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Relations Among Storage, Yield and Instream Flow

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Abstract

An extensive literature documents relations between reservoir storage capacity and water supply yield and the prerequisite properties of instream flow needed to support downstream aquatic ecosystems. However, the literature which evaluates the impact of reservoir operating rules on instream flow properties is limited to a few site-specific studies and as a result, few general conclusions can be drawn to date. This study adapts the existing generalized Water Evaluation And Planning model (WEAP) to enable general explorations of relations between reservoir storage, instream flow and water supply yield for a wide class of reservoirs and operating rules. Generalized relationships among these variables document the types of instream flow policies which, when combined with drought management strategies, are likely to provide compromise solutions to the ecological and human negotiations for water for different size reservoir systems. The concept of a seasonal ecodeficit/surplus is introduced for evaluating the impact of reservoir regulation on ecological flow regimes.

1. Introduction

It is no longer possible to exploit water resources for human needs without taking into consideration ecological flow needs. After two centuries of dam-building, only 2% of U.S. rivers remain free-flowing (Benke, 1990) which has caused large-scale hydrologic (Graf, 1999) and environmental disruption (Dynesius and Nilsson, 1994) both in the U.S. and elsewhere (Postel, 1995). Despite the widespread degradation of its river systems, the U.S. still has no comprehensive plan to secure the instream flows needed to support the diversity of freshwater life and to sustain ecological functions (Postel and Richter, 2003). The federal clean water act offers a broad and clear mandate to the U.S. Congress to protect river health because its goal is "to restore and maintain the chemical, physical, and biological integrity of the Nation's waters".

Yet, federal and state agencies administering this act have focused primarily on the chemical integrity of rivers by implementing best management practices, pollution control requirements and water quality standards. They have done little explicitly to regulate the quantity and timing of river flows to protect the physical and biological integrity of rivers (Postel and Richter, 2003). The federal Clean Water Act has clearly left water allocation decisions to the states, because Section 101(g) states "It is the policy of Congress that the authority of each state to allocate quantities of water within its jurisdiction shall not be superseded, abrogated, or otherwise impaired by this chapter." States have tackled the issue of allocation unevenly at best and with the lack of national policy in this area, it should come as no surprise that to date, there is still no comprehensive guidance available to managers of reservoir systems on how to deliver a reliable water supply yield while simultaneously maintaining the downstream aquatic ecosystem. The result of a lack of national policy is that there is very little literature devoted to methods for balancing human and ecological needs for water. In fact, the most relevant literature in this area originates in South Africa because they did institute a national policy. The rich literature now emerging from South Africa results in large part from legislative efforts which began in the mid 1990's to ensure that requirements for both basic human needs and the environment are met before potential future users can be licensed to abstract additional water (DWAF, 1997).

2. The Impact of Dams on the Ecological Flow Regime

There is now an extensive literature devoted to a description and evaluation of the general ecological impacts of dams on rivers (see Collier et al., 1996). There is also recent interest in defining the particular impacts of dams on the downstream hydrologic regime (see, for example, Magilligan and Nislow, 2005 and many others). Interestingly, few of the studies on this subject to date, have accounted for the impact of the operational aspects of the dams such as their storage volume, operating rule, demand schedule etc. on downstream hydrologic conditions. It is very clear from the theory of reservoir behavior that the impact of reservoirs on downstream hydrologic conditions will depend primarily upon their storage, S/μ and yield ratios Y/μ, where S, Y, and μ are the storage capacity, annual yield and annual inflow, respectively, to the reservoir system (Vogel et al., 1999). To fully understand the ecologic, geomorphologic and hydrologic impacts of dams it is necessary to integrate our knowledge of all factors which influence their operational behavior.

Consider a reservoir system with storage capacity S, fed by average annual inflows μ with two annual average releases, one for water supply Y, and the remainder for instream flow I. Figure 1 illustrates how I and Y vary with S where all three variables are standardized by dividing by μ. When evaporation, seepage and other losses are ignored, then all water not released as water supply yield Y ends up as instream flow I, hence $\mu = Y + I$, which further implies that the yield ratio and instream flow ratios sum to one so that $(Y/\mu) + (I/\mu) = 1$. Figure 1 considers two different values of the coefficient of variation of annual inflows Cv = 0. 3 and 1.0, roughly corresponding to temperate and semi-arid regions, respectively. Figure 1 illustrates that reservoir systems with small storage ratios lead to much greater values of average annual instream flow than systems with large storage ratios. In general, the instream flow ratio is inversely proportional to the storage ratio and tends to decrease as rapidly as water supply yields tend to increase with increasing storage ratio. Figure 1 illustrates that it is much more difficult to maintain instream flows for systems with large storage ratios than for systems with small storage ratios. If we consider a constant storage ratio, Figure 1 illustrates that reservoir systems in temperate regions (low Cv) will generally have a lower fraction of water available for instream flow (relative to the mean annual flow) than similar systems in arid regions. This is because for a given storage ratio, yields are greater in temperate regions where Cv is low, then in arid regions where variability is much greater.

Figure 1 was developed using the generalized storage-reliability-yield relations developed by Vogel and Stedinger (1987). Those relations for AR(1) lognormal annual reservoir inflows have been shown to provide a good approximation to the overall behavior of thousands of actual reservoir systems in the U.S. (Vogel et al. 1999), however, the remainder of this study uses the Water Evaluation And Planning model (Yates et al., 2005ab) with a daily time step, rather than the annual time step used to construct Figure 1.

The primary goal of this study is to explore the general behavior of water supply reservoirs with a view toward balancing both the human and ecological needs for water. A second goal is to provide a framework for the evaluation of different types of instream flow policies which lead to the most favorable tradeoffs between ecological and human needs for water. Here a favorable tradeoff between ecological and human needs for water is one which is amenable to negotiations between these two classes of users. The following sections provide a brief overview of the literature relating to the development of relationships between reservoir storage volume and the resulting properties of both the human and ecological needs for water.

3 Literature Review

Reservoirs, dams, locks, weirs and diversions are all operated to regulate the flow of rivers and all such regulation schemes impose an unnatural flow regime on aquatic ecosystems. It is now well understood that the ecological integrity of river systems depends upon their natural dynamic character and as result, Poff et al (1997) and many others argue that a natural flow paradigm offers a proven approach to restoring rivers.

There is an extensive literature devoted to determining how much water a river needs to sustain a healthy and diverse aquatic ecosystem (see recent review by Tharme, 2003). Similarly, there are well established approaches for determining how to operate single and multiple reservoir systems for the purpose of providing a reliable and resilient source of water to meet human needs (see reviews by Wurbs, 1993; and Labadie, 2004 and texts by Votruba and Broža, 1989; Revelle, 1999; Nagy et al., 2002; and McMahon and Adeloye, 2005). In spite of the extensive literature relating to the impacts of dams on rivers, methods for determining instream flow needs and the operation of water supply reservoirs to satisfy human water needs, there are surprisingly few studies which address all of these topics, simultaneously, which is the goal of this study.

3.1 Review of Literature on Reservoir Design and Operations for Human Water Needs: Most previous reservoir operations studies have focused on the allocation of human uses of water for water supply, hydropower, irrigation, recreation and flood control. There are two general mathematical approaches to a modeling the behavior of reservoir systems (1) optimization and (2) simulation. Simulation approaches to reservoir operations and design have been in use for over a century (Rippl, 1883) and are now so well developed that numerous textbooks are devoted primarily to the simulation of reservoir systems (Votruba and Broža, 1989; Wurbs, 1996; Nagy et al. 2002, McMahon and Adeloye, 2005). The U.S. Bureau of Reclamation maintains an inventory of generalized software packages for the simulation of reservoir and watershed systems (http://www.usbr.gov/pmts/rivers/hmi/index.html, accessed in Nov 2005). There is also an abundant literature which focuses on the optimization of multiple and competing releases of water from reservoirs for human water uses (see reviews by Wurbs, 1993; and Labadie, 2004 and texts by Revelle, 1999; Nagy et al. 2002 and McMahon and Adeloye, 2005).

3.2 Review of Literature on Reservoir Operations for Instream Flow:

3.2.1 Optimization Approaches: Of the hundreds of optimization-oriented reservoir operations studies reviewed by Wurbs (1993), Revelle (1999), Nagy et al. (2002) and Labadie (2004), we have identified a relatively small number of studies which focused on the optimal tradeoff among ecological and human flow needs (Sale et al., 1982; Cardwell et al., 1996, Flug et al., 2000; Jager and Rose, 2003; Chaves et al., 2003; Harman and Stewardson, 2005; Suen and Eheart, 2006). Within the context of optimization approaches, other than the above cited studies, instream flow is normally considered as a hard, fixed constraint assuring that, say, some minimum level of streamflow is provided . Recent literature has emphasized that instream flow needs are far more complex than a fixed aquatic baseflow requirement (Richter et al., 1996, 1997). As a result, there is now much greater attention being given to assessing the impact of reservoir operations on the downstream properties of instream flow.

There is a general evolution in the application of mathematical methods to reservoir (and other) problems. Our experience is that simulation approaches are usually developed before optimization approaches, in part because optimization approaches to reservoir operations always contain a simulation model of the behavior of the reservoir, embedded within the optimization model. Thus before one can integrate social, political, economic and other factors into the determination of optimal reservoir operations, it is first necessary to be able to simulate reservoir operations, in this case, corresponding to both the human and ecological needs for water. Therefore, rather than describe in detail the few previous studies (cited above) which have developed optimization approaches to the problem of balancing human and ecological flow needs, this study focuses instead on simulation approaches for evaluating the fundamental tradeoffs associated with this problem.

