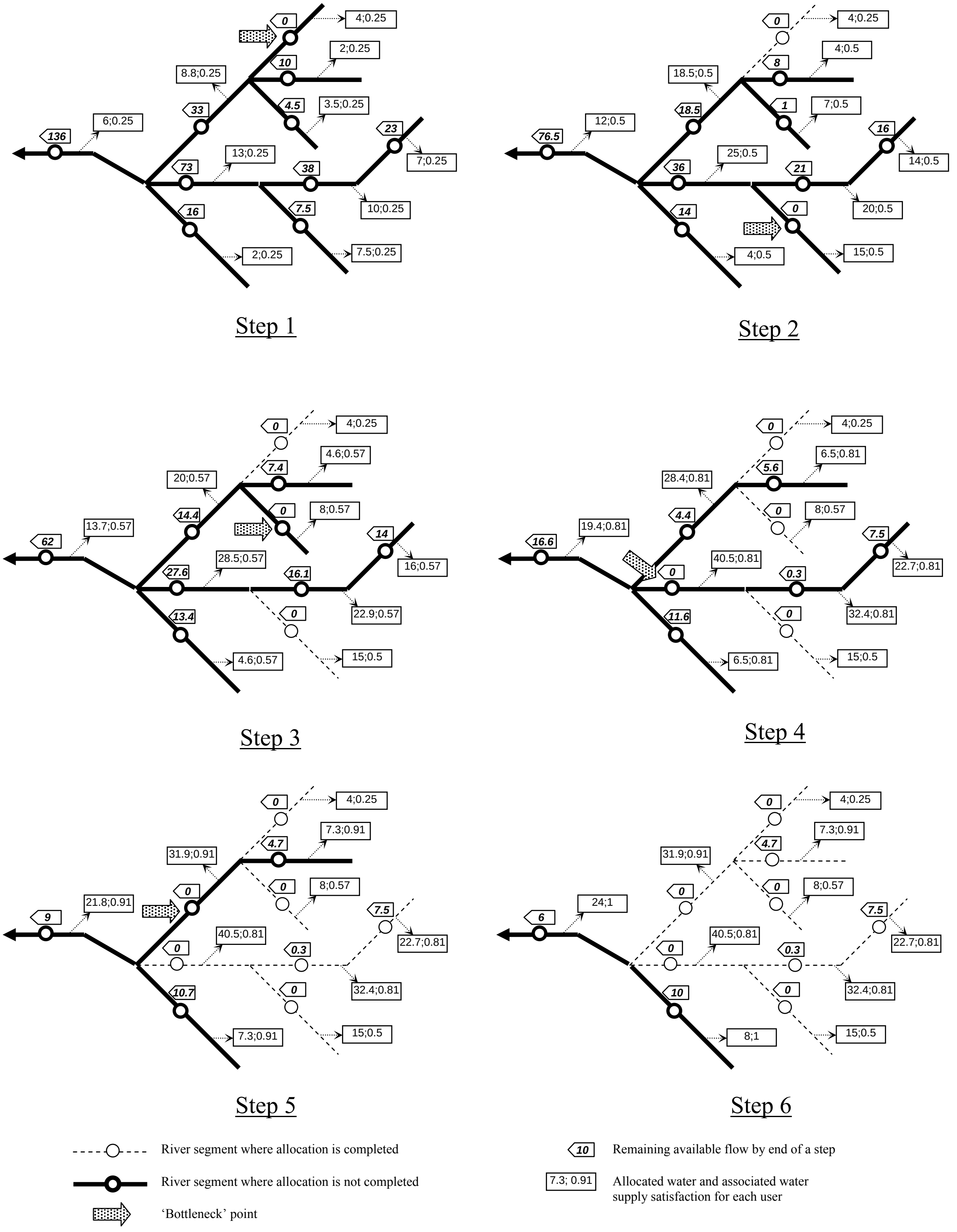


Figure 3.3 Bottleneck Algorithm for water allocation in the 10-gage river system. Allocation is completed in 6 iterations.

Several characteristics of the Bottleneck Algorithm can be observed from this example. First, in any branch of the dendritic stream network, the allocation always progresses from upstream to downstream. The most downstream user of the entire system remains in the unconstrained part of the system till the last iteration. Second, the remaining system is always dendritic at any iteration. Thus, model (3.10) can always be seen as a simpler version of model (3.8) and has a solution with the form similar to (3.9). Third, the degree of satisfaction of a downstream user is always no less than its upstream peers. Finally and the most importantly, in the Bottleneck Algorithm solution, a user cannot receive more water to achieve a higher degree of satisfaction without damaging some other(s) whose degree of satisfaction is equal or already lower, which is consistent with the definition of the proportionally fair allocation. This suggests that every user has maximized his or her share without taking any advantage of others, which forms a ground of fairness for the Bottleneck Algorithm.

3.3.4 Comments

Although Harrison (1990) successfully developed the initial form of the Bottleneck Algorithm, he did not explain why this allocation scheme is particularly significant to water resource management. The introduction of the Proportional Fairness Criterion in the late 1990s and the proof in this dissertation that the Bottleneck Algorithm generates the Proportionally Fair Allocation provides a compelling answer to the question. The proportionally fair allocation provides an objective and qualitative benchmark for fair sharing of water among competing users.

Both the convex programming approach and the Bottleneck Algorithm have their own advantages. The convex programming approach offers a concise representation for the problem. With the computerized spreadsheet technology today, water resource managers can easily set up the convex programming model for a large allocation network and quickly find the proportionally fair solution without going through all the iterative steps, which can be tedious when the system becomes large. Hence, from a manager's point of view, the convex programming approach is more convenient and efficient.

However, from a modeler's and a computer programmer's point of view, the algorithm is equally important as the model, because the model itself does not automatically produce a result. The solution must be obtained through an algorithm composed of a series of simple computational procedures. This study shows that the Bottleneck Algorithm not only provides an explanatory procedure to produce the Proportionally Fair allocation, but also offers an effective numerical algorithm to solve a convex programming model with the form of (3.5) or (3.6). Compared with many existing numerical algorithms, the Bottleneck Algorithm is able to find the precise optimum in a finite number of simple actions, and can therefore achieve higher efficiency. It may be significant for future studies to explore further the forms of problems that can be solved by the Bottleneck Algorithm and its variations and to integrate the algorithm into the solver toolboxes in existing optimization software packages.

It should be pointed out that the present study only proved the equivalence between the convex programming model and the Bottleneck Algorithm for a system without return flow. Further investigation is needed to study the performance of the two approaches for systems where return flow occurs.

3.4 Downstream Priority Allocation (DPrio)

The water rights reform in the Eastern US has more or less been influenced by strongly the Appropriation Doctrine, which is widely exercised in the western US. Several Eastern states have adopted or partially adopted some kind of prioritized permitting system (Knapp and Singh, 1985; Sherk, 1990; Foran, 1995) to address conflicting water demands in times of shortage. Hence, it is meaningful for this study to examine the performance of the priority-based allocation programs as alternative mechanisms for the Eastern states.

In a priority-based system, water rights are exercised in the order of priority ranking. In times of drought, users with lower priority ranks cannot withdraw any water until the users with higher ranks are fully satisfied.

The allocation outcome of a given river basin depends heavily on the how the user priorities are assigned, which, depending on the water rights history and policy arrangements, can be quite variable. As the number of users in the system increases, the number of possible priority sequences increases factorially (a system with n users can have $n!$ possible priority sequences). Although many of these sequences will likely be equivalent to each other for a particular allocation system, the variability of possible outcomes is still prohibitively large, which poses a challenge to the present analysis. It is not only extremely time-consuming, but also unnecessary to investigate every single case of such priority programs. Instead, this study is focused only on three priority arrangements of particular practical significance.

These three programs are 1) Downstream Priority (DPrio), 2) No Rule (NR), which can be viewed as upstream priority, and 3) Upstream Priority with Municipal and Industrial User Privilege (UMIPrio).

The Downstream Priority mechanism is based on the arrangement where the water rights priorities are granted in the order of closeness to the outlet of the river basin. The farther downstream a user is located, the higher priority he or she is entitled to. The DPrio program can be represented by the following linear optimization problem:

$$\max \sum_i \omega_i x_i \tag{3.12.a}$$

Subject to

$$\boldsymbol{Ax} \le \boldsymbol{Q_a} \tag{3.12.b}$$

$$0 \le x_i \le x_{i,\,opt} \quad \text{for all } i \tag{3.12.c}$$

where w_i is the weight that reflects the priority of user i. The weights can be assigned arbitrarily as long as they satisfy:

$$\omega_i > \omega_j \qquad \text{for any } i \textbf{ downstream} \text{ of } j. \tag{3.12.d}$$

Because of the linear feature of the objective function, available water will go first to the user with the highest weight and then the subsequent ones in order of decreasing weight.

3.5 'No-Rule' Allocation (NR)

The 'No-Rule' (NR) mechanism reflects the situation where withdrawals are subject to minimal regulation and users can withdraw water based largely on their free will. Depending on water availability, a user can withdrawal either the amount of water that maximizes his net benefit or all available water that is flowing through his or her local reach, whichever smaller. Hence, the NR allocation is by its nature equivalent to an upstream-advantage or upstream-priority program, which to some degree reflexes the current situations in the eastern states with weak or no surface water rights regulation.

The model that simulates the NR allocation has the same form as the DPrio model:

$$\max \sum_{i} \omega_i x_i \tag{3.13.a}$$

Subject to

$$\boldsymbol{Ax} \leq \boldsymbol{Q_a} \tag{3.13.b}$$

$$0 \leq x_i \leq x_{i,\, opt} \quad \text{for all } i \tag{3.13.c}$$

However, the weights are assigned opposite to those in the DPrio program. The upstream users always receive higher weights than their downstream peers:

$$\omega_i > \omega_j \qquad \text{for any } i \textbf{ upstream} \text{ of } j. \tag{3.13.d}$$

This is because water is available to upstream users before it flows to downstream users. In order to compare the selected programs on the same quantitative basis, this study assumes that the NR program still needs to comply with the minimal in-stream flow standard. Thus, the available flow vector Q_a in (3.13.b) is the same as in (3.12.b).

3.6 Upstream Priority with Municipal and Industrial User Privilege (UMIPrio)

Many Eastern States have adopted some form of priority programs based on types of water use (see the Literature Review chapter for examples). The UMIPrio program is developed to address arrangements of such kind. The program ranks users first based on their types of use, and then on their locations. In this study, we are particularly interested in two types of users, municipal/industrial (M&I) and agricultural, with the priority given to the former. Within each type, the users are then ranked in order of ‘upstreamness’.

The model that simulates the UMIPrio program takes the same form as the one for the DPrio and NR programs (3.12), except that the weights are assigned differently. In this case, if i and j are M&I and agricultural users, respectively, then $\omega_i > \omega_j$. If i and j are of same type, then $\omega_i > \omega_j$ if i is upstream of j.

3.7 Analysis of Market-based Water Rights Transfer

The idea of water rights market is simple: users are allowed to buy others’ or sell their own existing water rights to increase profitability. There may be situations where a water market works as a primary allocation mechanism, such as permit auction programs directed by regulators (Wong and Eheart, 1983). But more often, a water market is a secondary mechanism, which reallocates existing water rights holdings through voluntary transactions between buyers and sellers. The result of the water market is often an increased aggregate net benefit from a group of individually based buying and selling decisions.

The purpose of the present trading analysis is to evaluate the physical and economic outcomes of a water market based on different initial allocation mechanisms. The analysis is particularly concerned with an idealized free market where prices are determined purely by supply-demand conditions, assuming that third party effects and transaction costs are minimal. Several quantitative characteristics of the water market are simulated, including the amount of water transferred, the total revenue of water rights sale, the prices at which water is sold, and the aggregate gain in net benefit (or total profit) of the entire system.

In a water market, equilibrium is reached when no more voluntary exchanges can increase the total aggregate profit of all buyers and sellers. At this equilibrium the aggregate net benefit of the entire market is maximized. Thus, the trading activities in a water market can be simulated by the following optimization model:

$$\text{Max. } \sum_i \left[NB_i(x_{0,i} + t_i) - p_{t,i}t_i - c_{t,i}|t_i| \right] \tag{3.14.a}$$

Subject to

$$\boldsymbol{A}(\boldsymbol{x_0} + \boldsymbol{t}) \leq \boldsymbol{Q_a} \tag{3.14.b}$$

where $x_{0,i}$ is the known pre-market allocation to user i, t_i is the amount of water transfer to be determined by user i, $p_{t,i}$ is the direct purchase price for user i at which the water is transferred, and $c_{t,i}$ is the transaction cost , which is a collective result of all other costs associated with the transfer in addition to the direct purchase cost. Different from the initial allocation models where the decision variables can only take non-negative values, the decision variables $\boldsymbol{t}$ here can take either a positive value, indicating a buy, or a negative value, indicating a sale.

Under idealized market conditions, the transaction cost term in (3.14.a) can be dropped. The aggregate amounts bought and sold always equal each other, so that the purchase costs cancel out in the aggregate formula:

$$\sum_i \left[NB_i(x_{0,i} + t_i) - p_{t,i}t_i \right] = \sum_i NB_i(x_{0,i} + t_i)$$

Therefore, the final allocation resulting from the market simulation model (3.14) is equivalent to the solution to the Benefit Maximizing model (3.1). Hence, $\boldsymbol{t}$ can be simply derived as

$$\boldsymbol{t} = \boldsymbol{x}_{MB} - \boldsymbol{x}_0 \tag{3.15}$$

where $\boldsymbol{x}_{MB}$ is the benefit maximizing allocation and $\boldsymbol{x}_0$ is the initial allocation from a primary water withdrawal program, in this case one of the solutions to the ProFair, DPrio, UMIPrio, and NR programs. The aggregate gain in net benefit from the market program, denoted by G, can then be easily calculated by taking the difference between the aggregate net benefits of the MaxBen and any of the alternative programs:

$$G = \sum_i NB_i(x_{MB,i}) - \sum_i NB_i(x_{0,i}) \tag{3.16}$$

Water transfers can take various forms depending on their purposes and effective duration (Lund and Israel, 1995). As stated in Chapter 1, this study is mainly concerned with a ‘spot market’ where water rights are transferred or leased on a short-term basis (typically completed within a single water year) to meet immediate needs. Compared to some of the long-term to permanent transfer options, a spot market is considered to be more cost-effective in managing sporadic, short-term deficiencies (Characklis et al., 2006), which are often of the greatest concern in the eastern United States. Chapter 4 will discuss the setup of spot market simulation in more details.

The pricing of water is slightly more complicated. Due to the physical constraints created by the geographical distribution of water inputs and the unidirectional feature of the river network, the users in the market do not have equal access to all supply. The more downstream a potential buyer is located, the better chance he or she has to find a seller. On the other hand, a user located near a headwater may find very limited buying opportunity on the market. Hence, the buying or selling opportunity (and therefore, price) is a function of the user’s location.

In a free market, the prices should evolve such that the market can reach an equilibrium, where no further transfers are profitable. At this equilibrium, the buying or selling price for each user should be equal to his or her marginal water use benefit, which is determined by water availability. From basic microeconomic theories we know that the prices can be obtained by solving the Lagrange multipliers of the Benefit Maximizing problem (3.1) or, equivalently, the trading problem (3.14).

Let's define the Lagrangian for problem (3.1) as

$$L(\boldsymbol{x},\boldsymbol{\lambda}) = f(\boldsymbol{x}) + \sum_i \lambda_i (\boldsymbol{A}_i \boldsymbol{x} - Q_{a,i}) \tag{3.17}$$

where $\boldsymbol{x}$ is the water allocation vector to be decided, $f(\boldsymbol{x})$ denotes the net benefit maximizing objective function, $\Sigma NB_i(x_i)$, λ_i is the Lagrange multiplier for constraint i associated with zone i, $\boldsymbol{A}_i$ is the ith row in the water availability matrix, a 0-1 vector, and $Q_{a,i}$ is the available flow through zone i. The solution to $\boldsymbol{x}^*$ and $\boldsymbol{\lambda}^*$ can be obtained by solving the following Karush-Kuhn-Tucker conditions (Nocedal and Wright representations, 1999):

$$\nabla_x L(\boldsymbol{x}^*,\boldsymbol{\lambda}^*) = \mathbf{0} \tag{3.18.a}$$

$$\boldsymbol{A}_i\boldsymbol{x}^* - Q_{a,i} = 0 \quad \text{when constraint } i \text{ is binding} \tag{3.18.b}$$

$$\boldsymbol{A}_i\boldsymbol{x}^* - Q_{a,i} \leq 0 \quad \text{when constraint } i \text{ is not binding} \tag{3.18.c}$$

$$\lambda_i^* \geq 0 \quad \text{for all } i \tag{3.18.d}$$

$$\lambda_i^*(\boldsymbol{A}_i\boldsymbol{x}^* - Q_{a,i}) = 0 \qquad \text{for all } i \tag{3.18.e}$$

The buying or selling price $p_{t,i}$ for user i would be equal to the Lagrange multiplier associated with the nearest downstream binding control point. The cost or revenue of the transfer related to user i would then be $| p_{t,i}t_i |$, and the total revenue (T) generated by the entire market would be

$$T = \frac{\sum_i |p_{t,i} t_i|}{2} \tag{3.19}$$

since the amount of permits bought equals that sold.

3.8 Measurement of Fairness

Traditionally, water allocation studies, conducted mostly in the context of the Western US, focus primarily on economic efficiency, attempting to design allocation programs that maximize economic benefit while satisfying various underlying hydrologic, operational, and policy constraints. As water scarcity emerges in the Eastern US, the interest of water allocation research is shifting toward the development of withdrawal programs that not only result in sound economic efficiency, but also achieve reasonable degree of fairness. Such shift of interest is largely driven by the legal reality of the eastern water rights, wherein the Riparian Doctrine, which in essence requires equitable sharing of water, remains the fundamental guidance for water policy development and engineering practices.

In this study, a dimensionless criterion called Equity Index (*EI*) is used to measure the degree of fairness achieved by selected water allocation mechanisms. The index is a modification from a similar concept introduced previously by Harrison (1990). The formula that calculates the index is:

$$EI = \left[1 - \sqrt{\frac{\sum_i (\phi_i - \bar{\phi})^2}{N(N-1)}} \Big/ \bar{\phi} \right]^2 \tag{3.20}$$

where ϕ_i is user *i*'s satisfaction coefficient defined by the ratio of his or her allowable withdrawal over demand (Eq. (3.3)), $\overline{\phi}$ is the average satisfaction coefficient over all users, *N* is the total number of users in the allocation system. One can immediately notice that part of the above equation is equivalent to certain commonly used statistical parameters and hence can be simplified as

$$EI = \left[1 - \frac{\sigma(\phi) / \overline{\phi}}{\sqrt{N}} \right]^2 = \left[1 - \frac{CV(\phi)}{\sqrt{N}} \right]^2 \qquad (3.21)$$

where $\sigma(\phi)$ and $CV(\phi)$ are the standard deviation and coefficient of variation of ϕ_i's, respectively.

A property that makes *EI* a convenient measurement for fairness is that its value falls strictly between zero and one. An *EI* value of one indicates a perfectly equitable allocation, where all users receive exactly the same level of satisfaction. Conversely, an *EI* value of zero indicates a perfectly inequitable allocation, where water is allocated to only one user and nobody else (i.e. ϕ is some positive number for one user and zero for everybody else). In practice, this index can be used to evaluate and compare the degree of fairness achieved by alternative water allocation programs.

APPENDIX 3.A. Equivalence between Convex Programming Model and Bottleneck Algorithm in Producing Proportionally Fair Allocation

To prove the equivalence between the convex programming model (3.4) and the Bottleneck Algorithm in producing the Proportionally Fair Allocation solution, we only need to prove the following propositions:

1) The solution to the convex programming problem (3.4) satisfies the Proportional Fairness Criterion;
2) The solution produced by the Bottleneck Algorithm also satisfies the Proportional Fairness Criterion; and
3) For a given problem, the Proportionally Fair solution is unique.

Proof for proposition 1:

Because the objective function of problem is $f(\boldsymbol{x}) = \sum_i m_i \ln x_i$, the left hand side of the Proportional Fairness Criteria in this case can be written as

$$\sum_i m_i \frac{x_i - x_i^*}{x_i^*} = (\boldsymbol{x} - \boldsymbol{x}^*) \cdot \nabla f(\boldsymbol{x}^*)$$

where x^* is the optimal solution to problem (3.5), x is any other feasible solution. Thus, to prove proposition 1 is true, we only need to show

$$(\boldsymbol{x} - \boldsymbol{x}^*) \cdot \nabla f(\boldsymbol{x}^*) \le 0 \tag{A.1}$$

First, we assume x is located in a sufficiently small neighborhood of x^*. Since $f(x)$ is continuously differentiable, by Taylor's Theorem we have that

$$\begin{aligned} f(\boldsymbol{x}) &= f(\boldsymbol{x}^*) + (\boldsymbol{x} - \boldsymbol{x}^*) \cdot \nabla f(\boldsymbol{x}^*) + o(\|\boldsymbol{x} - \boldsymbol{x}^*\|) \\ &\approx f(\boldsymbol{x}^*) + (\boldsymbol{x} - \boldsymbol{x}^*) \cdot \nabla f(\boldsymbol{x}^*) \end{aligned} \tag{A.2}$$

Since x^* is the maximizer of problem (3.5), it must be true that $f(\boldsymbol{x}) - f(\boldsymbol{x}^*) \leq 0$. Therefore, by rearranging (A.2) we get:

$$(\boldsymbol{x} - \boldsymbol{x}^*) \cdot \nabla f(\boldsymbol{x}^*) = f(\boldsymbol{x}) - f(\boldsymbol{x}^*) \leq 0 \tag{A.3}$$

For any feasible solution y that is remote from $\boldsymbol{x}^*$, because of the convexity of the feasible space, we can always find a scalar τ and a feasible solution $\boldsymbol{x}$ within a sufficiently small neighborhood of $\boldsymbol{x}^*$ that satisfies (A.2) (see Figure A.1) so that

$$\boldsymbol{y} - \boldsymbol{x}^* = \tau(\boldsymbol{x} - \boldsymbol{x}^*) \tag{A.4}$$

Thus

$$(\boldsymbol{y} - \boldsymbol{x}^*) \cdot \nabla f(\boldsymbol{x}^*) = \tau(\boldsymbol{x} - \boldsymbol{x}^*) \cdot \nabla f(\boldsymbol{x}^*) = \tau \sum_i m_i \frac{x_i - x_i^*}{x_i^*} \leq 0$$

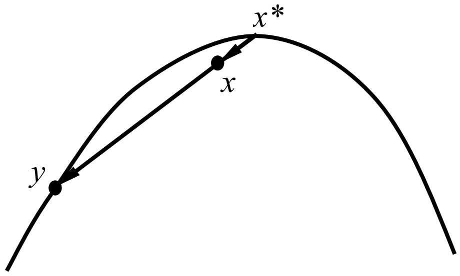


Figure A.1. In a convex space, any remote point y from the optimum x^* is on the direction defined by the optimum and some nearby feasible point x

Proof for proposition 2:

Without loss of generality, we suppose there is a system consisting of n zones, which can be allocated by the Bottleneck Algorithm in m steps to arrive at the Proportionally Fair Allocation. Readers should note that m is different from the notation for water rights entitlement m_i. To prove the allocation is proportionally fair, we only need show the following:

$$\sum_{i\in S} m_i \frac{x_i - x_i^*}{x_i^*} = \sum_{i\in S^{(1)}} \frac{x_i - x_i^*}{\Phi_1} + \sum_{i\in S^{(2)}} \frac{x_i - x_i^*}{\Phi_2} + \ldots + \sum_{i\in S^{(m)}} \frac{x_i - x_i^*}{\Phi_m} \le 0 \qquad \text{(A.5)}$$

where S is the set of all users in the allocation system, i.e. $S = \{1,2,\ldots,n\}$, $S^{(k)}$ ($k = 1, 2, \ldots, m$) is the set of users whose allocation is directly completed by step k, and Φ_k is the water supply satisfaction finally found for the users in $S^{(k)}$. By definition, we know that

$$S^{(i)} \cap S^{(j)} = null \qquad \forall\ i,j = 1, 2, \ldots, k \text{ and } i \ne j \qquad \text{(A.6)}$$

$$S^{(1)} \cup S^{(2)} \cup \ldots \cup S^{(m)} = S \qquad \text{(A.7)}$$

Also by (3.11) we know that

$$0 < \Phi_1 < \Phi_2 < \ldots < \Phi_m \qquad \text{(A.8)}$$

From the definition of the Bottleneck Algorithm, we know that there must be m bottlenecks in the system. In other words, of the constraints given by

$$\boldsymbol{Ax} \le \boldsymbol{Q_a} \qquad \text{(A.9)}$$

there must be m of them that are binding. Thus, for any other allocation $\boldsymbol{x} \ne \boldsymbol{x^*}$, it must hold that:

$$\begin{aligned} \boldsymbol{A}_k \boldsymbol{x} - Q_{a,k} &= \boldsymbol{A}_k \boldsymbol{x} - \boldsymbol{A}_k \boldsymbol{x}^* \\ &= \sum_{i\in S^{(1)}} (x_i - x_i^*) + \sum_{i\in S^{(2)}} (x_i - x_i^*) + \ldots + \sum_{i\in S^{(k)}} (x_i - x_i^*) \\ &= \sum_{i\in S^{(1)}\cup S^{(2)}\cup\ldots\cup S^{(k)}} (x_i - x_i^*) \le 0 \qquad \forall\ k \in \{i \mid \boldsymbol{A_i x^*} - Q_{a,i} = 0\} \qquad \text{(A.10)} \end{aligned}$$

where $\boldsymbol{A_k}$ is the k^{th} row of the water availability matrix $\boldsymbol{A}$, and $Q_{a,k}$ is the k^{th} element in the available flow vector $\boldsymbol{Q_a}$. Particularly, when $k = n$

$$\sum_{i\in S} (x_i - x_i^*) = \sum_{i\in S^{(1)}} (x_i - x_i^*) + \sum_{i\in S^{(2)}} (x_i - x_i^*) + \ldots + \sum_{i\in S^{(m)}} (x_i - x_i^*) \le 0 \qquad \text{(A.11)}$$

Otherwise, the move from x^* to x will be infeasible by violating (A.9). Therefore,

$$\sum_{i\in S} m_i \frac{x_i - x_i^*}{x_i^*} = \sum_{i\in S^{(1)}} \frac{x_i - x_i^*}{\Phi_1} + \sum_{i\in S^{(2)}} \frac{x_i - x_i^*}{\Phi_2} + \ldots + \sum_{i\in S^{(m)}} \frac{x_i - x_i^*}{\Phi_m}$$

$$\le \sum_{i\in S^{(1)}\cup S^{(2)}} \frac{x_i - x_i^*}{\Phi_2} + \sum_{i\in S^{(3)}} \frac{x_i - x_i^*}{\Phi_3} + \ldots + \sum_{i\in S^{(m)}} \frac{x_i - x_i^*}{\Phi_m}$$

$$\le \sum_{i\in S^{(1)}\cup S^{(2)}\cup S^{(3)}} \frac{x_i - x_i^*}{\Phi_3} + \sum_{i\in S^{(4)}} \frac{x_i - x_i^*}{\Phi_4} + \ldots + \sum_{i\in S^{(m)}} \frac{x_i - x_i^*}{\Phi_m}$$

$$\ldots$$

$$\le \sum_{i\in S^{(1)}\cup S^{(2)}\cup\ldots\cup S^{(m)}} \frac{x_i - x_i^*}{\Phi_m} = \frac{1}{\Phi_m}\sum_{i\in S}(x_i - x_i^*) \le 0$$

The last inequality results from (A.7), (A.8), and (A.11). Proposition 2 is proved.

