MULTIOBJECTIVE MANAGEMENT OF POTOMAC RIVER CONSUMPTIVE USE

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ABSTRACT: Multiobjective systems analysis is used to size reservoir storage and identify noninferior system operating rules that mitigate the impacts of consumptive appropriations. The marginal impacts of consumptive use are offset by adding reservoir storage to the system, balancing technical efficiency, economic efficiency, and equity. The ''price'' to receive a consumptive appropriation permit (augmentation storage) is effectively equal to the marginal cost of the new withdrawal. In this context, prices and costs are measured not in dollars, but in units of storage, days at minimum instream flow, and the other direct operating impacts of consumptive use. In return for ''paying'' the efficient marginal price to join the system, new appropriators become equal participants in regionally coordinated operation, with equal reliability of meeting unrestricted demands. Parametric operating rules to size augmentation storage are developed as a multiobjective extension of firm yield analysis, applied to forecast-based operation of a multireservoir system. Examples drawn from Maryland's Potomac River consumptive use regulation illustrate how operational definitions of equity and reliability offer a normative framework to manage risk-based appropriation within a permitted riparian regulatory system.

INTRODUCTION

The Potomac River is the primary water supply for the Washington, D.C., metropolitan area (WMA) and is shared by water suppliers in the states of Maryland and Virginia and the District of Columbia. Rapid growth in the Washington suburbs, combined with significant droughts in the 1960s and 1977, created the potential for significant conflict over the appropriation of the Potomac. Instead of litigating interstate water rights, the states of Maryland and Virginia, the District of Columbia, the federal government, and the major regional water suppliers entered into a unique agreement governing the cooperative use of this shared interstate resource. Signed in 1978, the Potomac River Low Flow Allocation Agreement provides for the equitable use of the Potomac during times of shortage. In addition, the Water Supply Coordination Agreement, signed in 1982, commits the major regional water suppliers to cooperative management, guiding systems operation of the Potomac River. These agreements institutionalize regional cooperation and uniquely prescribe explicit reliability goals for joint operation. Also unique in these agreements is the commitment among the cooperating suppliers to optimal use of available supplies during drought, irrespective of their degree of participation in funding jointly owned storage. Efficient system operation is separated from issues of ownership, water rights, and the fair and equitable allocation of costs. The cooperative agreements also coordinate regional water supply planning by requiring pentannual reviews of projected supply and demand. System reliability has thereby been defined operationally as the ability to meet unrestricted regional demands projected for a common planning horizon, under projected design conditions.

Cooperative operation of the Potomac has been shown to result in substantial increases in yield and system reliability (Hirsch et al. 1977; Palmer et al. 1982; ''Water'' 1983; Eastman 1986; Smith 1989). The commitment to largely nonstructural cooperative operation has been credited with avoiding the costs of building 15 of 16 new reservoir projects recommended by the U.S. Army Corps of Engineers (COE) (COE 1963; Eastman 1986) while providing operational capacity to meet unrestricted demands through the year 2030 (Okun 1981; ''Water'' 1983).

Ironically, the cooperative operations that increase system reliability also increased the vulnerability of the WMA system to uncoordinated upstream consumptive withdrawals. Anticipating growth in upstream consumptive uses for evaporative cooling by electric power producers, the state of Maryland supported the development of a regulatory framework governing consumptive appropriation permits for Potomac withdrawals, described in this paper. The regulatory framework sought to preserve the reliability of Washington's municipal water supply while providing for the equitable and efficient use of the Potomac River. The regional commitment to cooperative operation and the precedent of efficient and equitable allocation of risk and reliability provided a normative framework for the consideration of competing interests in consumptive use policy.

The proposed structure for a regulatory framework required consumptive users to provide augmentation storage equal to the volume of their permitted withdrawal over a ''critical period.'' The initial supporting analysis sought to determine the length of the critical period τ, during which augmentation would be required. For a permitted withdrawal rate q, the required volume of augmentation storage V could be estimated as τq. This simple approach is analogous to firm yield design or reservoir sizing using the sequent peak algorithm (Potter 1977), summarized by Loucks et al. (1981) as

$$V = \max_{1 \le i \le j \le \tau} \left[\sum_{t=i}^{j} (R_t - I_t) \right] \tag{1}$$

where capacity is determined as the maximum cumulative difference between release R_t and inflow I_t over a critical period or design event. It has the benefit of simplicity in explanation and computation and establishes an intuitively equitable operational criterion: storage offsets critical impacts by replacing consumptive withdrawals with augmentation releases during the critical period. A similar approach to consumptive use management has been implemented on the Susquehanna River basin under 18CFR803.42, where consumptive users are required to augment streamflow whenever gauged discharge at key locations falls below ${}_7Q_{10}$. Managing consumptive use in this way roughly conserves mass between streamflow and consumptive withdrawals and has the desirable property of requiring increasing augmentation storage for increasing consumptive use.

A primary disadvantage of critical period sizing of augmen-

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tation storage is that, like firm yield calculations, the operating rules for the storage implicitly assume perfect foresight, or 100% utilization of releases. Augmentation storage needs to be operated to offset the impacts of consumptive use *at the location of impact*. The required storage volume must therefore be determined based on realistic operating rules that can be implemented with real-time forecast information. Besides impact mitigation, flexibility in decoupling the location of storage from the location of the consumptive withdrawal was sought to ease compliance for new consumptive users. This required an analytical framework linking location and sizing decisions through realistic reservoir operating rules. Viewed in this way, the primary goal of mitigating the impact of consumptive use with augmentation storage becomes a problem of formulating efficient reservoir operating rules.

New augmentation storage, referred to here and throughout as consumptive use storage, is sized to minimize the volume required to offset the impacts of consumptive use. In contrast to storage yield analysis focused only on satisfying a target or design demand, the impacts of a consumptive withdrawal are multiobjective in nature, reflecting marginal changes in system reliability and operating costs. The need to quantify the impacts of a consumptive use and evaluate the operational tradeoffs among proposed operating alternatives motivates a multiobjective analysis.

The second section describes storage yield analysis through the optimization of parametric operating rules and deterministic simulation. Sizing consumptive use storage is developed as a multiobjective extension of firm yield analysis to forecast-based operation in a multireservoir system. The third section describes the identification of preferred operating rules within the noninferior set of forecast-based parametric operating rules. Forecast-based operating rules are analyzed in the fourth section, illustrating the importance of operational forecasting in water resources management. Detailed examination of a simple augmentation release policy highlights the importance and distinction between forecast quality and forecast value. Policy implications for managing consumptive use are discussed in the fifth section emphasizing equity and efficiency in allocating drought risks, and the normative implications for equitable allocation of future demands on the Potomac. Summary and conclusions are presented in the sixth section.

PARAMETRIC OPERATING RULES

Consumptive use storage is sized through the identification of parametric operating rules, evaluated through deterministic system simulation. Smith (1989) characterized parametric operating rules as rules in which releases are specified as a function of previous inflow and a finite number of real valued parameters. Nalbantis and Koutsoyiannis (1997) described the familiar practice of optimizing the parameters of heuristic operating rules—evaluating the system objectives for each parameter set with deterministic simulation.

Single reservoir storage-yield analysis can be described as single objective optimization of the parametric standard operating policy (SOP) (Hashimoto et al. 1982; Shih and Revelle 1994) in which the objective function is evaluated through deterministic simulation over critical period hydrology. Traditional storage-yield analysis implicitly assumes perfect foresight or 100% efficiency in using reservoir releases. A simple parametric operating rule is presented that represents more realistic operating decisions that use imperfect forecast information. Used in deterministic simulation, this parametric operating rule introduces hedging into storage-yield analysis. In contrast to single objective optimization of yield or reservoir capacity, operating rule parameters can also be identified using multiple objective analysis, quantifying operational trade-offs through deterministic simulation. Consumptive use storage is sized as a multiobjective extension of traditional storage yield analysis with forecast-based operation.