3.2.2 Simulation Approaches: Surprisingly, none of the books dealing with the simulation of reservoir systems (Votruba and Broža, 1989; Wurbs, 1996; Nagy et al. 2002; and McMahon and Adeloye, 2005) provide guidance on the allocation of water to meet both human and ecological needs for water other than the prescription of a minimum flow standard. Palmer and Snyder (1985) were one of the first researchers to simulate the general impacts of instream flow requirements on the overall performance of a water supply system. Palmer and Snyder (1985) showed that instream flow requirements can decrease the performance of a water supply system in terms of its ability to meet human water needs, by an order of magnitude. Nearly a decade later, reservoir simulation studies began to appear which investigated the impact of various instream flow policies on the resulting ecological flow regime below dams for particular reservoir systems (Alves and Henriques, 1994; Hughes and Ziervogel, 1998; Benjamin and Van Kirk, 1999; and Shiau and Wu, 2004).

Alves and Henriques (1994) compared numerous methods for computing instream flow requirements downstream from dams, all of which are improvements over the approach in use in Portugal at that time, which was to set a minimum ecological flow somewhere between 2.5% and 5% of the mean annual streamflow and to prohibit reservoir flow diversions when reservoir inflows drop below that minimum ecological flow.

Most previous research on approaches for determining reservoir operating rules which ensure the protection of instream flow regimes originate in South Africa. Hughes et al. (1997)

and Hughes and Ziervogel (1998) summarize the development of an instream flow model combined with a reservoir simulation model which together can evaluate a range of reservoir operating rules on characteristics of instream flow. Attempts to reproduce the natural flow regime are made by comparing the output from the reservoir simulation model to predetermined flow percentiles taken from daily flow duration curves constructed for each month. Their instream flow model accounts for the maintenance of low flows, peak flows and the durations of those events in each month, in an effort to reproduce important properties of the natural flow regime. The operating rule built into their model compares the cumulative deficit in yields with predetermined values to determine when and how much to reduce the recommended instream flows. Hughes and Ziervogel (1998) developed a modeling system which is very similar to the modeling system introduced here, however, they have not considered the wide range of operating rules considered here, nor is their system based on a comprehensive and widely used water resource planning model as is the case here (WEAP).

Wollmuth and Eheart (2000) evaluated the impact on instream flow resulting from five different release rules for reservoir systems under irrigation demands: (1) no irrigation releases allowed (2) provide as much as irrigators need, whenever they wish (current practice in most eastern states), (3) irrigators release whatever they wish as long as downstream minimum flow standard is met, (4) release only a fixed volume of water per unit of irrigated land as long as the minimum downstream flow requirement is met, and (5) provide as much irrigation as farmer desires as long as the minimum downstream requirement is met and as long as a fraction of the inflow is set aside for release downstream. In general, they found that regulatory scenarios (1), (2) and (3) were not viable options and that of the two viable options, the fractional flow set aside scenario (5) is more effective and robust than the fixed volume permit scenario (4). In a subsequent study, An et al (2004) found that the any reservoir operations policy which ties allowable withdrawals to flows measured downstream of the reservoir can result in unstable feedback, which in turn can lead to severe variability of both the withdrawals and the resulting instream flows.

Shiau and Wu (2004) and Benjamin and Kirk (1999) describe the use of the Indicators of Hydrologic Alteration (IHA) and the Range of Variability (RVA) approach introduced by Richter et al. (1997) to evaluate the hydrologic impacts of flow regulation on specific dam systems. Shiau and Wu (2004) show that a reduction in dam diversions combined with a minimum flow requirement can alleviate some of the negative impacts associated with the altered flow regime. Similarly, Benjamin and Kirk (1999) describe the reservoir conditions and frequency with which instream flow requirements can and cannot be achieved.

In spite of these efforts, little guidance exists on suitable reservoir operations policies for assuring adequate water for both human and instream flow needs. The experiments reported below are an initial attempt to derive more generalized conclusions by examining the tradeoff between water supply yield and instream flow properties for a wide class of reservoir systems.

4.0 Evaluating Reservoir Management Using the Ecodeficit

It is common practice to summarize the behavior of water supply yield by reporting only one or two summary statistics such as the mean annual yield and reliability. Summarizing instream flow properties is more complex because instream flows range over several orders of magnitude making it necessary to examine their seasonal or monthly frequency, magnitude and duration of occurrence. Tharme (2003) and Annear et al (2004) review a wide variety of approaches for defining watershed-specific instream flow prescriptions. More recent instream flow methods are now based on the premise that departures from the natural flow regime can be expected to result in degradation in river health (Poff et al. 1997). One of the most commonly used approaches for evaluating the degree of alteration of the hydrologic flow regime is the range of variability approach (RVA) (Richter et al., 1997) which involves defining instream flow goals based on up to thirty-two different hydrologic statistics. However, in order to construct relationships between storage, yield and instream flow, a single, overall measure of instream flow protection is needed. We recognize that a single metric is not adequate to quantify instream flow protection. Nonetheless, for this initial case study we introduce a single metric, the ecodeficit, which is based on a flow duration curve .

Flow duration curves are commonly used in a variety of instream flow assessment methods (Vogel and Fennessey, 1995; Annear et al, 2004; Acreman, 2005), because they provide a graphical illustration of the overall hydrologic state of a river system. A flow duration curve (FDC) is simply a plot of the ordered daily streamflow observations $Q_{(i)}$ (where i=1 is the largest flow) as a function of their exceedance probability $p_i = i/(n+1)$, where n is the number of days of flows and i is the rank. Two different types of FDC's are possible: (1) period-of-record FDC's and (2) a median annual or seasonal FDC - representing the exceedance probability of daily flows in a median year or season - (see Vogel and Fennessey, 1994). In this study we employ median seasonal FDC's instead of median annual FDC's because annual FDC's mask the impact of seasonal variations in the flow regime. For example, a median summer FDC is constructed by developing n summer FDC's corresponding to each of the n-years of flow records and than reporting the median of those FDC's. The resulting median summer FDC represents the exceedance probability of daily streamflow in a typical, or median summer. In this study we divide the year into three seasons: Spring (March-June), Winter (November-February) and Summer (July-October). These periods were selected based on their biological and hydrological similarity for rivers in the northeastern United States.

Figure 2 uses a light gray curve to illustrate the FDC for a river which is not subject to any withdrawals, hence is said to be unregulated. The solid black curve in Figure 2 represents a simulated FDC for the same river when subject to withdrawals. The area depicted in Figure 2 which is both below the unregulated FDC and above the regulated FDC is termed the ecodeficit. The ecodeficit area represents the net volume of water which is now unavailable for instream flow needs due to the water withdrawals. Conversely, the area which is both above the unregulated FDC and below the regulated FDC is termed the ecosurplus. Despite the connotation associated with the term "ecosurplus," we note that any change in the natural flow regime, whether higher or lower, can impair ecological integrity, depending on the magnitude, timing, duration, and frequency of those deviations (Poff *et al*, 1997). Ecosystems depend upon both high flows and low flows for optimal health. When calculated seasonally, we divide the seasonal ecodeficit by the mean seasonal inflow to the reservoir to quantify the fraction of streamflow which is no longer available to meet instream flow needs during a particular season .

The ecodeficit/surplus provides a simplified representation of hydrologic impacts, as compared to the use of the more complex IHA and RVA hydrological approaches. The ecodeficit/surplus concept can also be applied to habitat duration curves (see Vogel and Fennessey, 1995). Even though flow duration curves do not account for the timing or duration of particular flow events, the use of seasonal, or monthly FDC's can capture some timing impacts. In addition, the eco-deficit defined in Figure 2 provides a graphical representation that provide an easily understood visualization of changes to flow conditions and therefore offers significant potential as a communication tool. Future research needs to be performed to evaluate the ability of the ecodeficit to adequately and fully address the ecologically-based instream flow needs.

5.0 Case Study Approach and Goals

Our initial goal is to evaluate the tradeoff between meeting instream flow needs and human needs for water for reservoir systems by developing relationships between reservoir storage volume S, and properties of both water supply yield Y and instream flow, I. Another goal is to develop a methodology which can be used for evaluating the impact of alternative reservoir operating rules on the tradeoff between meeting ecological and human flow requirements. To enable our work to be general and to support follow-on studies, we adapt an existing water resource planning model to achieve our goals. Numerous different reservoir operating policies have been embedded into the generalized WEAP model (Yates et al., 2005ab) which is described below. Thus an important feature of this research is that it results in extensions to an existing water planning model which should enable future evaluations of the tradeoffs between ecological and human needs for water. The following sections describe WEAP, the operating policies added to WEAP and the results of our simulation experiments.

5.1 The W̲ater E̲valuation a̲nd P̲lanning Model WEAP: The Water Evaluation and Planning (WEAP) model is a scenario-driven decision support system (DSS) designed to support water planning. WEAP operates on the basic principle of water balance accounting, where both engineered and biophysical components of a water system are represented to facilitate multi-stakeholder water management dialogue on a broad range of topics including, among others, reservoir operations and ecosystem requirements on which this research is focused. The structure of the WEAP model is unique in that it integrates the physical hydrologic processes of a system with the management of institutions and infrastructure governing the allocation of water resources (Yates et al., 2005ab). As such, the model provides an ideal framework within which to evaluate the relationship between a reservoir's storage, yield and instream flow requirements (Lévite et al., 2003; and Yates et al., 2005b)

The WEAP framework and data objects are graphically oriented, with the software built using the Delphi Studio® programming language (Borland Software Corporation), and also utilizing MapObjects® software libraries from the Environmental Systems Research Institute (ESRI). The framework allows for spatial referencing of watershed attributes (e.g. river and groundwater systems, demand sites, wastewater treatment plants, watershed and political boundaries, and river reach lengths) (Yates et al., 2005ab). In this study, the data object framework in WEAP was used to describe a simple system containing one river with a reservoir and an instream flow requirement on the river downstream.