Proof for proposition 3:

For proposition 3, we can use proof by contradiction. Suppose there is another allocation $\boldsymbol{y} \neq \boldsymbol{x}^*$, which satisfies the Proportional Fairness Criterion. Then by the definition of the Proportional Fairness Criterion, we have that:

$$\sum_i m_i \frac{y_i - x_i^*}{x_i^*} \le 0 \tag{A.12}$$

$$\sum_i m_i \frac{x_i^* - y_i}{y_i} \le 0 \tag{A.13}$$

Add (A.12) and (A.13) to get

$$\sum_i m_i \left[\frac{y_i - x_i^*}{x_i^*} + \frac{x_i^* - y_i}{y_i}\right] = \sum_i m_i \left[\frac{y_i}{x_i^*} + \frac{x_i^*}{y_i} - 2\right] \le 0 \tag{A.14}$$

By Cauchy-Schwarz Inequality, for any $x_i^* > 0$ and $y_i > 0$, (A.14) holds only when $x_i^* = y_i$ for all i. Hence $\boldsymbol{y}$ must be equal to $\boldsymbol{x}^*$, which contradicts the earlier assumption. Therefore, $\boldsymbol{y}$ does not exist and the Proportionally Fair Allocation must be unique.

CHAPTER 4. WATER ALLOCATION PROGRAM EVALUATION – A CASE STUDY IN SANGAMON RIVER WATERSHED, IL

4.1 Watershed Characteristics

The Sangamon River (Figure 4.1), located in Central Illinois, is a tributary to the Illinois River with a watershed area of about 14,040 km^2. Located in a humid continental climate region, the Sangamon River watershed normally experiences warm (ca. 35 ^{o}C maximum), humid summers and cold, dry winters. Average annual precipitation is about 970 mm. Average growing degrees day is about 1940 Celsius degrees, which is normally suitable for one crop per year.

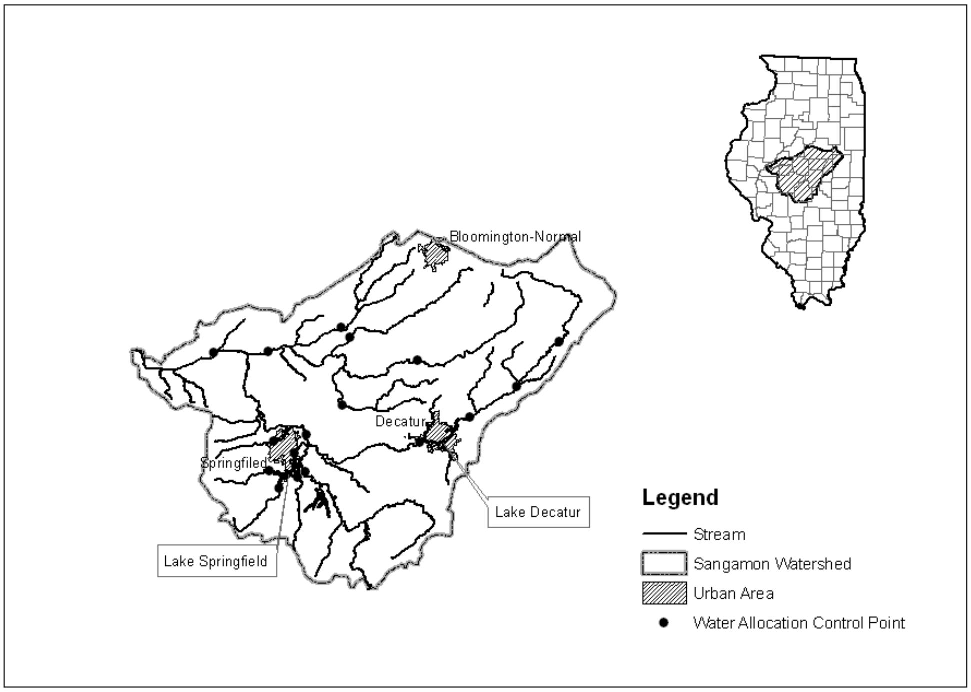


Figure 4.1 The Sangamon River Watershed in Illinois

The watershed is dominated by agricultural land with corn and soybeans cultivation (>90% of the basin area). Statistics (NASS, 2006) show that corn and soybean yields have both increased by about 5 fold from the 1930s to the early 21st century. There are three major metropolitan areas in the watershed, Bloomington-Normal, Decatur, and Springfield, with populations of 76,000, 82000, and 108,000, respectively as of 2006.

Several reservoirs are located on the Sangamon River, serving the needs of municipal and industrial users. Reservoirs of prominence are Lake Decatur, Lake Springfield, and Clinton Lake. The first two are controlled reservoirs currently serving as drinking and industrial water supply for the cities of Decatur and Springfield. The third, with an uncontrolled spillway, provides cooling water for the Clinton Nuclear Power Plant, which returns about 99% of its withdrawal back to the lake.

Historically, the Sangamon River region has largely enjoyed abundant water resources. Irrigation practice is rare because rainfall is sufficient to meet the needs of the crops in normal years and the economic incentive is not strong enough to support a wide adoption of irrigation. As of 1995, total water withdrawal for irrigation in the Sangamon River watershed is about 14 mgd, or 0.61 m^3/s (USGS, 1999).

With limited irrigation, water demand comes mostly from non-agricultural sectors, including primarily commercial, residential, industrial, and thermoelectric power uses. The two largest municipal water supply reservoirs, Lake Decatur and Lake Springfield, support average withdrawals of 1.7 m^3/s (39 mgd) and 1.2 m^3/s (28 mgd), respectively (Makowski et al., 1986; Keefer and Bauer, 2005).

Because of the lack of irrigation facilities, agriculture becomes vulnerable in times of drought. Although corn is generally a drought-tolerant crop, it is highly sensitive to water stress during its flowering stage, which has been identified as about 2 weeks before through 2 weeks following pollination (Nafziger, 2003). A thirsty condition at that time will prevent healthy silk emergence and pollination, and cause serious yield loss

(Heatherly and Ray, 2003). A study shows that moisture stress during the pollination period may cause 3-8% of corn yield loss for each day of stress (Lauer, 2006). Statistics (NASS, 2006) also show that Illinois has historically suffered substantial corn yield loss from droughts. For instance, while it is difficult to separate the effects of drought and heat, the corn yields in 1988, 1995, and 2005, when both extensive droughts and higher temperatures occurred across the state, are 45, 28, and 21% lower than the yields in the respective previous years.

In recent years, corn price has both been rising sharply and increasingly tied to the world price of oil, in light of growing demand for corn-based ethanol fuel. Additionally, an international food shortage (caused in part by the increasing use of ethanol fuel), and the concerns about more erratic drought patterns caused by global warming have contributed to the price rise. As of the summer of 2008, corn price has at times topped \$8/bu (\$315/t), according to the Chicago Board of Trade (www.cbot.com), although at current writing, it is back down in the \$4 (\$182/t) range. As a result, irrigation may be considered increasingly economically practical for Illinois farmers to safeguard their crop yield and income. Eheart and Libby (1981) showed that irrigation would be profitable when corn price reaches about \$6 per bushel or higher.

The competition between agricultural and non-agricultural users would emerge if irrigational withdrawals from surface water increase. The safe yields of the two major municipal water reservoirs, Lake Decatur and Lake Springfield, are currently sufficient for their respective cities. When filled at normal pool level, the reservoirs can meet the cities' needs for more than 12 months without inflow. However, irrigation, if becoming common in the watershed, would reduce the inflow to, and consequently the safe yields of, the lakes. Moreover, downstream irrigators may exercise the Riparian Doctrine and claim their rights to part of the reservoir water, which would further decrease the availability of the reservoir water for the cities. Such competition would likely be further intensified by a prolonged drought, such as the ones that happened in 1988 and 1989.

4.2 Setup for Allocation Analysis

4.2.1 The Allocation Network

In a water allocation analysis, river channels, storage, and water intake facilities are often conceptualized into a simplified network system. In this study, a river is simplified as a dendritic network system consisting of zones and control points. Control points are river cross-sections where streamflows are measured or regulated, such as gages and reservoir outlets. Zones are river segments or water storages confined by immediate upstream and downstream control points. Each zone receives water from its upstream neighboring zone(s) through its upstream control point(s) and local drainage, distributes the water between local users, and then passes the remaining water to downstream zones. It is assumed that the river system is at steady state and that channel lag times are nonexistent. This assumption is sufficiently accurate when allocation is administered on monthly or seasonal basis.

In this study, the Sangamon River is considered to consist of 17 zones and the same number of control points (figure 4.2). Qualified control points are defined as stream gages and reservoir inlets and outlets. Two reservoirs, Lake Decatur and Lake Springfield, are included as storage zones supplying municipal and industrial (M&I) users. Clinton Lake is not considered because the power plant returns nearly 99% of the cooling water back to the lake, and hence, has limited impact on mid- to long-term availability of the streamflow. Hence the remaining 15 zones are all considered to be free running streams supplying agricultural users. It is assumed that the water allocation network holds two essential properties, unidirectionality and dendricity. Unidirectionality refers to the fact that water can only flow from upstream to downstream (in this case, right to left), but not the reverse. Dendricity implies that a zone can have multiple upstream inlets, but only one downstream outlet. For examples, zones 11 and 15 have 4 and 3 inlets, respectively, but both have only one outlet.

While corn and soybean cultivations are highly mixed in this region and the ratio of the two crops varies widely from year to year, it is assumed, for convenience, that all the riparian agricultural land is planted with corn, so that the allocation result from each year can be obtained on the same demand basis. Since corn normally requires considerably more irrigation than soybeans (Heatherly and Ray, 2003), the all-corn assumption represents a scenario that requires maximal agricultural water demand under the existing farming conditions in central Illinois. It is further assumed that all the users in an agricultural zone can be regarded as one aggregated user with a coordinated irrigation schedule. The two cities are also each treated as a single M&I user, since they withdraw water through only one intake from their respective lakes. Hence, in this conceptualized allocation system the Sangamon River system serves a total of 17 users, 2 of them being M&I users and 15 of them agricultural. In reality, of course, uses of different types and schedules are more geographically mixed. For example, in light of the recent Locavore Movement (see e.g. Weber and Matthews, 2008), there is a trend toward local production of fruits and vegetables, which require considerably more irrigation than traditional grains. This issue can be addressed by declaring a control point somewhere between two users of different types, even if there is no significant tributary near that point.

Furthermore, the following conditions are assumed:

1) All withdrawals are consumptive, i.e. no return flow is considered.
2) In each zone, the withdrawal happens just above the downstream control point, so that the user has the full access of the water available to that zone.
3) The free running stream channels have zero water retention capacity.
4) No inter-basin water transfer exists (although trans-boundary water input and output can be easily incorporated with minor modification of the system).

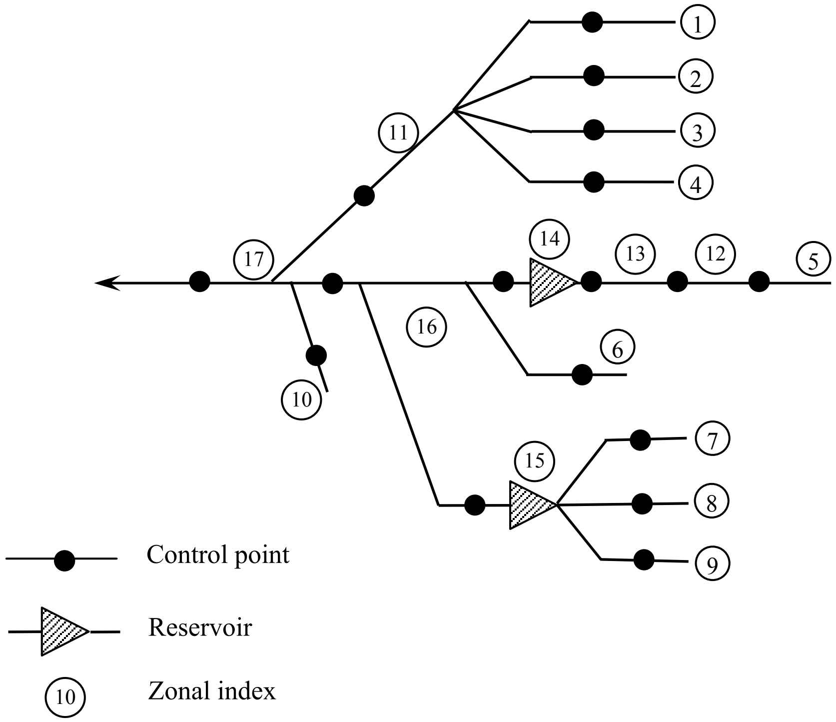


Figure 4.2 Sangamon River water allocation network

4.2.2 Sources of Water

Three sources of water are considered in the present allocation study: rainfall, streamflow, and release from reservoir storage.

Rainfall is an important water input and favorable irrigation substitute for agricultural users. In wet years, abundant rainfall alone can fully meet the needs of plant crops and leave irrigation activities unnecessary. Rainfall information is also critical in determining the relationship between water input and crop yield, which is required to derive the water use benefit function for the allocation analysis. In this study, historical rainfall is obtained from the National Climate Data Centre database. A total of 22 weather stations with available daily precipitation are identified within the Sangamon River watershed. Missing data are generated using the records at the nearest station. Average rainfall is calculated for each of the agricultural riparian zones.

When rainfall is insufficient to supply crop needs, riparian farmers will turn on their irrigation systems, which are assumed to take water directly out of nearby streams. Hence, the availability of natural streamflow is also critical information for the allocation analysis. In this study, historical flow records are collected from 12 USGS stream gauges. Streamflow data at ungauged control points or gauges with incomplete records are estimated using the hydrological model Soil and Water Assessment Tool (SWAT) (Arnold et al., 1998; Neitsch et al, 2002). The SWAT model is calibrated following the same procedure reported by Hu et al. (2007).

The hydrologic impacts of the reservoirs should also be properly accounted for in order to reconstruct the natural flow conditions. The existing data at gages downstream of the reservoir reflect the streamflow that has been affected by the M&I withdrawal. Hence, when downstream flow measurements are available, the natural streamflows are estimated by those measurements plus an amount that is equal to the M&I withdrawal rate. When downstream flow measurements are not available, the natural streamflows are estimated by the simulated streamflows, which are generated by SWAT based on a reservoir-free condition, less an estimated reservoir loss (mainly evaporation). Note that although SWAT itself has the ability to simulate reservoir storage, the model is not configured to perform this task in this study. Rather, it is used only to produce the pre-reservoir streamflows. The impact of the reservoirs is handled separately in a spreadsheet using the method described above, which appears to be technically more convenient.

The amount of stream water that is available for withdrawal is affected by the minimum in-stream flow standard. In-stream flow is mandatorily required to maintain sound ecological functions of the streams. In this study, the 7-day 10-year low flow (7Q10) is chosen to be the minimum in-stream flow standard, but any other constant or seasonally-specified value could be used. The 7Q10 values at different sections on the Sangamon River have been well documented by the Illinois State Water Survey (ISWS, 2002). It is necessary to point out that 7Q10 is a fairly optimistic choice for a low flow standard, since many states require a considerably higher environmental flow, such as the 10th percentile of the flow. It has by no means been determined that such a standard will adequately protect the aquatic ecosystem; the standard is used here because it is so readily available. It should be clear, however, that any other standard could be used.

Knowledge about the initial reservoir storage in each simulation period is also needed for the water allocation simulation in this study. Ideally, the available reservoir storage of the two lakes in each allocation period should be determined through a continuous reservoir routing analysis, which requires a detailed water balance accounting.

Such study requires accurate information about the hydrological inputs and outputs. In this case, however, some of the water budgets, such as runoff from ungaged tributaries that go directly into the reservoir, evaporation, and exchange between impounded and underground water, etc., are poorly understood. In a long-term allocation simulation, error introduced by inaccurate data may accumulate rapidly as the water balance progress over time, causing the analysis to fail in short order. Calibration using existing lake storage data is an effective way to control the error, but unfortunately, historical lake storage records are not available for this study.

Instead of conducting an extensive water balance to determine reservoir storages, the present study chooses a series of storage availability (reservoir capacity) conditions from 0% to 100% of the actual reservoir capacity (which is regarded here as a maximum capacity) as the input for the water allocation simulation. For each simulation run, only one level of reservoir capacity (as a fraction of the maximum) is selected for both reservoirs throughout the entire simulation span, regardless of the actual weather and hydrologic conditions. As a result, the simulation generates two extremes of possible allocation outcomes under different reservoir conditions. The actual allocation and the performance of the system will probably lie somewhere between these two extremes.

4.2.3 User Specification

All agricultural withdrawals are assumed to be used on riparian land. It is assumed that the farmland irrigated by stream water extends an average distance of 0.2 to 0.8 km from the waterfront on both sides of the stream, depending on the size of channels (Table 4.1). The down stream channels with relatively higher flow can support larger irrigation areas than the smaller channels upstream. The length of the channels is estimated based on the USGS digital map of Streams and Waterbodies of the United States (National Atlas of the US, 2006). This will result in a total area irrigated by surface water of about 1.25×10^5 ha. The total volume of water needed by each agricultural user during the selected allocation period is equal to the rainfall deficit times the land area owned by the user.

Moreover, it is assumed that all the agricultural users have already installed an irrigation system. As a result, the water allocation is not affected by capital investment considerations.

Table 4.1 Agricultural riparian zone width.

User No.	1	2	3	4	5	6	7	8
Riparian zone width (km)	0.2	0.2	0.2	0.2	0.2	0.3	0.2	0.2
User No.	9	10	11	12	13	14	15	
Riparian zone width (km)	0.2	0.2	0.6	0.6	0.6	0.8	0.8	

The current water demands by the M&I users, namely the cities of Decatur and Springfield, are about 1.71 m^3/s (39 mgd) (Keefer and Bauer, 2005) and 1.19 m^3/s (22 mgd) (Fitzpatrick and Harbison, 1986; Skelly, 2007), respectively.

Each agricultural or M&I user is assumed to hold an entitlement to water right, which is considered to be freely transferable from one riparian user to another. The size of the entitlement is determined by averaging the multi-year optimal demand for both agricultural and M&I users. The users' entitlements not only specify the withdrawal limit for the users, but also provide the numerical basis for the proportionally fair allocation. Moreover, it is assumed that all users are rational individuals who have perfect knowledge of their optimal demand and are able to maximize their economic benefit given a specific set of physical and regulatory constrains. No user would consume more than his or her optimal demand.

4.3 Allocation Horizon

In this study, allocation is implemented only during the critical period of each growing season, which is usually several weeks before and after corn tassel emergence. In this case, each year's allocation horizon is considered to be the period of 30 days before through 20 days after corn tassel emergence based on the work of Calvino et al. (2001) (see section 4.4 for detail). For the rest of the year, agricultural water demands are assumed to be negligible compared to this period.

The current analysis also assumes that a withdrawal and transfer plan is made only once at the beginning of the allocation horizon each year. Users follow the plan strictly throughout the period. It is assumed that the water allocation decisions are made with perfect foresight of the amount of rainfall, streamflow, and available reservoir storage during the entire allocation period. The perfect-foresight allocation will set a benchmark of what can best be obtained under each different allocation mechanism.

Allocation analysis is performed once a year from 1977 through 2006. This 30-year period covers a wide range of climatic conditions, containing extremely dry years, such as during 1988 and 1989, several moderately dry years, such as the ones in 1991, 1997, and 2005, a very wet year, 1993, and many normal to wet years. It is largely representive of the spectrum of moisture conditions Central Illinois has received historically.

4.4 Development of Water Use Benefit Functions

4.4.1 Agriculture

The present water allocation analysis requires a suitable irrigation benefit function, which links the amount of water applied and the consequent profit gain received by the agricultural users. The function should contain an embedded water-yield model which quantifies the impact of water input on corn yield. The water-yield model should be able to capture the maximal beneficial water input, beyond which no or negative improvement in corn yield can be resulted from additional water input. The maximal beneficial water input serves as a basis to determine each user's initial water rights entitlement. Moreover, the water-yield model for this study needs to capture the increasing trend in corn yield over years due to advance in agricultural technologies. Finally, the water use benefit function should have a concave property, so that the water allocation models can generate a unique optimal solution.

Based on the criteria described above, the present study reviewed several existing water-yield models for corn (Runge and Odell, 1958; Runge, 1968; Yaron, 1967; Leeper et al., 1974; Calvino et al., 2001; Diaz and Brown, 1997; Burke et al., 2004; Cai et al., 2007), but found that none of them meets all the requirements. Instead of adopting one of them, his study borrows some features from these models and developed the following log-quadratic relationship:

$$\ln Y = a_0 + a_1 yr + a_2 yr^2 + a_3(R + w) + a_4(R + w)^2 + a_5 GDD \qquad (4.1)$$

where $\ln Y$ is the natural logarithm of corn yield (kg/ha), yr is calendar year, R is total natural rainfall during the period of 30 days before through 20 days after corn tassel emergence (mm), w is the amount of irrigation applied during the same period (mm), GDD is the total growing degree day in this period (^{o}C), and a_0 through a_5 are coefficients to be determined by regression.