Storage Yield Analysis

For a fixed capacity of usable storage C, traditional practice in storage-yield analysis determines the maximum target demand that can be satisfied without failure over a critical period $t = 1, 2, \ldots \tau$, as

max y subject to:

$$S_t = S_{t-1} + I_t - R_t, \quad t = 1, 2, \ldots \tau;$$

$$R_t \geq y, \quad t = 1, 2, \ldots \tau;$$

$$S_t \leq C, \quad t = 1, 2, \ldots \tau;$$

$$S_t \geq 0, \quad R_t \geq 0, \quad S_0 = S_\tau = C \tag{2}$$

The complementary reservoir sizing problem for a fixed target yield is to

min C subject to:

$$S_t = S_{t-1} + I_t - R_t, \quad t = 1, 2, \ldots \tau;$$

$$R_t \geq y^*, \quad t = 1, 2, \ldots \tau;$$

$$S_t \leq C, \quad t = 1, 2, \ldots \tau;$$

$$S_t \geq 0, \quad C \geq 0, \quad S_0 = S_\tau = C \tag{3}$$

where y^* = nominal yield target. Smith (1989) noted the implicit assumption in (2) and (3) that releases were immediately available to satisfy the target demand. Many variations on (2) and (3) have been formulated for monthly to daily time steps and varying levels of detail in the representation of losses (McMahon 1993) and temporally varying demand (Smith 1988, 1989).

The complimentary storage-yield problems [(2) and (3)] can also be solved through the optimization of a parametric operating rule evaluated using deterministic simulation. Consider the SOP used to satisfy a release target T

$$R_t = \min(S_t + I_t, T), \quad 0 \leq S_t + I_t \leq C \tag{4a}$$

$$R_t = S_t + I_t - C, \quad S_t + I_t - T > C \tag{4b}$$

With suitable constraints for continuity, the solutions to optimization problems (2) and (3) can be found by optimizing the SOP over critical period hydrology. In this simple example of simulation and optimization with a parametric operating rule, the objective function is the operating rule parameter (y or C). For reservoir systems in which releases must be based on imperfect forecasts of downstream discharge or demand, storage yield analysis must also account for the need to hedge against uncertainty.

Target Seeking Operating Rules

Within the class of parametric operating rules, Schwartz (1989) described as *target seeking*, operating rules $R(t)$ that determine reservoir release as a function of a target release, $R_T(t)$ and a hedging release $R_H(t)$. Smith et al. (1987) and Schwartz (1989) observed that a wide range of operating rules, from the simple SOP to coupled stochastic control techniques, can be characterized as target seeking rules of the form

$$R(t) = R_T(t) + R_H(t) \tag{5}$$

Note that (5) has the form of a neutral control law (Jacobs 1980) where the optimal control can be decomposed into deterministic $[R_T(t)]$ and cautious $[R_H(t)]$ controls. Target releases to satisfy a constant or variable demand have formed the basis for much of the traditional practice in storage-yield analysis (Rippl 1883; Klemeš 1977; Loucks et al. 1981; McMahon and Mein 1986; Smith and Lampe 1988). Examples of typical targets include a constant draft representing the reservoir yield (Bayazit and Ünal 1990; Bakken and Bruns 1991), or some fraction of mean annual flow (Burges and Linsley 1971; Stedinger et al. 1983; Vogel and Stedinger 1988). Hedging releases reflect a need for caution and provide a safety factor for uncertainty. Hedging is characterized (Schwartz et al. 1988; Schwartz 1989) as decisions that incur costs or forego benefits with certainty in order to reduce the probability of future losses. Although the costs of hedging are incurred with certainty, the less tangible benefits from hedging are realized as the ability to reduce risk by favorably altering the probability distribution of future losses. Explicit treatments of hedging in reservoir operation can be found in Bower et al. (1962), Loucks et al. (1981), Hashimoto et al. (1982), Moy et al. (1986), Bayazit and Ünal (1990), and Shih and Revelle (1994).

Example of Hedging in SOP

Consider the SOP [(4)]. With constraints for continuity during spill and shortage, the SOP is clearly a target seeking rule with target release T and hedging release of zero. Two forms of hedging in the SOP are shown in Fig. 1. The hedged SOP rule, $R(t) = T + H^{+}$, includes a hedging release made in addition to the nominal target. This is a common hedging strategy for reservoir releases that augment unregulated streamflow to satisfy a downstream target. For travel times that require forecast-based release decisions, a release like H^{+} hedges against the uncertainty in future streamflow. The hedging decision H^{+} is to forego the benefits from future release of H^{+} —releasing water in excess of the downstream target—to reduce the probability of a downstream shortfall. Hedging releases like H^{-} represent risk management decisions such as the decision to impose rationing or water use restrictions. The hedging decision H^{-} is to incur the ''cost'' of a shortage in the current decision period—in order to preserve storage—reducing the probability of more damaging future shortages. For example, substantial restrictions on municipal water supply may be acceptable near-term costs during a severe drought, to preserve adequate storage to reliably pressurize the distribution system for fire fighting.

Hedging results in lower operational yields and larger operational storage requirements than those calculated in (2) and (3). The use of target seeking rules in (2) and (3) allows the optimal storage (yield) to be partitioned explicitly into target storage (yield) and hedging storage (yield), just as the criteria or value function of a neutral stochastic control problem can be partitioned into deterministic and cautious components (Bar-Shalom and Tse 1974; Bar-Shalom 1981; Kitanidis 1983; Stengel 1993). Reduced uncertainty through improved forecast skill supports reduced hedging releases, thereby reducing the required volume of (hedging) storage. Improving usable forecast skill can therefore be equivalent to increasing the usable storage in existing reservoirs.

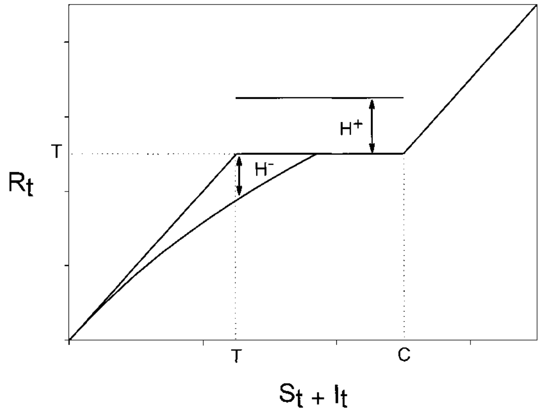

FIG. 1. Hedging in SOP

Parameter Estimation—Objective Functions

The simulation and optimization of parametric operating rules can utilize a wide range of objective functions [e.g., Johnson et al. (1991) and Nalbantis and Koutsoyiannis (1997)]. For the simple example optimizing the SOP in firm yield analysis, the operating rule parameter was also the objective function. A variety of yield-based objective functions are formulated for parametric operating rules in Smith (1989).

Smith (1989, 1993) described operating rule parameter estimation based on the order statistics of the random variable *annual yield* Y_i, where the annual yield for year i, Y_i, is defined as the solution of optimization problem (2) for year i. Assuming independence of annual flow sequences (e.g., for systems that refill annually) the sequence of annual yields, $Y_1, Y_2, \ldots, Y_N$, with order statistics $Y_{(1)} \le Y_{(2)} \le \cdots \le Y_{(N)}$ supports nonparametric estimation of the empirical distribution function $F_Y(y) = \Pr(Y_i \le y)$. The quantile function of the distribution function of Y_i is used to specify the quantile yield operating rule $R(t) = Q(p) = F_Y^{-1}(p)$ [see Smith (1989) for details]. Traditional engineering practice varyingly refers to $Y_{(1)}$ as a reservoir's safe yield or firm yield. The nomenclature adopted here follows that of Smith (1993), using safe yield when referring to $Q(0)$, and preferring historical yield to refer to $Y_{(1)}$, as in Palmer et al. (1982), emphasizing the dependence of the historical yield on the historical period of record used in its computation.

Smith (1989) extends parametric operating rules to a two-reservoir system including coordination of upstream and downstream reservoirs with routed upstream releases and a stochastically varying parameterization of mean daily water use. The operating rule parameters are determined through optimization of a function of the weighted yield $f(w_i Y_{(i)})$. The rules thus achieve hedging benefits, explicitly modifying the probability distribution of system yield by optimizing the single objective, weighted yield.

Multiobjective System Rules

Single objective optimization of parametric operating rules can be extended to multiple objectives, reflecting the range of feasible operational trade-offs. System performance can be characterized by a vector of operationally relevant performance measures, $\mathbf{Z}(R(t)) = \{z_1, z_2, \ldots, z_n\}$. Each objective z_k is quantified through deterministic simulation and depends implicitly on the parameters of the system operating rules $R(t)$. In contrast to storage yield analysis with single objective optimization as in (2), (3), and Smith (1989), operating rule parameters can be identified by optimizing the vector of potentially conflicting incommensurate performance measures in $\mathbf{Z}$ with multiobjective analysis.