Reservoirs in the WEAP DSS are considered demand sites (when filling) and can be configured to store water that becomes available either through the solution of a physical hydrology module or from a user-defined time-series of inflows from upstream. A reservoir's operating *rules* in WEAP determine how much water is available in the current time step for release to satisfy downstream demand(s) including, among others, instream flow requirements. Instream flow requirements in WEAP are used to represent established or new regulatory requirements of minimum flows in a river. These data objects are placed on the river, and are assigned a priority and minimum flow value that must be maintained during a specified period.

WEAP employs an iterative Linear Programming (LP) algorithm to solve water allocation problems. The objective of the LP is to maximize water delivered to all demands and instream flow requirements according to their ranked priorities, with demands of the same priority referred to as *equity groups*. Within WEAP, reservoirs, instream flow requirements and other entities are assigned a unique Priority Number; integers that range from 1 (highest priority) to 99 (lowest priority). Those entities with a priority 1 ranking are members of equity group 1, those with a priority 2 ranking are members of equity group 2, and so on. The LP constraint set is written to supply an equal percentage of water to the members of each of the equity groups (Yates et al., 2005ab).

The research herein assigns priority values in WEAP in order to define a variety of instream flow scenarios. To capture a temporally changing regulatory environment, for instance, the priority value of an instream flow requirement was increased, raising the minimum standard of flow in any given year or simulation. If the priority assigned to storing water in a reservoir is less than downstream demands or instream flow requirements, WEAP only releases available storage as is needed to satisfy demand and instream flow requirements, taking into consideration releases from other reservoirs and withdrawals from rivers and other sources.

An application programming interface (API) was developed in conjunction with WEAP, which allows the user to control WEAP data values directly using another program, programming language, or scripts. This feature was particularly useful in our evaluation of storage, yield and resulting instream flow, as it enabled repetitive simulations each with different input parameters. The API automatically changes reservoir data values in WEAP, calculates results and outputs the results. In addition to changing priority structures in the scenarios developed herein, the API function allows a user to asses a variety of reservoir operation and instream flow requirement policy combinations with ease.

5.2 Simulation Experiments Simulation experiments were performed using WEAP to explore the tradeoff between instream flow properties and reservoir yield corresponding to a range of instream flow policies for a wide class of reservoir systems with storage ratios S/μ in the range [0, 3]. Figure 9 in Vogel et al. (1999) and both Table 1 and Figure 1 in Graf (1999) document that storage ratios in the range [0, 3] should capture the behavior of most reservoirs across the U.S. with values below 1 typical of temperate regions and values above 1 typical in the more arid regions of the U.S.

Daily reservoir system simulations are performed using WEAP over the 20-year period 1960-1979, using daily streamflows for the Green River at Williamstown, MA (USGS Gage 01333000) which has a drainage area of 42.6 sq. miles. This streamflow record was used because it is a relatively unregulated gage and includes the drought of record for this region. A double-cycling sequent peak algorithm (see Vogel and Stedinger, 1987, for advantages of this approach) is employed to determine the steady-state water supply yield which can be delivered without failure over the 20-year period for all reservoir operating rules described below, over a wide range of storage ratios. The sequent peak algorithm is identical to the graphical mass curve approach introduced by Rippl (1883) and is the approach which was used to design most surface water supply reservoirs in the U.S. The resulting reservoir yield is termed a 'safe yield' because that is the standard parlance used in practice. The algorithm assumes that the reservoir starts full and requires that the storage reservoir must refill at some point after the worst drought on record. The resulting reliability associated with the reservoir yield and the instream flow are both 100% over the 20-year historical simulation period. In practice, one may allow failures, however, to reduce the complexity of the problem and the number of degrees of freedom in this initial study we only consider failure-free operations over the 20-year historical planning period. Although average annual yields are reported, we allowed actual daily reservoir yields to vary seasonally based on average seasonal use factors for 42 surface water dominated drinking water reservoirs in Massachusetts (Waldron and Archfield, 2006).

5.3 Reservoir Operations Policies:

This study considers a wide range of alternative reservoir release rules which have been incorporated into WEAP to enable future extensions to this work. The instream flow releases and the human demands for water both operate as demands on the reservoir. Instream flow is defined as the streamflow requirement immediately downstream of the reservoir. A wide range of policies are considered in an effort to capture policies in common use as well as some promising policies suggested in the literature. The policies considered do not necessarily represent policies that would protect the ecological integrity of downstream aquatic systems. The following operating policies are considered:

5.3.1 No Instream Flow Requirements**:** There are no instream flow requirements but all human water demands are met. Instream flows occur only when the reservoir spills.

5.3.2 Fraction of Inflow (FOI)**:** A fraction of the reservoir inflow is released as instream flow. In practice, one would only have access to yesterdays reservoir inflow, hence our model assumes reservoir inflow is yesterdays inflow. Here we only consider a fractional release that is 40% of reservoir inflow. This fractional release is not presumed to be protective of ecological function.

5.3.3 Fixed Minimum Release**:** Requires a fixed minimum instream flow release equal to the default summer aquatic base flow (ABF) defined by the U.S. Fish and Wildlife Service in the Interim Regional Policy for New England Stream Flow Recommendations as the August median daily streamflow, when data is available for its estimation (Lang, XXXX). For watersheds in New England over 50 square miles, where site specific data is not available, ABF=0.5 cfsm. We used the default ABF for illustrative purposes despite the fact that our watershed size was just below 50 square miles. Thus, ABF = 21.3 cfs = 13.76 mgd which corresponds to a daily flow which is exceeded 79% of the time in a typical or median year. If the reservoir inflow is less than the minimum instream release requirement, then only the reservoir inflow is released.

5.3.4 Fixed Minimum Flow with Augmentation**:** Requires the ABF minimum instream flow release at all times, even when the reservoir inflow is less than the ABF flow requirement.

5.3.5 Flow Components (FC): This rule follows the fraction of inflow (FOI) release rule (see above), with one exception. It attempts to incorporate occasional high flow releases for habitat improvement. Flows are considered to be a high flow if they fall above a threshold which, in this simulation, is the 75th percentile of all flows. After at least 3 high flow events have occurred in a season, each subsequent high flow event that season is not released. For these "surplus" high flow events, the FOI rule applies only up to the 50th percentile flow level.

5.3.6 Drought Management**:** In addition to the above instream flow release policies, we introduce a drought management policy which can be implemented with any of the above instream flow policies. If reservoir drops into the buffer zone (below 50% full), both yield and instream flow releases are reduced equally and proportionally. The lower the reservoir level falls, the greater the reduction. The reduction gradually increases from 0% to 35% as the reservoir level falls from 50% full to 0% full. The reservoir yield reported in this case is the 'effective yield' which accounts for the reduction in yield due to drought management. In this initial study, drought management is only illustrated for the FOI policy.

6.0 Results

6.1 The Storage-Yield Relationship: Figure 3 illustrates storage yield curves corresponding to each of the instream flow policies. As expected, all policies generally lead to lower yields than the ‘no instream release’ policy. From Figure 3a it is evident that the type of operating rule has an enormous impact on the storage yield relationship for nearly all storage ratios. Naturally the lowest reservoir yields result from the minimum flow with augmentation policy, because releases are required even when reservoir inflows are lower than the required release (ABF).

Of particular interest in Figure 3 are the results for the fraction of inflow policy (FOI=0.4) with drought management. The FOI policy combined with drought management led to an almost identical storage yield relationship as for the case of no instream flow release, for all storage ratios below 0.3. Similar results were obtained when the flow components (FC) policy was combined with drought management. This implies that from the perspective of human water use requirements, the FOI and FC policies combined with drought management can lead to human water yields which are commensurate with yields for systems with no instream flow requirements for small storage ratios.

Of further interest is the shape of the storage yield curve when drought management is added to the FOI policy as highlighted in Figure 3b. Here yields actually reduce as the storage fraction increases above 1.0. How can reservoir yield decrease as reservoir storage increases? When drought management is implemented, the effective yield (after drought management) is reported in Figure 3. Apparently, for storage ratios above 1.0, the marginal increases in reservoir yield resulting from marginal increases in storage, are less than the marginal decreases in reservoir yield resulting from marginal increases in drought management. Essentially the same result was obtained when drought management was combined with the FC policy. We conclude that drought management will have its greatest impact for reservoir systems with small storage ratios.

It is important to realize that drought management will always be an effective management strategy for reducing water use, however, Figure 3b illustrates additional gains in overall reservoir yield which are above and beyond the magnitude of the reductions in demand. Another way to understand why average annual reservoir yields increase due to drought management is because drought management curtails water use during the driest periods (when storage is drawn down), enabling the storage reservoir to deliver reduced yields during the worst drought on record leading to a greater long term average annual "safe" yield. This effect is most apparent for smaller storage ratios because such systems have the greatest marginal increase in yields for a given marginal increase in storage due to the 'flattening' of the storage yield curve as storage ratios increase. The overall gains in net or effective yield due to drought management corresponds to the region between the two storage yield curves illustrated in Figure 3b.