The growing degree day during each year's simulation horizon is calculated as

$$GDD = \sum_{i=d_s-30}^{d_s+20} \left(\frac{T_{\max,i} + T_{\min,i}}{2} - 10 \right) \tag{4.2}$$

where $T_{\max,i}$ and $T_{\min,i}$ are the maximum and minimum temperature of Julian day i, and d_s is the Julian date of corn tassel emergence. Each year's corn tasseling date is determined by the cumulative growing degree days since the beginning of the corn growing season, i.e. the corn seeding date. This study assumes the corn seeding date to be May 1st, based on Hu et al. (2007) and the growing degree days needed to bring corn to tassel emergence to be 708.3 ^{o}C-days, based on Nafziger (2003) for all simulation years.

This water-yield model combines features from several existing models. It adopts the quadratic form of the Yaron function (Yaron, 1967), incorporated the temperature effect considered by Runge (1968) and Leeper et al. (1974), chooses the irrigation period suggested by Calvino et al (2001), and borrows from the Runge and Odell (1958) the idea of using year as a predictor to capture the increasing trend in annual yield. In addition, a log transformation is applied to the corn yield term in order to improve the goodness-of-fit between model prediction and historical data. Furthermore, in addition to the single linear year term in the Runge-Odell model, the present model includes a quadratic year term, which is shown to be statistically significant based on historical data.

Regression analysis based on the basin total corn yield from 1930 through 2006 (NASS, 2006) shows that all the coefficients in the yield model (4.1) are statistically significant with *p*-value <0.002, suggesting that all the terms in the model are statistically important predictors of the corn yield. The resulting R^2 is 0.944 (Table 4.2 and Figure 4.3).

Table 4.2 Coefficients in the crop yield function for the entire Sangamon River basin

Coefficients	Value	Standard error	*t*-value	*p*-value
a_0	-662.5	60.0	-4.80	8×10^{-6}
a_1	6.61×10^{-1}	6.09×10^{-2}	4.71	1×10^{-5}
a_2	-1.63×10^{-4}	1.55×10^{-5}	-4.57	2×10^{-5}
a_3	5.35×10^{-3}	4.28×10^{-4}	5.44	7×10^{-7}
a_4	-1.23×10^{-5}	1.16×10^{-6}	-4.62	2×10^{-5}
a_5	-1.15×10^{-3}	1.55×10^{-4}	-3.23	2×10^{-3}

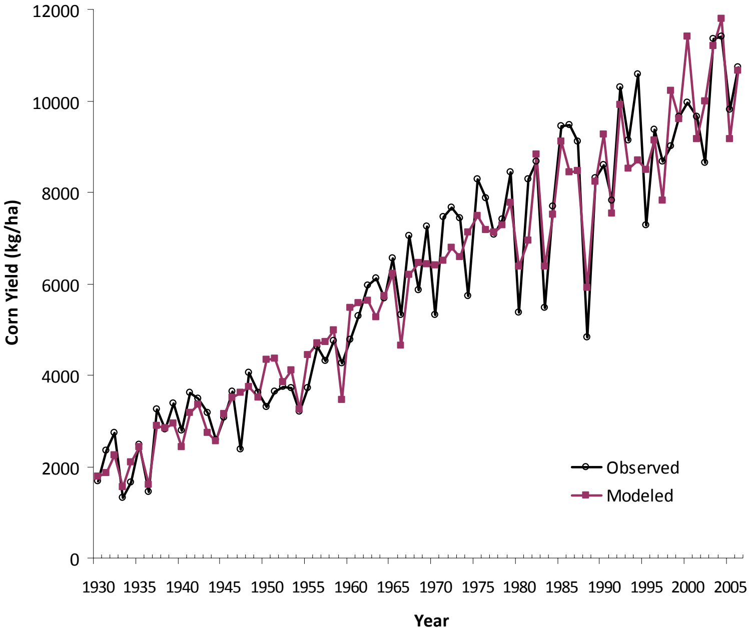


Figure 4.3 Observed and modeled corn yield

It is worth noting that alternative crop yield models and combinations of predicting terms have also been evaluated. For example, the Leeper model, incorporated with the first- and second-order year terms, produces an R^2 of 0.940. For another example, using 6 weeks before through 4 weeks after corn tassel emergence, which is suggested by Runge (1968) and Leeper et al. (1974) as the critical irrigation period, Equation (4.1) achieves an R^2 of 0.932. It is found finally that, of all the alternatives Equation (4.1) with 30 days before through 20 days after corn tassel emergence as the critical period achieve the highest R^2 value.

To capture the zone-to-zone variation in crop production, a yield-water use function is developed for each of the agricultural zones. The coefficients are listed in Appendix. 4.A.

Given the crop yield function, the net benefit ($/ha) generated by irrigation in a given year is calculated as:

$$NB_{ag} = p_c Y(w) - p_c Y(0) - c_v w - C_f \tag{4.3}$$

where p_c is the sales price for corn ($/kg), $Y(w)$ is the corn yield calculated by equation (4.1) with irrigation of w unit of water (kg/ha), $Y(0)$ is the corn yield with no irrigation (kg/ha), and c_v is the variable irrigation cost consisting primarily of energy, maintenance, and other operation-related costs that are directly proportional to the use of the equipment ($/ha-mm), and C_f is the annualized fixed irrigation cost associated with the capital investment and ownership of the equipment ($).

Depending on the purpose and setup of the problem, the fixed irrigation cost can be treated in two different ways, which would in turn affect how the allocation analysis is performed and how the results are interpreted. If all the agricultural users in the allocation system have already installed irrigation equipment, and water allocation and/or water rights transfers are to be determined independently on a year-to-year basis, then the fixed costs should be treated as sunk costs, which appear as zero in the users' net benefit functions. This is referred to as Case I. As shown in Figure 4.4, since the fixed costs are treated as sunk cost with no value, the net benefit curve starts as a zero value, since the fixed costs are sunk. In that case, the values of fixed costs do not affect the users' marginal benefits, and therefore have no impact on the solutions to the MaxBen and water rights market models as described in Chapter 3. As stated in section 3.7, the water rights market that exists under such conditions is a 'spot market', where water rights are transferred to meet short-term needs.

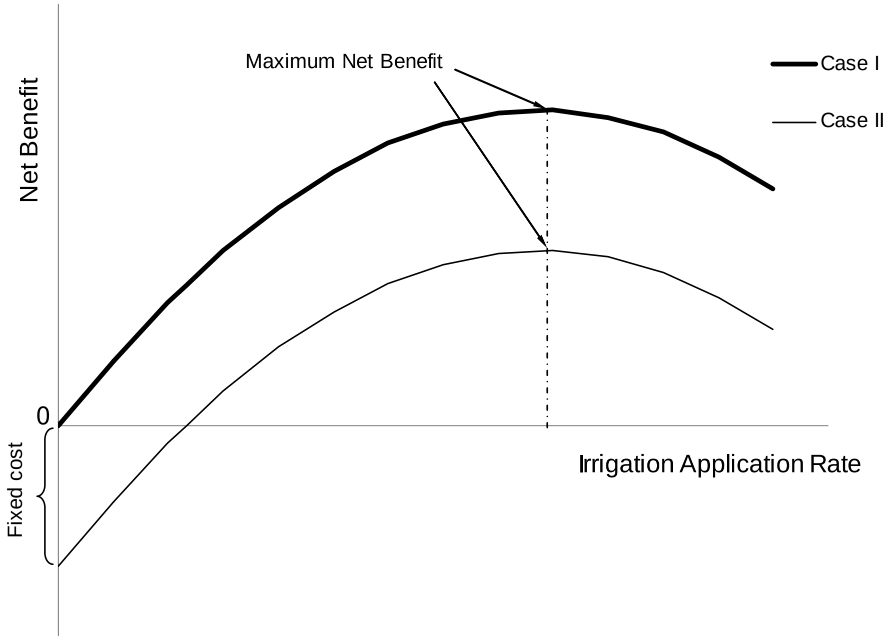


Figure 4.4 Functions of irrigation cost, benefit, and net benefit

On the other hand (Case II), if few or no users, have installed irrigation equipment and capital investment decisions are involved in the allocation process, then the analysis will be conducted in a different way. In that case, the net benefit function for non-irrigating agricultural users should be modified from Equation (4.3) to:

$$NB_{ag} = p_c Y(dw) - p_c Y(0) - c_v dw - dC_f \tag{4.4}$$

where *d* is a newly-introduced binary decision variable that indicates whether an investment in irrigation equipment will be made, 1 for yes, and 0 for no. If a user chooses not to install irrigation equipment, then her withdrawal, as well as the resulting net benefit, will either be zero, if the right is retained, or positive if it is sold to another user for revenue. If the user chooses to install irrigation equipment, then the Case II curve in Figure 4.4 is applicable. This curve shows a net benefit equal to the negative capital cost if equipment is bought but not used. To justify the capital investment, the user needs to acquire enough water to ensure that her investment is profitable, i.e. the total net benefit within a reasonable investment life (normally 15 to 20 years) is positive and may (or may not) thus choose to purchase some rights from another user. Therefore, a water allocation analysis of the sort that is the subject of this thesis would be performed on a 15 to 20 year basis, and the results would be seen as a long-term allocation and/or water rights transfer plan, which is tied to the joint capital investment decisions of all users.

For convenience, this study chooses Case I, i.e. capital costs are assumed sunk and capital decisions do not affect users' decisions on withdrawals. Case II, where water allocation and capital investment decisions are considered together, is left for future studies. Because it has no impact on water allocation solutions, the capital cost term is simply eliminated from the irrigation net benefit functions. As a result, the agricultural net benefits calculated based on the allocation solutions will only reflect irrigation-related net economic gain without capital costs.

Up-to-date irrigation cost information based on Illinois farmland is very limited. The present study utilized the data obtained from a detailed irrigation cost study recently conducted in Kansas (Dumler and Thompson, 2006; Dumler and Rogers, 2006). Based on the study, the energy cost for a diesel-powered, low head lift central pivot irrigation system, which is likely to be suitable for the riparian farmlands in Illinois, is, in 2008, about \$0.5/ha-mm when diesel fuel price is \$0.79/L (\$3/US gal). Labor and Maintenance cost adds about another 0.1 \$/ha-mm, assuming an average irrigation of about 100mm per year. Therefore, the total variable cost is estimated to be 0.6 \$/ha-mm. This cost is treated as a baseline cost representing the existing condition in the study watershed.

4.4.2 Municipal and Industrial (M&I) Use

The M&I users are assumed to follow the benefit function developed by Diaz and Brown (1997). The marginal water use benefit is expressed as the following exponential function of M&I water withdrawal:

$$b(w) = \alpha e^{-w/\beta} \tag{4.5}$$

where b is the marginal water use benefit for M&I users (\$/m^3), w is the flow rate of M&I withdrawal in the allocation period (m^3/s), and α and β are coefficients with the units of \$/m^3 and m^3/s, respectively. In economic terms, Equation (4.5) is also called the inverse demand function, which indicates the water use cost needed to balance out the benefit at a given consumption level. As Figure 4.5 shows, this function generates a reducing marginal benefit as the amount of water use increases. The benefit B is then the integral of the marginal benefit function from 0 to w:

$$B(w) = \alpha \cdot \beta\, [1 - \exp(-\, w/\beta)] \tag{4.6}$$

Thus, the net benefit for M&I use is

$$NB_{\mathrm{M\&I}} = B(w) - c_w w \tag{4.7}$$

where c_w is the marginal cost associated with M&I water use in \$/m^3. The unit of B and $NB_{\mathrm{M\&I}}$ in (4.5) and (4.6) is \$/s. They need to be multiplied by the total number of seconds in the entire allocation period to arrive at the total M&I benefit and total net M&I benefit in \$. As Figure 4.6 shows, this function has a unique maximum, at which the marginal benefit equals the marginal cost of water.

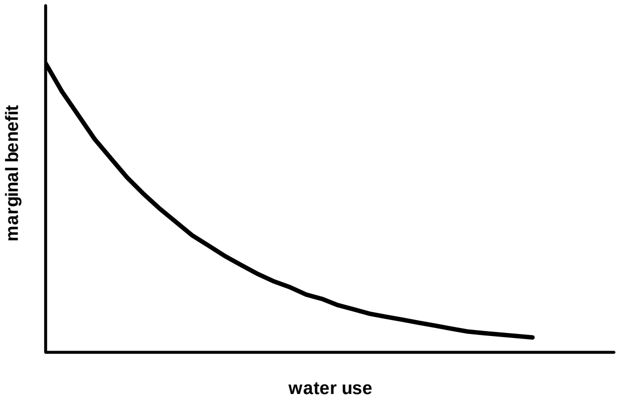


Figure 4.5 Marginal benefit of M&I water use.

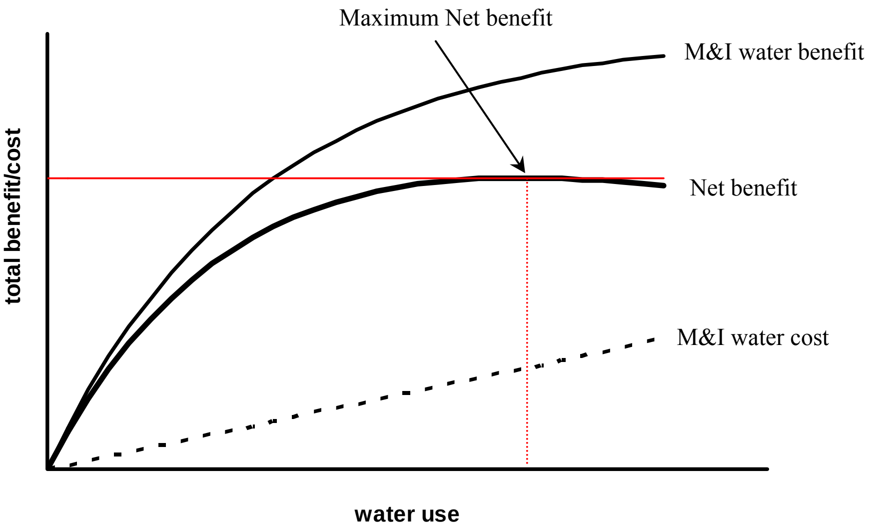


Figure 4.6 Benefit, cost, and net benefit of M&I water use.

Now the question is how to determine the values of α and β. The present study follows Diaz and Brown (1997) in estimating these two parameters. First, the value of β is calculated using the price elasticity, which is defined by the proportional change in the amount of water used as a result of per unit change in water use cost. When demand and supply are at equilibrium, which is assumed for the M&I users in this study, the marginal cost is equal to the marginal benefit calculated by (4.4). Thus, the price elasticity in this case is formulated as:

$$\varepsilon = \frac{\partial w / w}{\partial b / b} = \frac{b(w) / w}{b'(w)} \tag{4.8}$$

Substituting (4.5) and its first derivative into (4.8), we have:

$$\varepsilon = -\frac{w}{\beta} \tag{4.9}$$

Water supply price elasticity has been widely studied in the United States. Diaz and Brown (1997) summarized 39 recent studies and found that ε varies from -0.02 to -1.24, with most between -0.3 and -0.7. Unfortunately, similar research has not been conducted in the Central Illinois region. After reviewing available literature, this study chooses ε = -0.5 for the M&I benefit functions for both Springfield and Decatur. A sensitivity analysis is conducted later to examine the impact of ε value on allocation outcomes.

Given the selected price elasticity, the value of β can be easily determined by rearranging (4.9). As stated above, the present study assumes that the current withdrawal and price reflect the equilibrium of demand and supply, i.e. a condition where the marginal cost is equal to the marginal benefit:

$$\alpha \mathrm{e}^{-w/\beta} = c_w \tag{4.10}$$

Hence, the value of α can be determined by rearranging (4.10) given a known marginal water use cost.

In this study, water use cost for M&I users is considered to include both water and sewer/wastewater costs. Water rate information is obtained from a study by Dziegielewski et al. (2004), which surveyed more than 400 community water systems in Illinois, including Lake Decatur and Lake Springfield. The study finds that the marginal water prices at 18.9 m^3/month (5000 gal/month) usage level, which represents approximately the average water rate of the systems, are \$0.45 and \$0.41/m^3 for the Decatur and Springfield, respectively. The sewer rate is available only for Springfield from the City Water, Light & Power (2008), which shows the sewer rate for Springfield residences is \$0.37 /m^3 as of 2008. Household sewer cost is normally calculated based on water meter reading without adjustment. Information about industrial and commercial water/wastewater costs in the region is unavailable for this study, but presumably the costs are greater than those of residential use. Considering the above information and effects, the current water use cost for both M&I users in this study is chosen to be \$1.0/m^3.

4.5 Allocation Scenarios

Two allocation scenarios are evaluated in this study: the ‘Current’ Scenario, which is based on the *status quo* of water demand and cost, and the Future Scenario, which imposes the projected water demand and cost. Quotation marks are used because the ‘Current’ scenario is based on the hypothetical condition that all the riparian farmlands have installed irrigation systems, which is not currently true in Central Illinois.

Nevertheless, the rest of the scenario largely represents the pre-existing conditions in the watershed.

The major input parameters for both scenarios are listed in Table 4.3. The 'Current' scenario calculates crop yield on the basis of the calendar year 2006 being used for *yr* in the yield model for the entire 30-year simulation period. As described earlier, current corn price and irrigation cost are set at \$0.16 /kg (\$4 /bu) and \$0.6 /ha-mm, respectively. Agricultural water demand by each user each year is determined as the water input that maximizes the net benefit function (4.3). Current M&I demands are fixed to 1.71 and 1.19 m^3/s for cities of Decatur and Springfield, respectively, for the entire 30-year period. The analysis of the 'Current' scenario will tell us what allocation outcomes would result from different water sharing and market mechanisms under the semi-hypothetical current demands and over a 30-year range of hydrologic conditions.

Table 4.3 Important parameters for the ‘Current’ and Future scenarios

	‘Current’	Future
Baseline year for crop production	2006	2030
Inflation adjustment	1	2.28
Irrigated area	×1	×2
Irrigation cost*	\$0.6 /ha-mm	\$1.68 /ha-mm
Corn price*	\$0.16 /kg (\$4 /bu)	\$0.37 /kg (\$9.4 /bu)
M&I water withdrawal		
Lake Decatur	1.71 m^3/s (39 mgd)	1.93 m^3/s
Lake Springfield	1.19 m^3/s (28 mgd)	1.59 m^3/s
Water price*	\$1.0 $/m^3$	\$2.3 $/m^3$
M&I water benefit function parameters:		
α (Decatur, Springfield)	7.4, 7.4	16.9, 16.9
β (Decatur, Springfield)	0.68, 1.3	0.60, 0.90

* In current dollar values.

The Future Scenario is based on the vision that both the amount and the cost of water consumption in the study watershed will increase in the future as a result of the increase in crop production, irrigation area, municipal development, and raw material prices. The year of the future scenario is chosen to be 2030, by which time both irrigation and municipal demands are expected to increase. The area of irrigated riparian land in the Future Scenario is assumed to be twice as much as in the Current Scenario. The doubled irrigation areas are comparable to the amount assumed used by An (2004). The M&I water demands in the Future Scenario are expected to increase by 1.34 and 1.13 times the current amount for the cities of Springfield and Decatur, respectively. This is based on the prediction of county-level water supply needs in the Midwest conducted by

Dziegielewski et al. (2004). Corn yield in this year is projected using the yield function (4.1), which predicts a growing trend yield. While continuous increase in corn yield in future is still a matter of debate, this prediction appears to be consistent with the results of several existing studies (Tannura et al., 2008; Troyer, 2006; Kucharik and Ramankutty, 2005; Garcia et al., 1987). Both benefits and costs of water use in the Future Scenario are projected based on their historical trend between 1980 and 2007. Corn price was increasing by about 3.0% per year on average in this period (see Figure 4.7, Agricultural Marketing Resource Center, 2008) and is predicted in this study to increase at a rate 1.2 times faster than this rate in the future, reflecting the augmenting demand for corn due to the boom of the corn ethanol industry and generally increasing petroleum price. This seemingly optimistic prediction is partially based on the assumption that corn ethanol will continue to be one of the main types of biofuel in the future and the global demand for energy will continue to rise. The uncertainty associated with this prediction will be addressed by sensitivity analysis and qualitative discussion. Irrigation cost is assumed to inflate at the same rate as the gasoline price, which has been about 3.7% on annual average (Figure 4.7). The cost of M&I water consumption is assumed to increase at the same rate as the Consumer Price Index (CPI) in the US (US Census Bureau, 2008), which has been about 3.5% on annual average (Figure 4.7). As a result, the corn price, irrigation cost, and M&I water cost in 2030 would be 2.3, 2.4, and 2.3 times higher than their respective value in 2006.

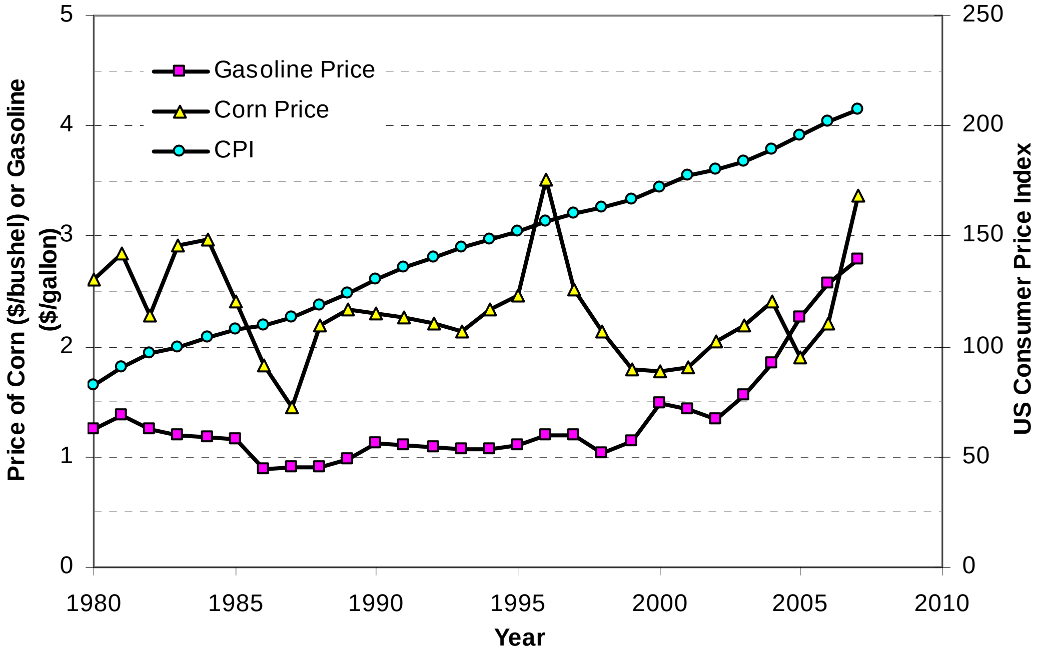


Figure 4.7 US Consumer Price Index and prices of gasoline and corn from 1980 to 2007
(1 corn bushel = 25.4 kg, 1 US gallon = 4.785 L)

Finally, in order to better compare the results between the ‘Current’ and the Future Scenarios, all monetary results are converted to the 2006 dollar using the average growth rate in CPI between 1976 and 2006.

4.6. Execution of Allocation Analysis

Figure 4.8 shows the framework of the computer program developed for the water allocation analysis. The allocation scenarios and net benefit functions are used to determine the formula of the objective functions of the allocation models. Raw data of flow, weather, and river geometry were used to develop the constraints of the models. Missing flow data are generated by the SWAT model, which also require raw flow and weather data for calibration. The program is developed using Visual Basic for Application (VBA) under the Microsoft Excel environment. The allocation model is solved using the Generalized Reduced Gradient Algorithm (Abadie and Carpentier, 1969) provided by Excel.