The vector objective function could be optimized using preference-oriented multiobjective methods (Cohon 1978). In this approach a priori identification or iterative approximation of preferred trade-offs among competing objectives allows the multiobjective optimization problem to be represented as a single objective problem. The equivalent single objective problem can be solved using conventional optimization techniques as in (2) and (3), or the combined use of simulation and optimization. In developing a regulatory policy for consumptive use management, the evaluation of trade-offs among operational, economic, and equity objectives was essential to the decision process. Generating methods (Cohon 1978) were therefore adapted to enable regulatory decision makers and affected stakeholders to scrutinize the trade-offs and range of choices embodied in the noninferior set of operating rules.

Two operating rules, $R1$ and $R2$, are noninferior if their system objective vectors are nondominated. The performance vector $\mathbf{Z}(R1)$ is dominated by $\mathbf{Z}(R2)$ if, for every attribute

$$z_1(R2) \le z_1(R1); \quad z_2(R2) \le z_2(R1), \ldots, z_n(R2) \le z_n(R1) \tag{6a}$$

$$z_k(R2) < z_k(R1) \tag{6b}$$

where (6*b*) holds for at least one attribute k. This assumes each objective is to be minimized; objectives to be maximized (e.g., reliability) are readily transformed by a change of sign: $z'_k = -z_k$). System performance $\mathbf{Z}$ is quantified through deterministic system simulation for each set of operating rule parameters.

Multiobjective Parameter Estimation

Operating rule parameters could be identified nonparametrically by optimizing a weighted function of the order statistics of $\mathbf{Z}$, $f(w_i\mathbf{Z}_{(i)})$, analogous to Smith (1989). Although more than 100 years of gauged streamflow data are available on the Potomac, the extreme nature of the drought of record dominated the distribution of impacts that are significant to decision makers. Parameter estimation was therefore conducted using critical period hydrology. In exploring operating rule parameters based on critical period simulation, considerable care was exercised to identify the limits beyond which parameter refinement would produce illusory operational benefits by simply overfitting the historical data (including the simulated daily forecast error). The identification of system operating rules from the noninferior set of target seeking rules can be viewed as a multiobjective extension of traditional storage-yield analysis applied to forecast-based operation of a multireservoir system. The following section describes the identification of preferred system operating rules and the equivalent problem of sizing consumptive use storage for the Potomac.

APPLICATION—TARGET SEEKING RULES AND CONSUMPTIVE USE

Target seeking rules are formulated for the coordinated operation of the combined WMA system, with a consumptive user. Previous operational planning for the WMA water supply system had identified acceptable system operations that satisfied unrestricted demands projected for year 2030. Operational performance measures calculated from deterministic simulation of these rules quantified baseline system performance under 2030 design conditions. Simulating design operation with consumptive users, included as an additional demand, consistently quantifies the effects of upstream consumptive withdrawals. Evaluating system impacts based on changes in simulated critical period operation is familiar and consistent with traditional engineering practice (Stedinger et al. 1983; Bakken and Bruns 1991) as well as the operationally defined reliability criteria used to guide regional planning and operation within the WMA. Changes in simulated system performance are mitigated through releases from a hypothetical reservoir representing consumptive use storage. The required usable volume of consumptive use storage is determined as the cumulative simulated drawdown of this hypothetical reservoir.

System Description

The major components of the WMA system are described in the literature (Palmer et al. 1982; ‘‘Water’’ 1983) and illustrated in Figs. 2 and 3. Water supply storage in Jennings Randolph Reservoir on the North Branch of the Potomac is jointly owned by the three major WMA water suppliers. Jennings Randolph’s releases augment the natural flow of the Potomac to support water supply withdrawals in the WMA (Fig. 3). These water supply releases are scheduled to account for the approximate 5-day travel time to the water supply intakes in the WMA using linear routing coefficients derived in Trombley (1982). The water utilities serving the Maryland and Virginia suburbs own and operate tributary reservoirs that directly supply associated treatment works. The Washington Suburban Sanitary Commission (WSSC) owns and operates two reservoirs in series on the Patuxent River that can be modeled as a single reservoir for water supply planning purposes. The Fairfax County Water Authority (FCWA) similarly owns and operates the Occoquan Reservoir and associated treatment facilities. The suburban utilities also withdraw water from the mainstem Potomac River to supply separate Potomac River treatment facilities in Maryland and Virginia. The Washington Aqueduct Division (WAD) of the U.S. Army COE treats Potomac River withdrawals and supplies treated water to whole-

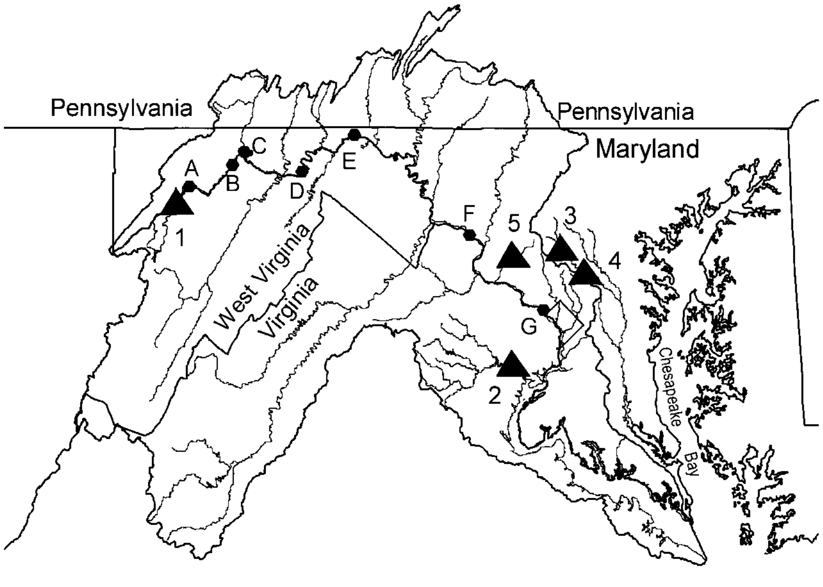

FIG. 2. Locations of Major Water Supply Reservoirs and Key Streamflow Gauges in Potomac River Basin (Reservoirs: 1—Jennings Randolph Reservoir, 2—Occoquan Reservoir, 3—Triadelphia Reservoir, 4—Duckett Reservoir, 5—Little Seneca Reservoir; Gauges: A—Luke, B—Pinto, C—Cumberland, D—PawPaw, E—Hancock, F—Point of Rocks, G—Little Falls)

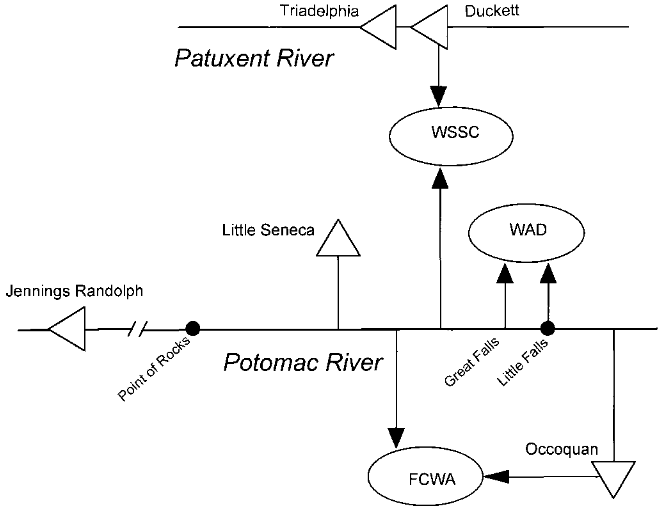

FIG. 3. Schematic of WMA Water Supply Facilities; Minimum Environmental Flowby Requirements Are Maintained below Great Falls and Little Falls

sale customers including the District of Columbia and the municipalities of Falls Church and Arlington, in the northern Virginia suburbs. The WAD withdraws raw water from the Potomac at Great Falls and Little Falls. Great Falls withdrawals flow largely via gravity to treatment works in the District of Columbia. Withdrawals at Little Falls incur substantially greater pumping costs to deliver raw water to these treatment facilities. Environmental flowby requirements of 1,135,620 $\mathrm{m}^3\ \mathrm{d}^{-1}$ at Great Falls and 378,540 $\mathrm{m}^3\ \mathrm{d}^{-1}$ at Little Falls constrain least-cost operations of mainstem Potomac withdrawals under low flow conditions. The proximity of Little Seneca Reservoir (on the Seneca Creek tributary of the Potomac) to the WMA intakes allows augmentation releases that effectively compensate for intraday supply deficits. This mode of operation, described in Sheer (1982), Eastman (1986), and Smith (1989), makes Little Seneca's value to the overall reliability of the system far greater than its nominal capacity or historical yield would suggest.