6.2 The Storage–Instream Flow Relationship: When plotting relations between storage and yield as in Figure 3, it is standard practice to report the mean annual yield, even though yields vary seasonally as in our experiments. There is no standard practice for plotting storage-instream flow relations and unlike water supply yield, instream flow varies by several orders of magnitudes during a typical year. Due to the gross variations in instream flow in a typical year, it is more informative to examine the median instream flow rather than the mean instream flow. We normalize the median instream flow by dividing by the mean reservoir inflow, which we term the median instream flow fraction. The median instream flow fraction represents the median daily instream flow as a fraction of the average inflow, so it represents the typical or median fraction of the total streamflow mass leaving the reservoir. Figure 4a reports the median instream flow fraction as a function of the storage ratio. Figure 4a documents dramatic reductions in the median instream flow fraction as reservoir storage ratios increase from 0 to 0.2, for all reservoir operating policies. Figure 4b illustrates the relationship between the maximum of the three seasonal ecodeficits (reported as a fraction of the mean reservoir inflow) and the storage fraction. Instead of reporting the total ecodeficit, we report (1 - maximum seasonal ecodeficit),,because the largest seasonal ecodeficit should be indicative of the most significant ecological impacts. As shorthand we refer to (1 – maximum seasonal ecodeficit) as the ecoflow indicator. Note that ecosurplus values were mostly zero, and the nonzero values were very small compared to the ecodeficit values, hence we do not report the ecosurplus values here.

A comparison of Figures 4a and 4b indicates that as the storage ratio increases, the decreases in ecoflow are generally similar to the decreases in the median instream flow fraction, however, the ecoflow indicator provides a much greater distinction between the impacts of the various policies than the median instream flow fraction. Figure 4b illustrates that for storage fractions below 0.4, the fixed minimum flow policies lead to much greater ecoflow values than any of the other policies, which is a different conclusion than would have been reached by viewing the median instream flow in Figure 4a. Figure 4a documents that with no instream flow policy, the river will be dry at least 50% of the time, for storage ratios above 0.25 and Figure 4b documents that those dry conditions will continue for at least an entire season. We also observe from Figures 4a and 4b that addition of drought management to the FOI policy always leads to slight decreases in the ecoflow indicator, in spite of the gains in yield reported earlier in Figure

3b. This is expected because the drought management policy reduces the reservoir releases in equal proportion to the reduction of yield.

Figure 4c illustrates that the coefficient of variation of the daily instream flow steadily drops for all operating rules as the storage ratio increases. Figure 4c also highlights that use of a fixed minimum release strategy, with or without augmentation, generally leads to instream flows with lower variability than the reservoir inflows, whereas all other policies led to increases in flow variability for storage fractions below 1.5. Figures 4b and 4c illustrate that the two indicators ecoflow=1-ecodefict, and coefficient of variation, yield different conclusions, because for storage fractions below about 0.4 a fixed minimum release leads to higher ecoflows yet a lower coefficient of variation. The ecological consequences of major reductions or increases in the variation of flows has not been fully explored in the literature. However, Poff and Allan (1995) found that differences in riverine fish communities in the upper Midwest could be explained fairly well by examining differences in the variability or stability in the daily flow regime. The results in Figure 4 are consistent with what was illustrated earlier in Figure 1, that is, it is more difficult to maintain instream flow properties for systems with large storage ratios than for systems with small storage ratios.

Figure 5 illustrates boxplots of the daily instream flows resulting from each of the instream flow policies for storage ratios of 0.1, 0.4, 1.0 and 2.0. Comparing the boxplots resulting from various operating policies with the boxplot of the reservoir inflows shown on the left in each panel, one observes the gross differences in the probability distribution of daily flows which result from use of a minimum flow policy, with the greatest differences occurring for storage ratios above 0.1. The FC and FOI policies lead to boxplots with a very similar shape to the boxplots of the reservoir inflows in all cases and one can see that the increased variability in instream flows associated with these policies results from the occurrence of some instream flows which are smaller than the lowest recorded reservoir inflow. Figure 5 clearly illustrates the limitations of fixed minimum release policies for systems with large storage ratios, since the boxplots of these policies for storage ratios 0.4, 1.0, and 2.0 are completely compressed. This demonstrates a loss of natural variability in flow associated with these policy types that would likely result in loss of river function and ecological intregrity if applied in the field.

6.3 The Tradeoff Between Instream Flow and Water Supply Yield It is instructive to view the tradeoff which exists between providing water supply yield and preserving the natural flow regime for a particular reservoir system. The tradeoff between average annual yield and average annual instream flow is a zero sum tradeoff for all reservoir operating rules considered. In other words, every gallon of water released as yield is no longer available for instream flow. However, if one views other statistics of instream flow, such as the median instream flow fraction or the ecoflow indicator, a zero sum tradeoff no longer results and it is this tradeoff which is of central interest in this study and is examined below.

Figures 6a, 6b, and 6c compares the ecoflow and yield fractions for storage ratios of 0.1, 0.4 and 1.0, respectively. Again, as was demonstrated before in Figure 4b, it becomes increasingly difficult to achieve high values of ecoflow, as the storage ratio increases. Consider a group of stakeholders attempting to reach consensus on a suitable reservoir operating policy to satisfy both ecoflow and yield objectives. An ideal policy would lead to values of both yield fraction and ecoflow, equal to unity in Figure 6, corresponding to a point in the upper right hand corner. Such an ideal policy does not exist, however, it helps us visualize our aspirations. Consider Figure 6b with a storage ratio of 0.4. Any increase in ecoflow above and beyond the results for no instream flow release will lead to a decrease in yield. Of all the policies considered, the FOI =0.4 policy with drought management, shown with an open square, gives the greatest increase in ecoflow, for the least decrease in yield fraction, hence it is more likely that a group of stakeholders could agree upon choice of this policy than any of the other policies. Similar results are obtained in Figures 6a and 6c and similar results were obtained for the FC policy but were not plotted here. In general, the greater the negative slope of the tradeoff between ecoflow and yield fraction in Figure 6, the more likely it is that stakeholders will be willing to decrease yield in order to increase ecoflows. Figure 6 documents that such negotiations are more likely for reservoir systems with small storage ratios, because such systems exhibit the largest negative sloped relations between ecoflow and yield fraction.

Figure 6 illustrates that for all three storage ratios, drought management always led to slight increases in the yield fraction, with only a slight reduction in the ecoflow indicator, so that drought management holds great promise for negotiating the tradeoff between ecoflow and yield. Another observation in Figure 6 is that the FOI policy (and by analogy the FC policy) provides a promising approach for spanning a wide range of tradeoffs between yield and instream flow, particularly for storage ratios greater than or equal to 0.4. By adjusting the fraction of inflow parameter from 0.1 to 0.8 (which we term a policy parameter), the FOI and FC policies can be used to ‘adjust’ the tradeoff between ecoflow and yield.

Overall, our simulations reveal that for larger reservoir systems, with storage ratios above about 0.4, both the FOI and FC policies as well as the drought management policy offer significant promise for aiding future negotiations between yield and instream flow with the FOI parameter used as a policy parameter. For smaller reservoir systems with storage ratios less than about 0.4, a minimum release policy with or without augmentation, combined with drought management, offers promise for aiding negotiations. This is due to the fact that for smaller reservoirs, higher flows are experienced by the downstream ecosystem due to frequent spill events allowing for protection of much of the natural flow regime without directed releases.

7.0 Conclusions and Recommendations

This is one of the first studies which has sought to generalize our understanding of the storage-yield-instream flow relationship and to improve our understanding of the impact of reservoir operating policies on the tradeoff between properties of instream flow and water supply yield. We have shown through a simple case study that the choice of a reservoir operating policy can have an enormous impact on the properties of both yield and instream flow and that different types of policies may be suited to different size reservoir systems (based on storage ratio). Overall, our simulations reveal that for larger reservoir systems (storage ratios above 0.4, approximately), both the FOI and FC policies in combination with drought management policy offer significant promise for aiding future negotiations between yield and instream flow with the FOI parameter used as a policy parameter. For smaller reservoir systems with storage ratios less than about 0.4, a minimum release policy with or without augmentation, combined with drought management, may offer promise, though we caution that the modification to the low flow variability of the instream flows needs attention in these cases. Here drought management involves reductions in both human and instream flow demands in when reservoir storage levels are low.

In general, drought management was shown to be an effective management strategy for reducing both human and instream flow water uses, and interestingly, for reservoir systems with storage ratios below 1 we found additional gains in overall reservoir yield which exceed the magnitude of the reductions in demand. This extra benefit associated with drought management results from the fact that the demand curtailments in both human and ecological water uses occur at the time when the reservoir is drawn down, leading to overall increases in net or effective safe yield. We also found that drought management is likely to have its greatest impact for reservoir systems with relatively small storage ratios, but that it is always a useful tool. Viewed only from the perspective of human water use requirements, the FOI and FC policies combined with drought management can lead to human water yields which are commensurate with yields for systems with no instream flow requirements for small storage ratios. Formalizing this type of drought management into actual reservoir operational guidelines is a challenge that appears to be worth pursuing.

We documented that it is much more difficult to maintain instream flows for systems with large storage ratios than for systems with small storage ratios. On the other hand, for a fixed storage ratio we documented the somewhat counterintuitive result that reservoir systems in temperate regions (low inflow variability) will generally have a lower fraction of water available for instream flow (relative to the mean annual flow) than similar systems in arid regions, which are subject to greater inflow variability.

There are several promising natural extensions to this initial study. Much more rigorous evaluations are needed to determine the ability of the ecodeficit concept introduced here, to distinguish ecologically significant departures from the natural flow regime. Our initial attempt to evaluate the tradeoff between human and ecological flow needs was approached using a daily reservoir simulation model. A natural extension would be to reformulate the reservoir operations problem in an optimization framework with the goal of exploring the Pareto frontier which exists between human and ecological flow needs, analogous to the work by Homa et al., (2005) and Suen and Eheart, (2006). Here a Pareto frontier is analogous to the tradeoff curves in Figure 6, but would be optimal in the context of particular human and ecological flow objectives.