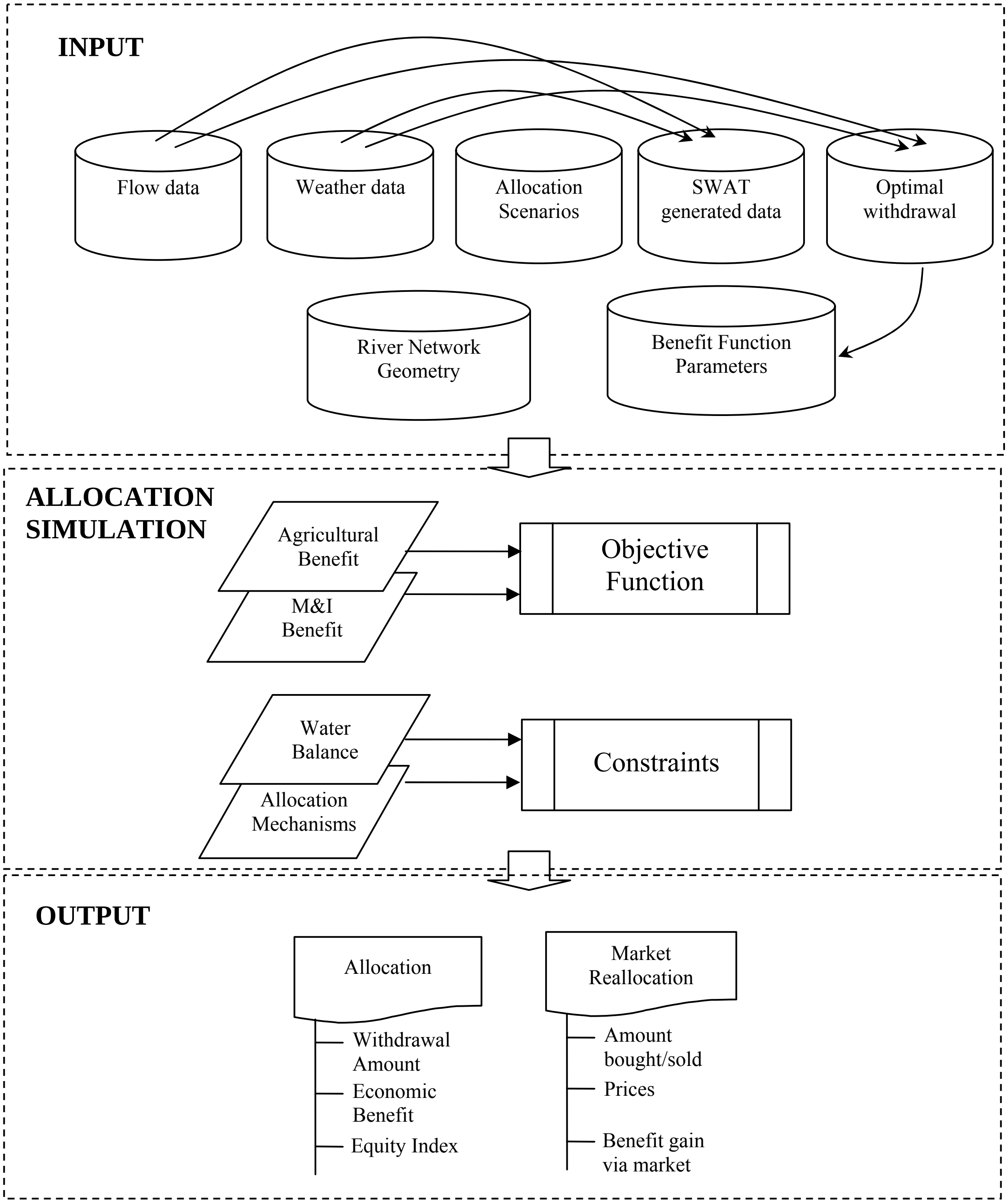


Figure 4.8 Diagram of water allocation simulation processes

APPENDIX. 4.A. Coefficients of Crop Yield Functions for Agricultural Users

	a_0	a_1	a_2	a_3	a_4	a_5
User 1	-212.8	0.2116	-5.156E-05	2.252E-03	-5.206E-06	-4.130E-04
User 2	-243.7	0.2428	-5.945E-05	2.286E-03	-5.372E-06	-4.092E-04
User 3	-280.4	0.2799	-6.882E-05	2.338E-03	-5.574E-06	-4.174E-04
User 4	-296.0	0.2953	-7.265E-05	2.781E-03	-6.444E-06	-4.992E-04
User 5	-289.9	0.2897	-7.137E-05	2.226E-03	-5.255E-06	-4.426E-04
User 6	-320.5	0.3199	-7.872E-05	2.452E-03	-5.600E-06	-8.918E-04
User 7	-320.5	0.3199	-7.872E-05	2.452E-03	-5.600E-06	-8.918E-04
User 8	-320.5	0.3199	-7.872E-05	2.452E-03	-5.600E-06	-8.918E-04
User 9	-257.5	0.2558	-6.247E-05	2.152E-03	-4.924E-06	-7.480E-04
User 10	-257.5	0.2558	-6.247E-05	2.152E-03	-4.924E-06	-7.480E-04
User 11	-282.7	0.2821	-6.938E-05	2.750E-03	-6.297E-06	-3.684E-04
User 12	-317.9	0.3182	-7.859E-05	2.252E-03	-5.336E-06	-5.186E-04
User 13	-298.5	0.2980	-7.333E-05	2.560E-03	-6.000E-06	-5.832E-04
User 16	-277.9	0.2767	-6.778E-05	2.339E-03	-5.382E-06	-7.616E-04
User 17	-289.3	0.2881	-7.069E-05	2.399E-03	-5.451E-06	-5.429E-04

CHAPTER 5. RESULTS AND DISCUSSION

Water allocation simulation for the Sangamon River system with 17 agricultural and M&I users is performed under two scenarios. The ‘Current’ scenario is based on a mixture of real and hypothesized economic conditions in 2006, whereas the Future scenario imposes water demands that are estimated based on projected economic changes in 2030. For each scenario, the five allocation programs introduced in Chapter 3, namely the Maximum Benefit (MaxBen), Proportionally Fair (ProFair), Downstream Priority (DPrio), Upstream Priority with Municipal and Industrial User Privilege (UMIPrio), and No Rule (NR) programs, are evaluated using the historical rainfall and streamflow data from 1977 through 2006 combined with a series of different reservoir storage conditions. Recall that storage conditions are expressed here as a percent of the maximum, which consist of 34.5 mcm at Decatur and 63.4 mcm at Springfield. The percentage is applied uniformly to the two reservoirs. The monetary results of the Future Scenario are converted to the 2006 dollar using a discount rate estimated from the long-term average growth in the Consumer Price Index.

5.1 Economic Benefits

5.1.1 Aggregated Net Benefit and Total Withdrawal

Figures 5.1 and 5.2 show the aggregated net benefits resulting from the selected water allocation programs under the Current and the Future demand scenarios, respectively, over the range of hydrologic conditions that occurred between 1977 and 2006. In the figures, the wide bars indicate the net benefits achieved when both Lake

Decatur and Lake Springfield are empty (i.e. zero-storage condition); and the narrow bars on top of the wide bars indicate the additional net benefit achieved when both reservoirs are full (i.e. 100% storage condition). The actual net benefits vary within the ranges of the narrow bars, depending on the actual reservoir storage conditions.

An immediate observation from Figure 5.1 and 5.2 is that under both demand scenarios, the aggregated net benefits achieved by the selected allocation programs are not significantly different from each other in the majority of the simulation years. Particularly, no difference among the programs is found in 16 and 13 of the 30 simulation years under the ‘Current ‘and the Future demand scenarios, regardless of the reservoir stage. Such a result reflects the fact that the humid Midwestern weather can provide sufficient water supply to meet all demands in normal years, and suggests that the choice of allocation mechanism is not important in those years. Considerable difference among programs happens in years where both rainfall and streamflow are remarkably low. For example, under the ‘Current’ scenario, the difference is most prominent under the 1988 condition, in which the basin-average rainfall and total streamflow in the allocation period are only 37 mm and 12.4 m^3/s, respectively, which are substantially lower than the average 163 mm and 118 m^3/s over all simulation years (see Figure 5.5). Under the Future Scenario, more notable difference among programs is found under less sever droughts, such as those of 1989 1991, and 2005, in which rainfall and runoff in the allocation time window are about 100 mm and 30s m^3/s, respectively.

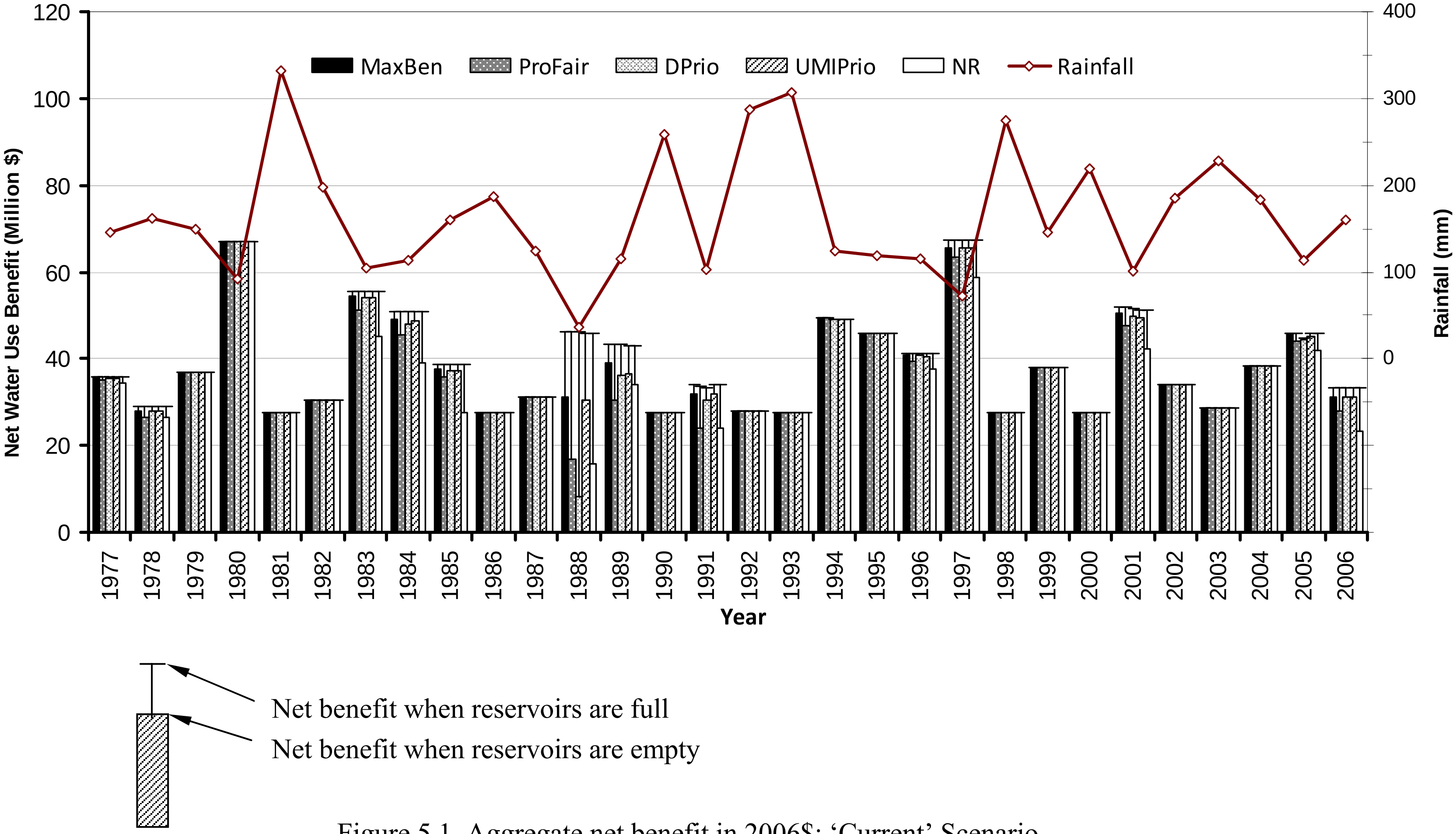


Figure 5.1 Aggregate net benefit in 2006$: ‘Current’ Scenario

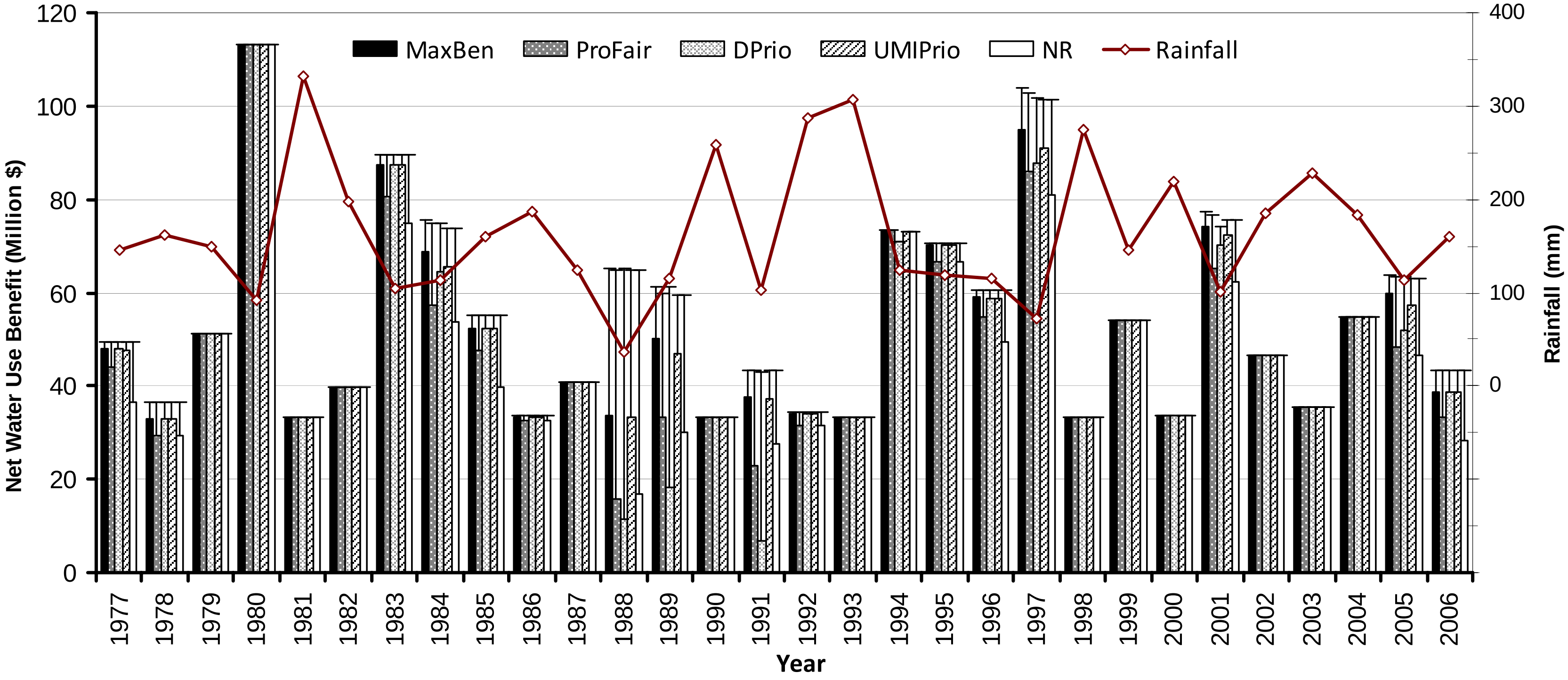


Figure 5.2 Aggregate net benefit in 2006$: Future Scenario

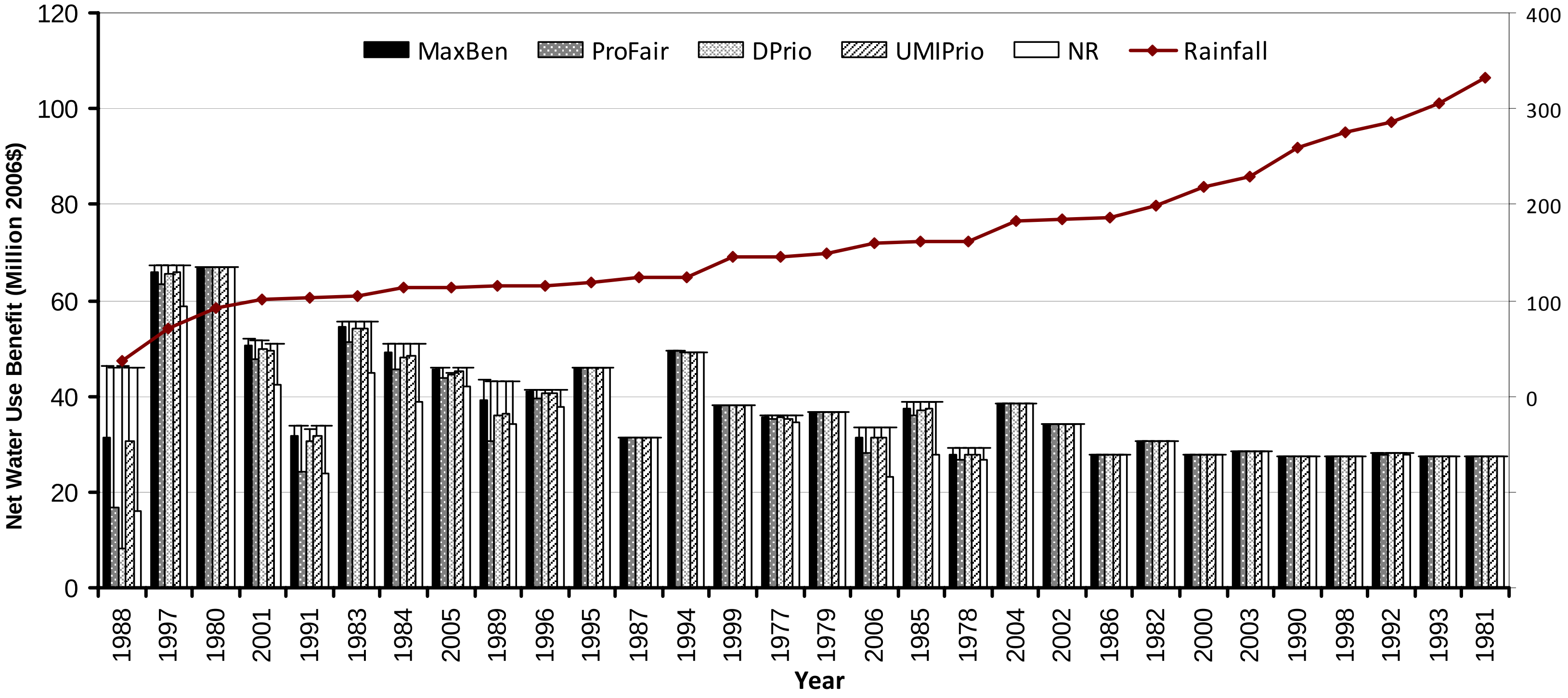


Figure 5.3 Aggregate net benefit in 2006$ sorted by rainfall: ‘Current’ Scenario

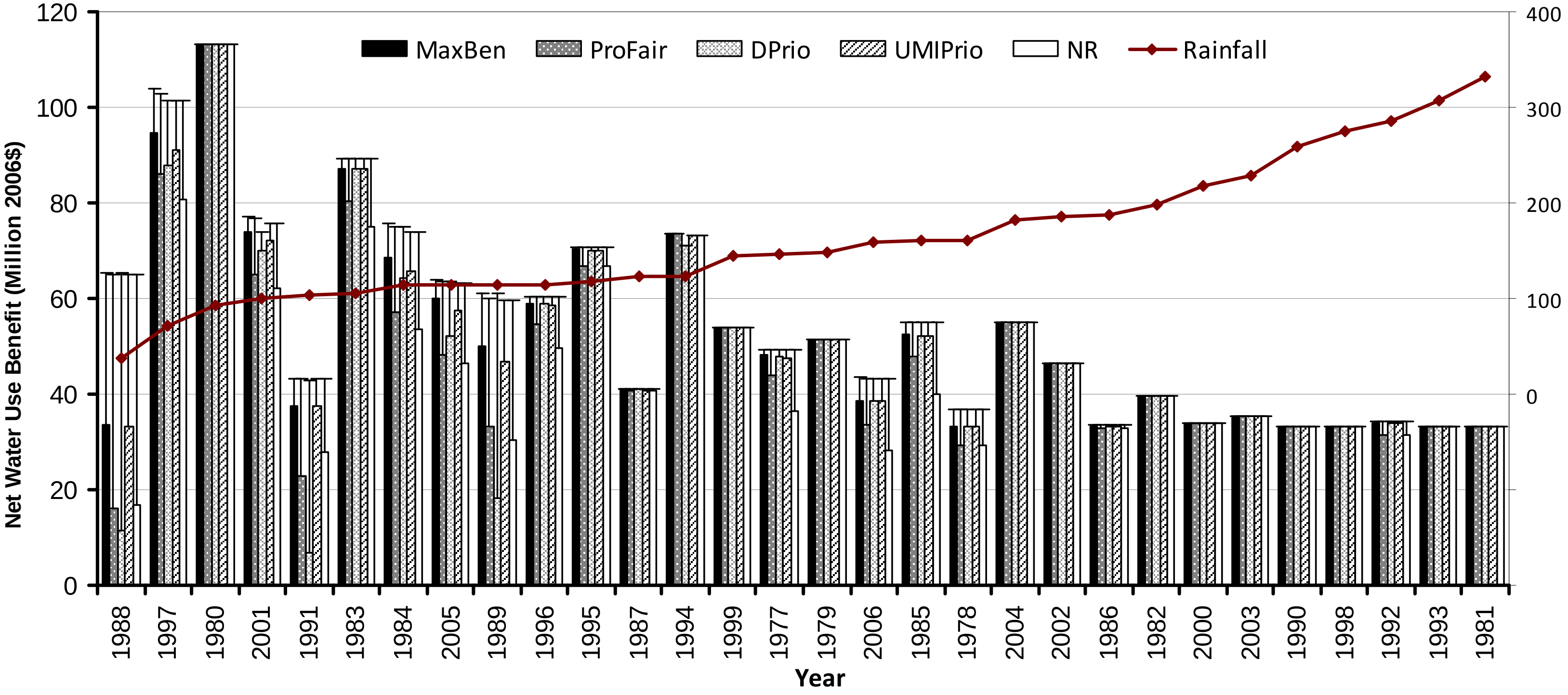


Figure 5.4 Aggregate net benefit in 2006$ sorted by rainfall: Future Scenario

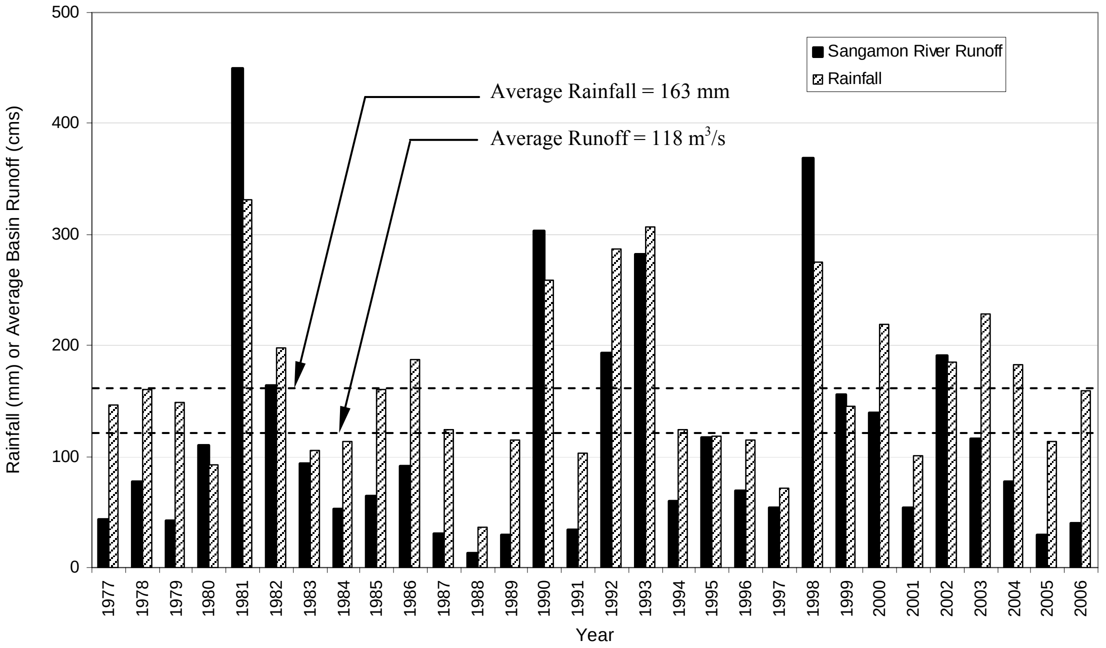


Figure 5.5 Sangamon River basin rainfall and runoff during allocation windows

The relationship between water availability and aggregate net benefit is better shown by Figure 5.3 and 5.4, which is nothing different from Figure 5.1 and 5.2, except that the results from individual years are sorted in ascending order of rainfall. The sorted figures show that the aggregated net benefit is generally negatively correlated to the rainfall. This result reflects the fact that water uses (especially agricultural uses) yield more economic benefit in dry years than in wet years. However, a notable exception is found under the hydrologic conditions of 1988, which marks the 8th driest year in the recorded Illinois weather history (Winstanley et al., 2006). Although water is much needed in this year, the net benefit from withdrawal is not as great as in many other dry years, especially under the low reservoir storage conditions. This is simply because the streamflows are so diminished by the drought that there is little water left for the users to withdraw, regardless of their locations and entitlements. Hence, although the water has a high marginal value in this year, the total water use benefit is not great due to the limited availability of water. A similar situation also occurs in 1991, but to a lesser extent. Aggregate net benefit is highest in years where rainfall is relatively low and streamflow is just enough to make up for the rainfall deficit, such as 1980 and 1997.