Water supply releases from Jennings Randolph Reservoir might normally be scheduled with a positive hedging release like H^+ in Fig. 1, due to the approximate 5-day travel time to reach the WMA intakes. It was therefore anticipated (Eastman 1986) that up to 70% of the water supply storage in Jennings Randolph Reservoir might be "wasted" in the sense that augmentation releases based on 5-day forecasts of net downstream needs would not actually be required when the routed releases reached the intakes on day $t + 5$. The valuable operational flexibility provided by Little Seneca Reservoir supports negative hedging releases for upstream augmentation storage (resulting in releases that are less than the net forecasted demand) without incurring a deficit. Upstream storage is thereby preserved for conditions when these releases will be used with high probability, increasing the effective storage available to the system.

Simulated Operation

Daily operations are simulated with parametric operating rules that coordinate the operations of the three WMA suppliers. These operating rules can be disaggregated into two coupled operating problems: upstream augmentation releases and downstream allocation decisions. Though largely separable on a daily basis, the two problems are coupled through the parametric operating rules that optimize system performance, $\mathbf{Z}(R(t))$.

Upstream Operations

Target seeking rules are utilized to schedule Jennings Randolph water supply releases in a fashion analogous to Smith (1989) as

$$R_1(t) = \max\{\lambda_1[D_1(t + 5)] + \gamma_1, 0\} \tag{7}$$

where $D_1(t + 5)$ = augmentation need predicted for day $t + 5$, when releases could be expected to reach the WMA intakes; it represents a target release and is computed as a function of consumptive use d^C, Little Falls instream flow requirements Q_{LF}, 5-day predictions of municipal demands $\hat{d}^M_{t+5}$, and downstream discharge $\hat{q}_{t+5}$.

$$D_1(t + 5) = \hat{d}^M_{t+5} + d^C + Q_{LF} - \hat{q}_{t+5} \tag{8}$$

Releases are further constrained by capacity and minimum release constraints for projected design conditions that may vary temporally. Allowing λ_1 to take values different from 1.0, or nonzero values of γ_1, introduces hedging into the forecast-based release rule. The general form of the operating rule admits great flexibility in specifying the target release. For example Mullusky and Schwartz (1996) developed target seeking rules for water quality storage in Jennings Randolph Reservoir in which the target release is a function of current storage and probabilistic seasonal inflow forecasts. Although two parameters completely prescribe the release in (7), the rules are additionally defined by the forecast models implicit in the determination of the target, $D(t + 5)$. Simulated operation therefore includes the simulation of imperfect forecast skill.

Downstream Operations

Downstream operation is summarized in Sheer (1982) and can be treated as a separable intraday allocation problem. Potomac withdrawals and off-Potomac releases are scheduled to meet intraday demands including instream flow requirements. Downstream operations allocate projected intraday demands between Potomac and off-Potomac sources, shown schematically in Fig. 3. These operating decisions also account for dynamic treatment, pumping, and distribution system preferences, while satisfying instream flow requirements at Great Falls and Little Falls. Daily demands that cannot be met by rebalancing daily withdrawals between instream and off-Potomac supplies are satisfied by supplemental intraday releases from Little Seneca Reservoir.

Consumptive Use Storage

The operating rule used to schedule releases from consumptive use storage is similarly formulated as a target-seeking rule

$$R_C(t) = \max\{\lambda_C D_C(t + \xi) + \gamma_C, 0\} \tag{9}$$

The location of this hypothetical reservoir is specified only by the effective ξ-day travel time for its releases to reach the WMA water supply intakes. The target $D_C(t + \xi)$ is similarly computed as a function of the Little Falls instream flow requirement and ξ-day forecasts of streamflow and demands

$$D_C(t + \xi) = \hat{d}^M_{t+\xi} + Q_{LF} - \hat{q}_{t+\xi} \tag{10}$$

Mainstem Potomac travel times derived in Trombley (1982) were verified through empirical analysis of historical low flow releases such as those shown in Fig. 4. These travel times were considered approximate since neither releases nor dye studies existed for the extreme low flow conditions expected under design drought operations. As suspected, reservoir releases made during the drought of 1999 indicated longer travel times could be expected during extreme low flow conditions. In ad-

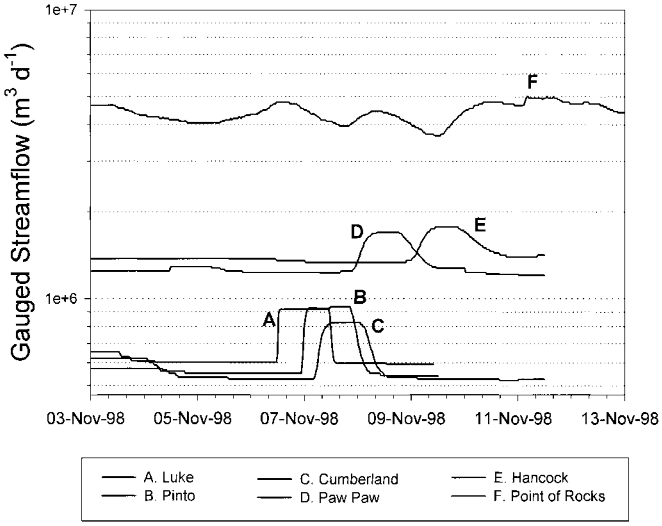

FIG. 4. Jennings Randolph Reservoir Test Release: Observed Discharge in Mainstem Potomac River

dition, test releases have identified the need for further coordination with low head run-of-river impoundments on the mainstem of the Potomac, suggested in Fig. 4 by the variability in 30-min discharge rates at Point of Rocks, Md.

System Objectives

The objective function vector is defined as incremental changes in simulated baseline performance measures. Diverse performance measures were reduced to a set of five key objective functions. Note the system objectives are computed as differences from baseline operation, denoted in Table 1 by Δ. The operating goals representing system reliability, environmental impacts, and costs are summarized in Table 1 and described below.

- Days at Flowby—Environmental flowby requirements are primarily based on the area of ''ideal'' instream habitat estimated for the reach extending approximately 16 km from Great Falls to below Little Falls. These requirements do not account for extensive instream environmental benefits resulting from low flow augmentation between Jennings Randolph Reservoir and Point of Rocks (Fig. 2). Reanalysis of these requirements, initiated during the drought of 1999, should address a more comprehensive characterization of low flow habitat trade-offs including the frequency, duration, spatial extent, and timing of minimum streamflow in the mainstem Potomac. In this analysis the incremental change in the number of consecutive days of minimum environmental flowby at Little Falls was used as the surrogate measure of environmental impact.
- Pumping Costs—The incremental change in cumulative withdrawals at Little Falls is a representative measure of the change in WAD pumping costs.
- Consumptive Use Storage—Minimum critical period storage in the hypothetical consumptive use reservoir represents the volume of usable storage required by each operating rule.
- Upstream Storage—The upstream storage objective is computed as incremental change in the minimum water supply storage in Jennings Randolph Reservoir during the critical period.
- Downstream Storage—The minimum critical period storage simulated in each of the off-Potomac reservoirs is also computed for each operating rule. Coordinated operation provides great flexibility to balance the distribution of usable storage in the Patuxent and Occoquan reservoirs. For this reason the downstream storage objective is quantified as the incremental change in total minimum usable storage in the two systems.

The use of minimum storage as a surrogate for water supply reliability is consistent with the managers' operational experience in evaluating drought risks and the need for water use restrictions during the drought of 1977 (Sheer 1980). Alternate approaches for explicit estimation of reservoir reliability are described in McMahon and Mein (1986) and Vogel and Stedinger (1987, 1988).

Trade-Off Analysis—Pruning Noninferior Set

Coordinated system operation embodies a range of operational options to mitigate the impacts of consumptive use. Impacts may be mitigated through a change in the rules used to operate consumptive use storage, a change in the coordinated operating rules for the water supply system, or a combination of the two. For specific forecasting models and downstream operating rules, the system rules are specified by operating rule parameters $[\lambda_1, \gamma_1]$ for Jennings Randolph water supply storage and $[\lambda_C, \gamma_C]$ for consumptive use storage.