Formulation of the problem as an optimization problem would enable us to optimize the various policy parameters associated with the reservoir operating policies which were recommended in this study with the goal of developing a Pareto frontier which would facilitate negotiations between the various stakeholders involved.

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References

Acreman, M. (2005), Linking science and decision-making: features and experience from environmental river flow setting, *Environmental Modeling & Software*, 20, 99-109.

Alves, M.H., and A.G. Henriques, (1994), Instream flow determination for mitigating environmental impact on fluvial systems downstream dam and reservoirs, *Advances in Water Resources Technology and Management*, Tsakiris & Santos (eds.), 351-358.

An, H., J. W. Eheart and R.D. Braatz, (2004), Stability-oriented programs for regulating water withdrawals in riparian regions, *Water Resources Research*, 40, doi:10.1029/2004WR003398.

Annear, T., Chisholm, I., Beecher, H., Locke, A., and 12 others. (2004) Instream Flows for Riverine Resource Stewardship (Revised Edition), Instream Flow Council, Cheyenne, Wyoming. 267 pages.

Benjamin, L., and R.W. Van Kirk, (1999), Assessing instream flows and reservoir operations on an eastern Idaho river, *Journal of American Water Resources Association*, 35(4), 899-909.

Benke, A.C., (1990) A perspective on America's vanishing streams, *Jour. of the North Amer. Benthological Soc.*, 9, 77-88.

Cardwell H, Jager H.I., and Sale M.J. (1996). "Designing instream flows to satisfy fish and human water needs." *Journal of Water Resources Planning And Management*, 122 (5), 356-363.

Chaves, P.T., T. Kojiri and Y. Yamashiki, (2003), Optimization of storage reservoir considering water quantity and quality, *Hydrological Processes*, 17(14), 2769-2793.

Collier, M., R.H. Webb and J.C. Schmidt, (1996) Dams and Rivers: A Primer on the Downstream Effects of Dams, U.S. Geological Survey, Circular 1126, Tucson, AZ, 94p.

Dellapenna, J. (Eds.), (1997), *Riparian Model Water Code for Traditionally Humid Areas*, American Society of Civil Engineers Publications, New York.

DWAF, (1997), White paper on a national water policy for south Africa, Department of Water Affairs and Forestry, Pretoria.

Dynesius, M. and C. Nilsson, (1994) Fragmentation and flow regulation of river systems in the northern third of the world, *Science*, 266, 753-762.

Flug, M., L.H. Seitz and J.F. Scott, (2000), Multicriteria decision analysis applied to Glen Canyon Dam, *Journal of Water Resources Planning and Management*, 126(5), 270-276.

Graf, W., (1999), Dam nation: A geographic census of American dams and their large-scale hydrologic impacts, *Water Resources Research*, 35(4), 1305-1311.

Harman, C. and M. Stewardson, (2005), Optimizing dam release rules to meet environmental flow targets, *River Research and Applications*, 21, 113-129.

Homa, E., R.M. Vogel, M.P. Smith, C. D. Apse, A. Huber-Lee and J. Sieber, An Optimization Approach for Balancing Human and Ecological Flow Needs, EWRI 2005 World Water and Environmental Resources Congress, Anchorage, Alaska, May 15-19 2005.

Hughes, D.A., J. O'Keeffe, V. Smakhtin and J. King, (1997), Development of an operating rule model to simulate time series of reservoir releases for instream flow requirements, Water SA, 23(1), 21-30.

Hughes, D.A. and G. Ziervogel, (1998), The inclusion of operating rules in a daily reservoir simulation model to determine ecological reserve releases for river maintenance, *Water SA*, 24(4), 293-302.

Jager, H.I., and K.A. Rose, (2003), Designing optimal flow patterns for fall chinook salmon in a central valley, California, river, *North American Journal of Fisheries Management*, 23, 1-21.

Labadie J.W., (2004), Optimal operation of multireservoir systems: State-of-the-art review, *Journal of Water Resources Planning and Management*, 130 (2), 93-111.

Lévite, H., H. Sally and J. Cour, (2003), Testing water demand management scenarios in a water-stressed basin in South Africa: Application of the WEAP Model, Physics and *Chemistry of the Earth*, 28, 779-786.

Magilligan, F.J. and K.H. Nislow, (2005), Changes in hydrologic regime by dams, *Geomorphology*, 71(1-2): 61-78.

McMahon, T.A., and Adeloye, A.J., (2005), *Water resources yield,* Water Resources Publications, Fort Collins, CO, 234 p.

Nagy, I.V., K. Asante-Duah, and I. Zsuffa, (2002) *Hydrological dimensioning and operation of reservoirs: practical design concepts and principles,* Kluwer, Dordrecht, 225p.

Palmer, R.N., and R.M. Snyder, (1985) Effects of instream flow requirements on water supply reliability, *Water Resour. Res*., 21(4), 439-446.

Poff, N.L. and J.D. Allan, (1995) Functional organization of stream fish assemblages in relation to hydrological variability, *Ecology*, 76(2), 606-627.

Poff, N. L., J. D. Allan, M. B. Bain, J. R. Karr, K. L. Prestegaard, B. Richter, R. Sparks, and J. Stromberg (1997), The natural flow regime: A paradigm for river conservation and restoration, *BioScience*, 47, 769-784.

Postel, S., (1995), Where have all the rivers gone? *World Watch*, 8(3), 9-19.

Postel, S. and B. Richter, (2003) *Rivers for Life: Managing water for people and nature*, Island Press, Washington D.C., 253p.

Revelle, C.S., (1999), *Optimizing reservoir resources*, Wiley, New York, N.Y., 180 pp.

Richter, B.D., Baumgartner, J.V., Powell, J., and Braun, D.P., (1996). "A Method for Assessing Hydrologic Alteration within Ecosystems". *Conservation Biology,* 10:1163-1174.

Richter, B.D., Baumgartner, J.V., Wigington, R., and Braun, D.P. (1997). “How much water does a river need?” *Freshwater Biology*, 37:231-249.

Rippl, W., (1883), The capacity of storage-reservoirs for water supply, *Minutes Proc. Inst. Civ. Eng.*, 71: 270-278

Sale, M. J., Brill, E.D. Jr.; and Herricks E.E. (1982). An Approach to Optimizing Reservoir Operation for Downstream Aquatic Resources. *Water Resources Research*, 18(4): 705-712.

Shiau, J-T and F-C, Wu, (2004), Assessment of hydrologic alterations caused by Chi-Chi diversion weir in Chou-Shui creek, Taiwan: Opportunities for restoring natural flow conditions, *River Research and Applications*, 20, 401-412.

Suen, J-P. and J.W. Eheart, (2006), Reservoir management to balance ecosystem and human needs: incorporating the paradigm of the ecological flow regime, *Water Resources Research*, 42(3), W03417, 10.1029/2005WR004314.

Tharme, R.E., (2003), A global perspective on environmental assessment: Emerging trends in the development and application of environmental flow methodologies for rivers, *River Research and Applications*, 19, 397-441.

Vogel, R.M. and J.R. Stedinger, (1987) Generalized reservoir storage-reliability-yield relationships, *Journal of Hydrology*, 89, 303-327.

Vogel, R.M. and N. M. Fennessey. (1994). “Flow Duration Curves I: A New Interpretation and Confidence Intervals.” *Journal of Water Resources Planning and Management*, 120(4) 485-504.

Vogel, R.M., and Fennessey, N.M.. (1995). “Flow Duration Curves II: A Review of Applications in Water Resources Planning.” *Water Resources Bulletin*. 31: 1029-1039.

Vogel, R.M., M. Lane, R.S. Ravindiran and P. Kirshen, (1999) Storage Reservoir Behavior in the United States, *Journal of Water Resources Planning and Management*, ASCE, 125(5), 245-254.

Votruba, L. and V. Broža, (1989), *Water Management in Reservoirs*, Developments in Water Science 33, Elsevier, The Netherlands, 444p.

Waldron, M. C., and Archfield, S. A., (2006), Factors Affecting Firm Yield and the Estimation of Firm Yield for Selected Streamflow-Dominated Drinking-Water-Supply Reservoirs in Massachusetts: U.S. Geological Survey Scientific-Investigations Report 2006-5044.

Wollmuth, J.C., and J.W. Eheart, (2000). Surface water withdrawal allocation and trading systems for traditionally riparian areas, *Journal of the American Water Resources Association*, 36(2), 293-303.

Wurbs, R.A., (1993), Reservoir-System Simulation and Optimization Models, *Journal of Water Resources Planning and Management*, 119(4), 455-472.

Wurbs, R.A., (1996), *Modeling and analysis of reservoir system operations*, Prentice-Hall, Upper Saddle River, N.J., 356 pp.

Yates, D., J. Sieber, D. Purkey and A. Huber-Lee, (2005a) WEAP21--A Demand-, Priority-, and Preference-Driven Water Planning Model: Part 1, Model Characteristics," *Water International*, 30, 487-500.

Yates, D., D. Purkey, J. Sieber, A.Huber-Lee and H. Galbraith, (2005b), WEAP21--A Demand-, Priority-, and Preference-Driven Water Planning Model: Part 2, Aiding Freshwater Ecosystem Service Evaluation, *Water International*, 30, 501-512.