Figure 5.3 and 5.4 also show that the range of impact of the reservoirs on water allocation, which is indicated by the differences between the full-storage and zero-storage net benefits (i.e. the height of the narrow bars in the figures), increases as the natural water supply from rainfall and runoff decreases. Such impact appears to become more obvious when rainfall in the allocation period drops below about 120 mm/yr. According to the results, low availability of reservoir storage not only reduces the economic output of the entire system, but also widens the gaps among alternative allocation programs. This result reflects the different preference each program has between agricultural and M&I users. Since the marginal benefit of M&I withdrawal is often much greater than that of agricultural withdrawal, the resulting net benefit of the entire system is heavily influenced by how much water the M&I users can finally receive, which is determined by the allocation rules. As the reservoir storage condition improves, the gaps among programs attenuate rapidly (Figure 5.6). At full storage, the difference among alternative programs becomes zero or insignificant in all simulation years.

The economic benefits of all water allocation programs escalate substantially as the demand scenario shifts from ‘Current’ to Future. The range of annual average aggregated net benefit across programs and reservoir storage conditions increases from 34.8 ~ 38.9 to 46.1 ~ 54.7 M$ in 2006 value, an increase of 31~40%. The agricultural and M&I sectors both contribute to this net benefit increase gaining 75~86% and 11~21%, respectively.

The growth in net benefit in the Future scenario is mostly a result of growing water need. It is found that the agricultural, M&I, and total water withdrawals all increase under the Future Scenario (Table 5.1 to 5.3). In contrast to the net benefit results, on which the selection of program has a considerable influence, the total water withdrawals are found nearly identical among alternative programs (Table 5.3). This result suggests that all the selected programs, although differ in economic results, are able to achieve overall similar level of physical efficiency. Depending on the reservoir condition, the average annual total withdrawal under the Future Scenario is 65 ~ 72% greater than that under the 'Current' Scenario. Both agricultural and M&I withdrawals appear to be largely consistent across the selected programs as well, except for some small variations (all within ±0.4 m^3/s) under low reservoir storage conditions. The withdrawals by the two sectors grow by 72~83% and 7~21%, respectively, under the Future Scenario depending on the reservoir storage condition.

Table 5.1. Annual average agricultural withdrawals under the 'Current' and Future Scenarios. "Reservoir Capacity" is tabulated as the percentage of maximum capacity.

Reservoir Capacity	'Current' agricultural withdrawal (m^3/s)					Future Agricultural withdrawal (m^3/s)				
	MaxBen	ProFair	NR	DPrio	UMIPrio	MaxBen	ProFair	NR	DPrio	UMIPrio
0%	11.8	12.1	12.1	11.8	11.8	20.8	21.4	21.4	21.0	20.8
10%	12.3	12.4	12.3	12.3	12.2	21.4	21.9	21.5	21.7	21.4
20%	12.4	12.5	12.4	12.5	12.4	21.9	22.2	21.9	22.1	21.9
30%	12.5	12.6	12.5	12.6	12.5	22.3	22.5	22.4	22.6	22.4
40%	12.6	12.6	12.6	12.6	12.6	22.6	22.8	22.7	22.8	22.7
50%	12.7	12.7	12.7	12.7	12.7	22.8	22.9	22.9	23.0	22.9
60%	12.7	12.7	12.7	12.7	12.7	22.8	23.0	22.9	23.1	22.9
70%	12.7	12.7	12.7	12.7	12.7	22.9	23.0	23.0	23.1	23.0
80%	12.7	12.7	12.7	12.7	12.7	23.0	23.1	23.1	23.1	23.1
90%	12.7	12.7	12.7	12.7	12.7	23.2	23.2	23.2	23.2	23.2
100%	12.7	12.7	12.7	12.7	12.7	23.2	23.2	23.2	23.2	23.2

Table 5.2. Annual average M&I withdrawals under the ‘Current’ and Future Scenarios.

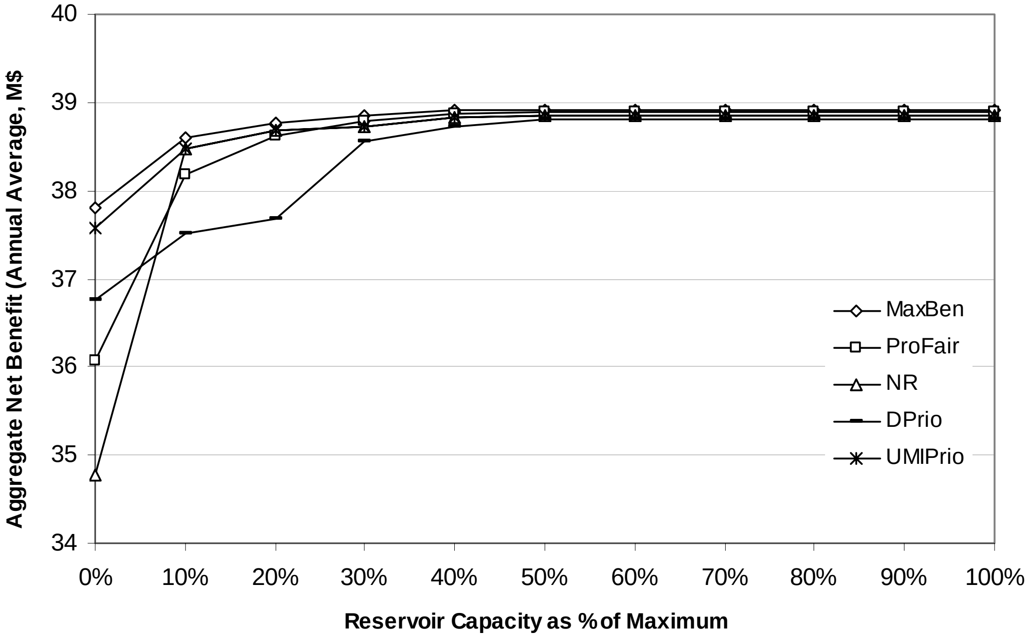
Reservoir Capacity	‘Current’ M&I withdrawal (m^3/s)					Future M&I withdrawal (m^3/s)				
	MaxBen	ProFair	NR	DPrio	UMIPrio	MaxBen	ProFair	NR	DPrio	UMIPrio
0%	2.7	2.4	2.4	2.7	2.8	3.2	2.6	2.6	3.0	3.3
10%	2.9	2.7	2.9	2.8	2.9	3.4	3.1	3.4	3.2	3.5
20%	2.9	2.8	2.9	2.8	2.9	3.5	3.2	3.5	3.4	3.5
30%	2.9	2.9	2.9	2.9	2.9	3.5	3.3	3.5	3.4	3.5
40%	2.9	2.9	2.9	2.9	2.9	3.5	3.4	3.5	3.4	3.5
50%	2.9	2.9	2.9	2.9	2.9	3.5	3.5	3.5	3.4	3.5
60%	2.9	2.9	2.9	2.9	2.9	3.5	3.5	3.5	3.4	3.5
70%	2.9	2.9	2.9	2.9	2.9	3.5	3.5	3.5	3.4	3.5
80%	2.9	2.9	2.9	2.9	2.9	3.5	3.5	3.5	3.5	3.5
90%	2.9	2.9	2.9	2.9	2.9	3.5	3.5	3.5	3.5	3.5
100%	2.9	2.9	2.9	2.9	2.9	3.5	3.5	3.5	3.5	3.5

Table 5.3. Annual average agricultural withdrawals under the ‘Current’ and Future Scenarios.

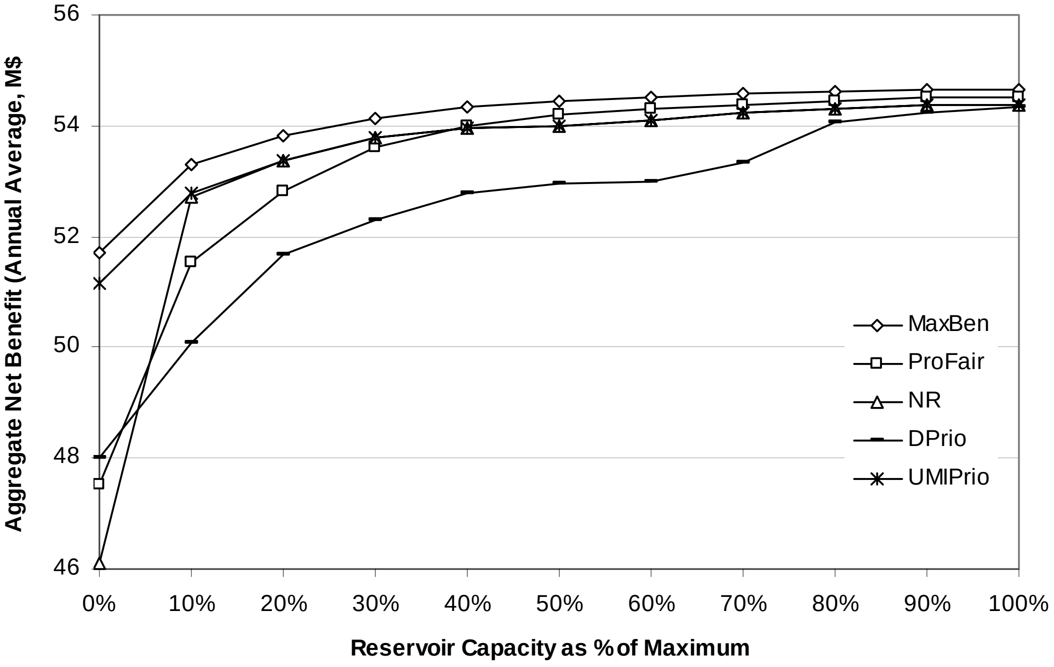
Reservoir Capcaity	Current total withdrawal (m^3/s)					Future M&I withdrawal (m^3/s)				
	MaxBen	ProFair	NR	DPrio	UMIPrio	MaxBen	ProFair	NR	DPrio	UMIPrio
0%	14.5	14.5	14.5	14.5	14.5	24.0	24.0	24.0	24.0	24.0
10%	15.2	15.1	15.1	15.1	15.1	24.8	24.9	24.9	24.9	24.9
20%	15.3	15.3	15.3	15.3	15.3	25.4	25.5	25.5	25.5	25.5
30%	15.4	15.4	15.4	15.4	15.4	25.8	25.9	25.9	26.0	25.9
40%	15.5	15.5	15.5	15.5	15.5	26.1	26.2	26.2	26.2	26.2
50%	15.6	15.6	15.6	15.6	15.6	26.3	26.4	26.4	26.4	26.4
60%	15.6	15.6	15.6	15.6	15.6	26.4	26.5	26.5	26.5	26.5
70%	15.6	15.6	15.6	15.6	15.6	26.4	26.5	26.5	26.5	26.5
80%	15.6	15.6	15.6	15.6	15.6	26.5	26.6	26.6	26.6	26.6
90%	15.6	15.6	15.6	15.6	15.6	26.7	26.7	26.7	26.7	26.7
100%	15.6	15.6	15.6	15.6	15.6	26.7	26.7	26.7	26.7	26.7

5.1.2 Comparing Economic Benefit of Alternative Allocation Mechanisms

One of the main purposes of the allocation analysis is to compare the performance of the selected allocation mechanisms. The MaxBen program is based entirely on the optimization of economic values, assuming that all utility functions for individual users are precisely known. No additional constraints are considered other than water balance. Therefore, the BM program always achieves the highest aggregate net benefit regardless of the supply/demand condition. It sets an economic bench mark for all allocation mechanisms.



(a)

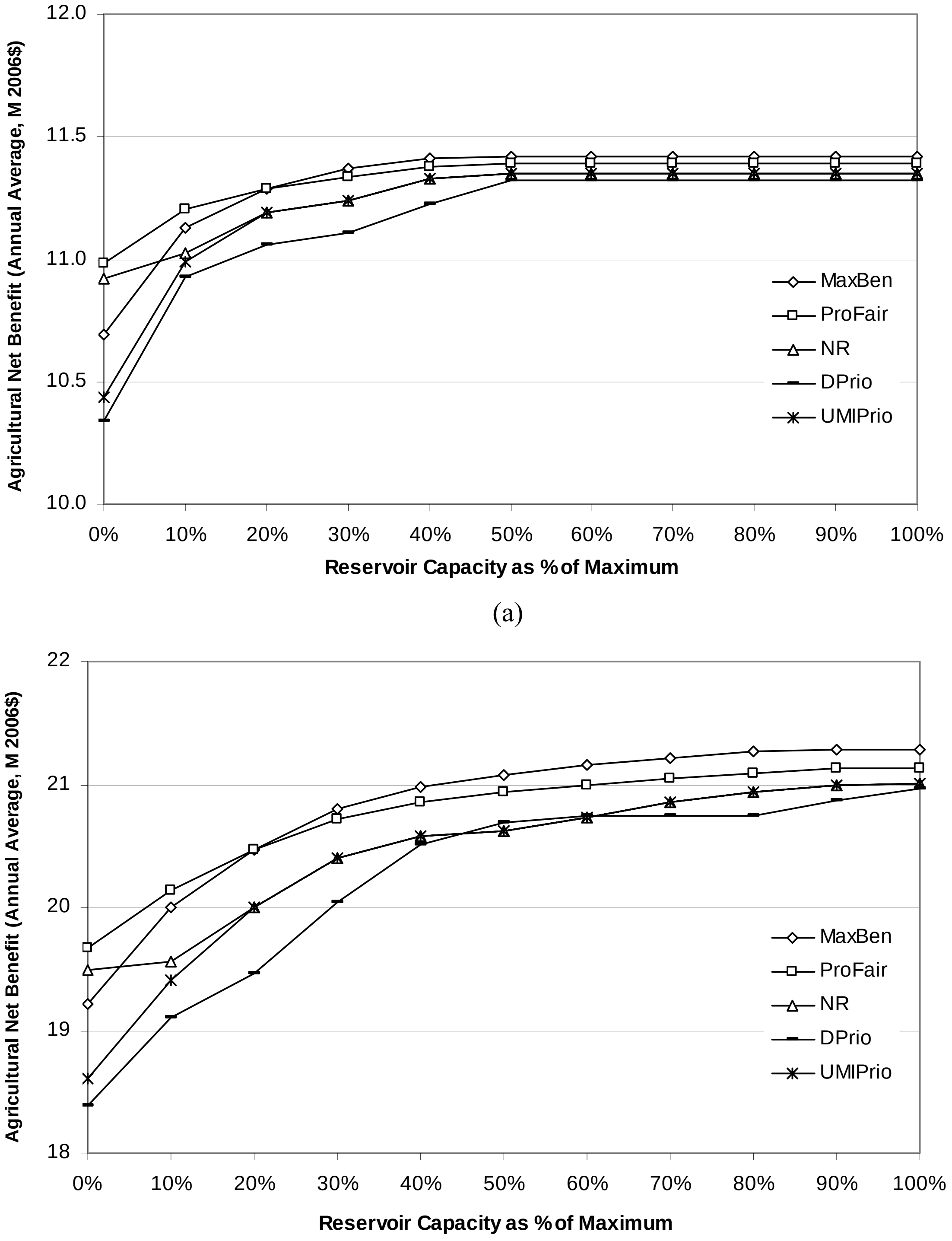


(b)

Figure 5.6 Average annual aggregated net benefit vs. reservoir storage condition under (a) 'Current' and (b) Future scenarios.

The economic performance of the rest of the programs is largely influenced by the reservoir storage conditions. When reservoir levels rise beyond about 30 to 40%, the ProFair program on average appears to achieve the closest economic benefit to MaxBen (Figure 5.6). When reservoir levels are at 10 to 30%, the NR and UMIPrio programs exceed DPrio and ProFair to achieve the second highest economic benefit. When the reservoirs are empty, the UMIPrio program, which first secures the high-value M&I consumption achieves the second highest economic benefit, whereas the NR program, which first benefits the upstream agricultural users in this case produces the lowest economic efficiency. The net benefit of the NR program increases more rapidly than any other program when the reservoir storage increases from zero to 10%. This is because the NR program, while allocating M&I users little or no water when the reservoirs are empty and streamflow is too low to even satisfy the upstream agricultural users, allows the M&I users exclusive access to the reservoir storage once available. Finally, the DPrio program, which prioritizes users in the reverse order of upstreamness, constantly produces the worst economic benefit under all, except for the 0%, reservoir conditions.

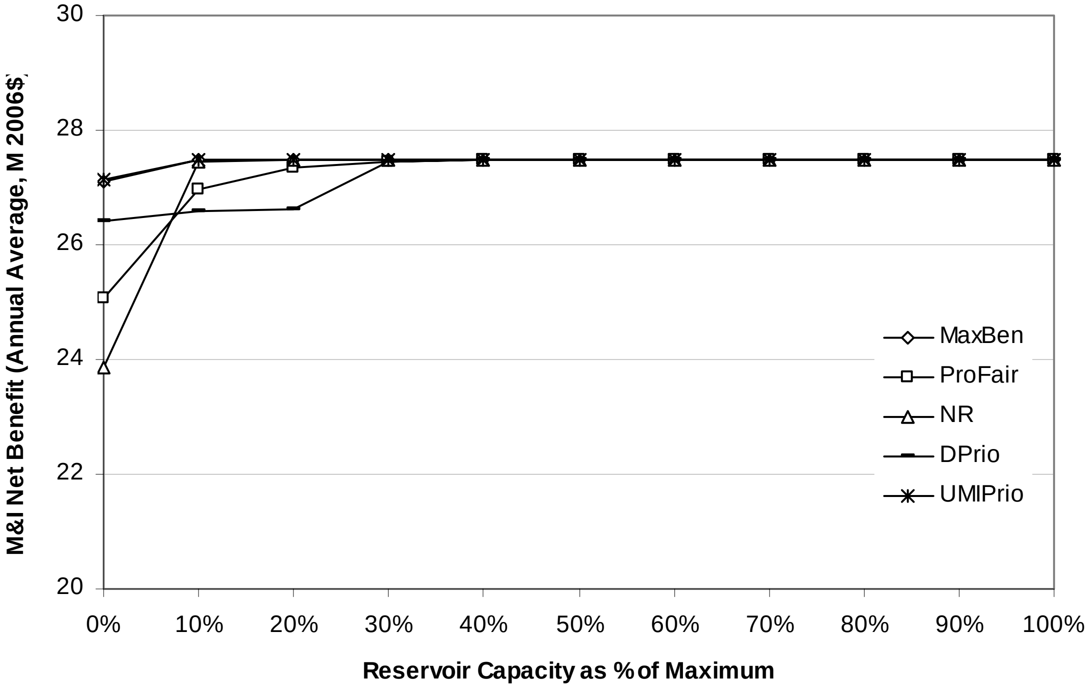
Closer examination of the breakdown of the agricultural and M&I sectors (Figure 5.7 and 5.8) reveals that the ProFair program constantly generates the greatest agricultural benefit among all the selected programs except for MaxBen. It even exceeds MaxBen in agricultural benefit when available reservoir storage is less than 20%. This result shows that a ProFair program would be slightly more beneficial for low-value than high-value users. On the other hand, the UMIPrio program, as expected, produces the highest M&I benefit under all reservoir and demand conditions.



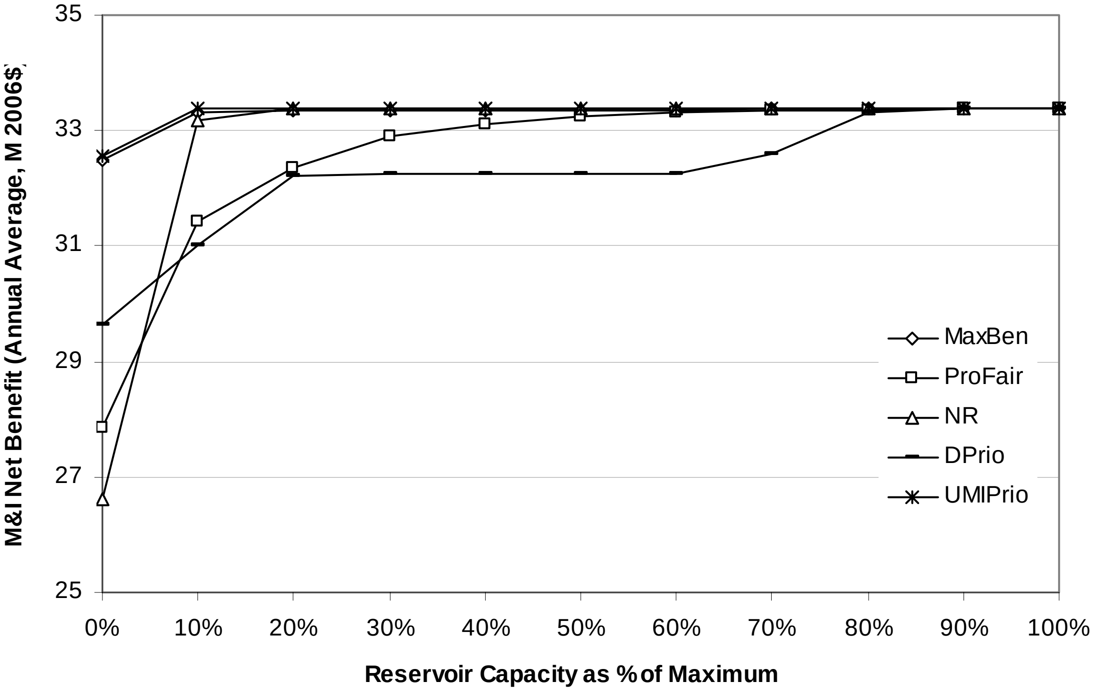
(a)

(b)

Figure 5.7 30-year average net agricultural benefit vs. reservoir storage condition under (a) ‘Current’ and (b) Future scenarios.



(a)



(b)

Figure 5.8 Average annual net M&I benefit vs. reservoir storage condition under (a) ‘Current’ and (b) Future scenarios.

These results show that no program other than MaxBen is able to dominate in economic efficiency under all hydrologic conditions. In a water shortage, a program that is able to secure high value M&I withdrawals first tends to achieve higher net benefit than a program that spreads water more evenly among users. A program that can neither guarantee high value withdrawals nor evenly share water among users, such as the DPrio program, is likely to result in the worst economic efficiency under all hydrologic conditions.

5.2 Equity

As explained in Chapter 3.7, the Equity Index (EI), defined by Eq. 3.20, is developed to quantify the fairness among users achieved by an allocation program. It measures the degree of similarity among users with respect to their water supply satisfaction, where water supply satisfaction is defined as the ratio of a user's actual withdrawal to its demand. The value of EI can range between zero and one, where a value of one indicates perfect fairness, in which all users receive the same level of water supply satisfaction, and an EI of zero indicates perfect unfairness, in which only one user is allowed to withdraw, nobody else.