One family of target seeking rules hedged the Jennings Randolph release with parameters $[\lambda_1, \gamma_1] = [1, -\delta_W]$, where δ_W represented the average withdrawal expected from downstream direct supply reservoirs. Coordinated operation with consumptive use storage was represented with an additional hedging factor δ_C interpretable as the average withdrawal expected from consumptive use storage. This simple formulation led to the exploration of system rules parameterized as $[\lambda_1, \gamma_1] = [1, -(\delta_W + \delta_C)]$ for water supply storage in Jennings Randolph Reservoir and $[\lambda_C, \gamma_C] = [1, -\delta_W]$ for augmentation storage.

Critical period simulation was repeated, systematically varying the hedging parameters δ_W and δ_C. The resulting set of operating rules is characterized by the set of P simulated realizations of $\mathbf{Z}_p = \mathbf{Z}_p(\delta_{W,p}, \delta_{C,p}) = (z_{1,p}, z_{2,p}, \ldots, z_{5,p})$, $p = 1, 2, \ldots, P$, that are noninferior in the sense of (6). Inherent

TABLE 1. Objective Functions

Objective number (1)	Objective (2)	Objective function (3)	Operational goal (4)
z_1	Pumping costs	$\Delta\ \Sigma_t\ (W_{4,t})$	Minimum operating costs
z_2	Flowby	$\Delta\ \Sigma_t\ I(q_t + g_C(R_{C,t}) + g_5(R_{5,t}) - \Sigma_i\ W_{i,t})$	Minimum habitat impacts
z_3	Upstream storage	$\Delta\ \min_t(S_{1,t})$	Maximum water supply reliability
z_4	Downstream storage	$\Delta\ \min_t(S_{2,t} + S_{3,t} + S_{4,t})$	Maximum water supply reliability
z_5	Consumptive storage	$\min_t(S_{C,t})$	Maximum compliance cost

Note: Σ_t and $\min_t$ are evaluated over the critical period, $t = 1, 2, \ldots \tau$; $I(q_t + g_C(R_{C,t}) + g_5(R_{5,t}) - \Sigma_i\ W_{i,t}) = 1$ if the discharge at Little Falls on day t is at the minimum flow standard Q_{LF}, 0, otherwise. $g_n(R_{n,t})$ represents the routed release from reservoir n available on day t; reservoirs are numbered as in Fig. 2; mainstem Potomac withdrawals W_i are indexed sequentially downstream: 1—FCWA, 2—WSSC, 3—WAD Great Falls, 4—WAD Little Falls.

trade-offs such as changes in upstream versus downstream storage, or pumping versus flowby objectives, resulted in a large set of noninferior operating rules. Some noninferior operating rules could be eliminated from further consideration by inspection. For example, some operating rules achieved a minor reduction in pumping costs along with lower levels of upstream and downstream storage, z_4 and z_5. Though noninferior in the sense of (6) these rules represented unacceptable trade-offs of pumping costs and system reliability and were therefore eliminated from further consideration.

As the noninferior set was heuristically pruned, the least desirable realization for each objective χ_k was identified over the remaining members of the reduced noninferior set

$$\chi_k = \max_p z_{k,p}, \quad k = 1, 2, \ldots, 5 \tag{11}$$

Any objective function z_m for which χ_m could be judged acceptable irrespective of the values of $z_{k,p}$ ($p = 1, 2, \ldots, P$; $k \neq$ m) could be neglected. When possible, this eliminates any alternatives that are only noninferior with respect to objective z_m; further analysis is thus confined to the reduced noninferior set defined by trade-offs among the remaining objective functions.

Significant trade-offs were explored in detail with stakeholders and regulators. Effected stakeholders included regional water suppliers and power producers, as well as regulators from Maryland's Water Resource Administration and resource managers from the Department of Natural Resources. Qualitatively, power producers were indifferent to changes in water supply reliability or flowby, but had understandably strong preferences to minimize consumptive use storage. Water suppliers were similarly indifferent to changes in consumptive use storage, but extremely sensitive to changes in water supply reliability or operating costs. The dialogue between stakeholders and regulators was supported by the explicit generation of performance alternatives, $\mathbf{Z} = \{\mathbf{Z}_1, \mathbf{Z}_2, \ldots, \mathbf{Z}_p\}$. The use of generating methods proved extremely useful in clarifying preferences among disparate stakeholders and translating these qualitative preferences to quantitative bounds on the acceptability of potentially competing operating goals.

Flowby

Changes in the flowby objective proved relatively insensitive to changes in operating rules. For several key species and life stages the area of "ideal habitat" between Great Falls and Little Falls actually increased at low flows, in some cases more than offsetting the decrease in habitat area below Little Falls [Maryland Department of Natural Resources (Md. DNR) 1981]. During a prolonged drought, the consequences of incremental changes in the number of days at flowby were judged to represent a negligible environmental impact. The least desirable flowby impact χ_2 was therefore judged to be acceptable, focusing the analysis on trade-offs among the four remaining objectives.

Pumping Costs

Uniquely among the objectives, pumping costs are readily expressed in monetary terms and represent a direct economic impact of consumptive use. These impacts could be mitigated by operating rules requiring larger volumes of consumptive use storage. Importantly, the stakeholders recognized that the incremental pumping costs would only be incurred during infrequent drought conditions. The expected value of these costs was therefore seen to be small compared with certain costs incurred to mitigate these impacts with consumptive use storage. Moreover, because incremental pumping costs are readily monetized, they could potentially be recovered or mitigated through nonstructural institutional mechanisms such as transfer payments or cost sharing among the effected parties. The worst-case pumping costs in the reduced noninferior set χ_1 were therefore also judged to be acceptable. The noninferior set was further reduced to trade-offs among the three remaining storage objectives, such as those illustrated in Fig. 5. Note the consumptive use storage in Fig. 5 is expressed as drawdown from the "baseline," $z_5 = (0 - \min_t\{S_{C,t}\})$. Significantly, the acceptability of χ_1 reduced the maximum consumptive use storage χ_5 in the reduced noninferior set.

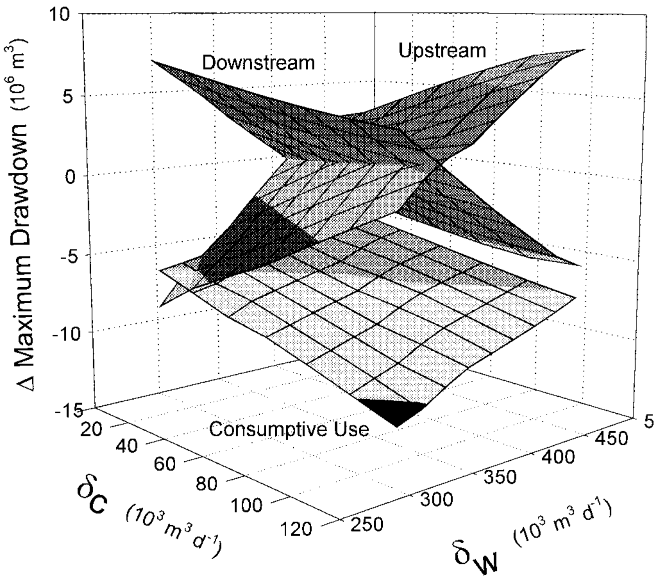

FIG. 5. Storage Trade-Offs

Upstream Storage

Within the limits of acceptable changes in flowby and pumping cost objectives the remaining operating rules were defined by trade-offs among the three storage objectives, z_3, z_4, and z_5. Operationally, downstream storage is considered more valuable than upstream storage as downstream reservoirs supply treatment facilities directly, without loss. One of the significant remaining trade-offs reflected differences between upstream and downstream storage (reliability) objectives. A quantitative estimate of the relative value of upstream and downstream storage (representing an acceptable trade-off) could have been estimated through detailed simulation of the operating rules. Such an analysis was judged to have a high likelihood of overfitting the critical period hydrology, rather than providing a meaningful estimate of relative storage value. Instead, the noninferior set was conservatively reduced, constraining $z_3 = 0$, to assure no net loss in upstream reliability.

Downstream Storage

The remaining noninferior operating rules were confined to trade-offs between the downstream storage and consumptive use storage objectives. Operating rules that resulted in net increases in downstream storage volumes were clearly preferable from the perspective of water suppliers, but required larger volumes of consumptive augmentation storage. Incremental reductions in downstream storage reduced the consumptive use storage required, but represented losses in direct supply reliability. Among these trade-offs the compromise solution was selected to minimize the volume of consumptive use storage required to realize no net loss in either upstream or downstream storage objectives. These final criteria are reasonable, intuitive, and consistent with the intent of the initial proposed augmentation requirement τq.