Figure 1 – The relationship between the storage ratio S/μ and both the yield ratio Y/μ and the instream flow ratio I/μ for coefficient of variations C_v=0.3 and C_v=1.0

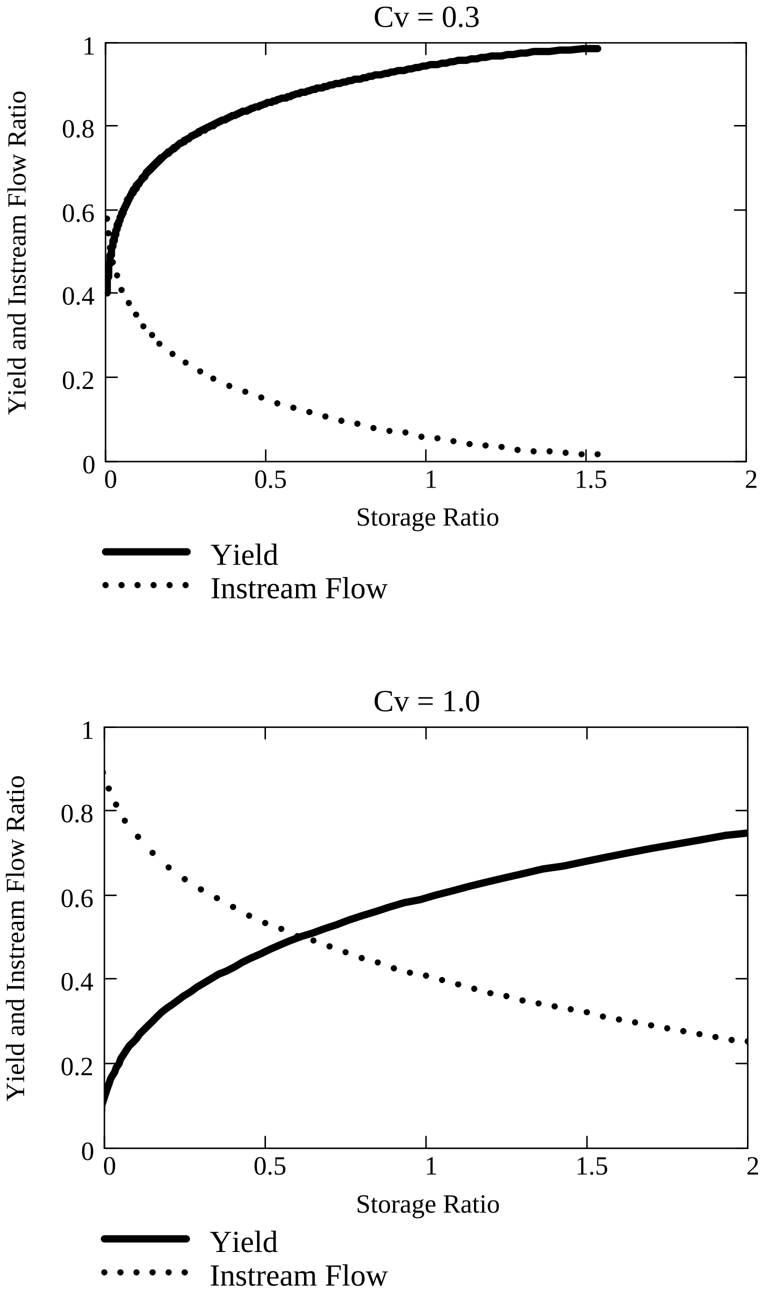


Figure 2 – Definition of the ecodeficit and ecosurplus regions corresponding to areas between regulated and unregulated FDC's

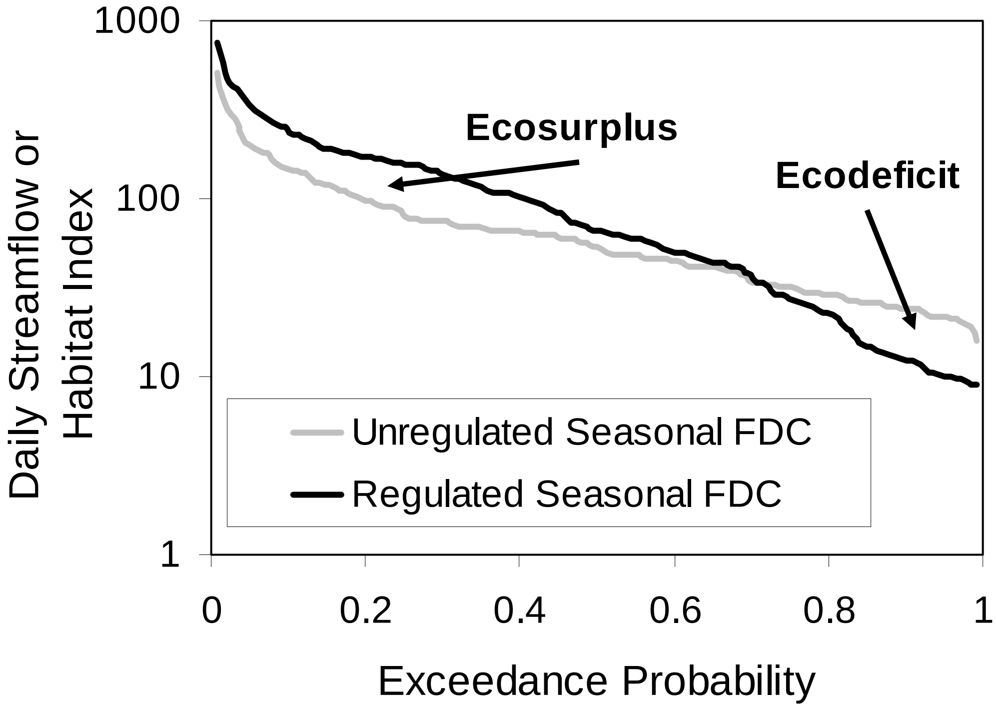


Figure 3 - The storage yield relationship for various instream flow policies

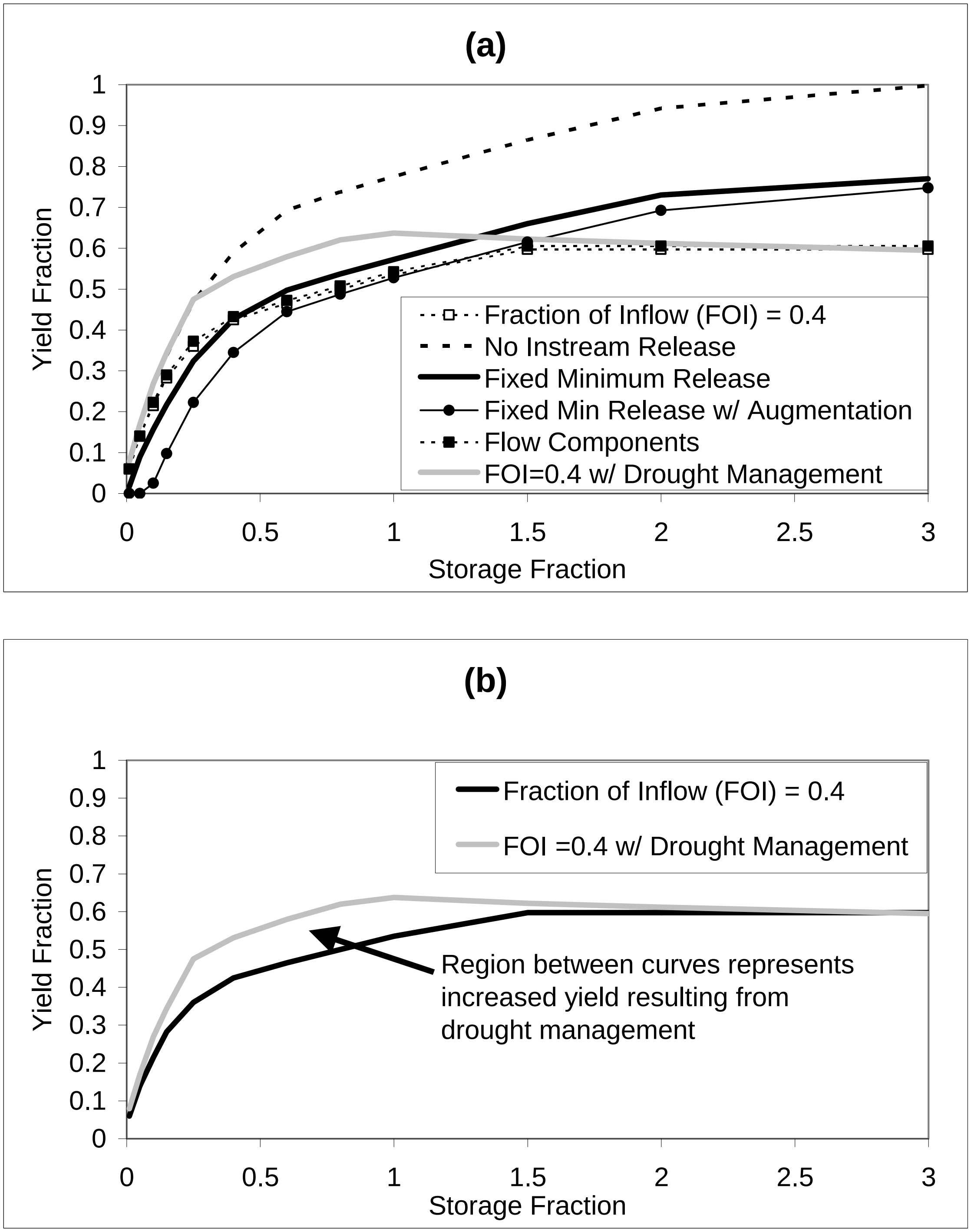


Figure 4 - The Storage – Instream flow relationship for various operating policies