5.2.1 General EI Results

Figure 5.9 and 5.10 show the 30-year EI series resulted from the studied programs under selected reservoir conditions. It can be observed that EI values are generally negatively correlated with rainfall under all programs and reservoir conditions. Perfect EI values (i.e. EI = 1) occur most frequently in wet years with rainfall in the allocation period greater than 200 mm, while the lowest EI values happens in dry years with rainfall less than 100 mm. EI differentiation among programs tends to escalate in dry years under low reservoir storage conditions, but attenuates as the reservoir levels improve.

Under the ‘Current’ scenario, EI values resulting from the selected programs are not substantially different from each other and range between 0.6 and 1 for most years. In 9 of the 30 simulation years, EI equals one regardless of program selection or reservoir storage conditions, suggesting that in those years rainfall and runoff together can provide enough water to fully satisfy every user’s need. In some other years, different programs produce nearly identical EI values that are substantially less than 1. This results because the moisture in those years is distributed such that it can fully satisfy all but a small number of headwater users, who, without any upstream input or access to outside sources, cannot improve their water supply condition no matter what program is selected.

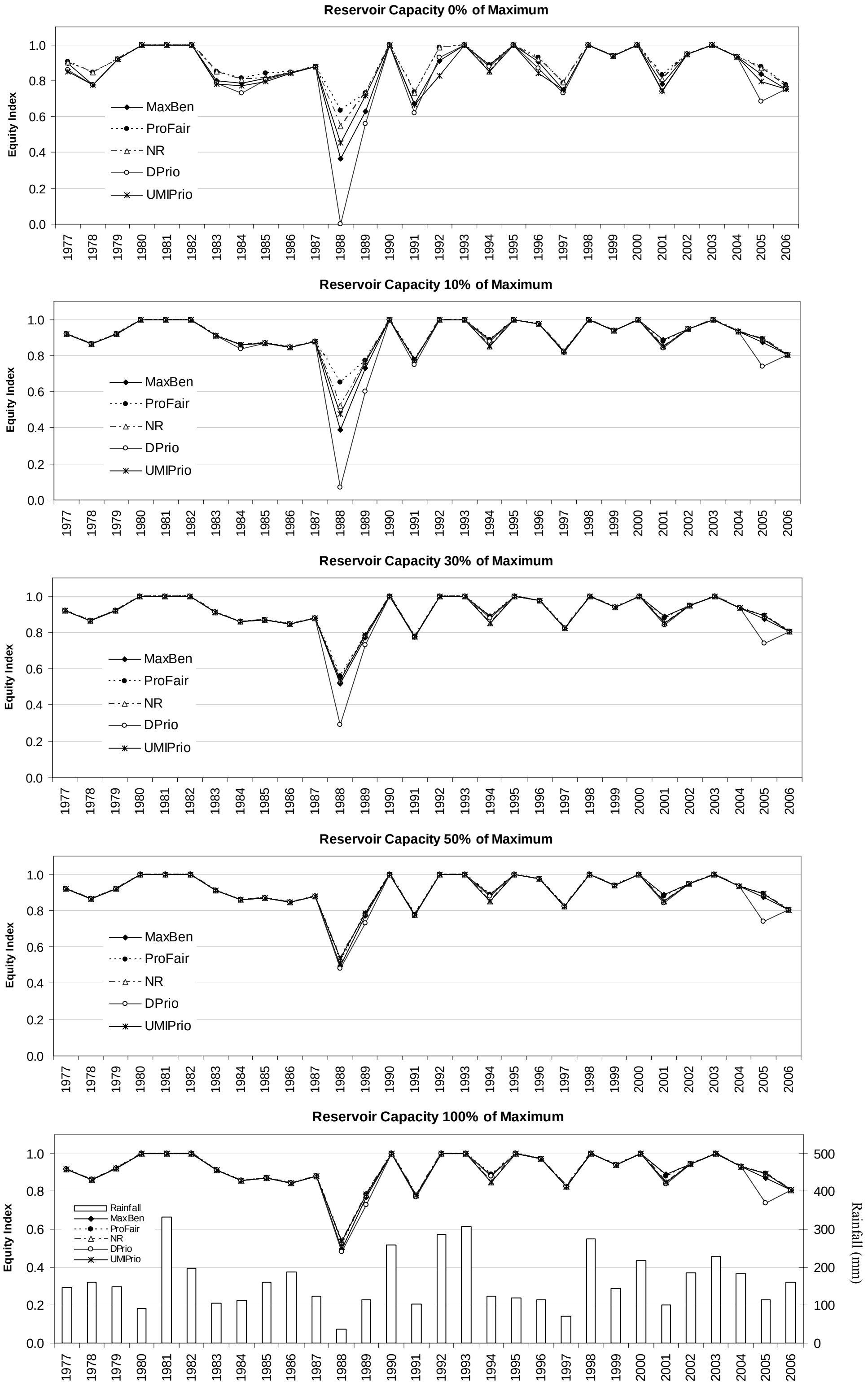


Figure 5.9 Equity Index series under selected reservoir storages: ‘Current’ scenario.

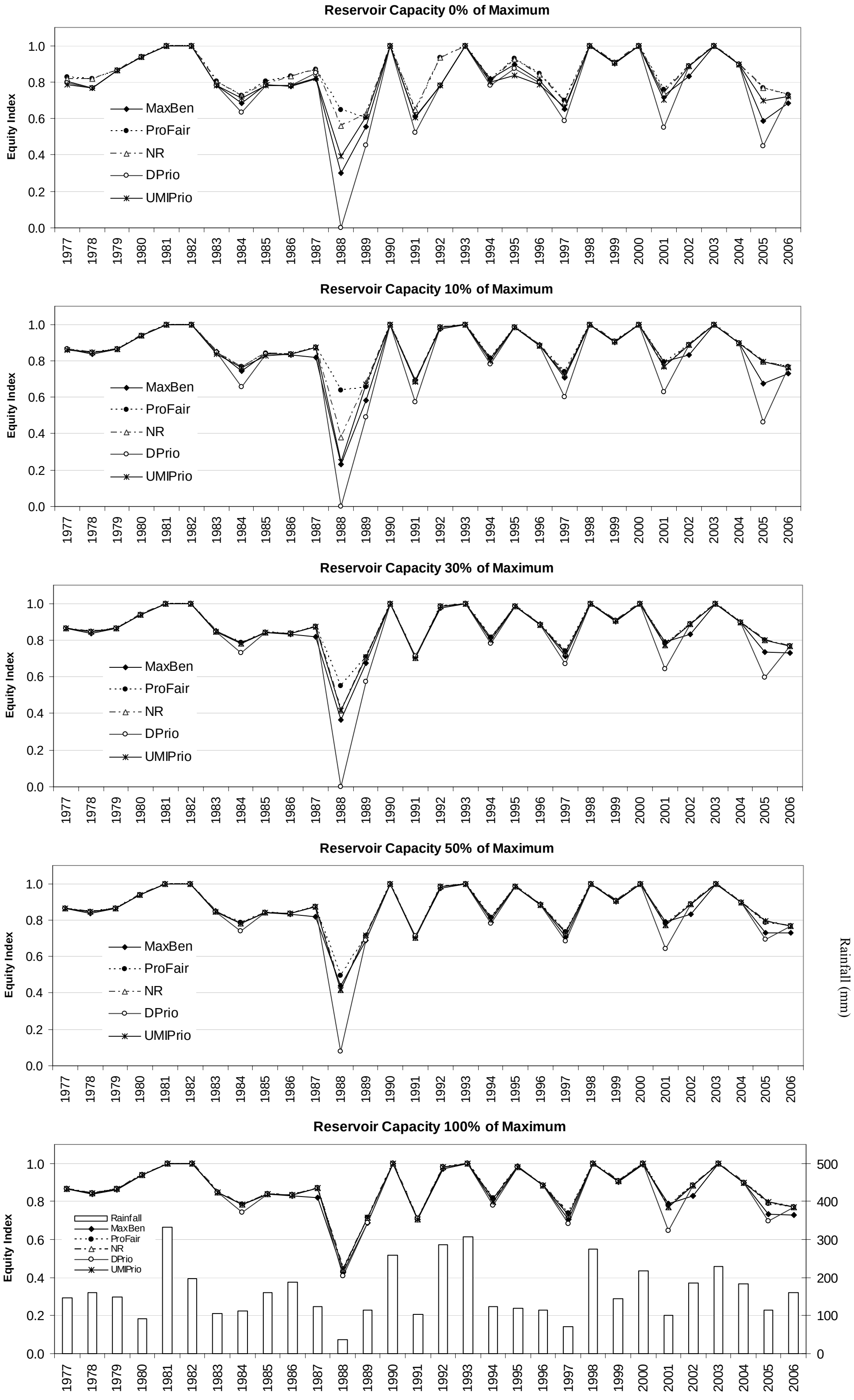
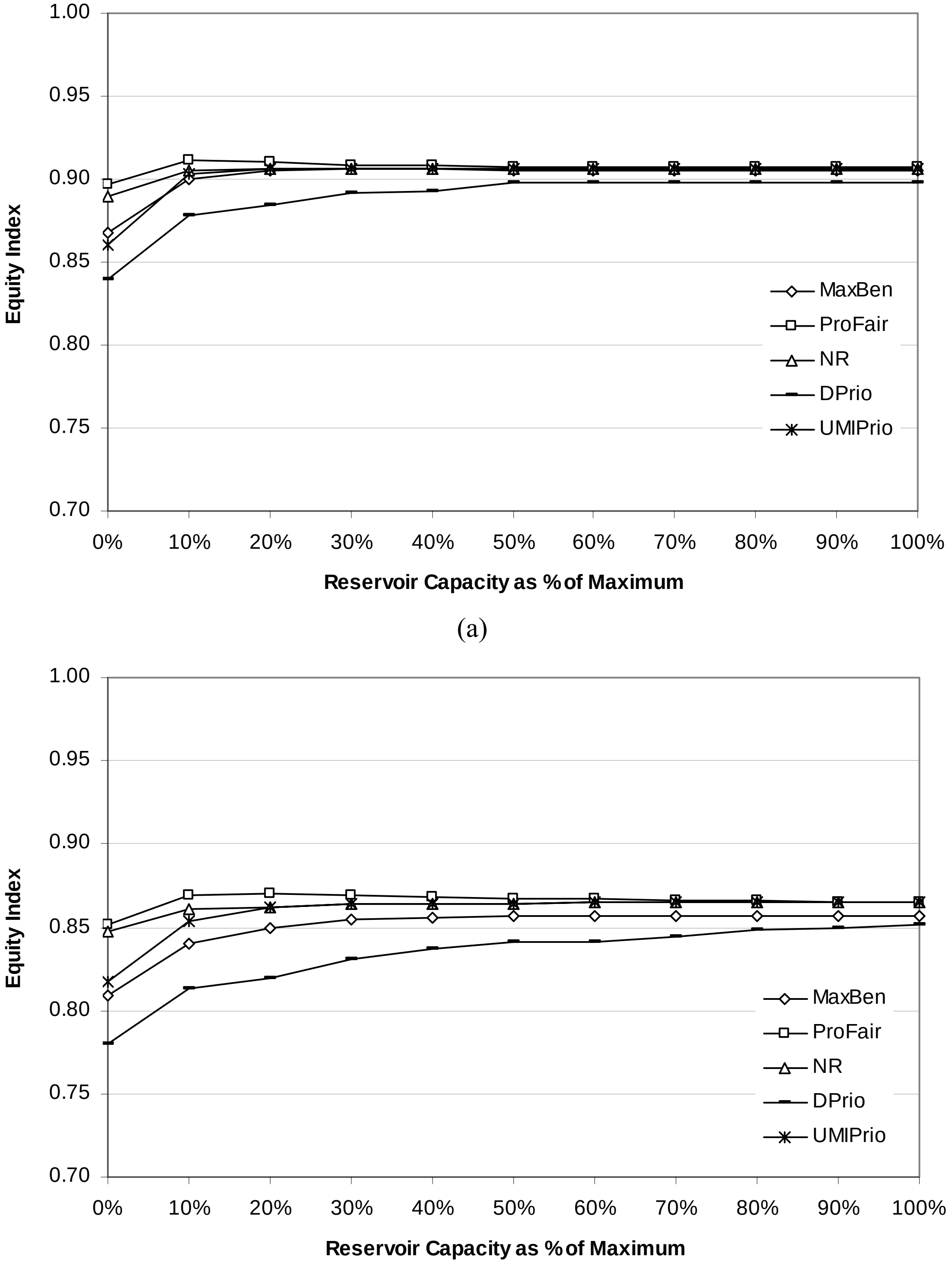


Figure 5.10 Equity Index series under selected reservoir storages: Future scenario.

The largest EI differentiation happens in the extraordinary drought of 1988, in which EI values vary greatly under low (<30%) reservoir storage conditions, ranging from 0 under the DPrio program to 0.65 under the ProFair program. The zero EI value reflects the fact that 1988 is so dry that all the available water in that year has, by the downstream priority rules, to be allocated to the most downstream user and no one else. As the reservoir condition improves, the difference attenuates quickly and EI values converge to about 0.5, which is the lowest of all years.

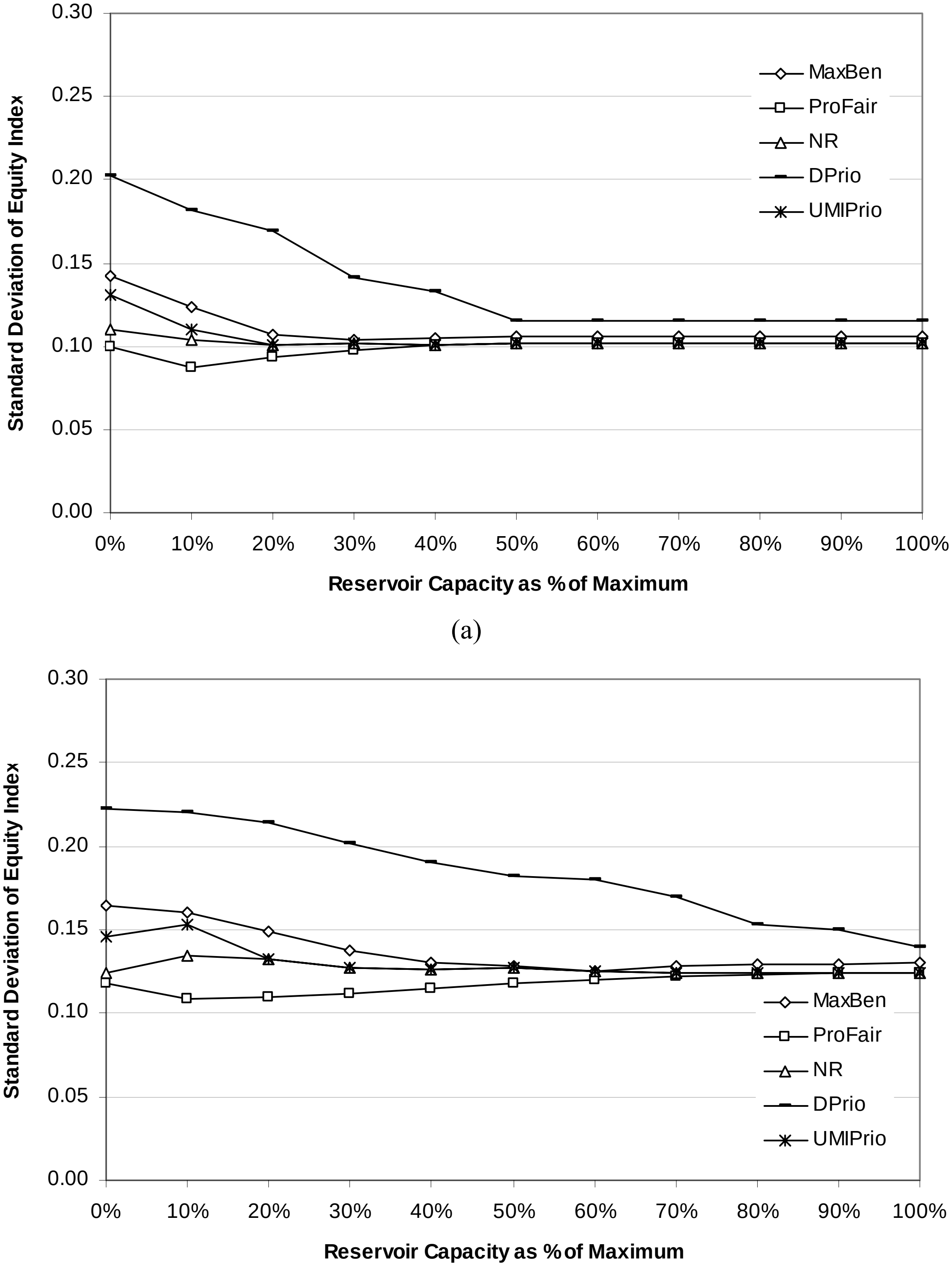
As the scenario changes from ‘Current’ to Future, EI values decrease and year-to-year variation increases in general for all programs and all reservoir conditions. The number of years in which EI equals one regardless of program selection or reservoir storage conditions decreases from 9 to 6 (Figure 5.10). Depending on the reservoir level, the 30-year average EI values from alternative programs (Figure 5.11) decrease by 5 to 11%, while year-to-year variation (Figure 5.12), measured by the 30-year standard deviations, increases by 10 to 59%. The difference in both mean and standard deviation of EI among the selected programs increase in response to the increased demands.



(a)

(b)

Figure 5.11. 30-year average EI value vs. reservoir storage condition under (a) 'Current' and (b) Future scenarios



(a)

(b)

Figure 5.12. 30-year standard deviation of EI values under different reservoir storage conditions under (a) 'Current' and (b) Future scenarios

Under the Future Scenario, the severe drought in 1988 continues to be the cause of the largest deviation in EI among alternative programs and the deviation remains pronounced when the available reservoir storage increases to 50%. Some other years, such as 1989 and 2005, also show considerable difference in EI under low reservoir storage conditions.

The above results suggest that as demand grows and supply shrinks, it becomes increasingly difficult for a water allocation program to retain fairness among users.

5.2.2 Comparing Equity of Alternative Allocation Mechanisms

Figure 5.11 shows that under both the ‘Current’ and Future Scenarios, the ProFair program achieves consistently the highest average EI value at all reservoir levels, although such advantage becomes quite small when the reservoirs approach full storage. This result is consistent with Figure 5.9 and 5.10, where we see the ProFair program achieving the highest equity index in nearly all simulation years, regardless of reservoir levels and demand scenarios. ProFair’s advantage is most pronounced in dry years, such as 1988, 1989, 2005, etc, with low reservoir storage conditions. Besides, the ProFair program appears to be more capable of maintaining stable fairness under variable hydrologic conditions than any other programs. As shown in Figure 5.12, the program results in the lowest standard deviation over the 30-year simulation span, regardless of the reservoir storage condition.

Under both demand scenarios, the NR program closely follows ProFair and consistently achieves the second highest average EI values at all reservoir levels (Figure 5.11). Its EI values become almost indistinguishable from ProFair as the reservoirs approach full storage. At the same time, NR results in the second lowest year-to-year variation. The 30-year standard deviation of its EI lies above ProFair and below the rest of the programs at low reservoir levels (<20%).

The UMIPrio program, which is in effect nothing more than a NR, except for the M&I-first aspect, generates the same EI values as NR when reservoir storages are greater than 20%, but falls below UMIPrio at lower reservoir storage conditions (Figure 5.11). The lower EI's at low reservoir levels are a result of less evenly apportioned withdrawal rights under the M&I-first rule. As the reservoir storages increase (>20%) and the M&I users become fully satisfied, UMIPrio and NR become equivalent to each other, and therefore start to produce identical EI values.

The MaxBen program, although it generates the highest net economic benefit, does not result in the best EI values. Under the 'Current' demand conditions, MaxBen largely follows the trend of NR, while under the Future demand conditions, it consistently falls below NR at all reservoir storage levels (Figure 5.11).

Under both demand scenarios, the DPrio program, which weights water rights in the order of downstreamness, consistently generates the lowest and least stable EI values at all reservoir capacity levels (Figure 5.11 and 5.12). Unlike the other programs, which all have some capability to protect upstream withdrawals, the DPrio program allows no withdrawal by an upstream user unless all his/her downstream peers have been fully satisfied. Hence, the DPrio program is likely to create more zero-withdrawal users than any other program, and hence result in the lowest EI values. As we have seen earlier, under an extremely dry year like 1988, DPrio program allocates all available water to only one user that is located at the downstream end of the watershed, resulting in an EI value of zero.

The above results suggest that among the studied programs, ProFair is capable of providing the most equitable allocation under all supply/demand conditions, where equity is measured by how evenly the water supply shortfall is distributed among all users. The MaxBen program, although it generates the greatest economic benefit, is not the fairest water allocation mechanism. The DPrio program appears to be the most unfair water allocation mechanism under all conditions.

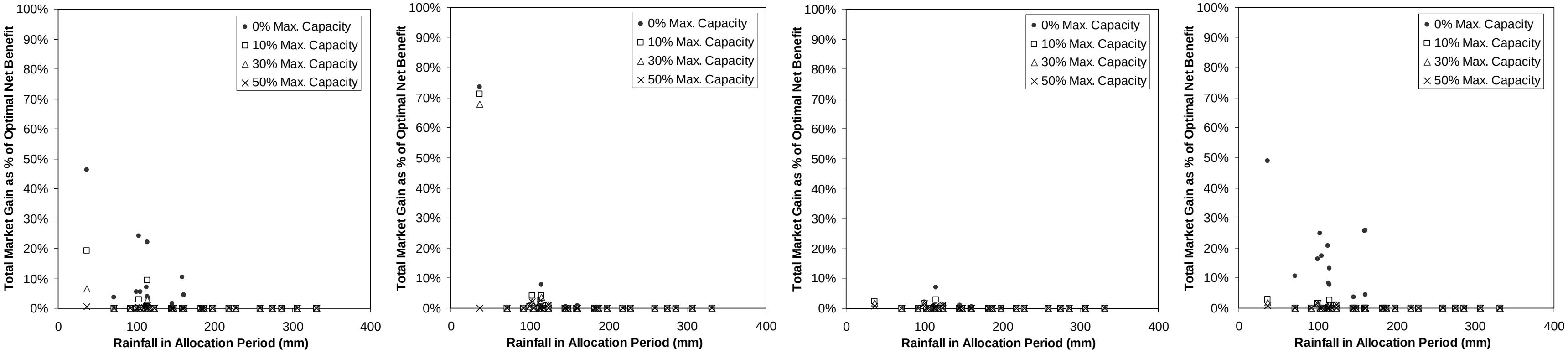
5.3 Water Market Analysis

The water market analysis (see Sec. 3.7) in this study is built upon the assumption that the water can be transferred in a perfect market, where buyers and sellers have complete information about demand/supply conditions and are subject to no transaction cost or externality. Besides, no capital investment is considered in the trading process since this study assumes that all infrastructures needed for water consumption are already in place. The impact of excluding externality and capital investment on water market simulation will be discussed later in this chapter.