TABLE 2. Storage Requirements for Consumptive Use

Withdrawal (m^3 d^{-1}) (1)	Travel Time (days)					
	0 (2)	1 (3)	2 (4)	3 (5)	4 (6)	5 (7)
3,785	337	469	469	469	469	469
37,854	3,407	4,542	4,921	4,921	4,921	4,921
75,708	6,814	9,085	10,221	10,221	10,221	10,221
113,562	10,599	13,627	15,142	15,142	15,520	15,520
151,416	14,385	17,191	20,063	20,063	20,441	20,441
189,270	18,548	23,091	25,362	25,362	25,362	25,362
227,124	22,712	27,255	30,662	30,662	30,662	30,662
264,978	26,498	32,554	35,961	35,961	35,961	35,961
302,832	31,419	37,097	41,261	41,261	41,261	45,425
340,686	35,583	42,775	46,939	46,939	47,696	47,696

Note: Storage values are expressed in $\times 10^3$ m^3.

Admitting parameterizations of the operating rules that could have substantially shifted the impacts and costs among users lent greater credibility to the operating rules that were finally selected. The use of generating methods allowed stakeholders to independently appraise the range of feasible alternatives and the distribution of impacts. For example, presenting the stakeholders and regulators with the noninferior set of alternatives allowed them to judge for themselves that changes in pumping costs would be relatively minor, experienced only during the most severe historical droughts, and potentially mitigated nonstructurally. Similarly, the Jennings Randolph release rule [(7)] demonstrated how coordinated operation would use water supply storage to satisfy consumptive demands when necessary through the target release $D(t + 5)$. This reinforced the sense of equitable burden sharing in drought planning. The stakeholders had greater confidence in the final solution in no small part because alternate solutions were not excluded a priori, but were only rejected when judged to be inferior to other feasible alternatives.

Having established the credibility and acceptability of the multiobjective framework and trade-off analysis, operating rules (and storage volumes) were identified for reservoir locations (expressed as travel time for releases to reach the WMA water supply intakes) ranging from 0 to 5 days from the WMA. At each location augmentation storage was sized for consumptive withdrawal rates from 3,785.4 to 340,686 m^3 d^{-1}. For each combination of consumptive use and storage location the set of noninferior operating rules was reduced to a ''preferred'' set of system operating rules. The selected operating rules equitably offset the impacts of consumptive use and determine the required volume of augmentation storage. Operating consumptive use storage within the overall system operating rules assured the reliable satisfaction of all demands, including consumptive withdrawals, municipal demands, and environmental flowby. The final volumes of augmentation storage summarized in Table 2 are explicitly incorporated in the Maryland consumptive use regulation (''Consumptive'' 1985).

OPERATIONAL FORECASTING

The augmentation requirements in Table 2 illustrate the significance of operational forecast skill in water resources management. Storage requirements in Table 2 increase as augmentation storage is located further upstream. This reflects the need to hedge against the decline in operational forecast skill with increasing forecast lead times. Although the required storage increases with forecast lead time, note that the rate of increase is extremely small for 3–5-day travel times. The small changes in required storage directly reflect the insignificant difference in operational forecast skill for 3–5-day forecast horizons.

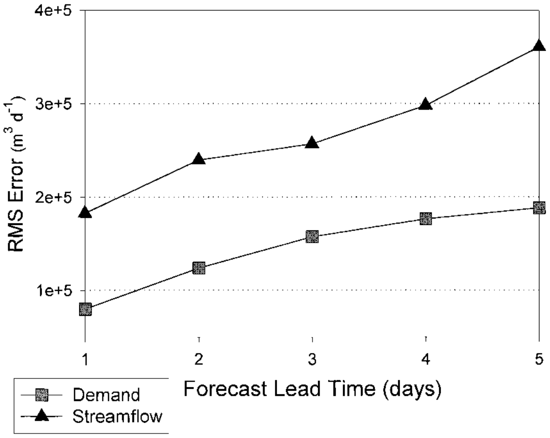

FIG. 6. Summer Season Forecast Skill: RMS Error

This result highlights the importance of evaluating forecast skill for water resources management in an operationally meaningful context. Fig. 6 shows typical summer season forecast skill, quantified as root-mean-square (RMS) error, for both streamflow and demand. Note that RMS error increases monotonically with forecast lead time. In contrast, the operational manifestation of forecast skill—augmentation storage—does not increase proportionately beyond Day 3. In developing the system operating rules described here, a variety of forecast techniques were compared. For low flow conditions, the persistence forecast of the 5-day streamflow consistently yielded superior operating results compared with recession-based forecasts (Hanson 1967) even though recession-based forecasts consistently showed lower RMS error. The explanation for this curious result requires a more thorough understanding of the operational implications of forecast errors.

Forecast-based releases from augmentation storage supplement natural discharge to make up short-term deficits between supply and demand. Substantially different consequences are associated with forecast errors that underestimate or overestimate the true deficit; operating penalties are asymmetrical functions of forecast error. Overestimation of actual deficits results in augmentation releases that are ''wasted'' from a water supply perspective (secondarily enhancing instream flows and freshwater inflow to the Potomac estuary). Underestimation of daily deficits results in shortfalls that must be made up through intraday operational adjustments that may include increases in pumping costs, decreases in environmental flowby, and incremental drawdowns in downstream reservoir storage. The asymmetrical relationship between operating impacts and forecast errors is imperfectly reflected in the symmetrical error measures commonly used to quantify forecast skill.

In addition to asymmetry, the operational consequences of

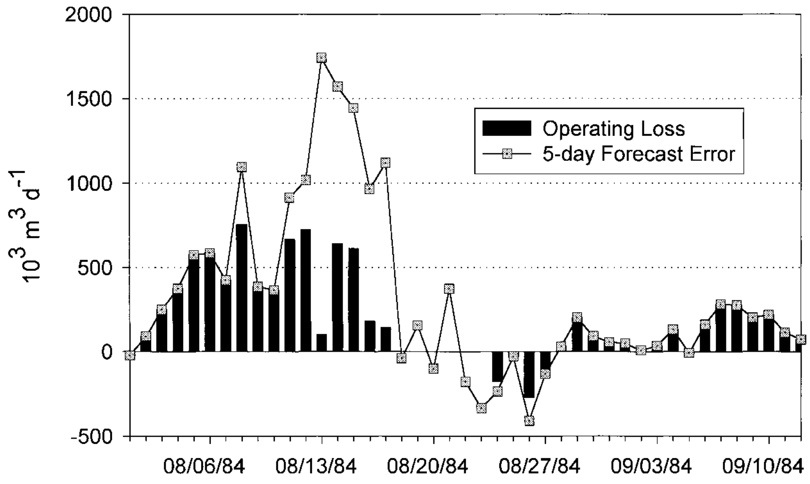

FIG. 7. Operational Forecast Skill for Low Flow Augmentation

forecast errors are bounded by the size of the reservoir release. Consider for example an augmentation release R_t scheduled to supplement a projected deficit on day $t + 5$. The largest errors in summer streamflow forecasting over this time horizon are commonly attributable to rapid increases in streamflow associated with local convective precipitation. For these events 5-day forecasts have little operationally useful skill. Local convective precipitation increases streamflow and reduces demands, thereby reducing the need for flow augmentation on day $t + 5$. The operational penalty associated with this forecast error is a function of the wasted release. Note that, no matter how large the forecast error, the maximum waste is bounded by R_t. In contrast, the unbounded RMS error contribution from summer thunderstorms can be disproportionately large while operationally insignificant.

The final source of decoupling between operating skill and traditional measures of forecast skill is the inherent skewness of low flow forecast errors. Although summer low flows are dominated by baseflow recession and largely controlled by slowly varying basinwide soil moisture, summer streamflow may rise quickly in response to intense convective precipitation. In contrast to these rapid short-lived rises that are largely unpredictable with 3–5-day lead times, baseflow recession represents a predictable lower bound for streamflow (Hanson 1967). For this reason 5-day low flow forecasts are more likely to underestimate than overestimate streamflow.

The decoupling of operational forecast skill and traditional statistical measures of forecast skill is illustrated in Fig. 7. The figure illustrates the simple case of a reservoir making augmentation releases with a 5-day travel time to satisfy a constant downstream target T. The unhedged release rule $R(t) = \max(T - q'_{t+5}, 0)$, uses the recession forecast, $q'_{t+\Delta t} = q_t \exp(-\kappa \Delta t)$. The daily forecast errors, $q_t - q_{t-5} \exp(-\kappa \Delta t)$, and the operational penalties associated with this simple augmentation release are shown in Fig. 7. For streamflow, underestimation results in waste, whereas overestimation results in deficits. Although the operational consequences of forecast errors are expressed here in units of daily volume, operational penalties for equal volumes of deficit and waste differ significantly, magnifying the asymmetry of forecast and operational penalties. Fig. 7 illustrates the bounded nature of operational penalties, reflected as a decoupling of volumetric operating penalties and forecast error starting on August 11. Note as well the possibility of forecast errors for which no operational penalties are incurred. This is illustrated on August 18–23, when discontinued augmentation releases resulting from a significant rise in streamflow made forecast errors irrelevant with respect to operational penalties.