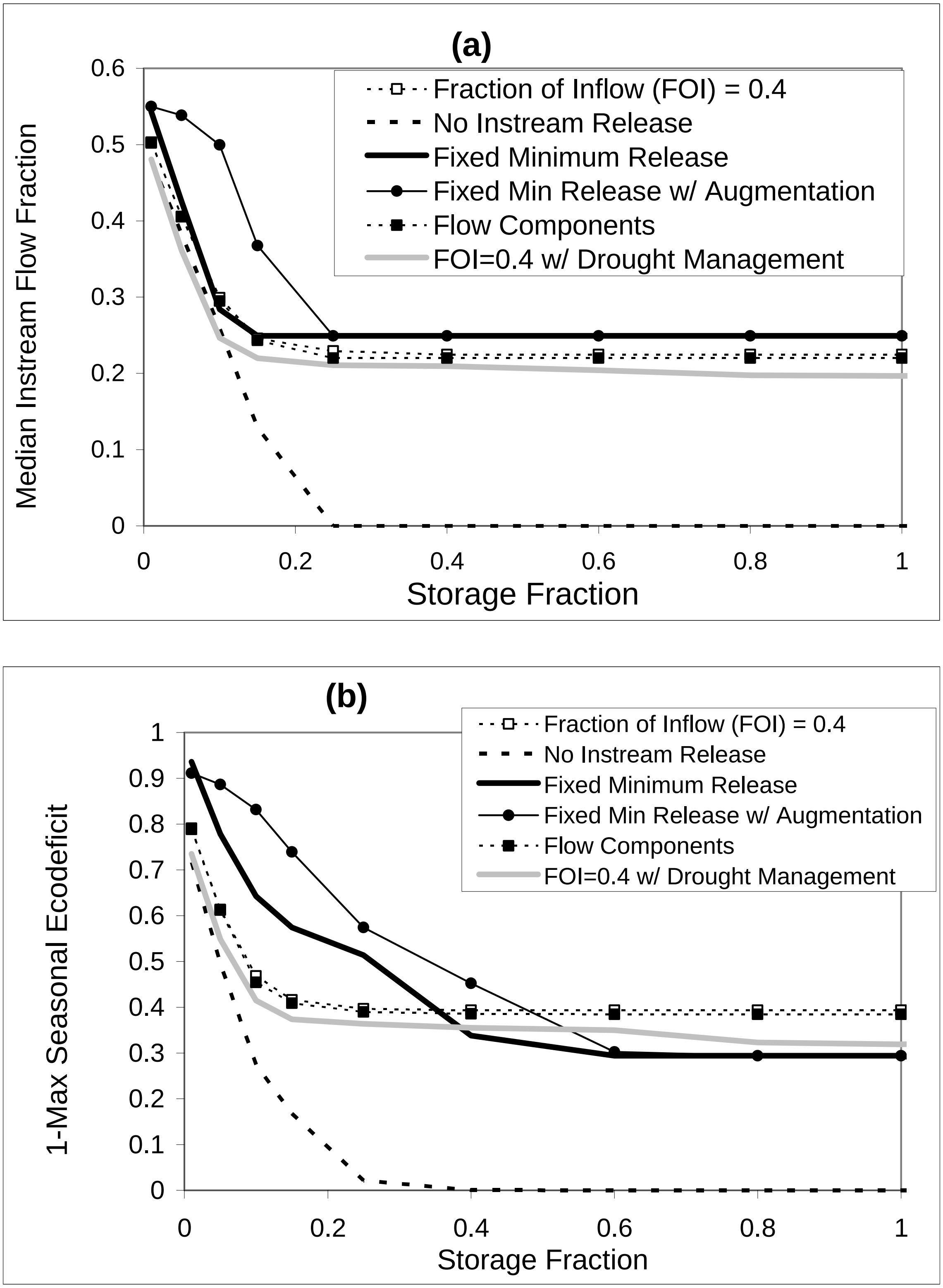


Fig 4 continued

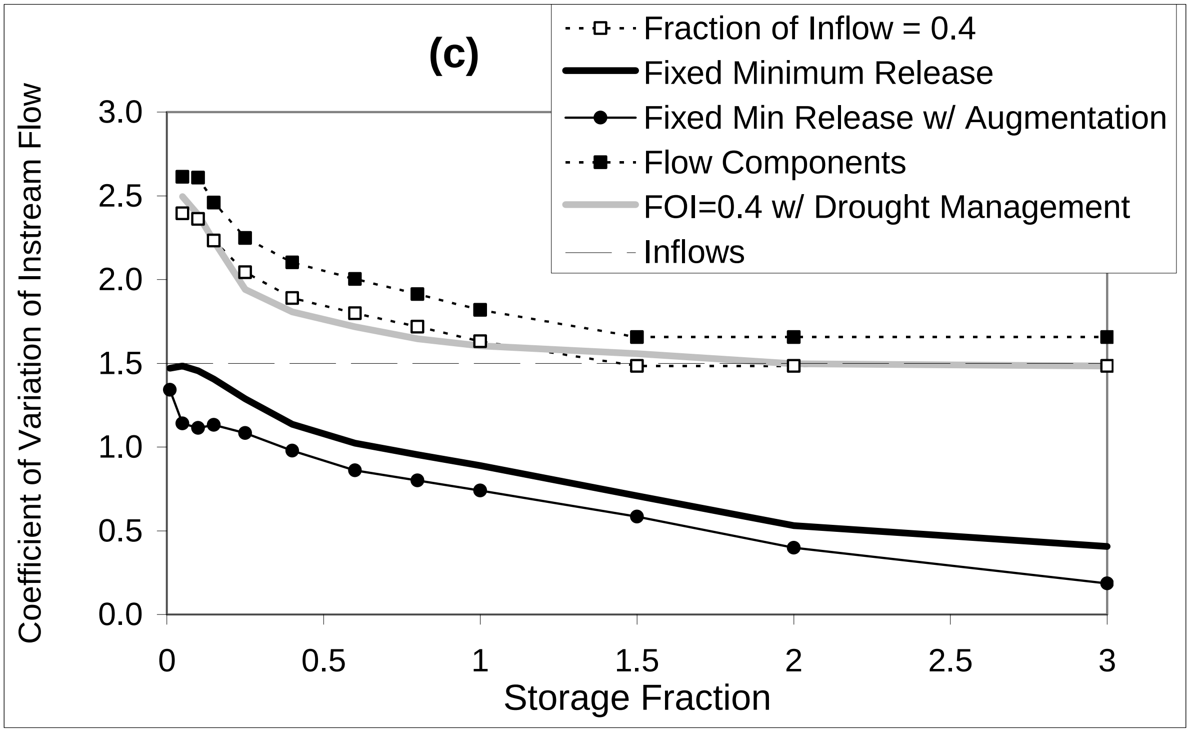


Figure 5 – Box plots illustrating the distribution of the instream flow resulting from various reservoir operating rules. Also shown for comparison are the distribution of the reservoir inflows.