5.3.1 Impact of Water Availability on Water Market

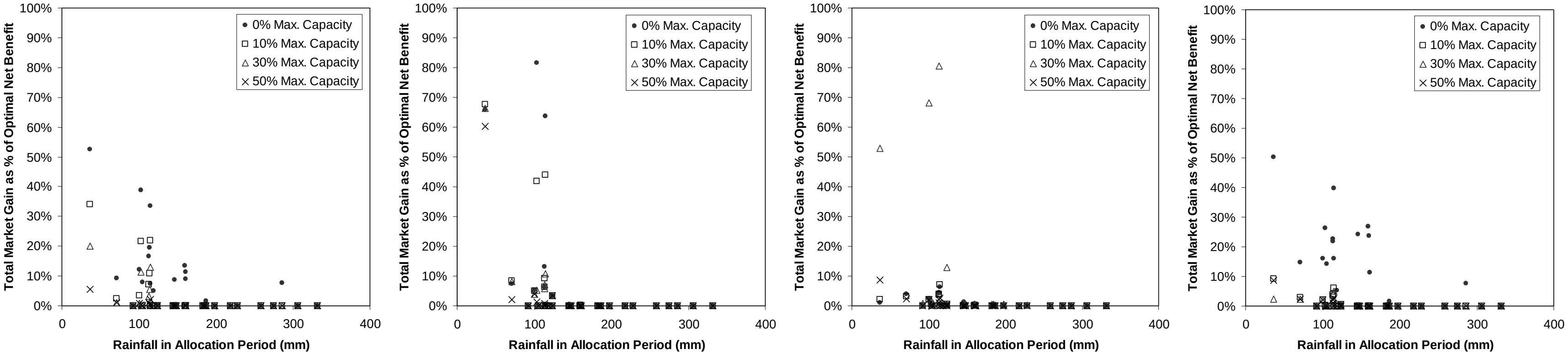
The market analysis discovered that water trading activities in a spot market setting are strongly affected by water availability. As a typical indicator of the level of market activities, the maximum aggregate market gain, calculated as the difference between the aggregate net benefit between the MaxBen and a given program, is found to be negatively correlated with the rainfall in individual allocation periods (Figure 5.13). Recall that Section 3.7 demonstrates the equivalence between the MaxBen allocation and the market equilibrium of any given initial allocation. Water transfers are likely to be profitable when rainfall is less than about 150mm, and become mostly unbeneficial when rainfall increases beyond 200mm. This result is consistent with the common perception about water market that high rainfall creates high water supply and results in low demand, whereas low rainfall reduces supply and stimulates demand.

The same trend is generally found in the relationship between market activity and reservoir storage, but with a small number of exceptions. As shown in Figure 5.13, the aggregate market gain generally declines as the storage of the reservoirs increases (the points representing higher reservoir storage conditions mostly fall below those representing lower storage conditions), reflecting a similar supply-demand interaction as described above. However, an opposite trend is sporadically observed, mostly under the Future Scenario of the UMIPrio program; that is, market gain sometimes increases with improving reservoir conditions. This opposite trend is particularly strong when rainfall is low (<120mm/yr). This result is simply because under that program the increased reservoir water is not allocated to the users with the highest marginal water use benefit. Hence, instead of easing the market demand, the additional water supply promotes more market activities.



i) ProFair ii) DPrio iii) UMIPrio iv) NR

(a) "Current" Scenario



i) ProFair ii) DPrio iii) UMIPrio iv) NR

(b) Future Scenario

Figure 5.13 Annual aggregate market gain as percentage of optimal allocation net benefit.

Also seen in Figure 5.13 is that regardless of the pre-market allocation program, the potential market gains under the Future Scenario generally exceed their corresponding values under the ‘Current’ Scenario. The range of rainfall conditions for profitable water transfer also becomes wider under the Future Scenario. This result suggests that the projected economic development and the consequential water demand increase will likely create more market opportunities for water rights transfer in the future.

5.3.2 Market-Creating Capability of Individual Programs

It is found that the DPrio is able to create some of the highest potential market gains in a single year among all the studied programs. However, those high market gains tend to occur only in extremely dry years, and market activities are quickly depressed as rainfall increases. On the other hand, the UMIPrio program provides the least market opportunity for water rights transfers and its resulting market gains are low under all rainfall conditions. The sharp difference between the two priority-based programs reflects the fact that given the current setup of this study, most water transactions in the Sangamon River watershed will be made between M&I and agricultural users. Under the DPrio program, the M&I users are forced to pass water to downstream agricultural users, leaving themselves short of water during a drought. Hence, M&I users have a strong incentive to pay the downstream farmers a reasonable price for keeping water in their own reservoirs. Under the UMIPrio program, on the other hand, the M&I users are already offered an advantage over agricultural users; so there is no agricultural user that they can buy water from. As a result, water market activity is low.

Compared with the agricultural-to-M&I water transfer, water transfers among agricultural users are limited under the current setup. Since the agricultural users are largely homogeneous in terms of water consuming activities and benefit functions, trading among agricultural users are often of relatively small scale. But again, this is based on the assumption that capital costs are not involved. Farmers may have interests in long-term water transfer agreements if capital costs are considered (see more discussion later in this Chapter).

Under the ProFair and NR programs, water transfers appear to be potentially profitable under a wider range of rainfall conditions (Figure 5.13), compared to the DPrio and UMIPrio programs. With the NR program as the pre-market allocation, trading can potentially occur most often when reservoirs are empty. As reservoir storage increases, the NR program allows the cities to get the first access to the reservoir water, which would rapidly reduce the M&I users' demand and their potential trading benefit. Thus, we see a quick drop of potential net benefit gain under the NR program. In contrast, market activities drops more slowly with increasing reservoir storage under the ProFair program, because the M&I users are required to share a portion of the added supply to their downstream peers.

It should be noted that the NR program is different from the other programs in that it is largely an unregulated program, which does not require a definition for each user's water rights entitlement. Strictly speaking, a water market cannot be effectively established under this program. However, the NR program can be seen as an 'Upstream Priority' program, which is mathematically equivalent to NR, but requires clear specification of water rights. In this sense, the market size calculated based on the NR rules is not for the NR program per se, but for a mathematically equivalent Upstream Priority program in which the physical advantage of an upstream location were converted into an equivalent legal advantage that allowed marketing of a resource by the first person to have the right to capture it. It is analogous to a northern duck hunter selling her right to shoot a duck to a southern duck hunter during the fall migration.

5.3.3 Water Market in the 1988 Drought

Due to the multi-user nature of the Sangamon River system, the trading relationship among the users can be quite complicated. To better understand such a water market, this study uses the year of 1988 as a special case to investigate closely the potential trading relationship among individual users and the trading outcomes. The year of 1988 is selected because it represents an extremely dry scenario wherein market opportunities are the greatest.

Several parameters are calculated to characterize the 1988 water market, including the amount of water that can be potentially transferred, the prices at which water is transferred, and the resulting total market revenue and profit. Table 5.4 shows the parameters that describe the potential trading activities of each of the users in the study watershed and the aggregate economic result of such activities under each of the selected water allocation programs in 1988. Figure 5.14 shows the trading relationship among the users, namely who are buying from or selling to whom. Both Table 5.4 and Figure 5.14 are generated based on the ‘Current’ Scenario and the zero reservoir storage condition.

Table 5.4 Water market under alternative allocation programs (Year = 1988, Scenario = 'Current', Reservoir storage = 0%)

	User Index	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	**Total**
	User Type	Ag	Ag	Ag	Ag	Ag	Ag	Ag	Ag	Ag	Ag	Ag	Ag	Ag	M&I	M&I	Ag	Ag	
A	MaxBen Allocation	0	0	0	0.22	0	0	0	0	0	0.07	1.84	0	0	0.74	0.52	0	2.71	**6.09**
B	Net Benefit under MaxBen ($M)	0	0	0	0.50	0	0	0	0	0	0.12	4.09	0	0	12.61	8.78	0	5.09	**31.2**
C	Marginal benefit under MaxBen ($M/$m^3$/s)	1.92	1.95	2.04	2.21	1.72	1.61	1.62	1.71	1.61	1.72	2.21	1.78	1.90	9.10	9.10	1.77	1.59	---
	Market under ProFair Program																		
D	Pre-Market allocation (m^3/s)	0.35	0.10	0.12	0.17	0.06	0.06	0.07	0.05	0.04	0.07	1.31	0.25	0.14	0.12	0.09	0.38	2.71	**6.09**
E	Pre-Market Net Benefit ($M)	0.66	0.20	0.24	0.39	0.11	0.09	0.12	0.09	0.06	0.12	2.92	0.43	0.27	3.16	2.15	0.64	5.09	**16.7**
F	Potential Water Transfer (m^3/s)[a]	-0.35	-0.10	-0.12	0.05	-0.06	-0.06	-0.07	-0.05	-0.04	0	0.53	-0.25	-0.14	0.62	0.43	-0.38	0	**1.62**[f]
G	Sales/Purchase Price ($M/$m^3$/s)	2.21	2.21	2.21	2.21	9.10	9.10	9.10	9.10	9.10	-	2.21	9.10	9.10	9.10	9.10	9.10	-	**---**
H	Sales Revenue/ Purchase Cost ($M)[b]	0.78	0.23	0.26	-0.10	0.55	0.51	0.68	0.49	0.33	0	-1.16	2.25	1.30	-5.61	-3.91	3.42	0	**10.8**[g]
I	Benefit gain/loss($M)[c]	-0.66	-0.20	-0.24	0.10	-0.11	-0.09	-0.12	-0.09	-0.06	0	1.17	-0.43	-0.27	9.45	6.63	-0.64	0	**14.5**
J	Net Gain through Water Transfer ($M)[d]	0.12	0.03	0.02	<0.01	0.44	0.42	0.56	0.40	0.27	0	0.01	1.82	1.04	3.84	2.72	2.78	0	**14.5**
K	Post-Market Net Benefit ($M)[e]	0.78	0.23	0.26	0.39	0.55	0.51	0.68	0.49	0.33	0.12	2.93	2.25	1.30	7.00	4.86	3.42	5.09	**31.2**
L	Post-Market Allocation (m^3/s)	0	0	0	0.22	0	0	0	0	0	0.07	1.84	0	0	0.74	0.52	0	2.71	**6.09**

Table 5.4 Water market under alternative allocation programs (Year = 1988, Scenario = ‘Current’, Reservoir storage = 0%) (Cont’d)

	User Index	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	**Total**
	User Type	Ag	Ag	Ag	Ag	Ag	Ag	Ag	Ag	Ag	Ag	Ag	Ag	Ag	M&I	M&I	Ag	Ag	
	Market under DPrio Program																		
D	Pre-Market allocation (m^3/s)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6.09	**6.09**
E	Pre-Market Net Benefit ($M)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	8.27	**8.4**
F	Potential Water Transfer (m^3/s)[a]	0	0	0	0.22	0	0	0	0	0	0.07	1.84	0	0	0.74	0.52	0	-3.38	**3.38**[f]
G	Sales/Purchase Price ($M/m^3/s)	-	-	-	2.21	-	-	-	-	-	1.72	2.21	-	-	9.10	9.10	-	M[g]	---
H	Sales Revenue/ Purchase Cost ($M)[b]	0	0	0	-0.48	0	0	0	0	0	-0.12	-4.05	0	0	-6.74	-4.69	0	16.1	**16.1**[g]
I	Benefit gain/loss($M)[c]	0	0	0	0.50	0	0	0	0	0	0.12	4.09	0	0	12.6	8.78	0	-3.17	**22.9**
J	Net Gain through Water Transfer ($M)[d]	0	0	0	0.01	0	0	0	0	0	<0.01	0.04	0	0	5.87	4.09	0	12.91	**22.9**
K	Post-Market Net Benefit ($M)[e]	0	0	0	0.01	0	0	0	0	0	<0.01	0.04	0	0	5.87	4.09	0	21.17	**31.2**
L	Post-Market Allocation (m^3/s)	0	0	0	0.22	0	0	0	0	0	0.07	1.84	0	0	0.74	0.52	0	2.71	**6.09**
	Market under UMIPrio Program																		
D	Pre-Market allocation (m^3/s)	0.57	0.10	0.12	0.32	0	0	0	0	0	0.07	0.95	0	0	0.61	0.64	0	2.71	**6.09**
E	Pre-Market Net Benefit ($M)	1.04	0.20	0.24	0.72	0	0	0	0	0	0.12	2.11	0	0	11.3	9.76	0	5.09	**30.6**
F	Potential Water Transfer (m^3/s)[a]	-0.57	-0.10	-0.12	-0.10	0	0	0	0	0	0	0.89	0	0	0.13	-0.13	0	0	**1.02**[f]
G	Sales/Purchase Price ($M/m^3/s)	2.21	2.21	2.21	2.21	-	-	-	-	-	-	2.21	-	-	9.1	9.1	-	-	---
H	Sales Revenue/ Purchase Cost ($M)[b]	1.25	0.23	0.26	0.23	0	0	0	0	0	0	-1.96	0	0	-1.15	1.15	0	0	**3.1**[g]
I	Benefit gain/loss($M)[c]	-1.04	-0.20	-0.24	-0.22	0	0	0	0	0	0	1.98	0	0	1.28	-0.98	0	0	**0.6**
J	Net Gain through Water Transfer ($M)[d]	0.21	0.03	0.02	0	0	0	0	0	0	0	0.01	0	0	0.13	0.17	0	0	**0.6**
K	Post-Market Net Benefit ($M)[e]	1.25	0.23	0.26	0.72	0	0	0	0	0	0.12	2.13	0	0	11.46	9.93	0	5.09	**31.2**
L	Post-Market Allocation (m^3/s)	0	0	0	0.22	0	0	0	0	0	0.07	1.84	0	0	0.74	0.52	0	2.71	**6.09**

Table 5.4 Water market under alternative allocation programs (Year = 1988, Scenario = ‘Current’, Reservoir storage = 0%) (Cont’d)

	User Index User Type	1 Ag	2 Ag	3 Ag	4 Ag	5 Ag	6 Ag	7 Ag	8 Ag	9 Ag	10 Ag	11 Ag	12 Ag	13 Ag	14 M&I	15 M&I	16 Ag	17 Ag	**Total**
	Market under NR Program																		
D	Pre-Market allocation (m^3/s)	0.57	0.10	0.12	0.32	0.11	0.06	0.07	0.27	0.21	0.07	0.95	0.34	0	0.20	0	0	2.71	**6.09**
E	Pre-Market Net Benefit ($M)	1.04	0.20	0.24	0.72	0.18	0.09	0.12	0.38	0.27	0.12	2.11	0.60	0	4.75	0	0	5.09	**15.9**
F	Potential Water Transfer (m^3/s)[a]	-0.57	-0.10	-0.12	-0.10	-0.11	-0.06	-0.07	-0.27	-0.21	0	0.89	-0.34	0	0.52	0.54	0	0	**1.85**[f]
G	Sales/Purchase Price ($M/$m^3$/s)	2.21	2.21	2.21	2.21	9.10	9.10	9.10	9.10	9.10	-	2.21	9.10	-	9.10	9.10	-	-	---
H	Sales Revenue/ Purchase Cost ($M)[b]	1.25	0.23	0.26	0.23	0.99	0.51	0.68	2.45	1.91	0	-1.96	3.11	0	-4.95	-4.69	0	0	**11.6**[g]
I	Benefit gain/loss($M)[c]	-1.04	-0.20	-0.24	-0.22	-0.18	-0.09	-0.12	-0.38	-0.27	0	1.98	-0.60	0	7.86	8.78	0	0	**15.3**
J	Net Gain through Water Transfer ($M)[d]	0.21	0.03	0.02	0.00	0.80	0.42	0.56	2.06	1.65	0	0.01	2.52	0	2.91	4.09	0	0	**15.3**
K	Post-Market Net Benefit ($M)[e]	1.25	0.23	0.26	0.72	0.99	0.51	0.68	2.45	1.91	0.12	2.13	3.11	0	7.66	4.09	0	5.09	**31.2**
L	Post-Market Allocation (m^3/s)	0	0	0	0.22	0	0	0	0	0	0.07	1.84	0	0	0.74	0.52	0	2.71	**6.09**

a. F = A – D. Positive values indicate purchases and negative values sales.
b. H = -G * F. Positive values indicate the revenue of the sellers and negative values the cost to the buyers.
c. I = B – E.
d. J = H + I.
e. K = E + J
f. The net total quantity of water rights that can be potentially transferred.
g. The net total worth of potential transactions.
h. Water bought by or sold to multiple users with different prices.

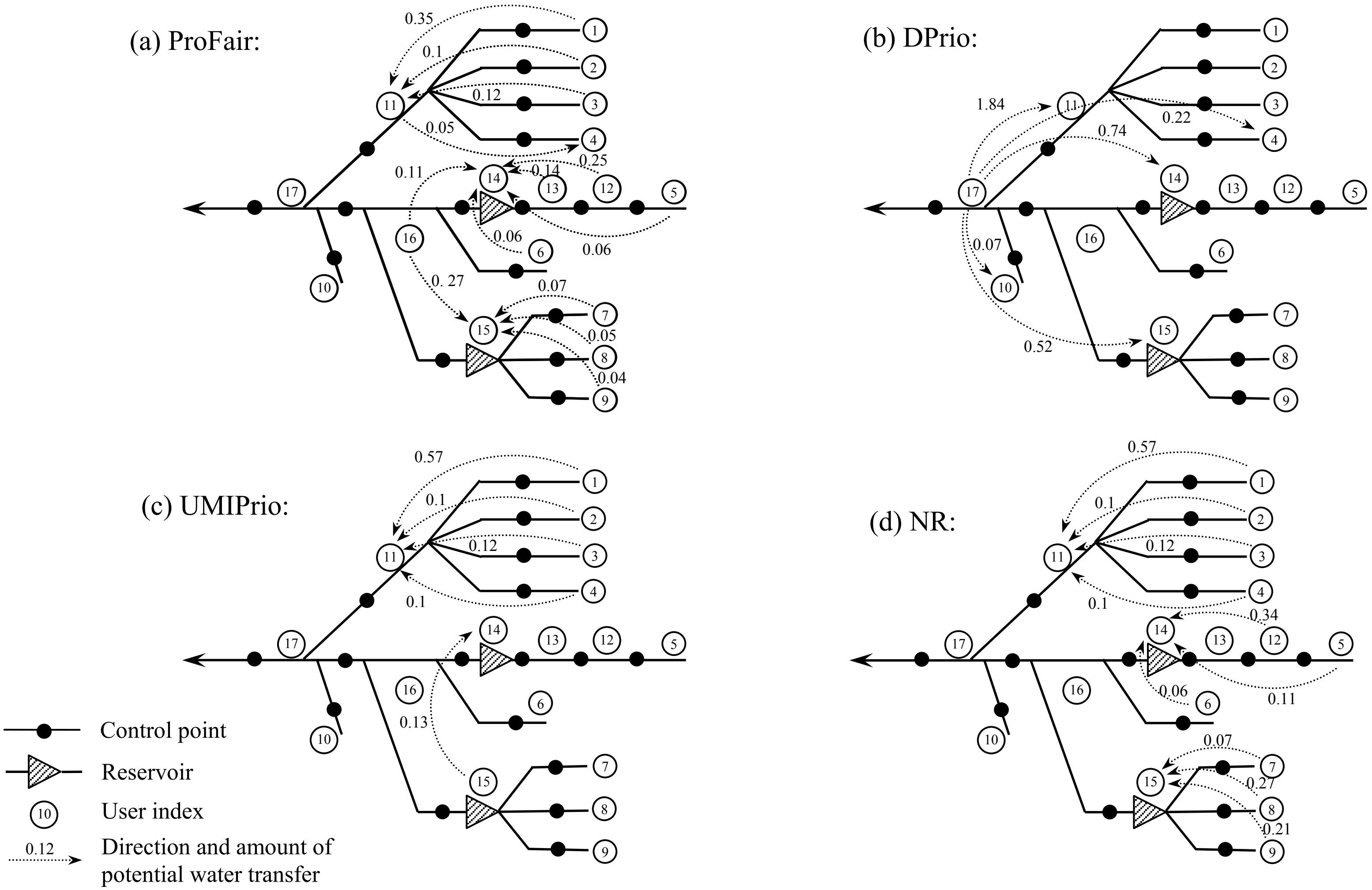


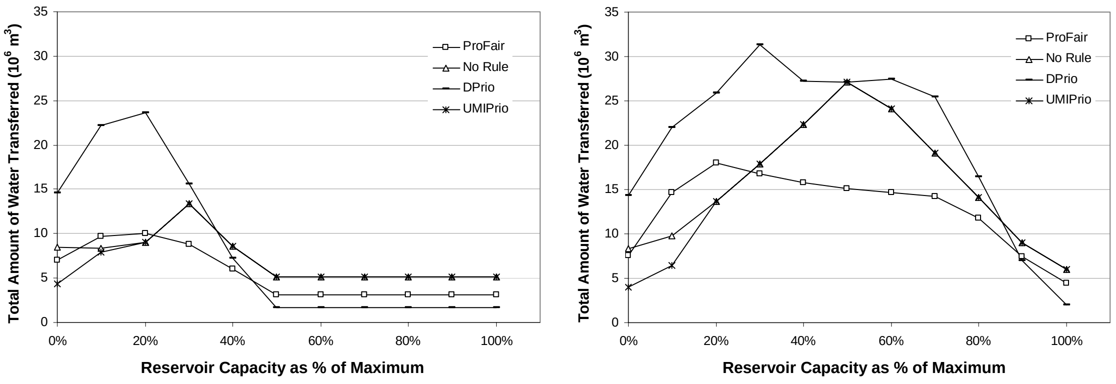
Figure 5.14 Water rights transfers among riparian water users along Sangamon River System (Year = 1988, Scenario = 'Current', Reservoir Storage = 0%)

As discussed in Chapter 3, allowing water to be freely traded on a perfect market would ultimately result in an equilibrium that is identical to the benefit maximizing allocation. Given any pre-market allocation, water rights would theoretically move, without violating the water balance constraints, from relatively low marginal benefit users to those with relatively high marginal benefits through market mechanisms, until all users' marginal benefits are as nearly equal as possible, within constraints, i.e. a market incentive no longer exists. The results in Table 5.4, which are derived from the solution to the optimization problem (3.14), demonstrate this process. Under the MaxBen allocation (rows A to C), the users who receive the most water are also those who have the highest marginal benefits. The marginal benefits under the MaxBen allocation also indicate the price each user is willing to pay for additional water. Under all the other programs, free-market trading always results in a post-market allocation (rows L) that is identical to the MaxBen allocation. The post-market aggregate net benefit is always equal to the one in the MaxBen allocation. For an individual user, the post-market net benefit (rows K) represents the potential economic worth of his/her initial allowable withdrawal.

The potential trading relationship among users and the amount of water traded are determined by water availability, pre-market allocation, user benefit functions, and the geometry of the river network. As Figure 5.14 shows, the trading relationship under the 1988 conditions can differ considerably under different allocation programs. The largest and smallest volumes of potential water transfers occur under the DPrio and UMIPrio programs, respectively (Table 5.4), which is consistent with the findings in Figure 5.13.

Table 5.5 presents the total economic gain as percentages of the total post-market net benefits for the 1988 data under both "Current" and Future scenarios. The table shows that the DPrio program would benefit the most from this perfect market arrangement; as much as nearly 67% of its total post-market net benefit could be obtained through water transfer. The UMIPrio program benefit the least from the perfect market, with market gain accounting for <10% of total percentage post-market net benefit. ProFair and NR program can both benefit substantially from the market when reservoir levels are low.

As stated earlier, the reservoir storage level has significant impacts on water transfer activities. Under both 'Current' and Future Scenarios, the total amount of potential transfer increases first and then decrease after a peak as the reservoir storage condition improves from 0 to 100%. Such trend is found in all the non-MaxBen programs (Figure 5.15).



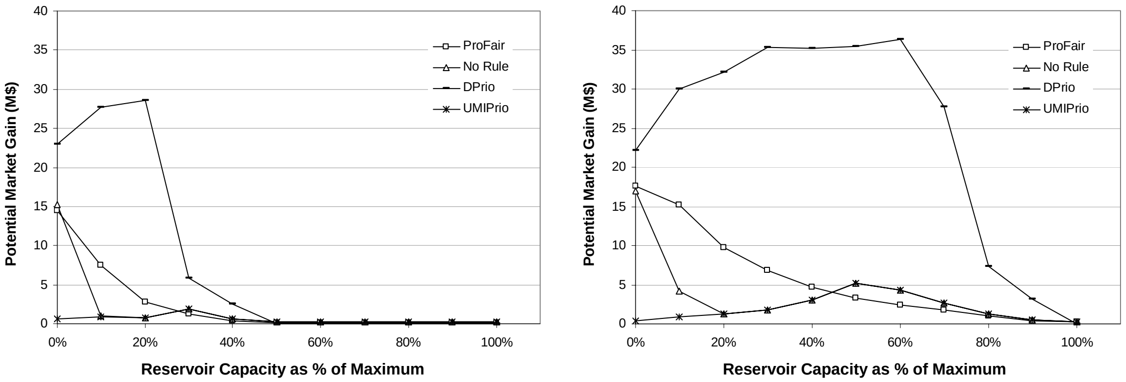
(a) (b)

Figure 5.15 Total amount of potential water transfer under the (a) 'Current' and (b) Future Scenario in the 1988 drought

Table 5.5. Total economic gain through water transfer as percentage of total post-market net benefit in 1988.