The equivalence of forecast skill and system reliability depends on operational forecast skill (i.e., forecast skill that can be effectively exploited to improve operating decisions). For many water resource systems, including the Potomac system described here, the common practice of evaluating forecast skill using unbounded symmetrical performance measures—such as RMS error—will not, in general, correspond to an increase in the bounded asymmetrical operating benefits in forecast-based water resources management. For this reason it is essential that efforts to improve forecasts for water resource management applications incorporate operational measures of forecast value in addition to traditional measures of forecast quality such as bias, RMS error, or percent reduction in RMS error.

POLICY IMPLICATIONS—EQUITY AND EFFICIENCY

The policy framework for consumptive use management integrates technical efficiency, economic efficiency, and equity. Technical efficiency is realized by minimizing the augmentation storage required to offset the impacts of consumptive use. The operating rules (and equivalent consumptive use storage) represent the preferred operational solution to satisfy a new (consumptive) demand irrespective of the allocation of augmentation storage costs. Separating cost allocation from the sizing decision for consumptive use storage promotes economically efficient solutions in two ways. First, once the required storage volume is identified by a particular consumptive user, storage can be provided through a wide variety of alternatives. These include new reservoir construction or the negotiation of a purchase, lease, or reallocation of storage in existing reservoirs anywhere in the upstream basin. Unambiguous compliance criteria along with administrative flexibility afford permittees the opportunity to minimize compliance costs.

Economic efficiency is also promoted through the cost allocation policy for augmentation storage. The regulatory policy requires the consumptive user to pay 100% of the costs for providing augmentation storage. Effectively, the price for a consumptive appropriation permit (manifested in the cost of providing efficient augmentation storage) is equivalent to the marginal cost that the consumptive withdrawal imposes on the system. This was particularly useful for regulated power producers seeking consumptive appropriation permits. For these consumptive users the Public Service Commission's acceptance of compliance costs in their rate base was a significant concern. The consistency of cost allocation with a marginal cost-based rate making doctrine helped earn this acceptance.

Beyond technical and economic efficiency, the consumptive use policy established an equitable allocation of risks and costs. Equity is reflected in the reliability realized by the new consumptive user. After paying the economically efficient marginal cost to join the system (i.e., storage) the entire system is operated to maximize the probability of meeting all unrestricted demands, including those of the new consumptive user. New appropriators become equal partners with an equally reliable supply after ''paying'' the marginal cost-based price to join the system.

Normative Framework

The technical and policy frameworks are grounded in efficient management of drought risk, equitable allocation of reliability, and marginal-cost-based allocation of costs. The regulatory policy also provides a normative framework supporting the implementation and interpretation of regulatory policy, illustrated in the following examples.

Example of Cumulative Impacts

One challenge for an operationally based framework centers on the cumulative impact of consumptive uses <3,785.4 m^3 d^{-1} (1 mgd) that are individually exempted from the regulation. Anticipating this challenge, the regulation includes the identification of storage volumes for a 3,785.4-m^3 d^{-1} consumptive use (Table 2). The impact from small consumptive users that cumulatively exceed the 3,785.4-m^3 d^{-1} threshold can be quantified and characterized by the storage volume required to offset their cumulative withdrawals. Cumulative impacts can be efficiently mitigated through combined, jointly operated augmentation storage. The potential pooling of consumptive impacts through, e.g., a third party market maker for storage, would allow small individual permittees to benefit from the economies of scale involved in acquiring reservoir storage. Cost recovery for this storage could be equitably and efficiently allocated as a permit fee for new consumptive appropriation permits.

Example of Interruptible Permits

A second way in which the normative framework helps guide regulatory interpretations is through clear explanation of regulatory intent. The nominal 3,785.4-m^3 d^{-1} exemption threshold for small users raised the question whether nonexempt consumptive users could avoid providing augmentation storage by curtailing withdrawals to a level <3,785.4 m^3 d^{-1} during critical periods. The analytical framework establishing the augmentation requirements provided the clear intention of the regulation. Augmentation storage is required to offset the impacts of consumptive use. Consumptive uses >3,785.4 m^3 d^{-1} must provide storage to offset those impacts. If the consumptive user curtailed only a portion of their withdrawal from the Potomac, but continued to make consumptive withdrawals at levels slightly less than the 3,785.4-m^3 d^{-1} threshold, there would clearly be unmitigated (though reduced) impacts to the reliability of the regional water supply system—including impacts to other consumptive permittees. The reliability criteria engendered in the consumptive use policy would not be satisfied through such a limited curtailment. The clear exposition of technical criteria, goals, and intent behind the regulation offers a normative framework for regulatory interpretations.

Example of Quality of Service

Consumptive users permitted to withdraw more than 3,785.4 m^3 d^{-1} have the option of interrupting their withdrawals when so directed instead of providing augmentation storage. By offering an interruptible withdrawal as another alternative for permitting consumptive appropriations, the consumptive use policy provides added flexibility in the creation of ''quality of service'' permittees (Schwartz 1988). For some consumptive users, economically efficient alternatives may make an interruptible permit more attractive than the flexible options for building, leasing, or reallocating reservoir storage within the basin. For example, an interruptible permit may be a more cost-effective alternative for a power producer with the capability to switch to nonevaporative cooling or purchase power on a regional power grid in time of drought.

CONCLUSIONS

Critical period analysis is used to identify the reservoir storage volume and system operating rules that efficiently mitigate critical period consumptive impacts under design conditions projected through year 2030. Critical period analysis of system rules is developed as a multiobjective extension of traditional storage yield analysis for a multireservoir system operated with real-time forecasts. The operational analysis is summarized in regulation as a storage requirement based on permitted withdrawal and storage location.

Hedging in forecast-based operating rules demonstrates the equivalence of reservoir storage, operating rules, and forecast skill in realizing water resource system reliability. Hedging through operating rules that effectively exploit forecast skill offers a cost-effective nonstructural alternative to reservoir storage as a means to maintain system reliability. Usable improvements in forecast skill can therefore be equivalent to increasing the usable storage in existing water resource systems. Operational forecast skill differs from statistical forecast skill. The decoupling of forecast quality and forecast value illustrates the critical importance of evaluating operational forecasts for water resource management with operational criteria, in addition to traditional measures such as bias, correlation, and RMS error.

Trade-offs in the allocation of yield risk and reliability make the evaluation of consumptive impacts and the identification of system operating rules an inherent multiobjective problem. Generating methods were adapted to sample and systematically evaluate the noninferior set of parametric operating rules over operationally meaningful system objectives. Admitting parameterizations of the operating rules that could have substantially shifted the impacts and costs among users, lent greater credibility to the process and the operating rules that were finally selected. Acceptance of the storage-based component of the regulatory policy was significantly enhanced by the fact that alternate solutions were not excluded a priori, but were only rejected when judged to be inferior to other feasible alternatives.

The regulatory policy is grounded in efficient management of drought risk, equitable allocation of reliability, and marginal-cost-based allocation of costs. Operational incorporation of technical efficiency, economic efficiency, and equity, establishes a normative framework supporting the implementation and interpretation of regulatory policy. Systemwide operating rules that assure equal reliability of unrestricted demands for all permitted appropriators integrate equitable and efficient allocation of the Potomac within the existing permitted riparian appropriation system.

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APPENDIX. REFERENCES

Bakken, J. D., and Bruns, T. M. (1991). ''Assessing the reliability of urban reservoir supplies.'' *J. AWWA*, 83(3), 47–51.

Bar-Shalom, Y. (1981). ‘‘Stochastic dynamic programming: Caution and probing.’’ *IEEE Trans. on Automatic Control*, AC-26(5), 1184–1194.

Bar-Shalom, Y., and Tse, E. (1974). ‘‘Dual effect, certainty equivalence, and separation in stochastic control.’’ *IEEE Trans. on Automatic Control*, AC-19(5), 494–500.

Bayazit, M., and Ünal, N. E. (1990). ‘‘Effects of hedging on reservoir performance.’’ *Water Resour. Res.*, 26(4), 713–719.