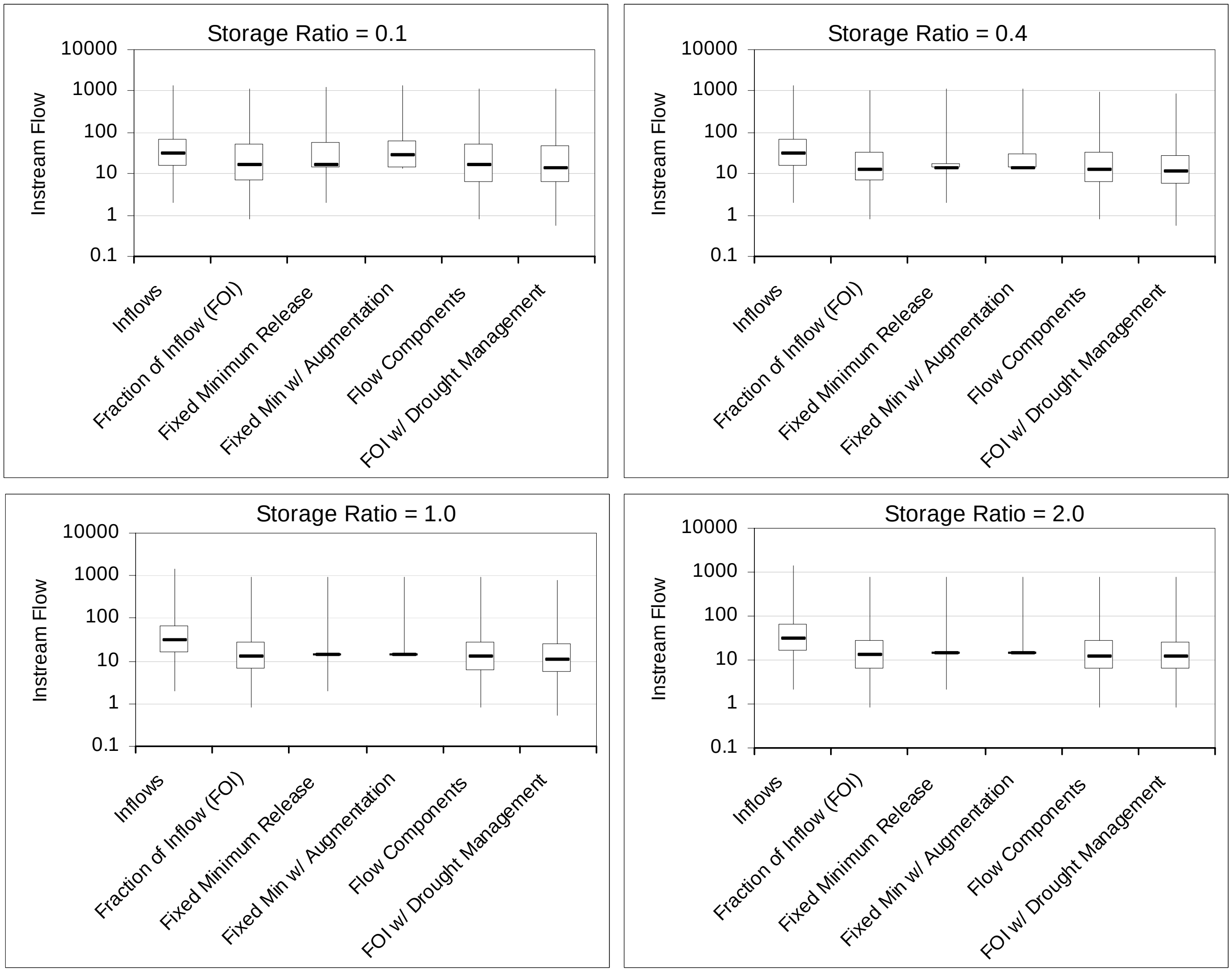
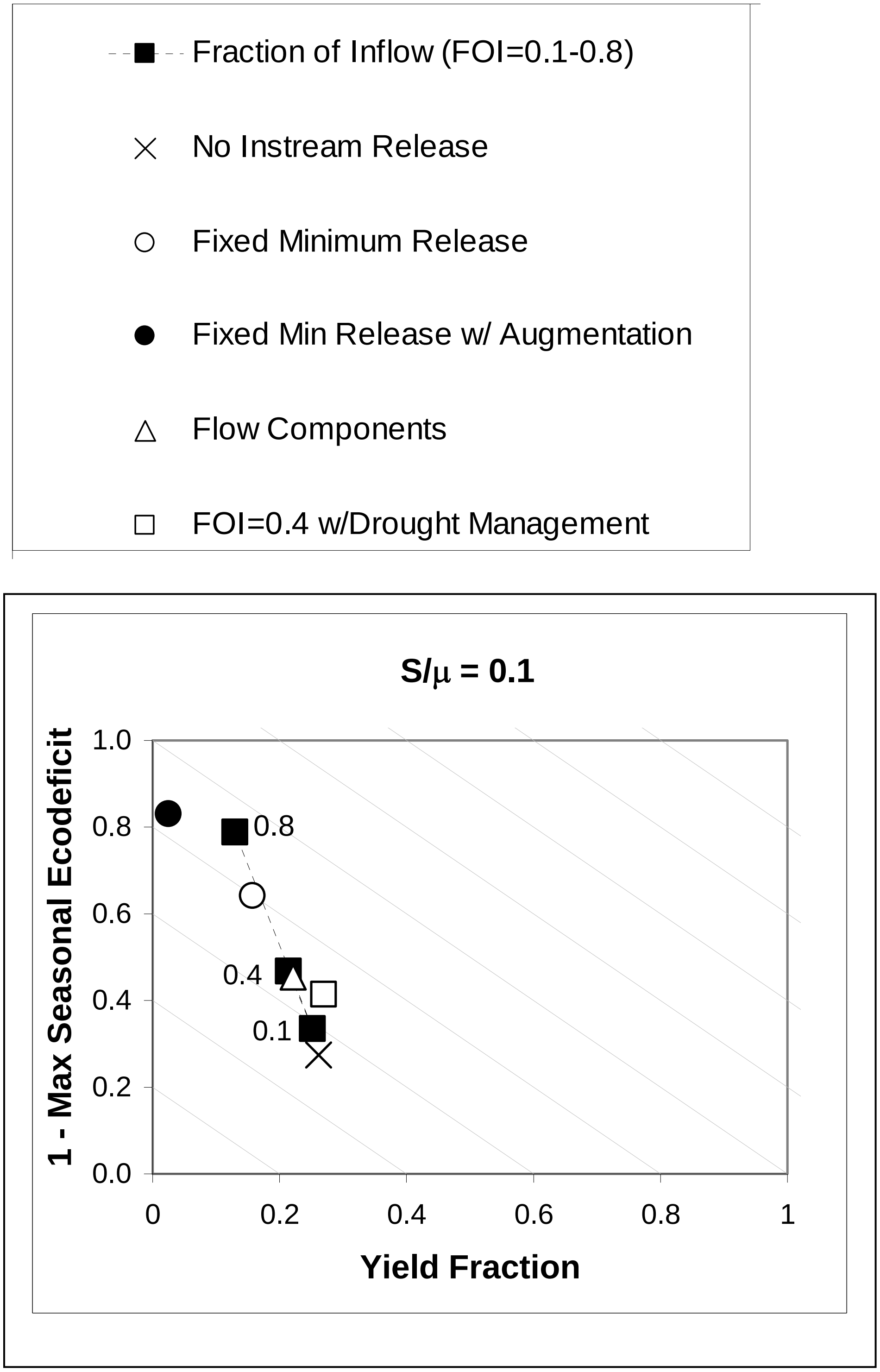
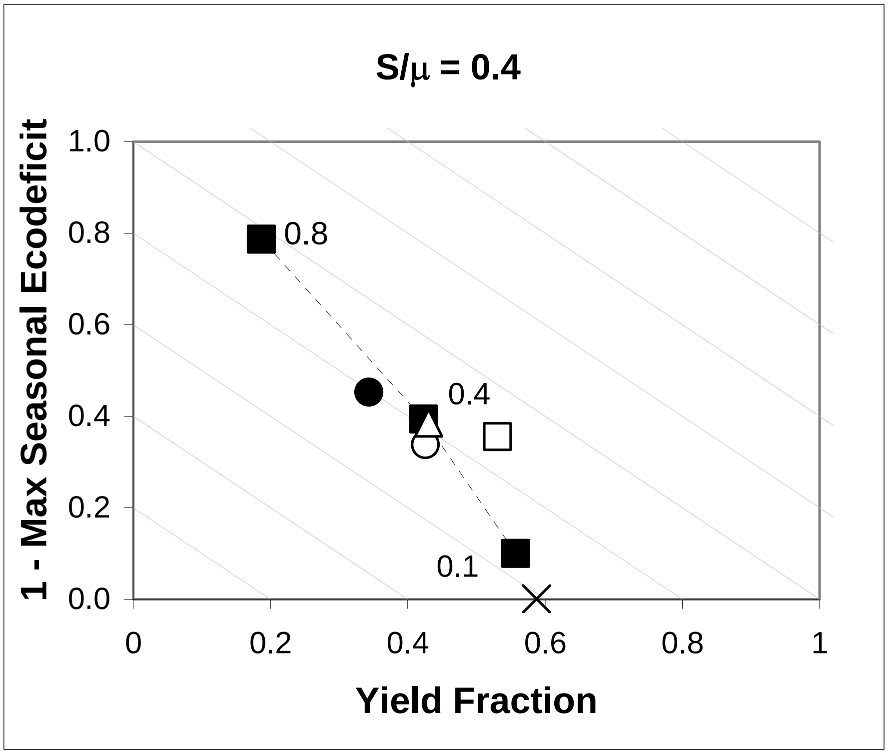


Figure 6 - Illustration of the tradeoff between instream flow and water supply yield. Increases in both yield ratio and [1-Max Seasonal Ecodeficit] correspond to improvements in yield and ecological flow regime, respectively.





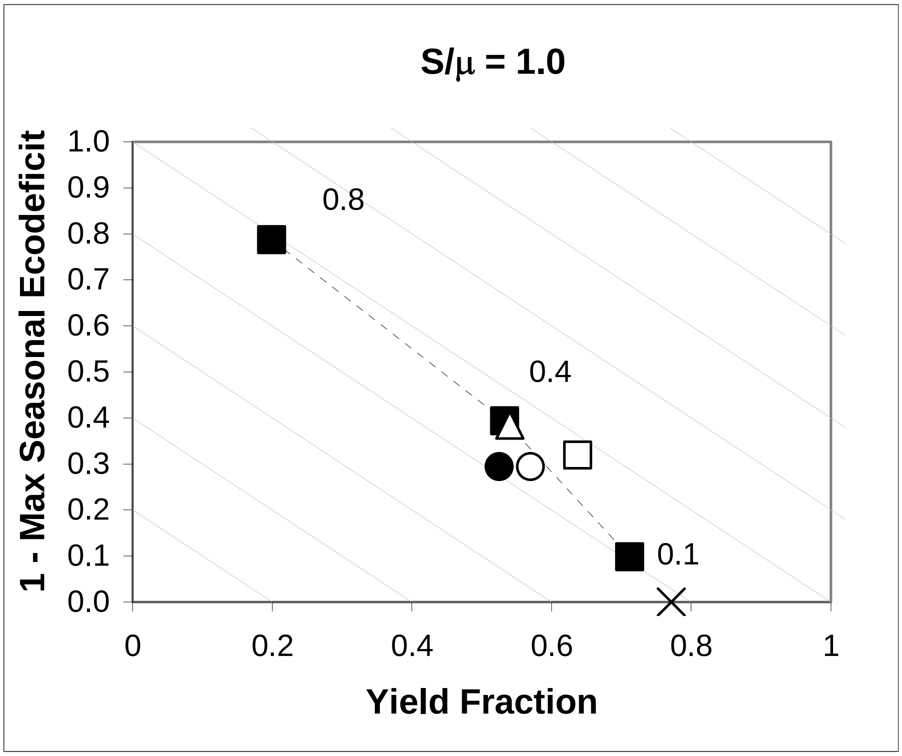


Figure 6 continued