Reservoir Storage Level	'Current' Scenario				Future Scenario			
	ProFair	DPrio	UMIPrio	NR	ProFair	DPrio	UMIPrio	NR
0%	46.3%	73.5%	1.9%	49.0%	52.6%	65.9%	1.1%	50.4%
10%	19.3%	71.3%	2.2%	2.8%	34.1%	67.5%	2.1%	9.3%
20%	6.5%	67.9%	1.8%	1.8%	20.1%	66.4%	2.5%	2.5%
30%	3.0%	13.1%	4.1%	4.1%	13.0%	67.7%	3.4%	3.4%
40%	0.9%	5.6%	1.3%	1.3%	8.5%	63.2%	5.5%	5.5%
50%	0.4%	0.1%	0.7%	0.7%	5.6%	60.3%	8.8%	8.8%
60%	0.4%	0.1%	0.7%	0.7%	3.9%	59.3%	7.0%	7.0%
70%	0.4%	0.1%	0.7%	0.7%	2.9%	43.9%	4.1%	4.1%
80%	0.4%	0.1%	0.7%	0.7%	1.6%	11.4%	2.0%	2.0%
90%	0.4%	0.1%	0.7%	0.7%	0.6%	4.9%	0.7%	0.7%
100%	0.4%	0.1%	0.7%	0.7%	0.3%	0.0%	0.5%	0.5%

The potential market gain is also affected considerably by reservoir storage condition (Figure 5.16). The DPrio program creates the highest market gain, which peaks at 30 and 60% reservoir storage conditions under the 'Current' and the Future Scenarios, respectively, and decreases rapidly thereafter. The ProFair program attains the highest potential market gain when reservoir level is zero under both demand scenarios. Its potential market gain decreases steadily with the increase of reservoir levels. The potential market gain under the UMIPrio program is relatively small compared with the other programs and forms a mild peak at a mid-storage condition. The NR program results in a potential market gain that is relatively high at the zero-storage condition, but rapidly reduces to the same as that of UMIPrio when reservoir levels reach beyond 20%.



(a) (b)

Figure 5.16 Total potential market gain under the (a) 'Current' and (b) Future Scenario in the 1988 drought

Comparing the 1988 market outcomes between the 'Current' and Future Scenarios, this study found that both the total volume and the total potential profit of the water market increases substantially given the projected future demand growth (Figures 5.15 and 5.16). For all the non-MaxBen programs, the maximal increases in potential water transfer take place at about 50~60% reservoir storage (Table 5.6), ranging from about 11.5 to 22 × 10^6 m^3. The maximal profit increases occur at different reservoir storages under different programs, ranging from about 5 M$ to 36 M$ (Table 5.6).

Table 5.6 Increase in amount of water transfer and profitability under projected future demand scenario.

Reservoir Storage Level	Increase in total water transfer (10^6 m^3)				Increase in total economic gain ($M)			
	ProFair	DPrio	UMIPrio	NR	ProFair	DPrio	UMIPrio	NR
0%	0.13	-0.08	-0.03	-0.07	3.2	-0.8	-0.2	1.6
10%	1.15	-0.34	0.34	-0.03	7.7	2.3	0.1	3.1
20%	1.85	1.07	1.07	0.50	7.0	3.6	0.4	0.4
30%	1.84	1.06	1.06	3.65	5.5	29.5	-0.1	-0.1
40%	2.26	3.20	3.20	4.63	4.3	32.6	2.4	2.4
50%	2.79	5.09	5.09	5.89	3.1	35.4	4.9	4.9
60%	2.68	4.40	4.40	5.96	2.2	36.3	4.0	4.0
70%	2.57	3.24	3.24	5.51	1.6	27.7	2.3	2.3
80%	2.01	2.08	2.08	3.42	0.9	7.3	1.0	1.0
90%	1.01	0.91	0.91	1.25	0.2	3.1	0.2	0.2
100%	0.32	0.22	0.22	0.09	0.0	0.0	0.0	0.0

5.4 Discussion

5.4.1 Advantages and Disadvantages of Studied Programs

The five mechanisms examined in this study can be seen as representing four fundamentally different water allocation principles: economic optimization (by MaxBen), equal sharing (by ProFair), non-regulation or deregulation (by NR), and prioritization (by UMIPrio and DPrio).

The MaxBen program is based on the economic optimization approach, which has been widely adopted in numerous water allocation studies. While the most economically efficient program in theory, the program can hardly be implemented directly by water authorities due to technical difficulties and potentially high administrative cost. The program requires comprehensive information about every user’s demand curve, which is often controlled by complicated and uncertain factors that are hard to apprehend. For example, how exactly would the economic value of a wetland property used for duck hunting change when its water level increases or decreases by a few inches? Or how to measure the economic loss of a community that reduces its lawn irrigation by 10%? Or, on a larger scale, how much would the state of Alabama benefit if its share of water from the Apalachicola-Chattahoochee-Flint River system is increased by one thousand cubic meters per day? Not to mention that users may alter their behavior under different water supply conditions, and hence make their demand curve even harder to determine. Even if such information is available, it would be extremely costly to obtain. Just imagine all the data collection, economic analysis, documentation, enforcement, and many other administrative efforts associated with every single user.

Despite being unrealistic, the MaxBen program is still quite useful from several perspectives. First, it sets a theoretical benchmark of the best economic outcome a water allocation program can possibly achieve. This benchmark will help water resources managers assess how far practicable programs fall short of the upper limit of economic benefit. Moreover, although a precise level of benefit maximizing management is impractical, the basic principle of the MaxBen program can be incorporated into water allocation regulations. For example, recognizing the difference in water demand elasticity between the agricultural and M&I consumptions, the regulators may design a program which allows M&I users to receive less withdrawal curtailment than agricultural users. The type-based priority program is another example, which embraces the idea of marginal benefit at a “ballpark” level. Furthermore, as discussed earlier, the result of MaxBen program can be used to represent the outcome of a perfect water rights market. A wisely instituted water market can encourage users to estimate their own demand functions and maximize their profit through water purchases or sales, which, as shown in Chapter 3, would ultimately lead to an equivalent result as the MaxBen program.

Compared to the equal-marginal-cost criterion of the benefit maximizing allocation, the equal-proportional-satisfaction criterion of the proportionally fair allocation appears to be easier to implement. The water authorities do not need to know every user's benefit function, which may be highly complicated and never precisely understood. Instead, they make allocation decisions based on easily observed water supply satisfaction coefficients, which are simply the ratios of the actual withdrawals to the originally permitted withdrawals or the users. The mathematics developed in Chapter 3 provides an operational guideline for the ProFair program. The Proportional Fairness Criterion tells us what the final allocation should be under a given water availability condition; whereas the convex programming model and the Bottleneck Algorithm tell us how exactly the ProFair allocation is computed. However, the ProFair program still requires highly coordinated operations of water utilities throughout the whole system. As a result, the ProFair program may be subject to moderate administrative cost. The program would also need to determine the initial entitlement for each user, but the administrative cost in that regard should not be much different from those under other permit programs.

Moreover, from a legislative point of view, one can argue that the ProFair program is even more consistent with the basic principles of the eastern water laws than the MaxBen program. Under MaxBen, a downstream farmer could lose all of his/her water rights to an upstream city in times of drought, simply because agricultural consumption is far less "valuable" than municipal consumption. In that case, the downstream farmer's Riparian water rights are not effectively protected. Under the ProFair program, however, a user, regardless of his/her size or economic productivity, can never be completely deprived of water rights, as long as he/she is a legal permit holder and there is still available water that can flow by the user's property. In this regard, the ProFair program is in better accordance with the fair sharing spirit of the Riparian Doctrine. One can further argue that the most reasonable allocation of a limited water resource would be letting all uses' satisfaction (or shortfall) ratios as equal to each other as possible, i.e. maximizing the allocation's Equity Index, while making sure the resource is fully utilized. As shown in the results, the ProFair program always achieves the most equitable water allocation among all studied programs, especially in times of shortage; whereas the MaxBen program only scores the third or fourth of the five alternatives in terms of fairness.

A major weakness of the ProFair is that it improves equity at the cost of losing economic efficiency. Historically, there have been court decisions that rejected the proportional approach to resolving water disputes, citing its inadequate consideration of economic impacts. As shown in the above results, the net benefit generated by ProFair can be substantially lower than MaxBen in times of drought, owning to the fact that ProFair may give the agricultural users too much credit. This drawback may be improved by adopting a better designed approach to determining the initial water permits, so that the economic concerns are carefully addressed from the very beginning. Alternatively, one can design a new allocation mechanism that allows the satisfaction coefficients of low value users to reduce faster (e.g. at a quadratic speed) than high value users. In that case, however, the proportional fairness criteria and the formula of the allocation model would have to be revised.

The advantage and disadvantage of the priority-based programs in the eastern-US setup has been extensively discussed in the literature review chapter. Despite the advocate of numerous scholars, the widely observed unpopularity and a number of reported failure of the time-based priority approach in the eastern US suggests that the Riparian states are yet ready to accept the western-style appropriative water rights. This study further illustrates that the economic and equity results of the priority based programs are heavily impacted by the geographical distribution of the priority ranks. Although the UMIPrio program can achieve the next highest economic benefit to MaxBen under many conditions, it requires all the upstream agricultural users to forgo their withdrawal rights to the downstream cities during extreme drought periods, which results in low fairness in the system. Unless the appropriative water rights have been firmly established by the administration and widely accepted by the general public, the program cannot effectively prevent the happening of water disputes, which can be subject to high legal cost. As for the other priority-based program examined in this study, the DPrio program produces the worst economic benefit and equity, and hence would not be a good choice for water agencies in the eastern states.

An interesting finding is that the NR program is able to generate higher economic benefit than ProFair under moderately low to high reservoir storage conditions, while maintaining reasonable fairness, ranking the second in equity index under most dry conditions. The NR program to some degree represents the traditional Riparian Doctrine approach and the status-quo of water regulation in many regions in the eastern US, including central Illinois. It is in effect similar to an upstream-priority approach. The most obvious advantage of this program is that it can save considerable administrative cost. Those results of this study suggest that for areas where water shortage problem is still not too serious, minimum regulation still seems to be a reasonable option for water agencies.

However, the results also shows that the NR program produces the lowest economic benefit under the worst water supply conditions, suggesting that the absence of regulation could cause the worst economic consequences during the most severe droughts. In the long-term, with the continuously growing water demand, deepening water shortage, and escalating water competition, minimum regulation may no longer be an option of the water agencies in the eastern states. They will ultimately transform their water regulations based on one or a combination of the three other philosophies, namely economic optimization, equitable sharing, and prioritization.

It should be noted that the simulation model for the NR program in this study overestimates the economic outcome by assuming that the M&I users, after their own demand is satisfied, would release the unused water from their reservoirs to downstream users, even if the release causes deficit in the reservoirs. In reality, M&I users will likely store the unused water until their reservoir is full, which will reduce water availability, as well as economic benefit, for the downstream users.

5.4.2 Limitations of Current Water Rights Market Simulation

The trading analysis in this study illustrates the potential of a water market in achieving a secondary allocation of improved economic efficiency. As mentioned earlier, however, from the modeling perspective the trading analysis is not able to capture two important aspects of water markets. One of the aspects is the impact of capital cost. The water market simulation in this study assumes that all users have installed adequate water use facilities. Trading decisions are made based on the market conditions of the current year. In other words, what this study simulates is a ‘spot market’, wherein water transfers are driven by short-term demands. Thus, the simulation is not able to reflect the impact of capital investment on the trading decisions. In the reality of the eastern US, however, a question that needs to be answered in the first place by any withdrawer, especially a farmer, is whether it is profitable to invest in water facilities. If capital costs are large, it takes a certain minimum quantity just to reap enough benefit to pay for it before a net benefit ensues. So, it is easy to envision an arrangement whereby one farmer pays another for enough water rights to justify irrigation capital cost; while the other farmer is satisfied with the revenue obtained through the water rights sale and saves the trouble of infrastructure development. The success of this arrangement would require the transfer agreements to have adequately long horizons so that the investors have enough time to recover their initial capital costs. To properly simulate a market with the impact of initial capital cost, a model like the one developed by Wong and Eheart (1983) is needed. The model should have a component that quantifies the capital cost and should have binary decision variables in the objective function to represent farmers’ capital investment decisions. The results of this model would represent the long-term or permanent water transfer market, which has quite different values and meanings from the spot market simulated in this study. In reality, a water market may likely be a combination of both long- and short-term water transfers.

Another item that is not captured in the simulation is the transaction cost. Although the initial model described in Chapter 3 (Eq. 3.14a and b) includes a transaction cost term in the formula, the term is dropped in the simulation because of the perfect-market assumption. A major reason for this study to exclude transaction cost is the lack of a reliable approach to quantify it. Experiences of water rights sales have been rare and poorly documented in the eastern US. There is little existing data about transaction cost, much less quantitative method. Thus, the economic gain of the market simulated in this study would be the maximum that a water market could achieve in theory.

Obviously, a regulated market requires the recognition of externalities. The effort to address these externalities would be ultimately translated into extra costs to be shouldered by the participating parties of the water rights transfer. Experience in the western US suggests that transaction costs arising from the harmful third parties and/or environmental impacts are one of the major economic barriers that discourage water transfer practices. It is expected that high transaction costs would preclude all but the most economically beneficial transfers, and hence create an unfavorable market environment for the programs with low market-creating capability. Numerous studies (e.g. McCann and Easter, 2004; Carey et al., 2002) focusing on transaction cost issues have been performed and several methods have been developed to evaluate transaction cost under the context of the western US. It would be interesting to see if some of those methods can be adapted to the situations of the eastern US. At the same time, it is recognized that the Internet holds the potential to lower transactions costs, but the spontaneous development of trading websites in all likelihood will have to be preceded by the establishment of a functioning market.

5.4.3 Other issues

A water budget issue that is not explicitly considered in the current programs, but can be significant in many cases, is groundwater. The interactions between surface water and groundwater are often complex, depending heavily on the relative locations of the sources and the geological conditions in the vicinity. Generally speaking, with a shallow aquifer formed of porous materials, hydraulically connected to the stream, the well withdrawal would likely have an immediate decreasing impact on the streamflow, whereas with a deep aquifer confined by impervious materials with a well a great distance from the stream, the well withdrawal may have little detectable impact on streamflow. Some other situations would be somewhere in between the above two extremes. Site specific surveys would be needed to quantify the impact of groundwater withdrawal, as well as the associated return flow, on streamflow and the system-wide water budgets.

Another issue the current allocation programs have yet to address is how the users' risk-averse behaviors impact the system efficiency when water supply uncertainty exists. Different from the retrospective analysis in this study, which utilizes real historical data, the practical decision making on water demand and water allocation often involves a high level of hydrologic forecasting and risk assessment. Many types of decisions on water use activities (e.g. agricultural) must be made with limited foresight of water availability during the activity life. Because of the fear of loss, water users may choose activities that are less prone to drought damage, and yet less profitable as well, even if the chance of a drought is low. They may also make extra investment in a variety of water conservation measures. The result of these risk-averse behaviors, both short-term and long-term, is a reduction of the overall economic benefit and loss of system-wide efficiency. Moreover, risk-aversion, if not well-addressed at the policy level, may create a major obstacle to transfers in a water rights market. A deal is less likely to be made if the buyer is uncertain of the water supply reliability that the seller can provide. Therefore, the costs of risk aversion should be properly reflected in the economic models in order to evaluate an allocation program more comprehensively.

It should be noted that the current allocation programs do not handle risk equally, and hence may result in different patterns of risk-averse behavior among users. The priority programs offer the best, if not full, protection to the users with the highest priority, while putting the users with lower priority at higher risk. In comparison, the ProFair program tends to distribute the risk evenly over the entire system. Although the 'total amount' of risk is the same under both types of programs, the economic impacts of user's risk-averse behaviors may differ considerably. It would be interesting to examine these impacts in future research.

CHAPTER 6. CONCLUSIONS AND RECOMMENDATIONS

Today, the eastern states of the United States are facing the challenge of growing water shortages that have emerged from rapid population growth, economic expansion, and changing weather patterns. There have been rising calls for reforming the loosely fashioned water allocation regulations in the eastern states, which have been built on the common-law Riparian Doctrine. Significant efforts have been made to transform the eastern water rights system toward the so-called 'Regulated Riparianism', which offers more accuracy and certainty to the water allocation management. However, important issues remain to be adequately addressed, such as the legal contradiction between fixed permit programs and the common-law doctrine, balance between economic efficiency and fairness, and so on.

The present dissertation examines five alternative water allocation mechanisms for their suitability for the eastern United States. These water allocation mechanisms are rooted in four different regulatory principles. The Benefit Maximizing (MaxBen) allocation is based on economic optimization, which has been widely examined in existing water allocation studies. The Proportional Fairness (ProFair) allocation is based on equitable sharing, which is believed to best represent the spirit of the Riparian Doctrine. The Downstream Priority (DPrio) and the Upstream Priority with Municipal and Industrial User Privilege (UMIPrio) mechanisms are based on prioritization, which has been widely established in the western United States under the Prior Appropriation Doctrine. Finally, the No-Rule (NR) allocation is based on the principle of minimum regulation, which somewhat reflects the current reality in many regions in the eastern US.

An important contribution of this study is the introduction of the ProFair program. The program borrows the Proportional Fairness Criterion from the bandwidth allocation in wired and wireless communication networks and is for the first time introduced to solve water allocation problems. Serious efforts are invested in the modeling of this program. In addition to the log programming model, which is adopted from existing communication network studies, this study discovers that a quadratic programming model and a simple greedy procedure named ‘Bottleneck Algorithm’ can also achieve the same Proportionally Fair Allocation.

Besides, a mathematical model is developed for each of the other water allocation programs. A linear programming model is each developed for the DPrio, UMIPrio, and NR programs. A non-linear programming model is developed for the MaxBen program.

The allocation programs are evaluated based on two criteria, namely economic efficiency and equity. Given a known allocation, the economic efficiency is calculated as the aggregate net benefit of all users. To quantify the fairness of a given allocation, a measurement called Equity Index is developed, which measures the level of uniformity in the water supply satisfaction levels among all users.

Following the primary allocation programs, this dissertation further develops a trading model to simulate the water market under each of the alternative programs. Based on the model, the study builds an analytical framework that can examine in detail several characteristics of a water rights market, such as the volumes of water transferred, prices at which water is transferred, transaction revenues, and net market gains.

Water allocation and water market simulations under the five allocation programs are performed for the Sangamon River system in Illinois. The simulations choose two economic scenarios: the ‘Current’ scenario is based on a mixture of real and hypothesized water demands and economic conditions in 2006; the Future scenario imposes projected water demands and economic conditions in 2030. Historical rainfall and streamflow data from 1977 through 2006 combined with a series of different reservoir storage conditions are used as hydrologic input for the analysis. The monetary results are all converted to the 2006 dollar.

The following findings emerge through the water allocation and reallocation simulation in the Sangamon River Watershed.

1) The net economic benefits resulting from each of the allocation programs are in general negatively correlated with water availability, because greater water availability usually implies more rainfall, which renders abstracted water less valuable. With the projected increase in water demand and changes in economic conditions in the future, not to mention the possibility of more intense or frequent dry periods as part of global climate change, the net economic benefit of water use would increase accordingly. Depending on the program and initial reservoir condition, the average water use benefit ranges from around 34 to 39 M$/yr and 46 to 55 M$/yr under the ‘Current’ and the Future scenarios, respectively. The amount of water allocated varies little across demand/supply conditions.
2) The difference in net benefit among the selected programs tends to increase when any of the following conditions occur: i) rainfall decreases, ii) reservoir storages

decrease, and 3) water demands increase (the scenario moves from ‘Current’ to Future).

3) The MaxBen program achieves theoretically the highest net economic benefit. The UMIPrio program on average generates the second best economic value when the reservoir capacities are less than around 30-40% of maximum, but falls behind the ProFair program as the reservoirs continue to rise. The NR program produces the worst economic benefit when the reservoirs stay empty, but quickly improves as reservoirs capacities recover, and becomes identical to the UMIPrio program when they reach 20% of maximum. The poorest economic performance is given by the DPrio program, which produces the lowest net benefit under all but the zero reservoir storage condition. The results suggest that the economic performance of a priority-based program depends heavily on how it assigns the priority ranks to the users.

4) The difference in Equity Index among programs appears to be insignificant in most of the simulation years, but is most pronounced in some of the driest years, such as 1988. Similar to the results of economic benefit, the program-to-program difference in the Equity Index tends to escalate with decreasing supply and increasing demand.

5) Comparing the fairness performance among the selected programs, it is found that the ProFair program generates the highest and most stable Equity Index under all water supply and demand conditions, whereas the MaxBen program on average only scores the fourth, behind NR and UMIPrio. Interestingly, the NR program is

able to achieve relatively high level of fairness because of the highly uniform geographical distribution of rainfall and runoff over the Midwestern watershed. The DPrio produces the lowest Equity Index under all conditions.

6) The market simulation shows that as rainfall decreases, the water market tends to become increasingly active, with both the volume of water transferred and the net market gain growing under all but the MaxBen programs. The water market appears to be most active when the rainfall in the allocation window is less than 150mm.

7) Given the projected demand increase in the future, the scale of the water market will also increase. With a 1988-type drought, the amount of water transfer and the associated economic gain under the Future demand conditions may, depending on the initial allocation program, increase by as much as 11.5 to 22×10^6 m^3 and 5 M$ to 36 M$, respectively, compared to those under the Current.

8) The DPrio program appears to be able to create some of the highest potential market gains in a single year among all the studied programs, whereas the UMIPrio program provides the least market opportunity. Under the ProFair and NR programs, water transfers appear to be potentially profitable under a wider range of rainfall conditions, compared to those under the priority-based programs.

9) The analytical framework presented in this study is able to simulate the trading relationship and price structure of a complicated multi-user water market.

Based on the above findings, the present study recommends that policy makers should give more consideration to the ProFair program. The program stresses fair sharing of available water, which is consistent with the reasonable-use legal theory of the Riparian Doctrine and hence reduces the chance of water disputes and the costs involved in the resulting legal procedures. As a favorable result, the policy makers in the eastern states may face fewer legal barriers in adopting this program than alternative options. The program may create lower economic efficiency than some of the other programs, but this shortcoming can be remedied by a water market arrangement that allows water rights to be transferred from low-value to high value users, either temporarily or permanently. The ProFair program is subject to other potential problems, such as difficulty in assuring the level of certainty desired by withdrawers. However, the purpose of this study is not to find a one-size-fits-all solution for the traditionally Riparian states. Rather, it explores one option that has some valuable advantages and is potentially more suitable in areas where belief in both a permit program the traditional Riparian Doctrine is strong.

The water allocation programs described in this study are the simplest translation of the four basic water management principles of economic optimization, proportional fairness, prioritization, and minimum regulation. Simplifying assumptions are made for ease of mathematical simulation. These programs, in their current forms, are certainly not able to account for many complex situations in water management reality. Future studies should extend the programs by incorporating more sophisticated regulatory components, such as more complicated reservoir operation rules, seasonal or tiered minimum in-stream flow requirements, return flows, water quality considerations, to name a few. More data should be collected and more complicated mathematical formulas should be integrated into the current models.

Moreover, the present study only considers the water allocation in a specified critical period each year. Future research should, with the help of more sophisticated reservoir models and more detailed hydrological data, conduct the water allocation simulation on a more continuous basis. It would also be very helpful if future research could develop a method to quantify the administrative and/or transactions costs associated with each water allocation program. In that way, the programs can be evaluated on a more comprehensive economic basis.

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AUTHOR'S BIOGRAPHY

Xuetao Hu, son of Jicui Hu and Shuzhao Zhang, was born in Beijing, China, in 1975. He graduated from Tsinghua University in 2001 with a Bachelor's degree and a Master's degree in environmental engineering. He completed another Master's degree in natural resources and environmental sciences at the University of Illinois at Urbana-Champaign in 2004, before he joined the Ph.D. program at the Department of Civil and Environmental Engineering at that university. He is currently working for Hazen and Sawyer, P.C. as a water resource engineer.