Bower, B. T., Hufschmidt, M. M., and Reedy, W. W. (1962). ‘‘Operating procedures: Their role in the design of water-resource systems by simulation analysis.’’ Chapter 11, *Design of water resource systems*, A. Maas et al., Harvard University Press, Cambridge, Mass., 455.

Burges, S. J., and Linsley, R. K. (1971). ‘‘Some factors influencing required reservoir storage.’’ *J. Hydr. Div.*, ASCE, 97(7), 977–991.

Cohon, J. L. (1978). *Multiobjective programming and planning*, Academic, New York.

‘‘Consumptive use of surface water in the potomac river basin.’’ (1985). *Code of Maryland regulations*, Title 8, Subtitle 5, Chapter 9, Supp. 7, 404-9–404-12.

Eastman, P. W. (1986). ‘‘Metropolitan Washington area water supply.’’ *Proc., Engrg. Found. Conf., Social and Envir. Objectives in Water Resour. Plng. and Mgmt.*, ASCE, New York, 57–69.

Hanson, R. L. (1967). ‘‘Characteristics of summer base flow of the Potomac River.’’ Profl. Paper 575-C, U.S. Geological Survey, Reston, Va., c212–c215.

Hashimoto, T., Stedinger, J. R., and Loucks, D. P. (1982). ‘‘Reliability, resiliency, and vulnerability criteria for water resource system performance evaluation.’’ *Water Resour. Res.*, 18(1), 14–20.

Hirsch, R. M. (1978). ‘‘Risk analysis for a water supply system—Occoquan Reservoir, Fairfax and Prince William counties, Va.’’ *USGS Open-File Rep. 78-452*, U.S. Geological Survey, Reston, Va.

Hirsch, R. M. (1982). ‘‘Stochastic hydrologic model for drought management.’’ *J. Water Resour. Plng. and Mgmt. Div.*, ASCE, 107(2), 303–313.

Hirsch, R. M., Cohon, J. L., and ReVelle, C. S. (1977). ‘‘Gains from joint operations of multiple reservoir systems.’’ *Water Resour. Res.*, 13(2), 239–245.

Jacobs, O. L. R. (1980). ‘‘The structure of stochastic control laws.’’ Chapter 7, *Stochastic programming*, M. A. H. Dempster, ed., Academic, New York.

Johnson, S. A., Stedinger, J. R., and Staschus, K. (1991). ‘‘Heuristic operating policies for reservoir system simulation.’’ *Water Resour. Res.*, 27(5), 673–685.

Kitanidis, P. K. (1983). ‘‘Real-time forecasting of river flows and stochastic optimal control of multireservoir systems.’’ *IIHR Rep. No. 258*, Iowa Institute of Hydraulic Research, Iowa City, Iowa.

Klemeš, V. (1977). ‘‘Storage mass-curve analysis in a systems-analytic perspective.’’ *Water Resour. Res.*, 15(2), 359–370.

Loucks, D. P., Stedinger, J. R., and Haith, D. A. (1981). *Water resources systems planning and analysis*, McGraw-Hill, New York.

McMahon, T. A. (1993). ‘‘Hydrologic design for water use.’’ Chapter 27 *Handbook of hydrology*, D. M. Maidment, ed., McGraw-Hill, New York.

McMahon, T. A., and Mein, R. G. (1986). *River and reservoir yield*, Water Resources Publications, Littleton, Colo.

Maryland Department of Natural Resources (Md. DNR). (1981). ‘‘Potomac River environmental flow-by study.’’ Maryland DNR, Water Resources Administration, Annapolis, Md.

Moy, W.-S., Cohon, J. L., and ReVelle, C. (1986). ‘‘A programming model for analysis of the reliability, resilience, and vulnerability of a water supply reservoir.’’ *Water Resour. Res.*, 22(4), 489–498.

Mullusky, M. G., and Schwartz, S. S. (1996). ‘‘Multiobjective risk-based reservoir operation on the Potomac River.’’ *Proc., 5th Water Resour. Operations and Mgmt. Workshop*, ASCE, Reston, Va., 315–319.

Nalbantis, I., and Koutsoyiannis, D. (1997). ‘‘A parametric rule for planning and management of multiple-reservoir systems.’’ *Water Resour. Res.*, 33(9), 2165–2177.

Okun, D. A. (1979). ‘‘October 10, 1979 testimony before the Subcommittee on Governmental Efficiency and the District of Columbia.’’ U.S. House of Representatives, 96th Congress, U.S. Government Printing Office, Washington, D.C.

Palmer, R. N., Smith, J. A., Cohon, J. L., and ReVelle, C. S. (1982). ‘‘Reservoir management in Potomac River Basin.’’ *J. Water Resour. Plng. and Mgmt. Div.*, ASCE, 108(1), 47–66.

Potter, K. W. (1977). ‘‘Sequent peak procedure: Minimum reservoir capacity subject to constraint on final storage.’’ *Water Resour. Bull.*, 13(3), 521–528.

Rippl, W. (1883). ‘‘The capacity of storage reservoirs for water supply.’’ *Proc., Instn. Civ. Engrs.*, London, 71, 270–278.

Schwartz, S. S. (1988). ‘‘Efficiency vs. equity in water resource allocation with interruptible permits.’’ *Tech. Rep. 88-5*, Interstate Commission on the Potomac River Basin, Rockville, Md.

Schwartz, S. S. (1989). ‘‘Non-structural hedging in multipurpose reservoir operation.’’ *Proc., 16th Annu. Conf., Water Resour. Plng. and Mgmt.*, ASCE, New York, 580–583.

Schwartz, S. S., Ellis, J. H., and Smith, J. A. (1988). ‘‘Uncertain hydrologic forecasts in real-time reservoir operation.’’ *EOS*, 69(44).

Sheer, D. P. (1982). ‘‘Assuring water supply for the Washington metropolitan area: twenty-five years of progress.’’ *A 1980’s view of water management in the Potomac River basin*, a report for the Subcommittee on Governmental Efficiency and the District of Columbia, U.S. Government Printing Office, Washington, D.C., 39–66.

Sheer, D. P. (1980). ‘‘Analyzing the risk of drought: the Occoquan experience.’’ *J. AWWA*, 72(5), 246–253.

Shih, J.-S., and ReVelle, C. (1994). ‘‘Water-supply operations during drought: Continuous hedging rule.’’ *J. Water Resour. Plng. and Mgmt.*, ASCE, 120(5), 613–629.

Smith, J. A. (1988). ‘‘A model of daily municipal water use for short-term forecasting.’’ *Water Resour. Res.*, 24(2), 201–206.

Smith, J. A. (1989). ‘‘Water supply yield analysis for the Washington metropolitan area.’’ *J. Water Resour. Plng. and Mgmt.*, ASCE, 115(2), 230–242.

Smith, J. A. (1993). ‘‘Conditional-yield operating rules for low-flow management.’’ *J. Water Resour. Plng. and Mgmt.*, ASCE, 119(3), 324–338.

Smith, J. A., Schwartz, S. S., Boland, J. B., and Whitcomb, J. (1987). ‘‘Multiobjective reservoir operation using forecasts of water supply and water use.’’ *Final Rep. Under USGS Water Resources Research Grant 14-08-0001-G1145*.

Smith, R. L., and Lampe, L. K. (1988). ‘‘Dependable yield evaluations.’’ *J. AWWA*, 80(9), 66–70.

Stedinger, J. R., Sule, B. F., and Pei, D. (1983). ‘‘Multiple reservoir system screening models.’’ *Water Resour. Res.*, 19(6), 1383–1393.

Stengel, R. F. (1993). *Optimal control and estimation*, Dover, New York.

Trombley, T. J. (1982). ‘‘Downstream effects of reservoir releases to the Potomac River from Luke, Maryland, to Washington, D.C.’’ *Investigations Rep. 82-4062*. U.S. Geological Survey.

U.S. Army Corps of Engineers (COE). (1963). *Potomac River basin report*, Vol. 1, Part 1, February, 12.

Vogel, R. M., and Stedinger, J. R. (1987). ‘‘Generalized storage-reliability-yield relationships.’’ *J. Hydro.*, Amsterdam, 89, 303–327.

Vogel, R. M., and Stedinger, J. R. (1988). ‘‘The value of stochastic streamflow models in overyear reservoir design applications.’’ *Water Resour. Res.*, 24(9), 1483–1490.

‘‘Water supply.’’ (1983). *Civ. Engrg.*, ASCE, 53(6), 50–53.