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Stability-oriented programs for regulating water withdrawals in riparian regions

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[1] Under permit programs stemming from regulated riparian systems of water withdrawal control, significant quantities of water cannot be withdrawn from the stream without a withdrawal-constraining permit. There are two versions of such a permit system, one of which fixes the allowable withdrawal, the other of which allows withdrawals to vary directly with streamflows. However, both tie allowable withdrawal to streamflow at some level, the former simply shutting off all withdrawals when the streamflow breaches a low flow standard. Simple logic and the simulation of such systems with hydrologic models predict, in cases where the indexing gauge is downstream of the withdrawal point, the possibility of unstable feedback, leading to severe variability of both streamflow and allowable withdrawal. In this paper we characterize the streamflow variability with three indices, namely, flow crossing, flow reversal, and standard deviation, and compare the difference in those indices to represent the degree of the streamflow variability under the fixed flow and fractional flow withdrawal permit programs. Techniques based on control theory are proposed for modifying the fractional flow withdrawal program to reduce the streamflow variability. It is concluded that regulatory programs modified by inclusion of a first-order filter are able to reduce streamflow variability without significant sacrifice in net benefit or low flow frequency. *INDEX TERMS:* 1884 Hydrology: Water supply; 6324 Policy Sciences: Legislation and regulations; 6344 Policy Sciences: System operation and management; 1812 Hydrology: Drought; *KEYWORDS:* water, water rights, water regulations, riparian law, feedback control

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1. Introduction

[2] Recently, the Water Law Committee of the American Society of Civil Engineers (ASCE) developed the regulated riparian model water code [*Dellapenna*, 1997] (hereinafter referred to as RRMWC) as model water allocation legislation for riparian areas. Under this code, no withdrawals from the public water bodies of the state may be undertaken without a permit [*Dellapenna*, 1997, §6R-1-01]. Later ASCE published an additional volume on riparian water regulation [*Eheart*, 2002] (hereinafter referred to as RWR) to provide detailed regulations and procedures necessary for day-to-day administration of such regulatory water withdrawal permit programs. RWR affirms withdrawal-constraining permit systems to be the most reliable and tractable way to regulate water use, and suggests the fixed flow and the fractional flow withdrawal permit systems as possible alternatives. RWR points out that regulating water withdrawal using such permit programs requires knowledge of streamwater availability at each withdrawal site. Because it is impossible to measure streamflow at every potential withdrawal site, it has been suggested that estimates serve as surrogates for measured streamflow. Such estimates are to be based on either a weighted average of the flows at two or more gauge sites [*Loucks et al.*, 1981] or regional flow duration curves that relate the recorded streamflows at neighboring gauge sites to the properties of drainage basins [*Fennessey and Vogel*, 1990; *Singh et al.*, 2001]. However, if only one gauging station exists within a reasonable distance in the watershed of interest, allowable withdrawal rates at ungauged sites must be determined directly according to the measured streamflow at that nearest gauge. For many users, that gauge may be located downstream of their withdrawal points. This withdrawal regulation process constitutes a feedback loop that could be unstable, depending on the time delay between the water withdrawal action and the response of the streamflow measured downstream. *An and Eheart* [2004] assess the advantages and disadvantages of the fixed and fractional withdrawal permit programs and show that such a feedback loop-embedded withdrawal process is very likely to yield significant streamflow fluctuations. In particular, the fixed flow permit program, while generally allowing no more than a fixed maximum withdrawal, requires abrupt decreases to zero withdrawals whenever the low flow standard is breached. This results in highly fluctuating streamflows at low flow levels, and frequent withdrawal interruption. On the other hand, the

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fractional flow permit program, which superficially might appear to be more susceptible to such instability, is found to preserve the general trend of the natural flow regime when the total allowable withdrawal fraction is optimally chosen. Controlling such exacerbations of streamflow fluctuations while keeping other water management objectives acceptable is important to achieving effective and efficient water allocation.

[3] *An and Eheart* [2004] characterize the exacerbation of the streamflow variation or fluctuation under alternative regulatory permit programs by the frequency with which the flow crosses the minimum flow standard. This measure is designed to emphasize flow variation at minimum flow level, ignoring flow variation at high, moderate, or moderate to low flows. However, it is desirable for water managers to be aware of flow regime alteration at the full range of flows. *Richter et al.* [1996] have developed an approach to evaluate anthropogenic effects on the natural flow regime by analyzing 32 statistical parameters, termed indicators of hydrologic alteration (IHAs). Among those IHA parameters, the one that best characterizes the frequency of streamflow variation after anthropogenic impacts is the frequency of streamflow rising and falling. Many studies [*Richter et al.*, 1997; *Galat and Lipkin*, 2000; *Magilligan and Nislow*, 2001; *Koel and Sparks*, 2002] have used this streamflow reversal to characterize streamflow variability under situations of flow disruption. We believe that the following three measures of streamflow variability provide sufficient information for the evaluation of alternative programs: (1) the frequency of crossing the low flow standard noted above, termed flow crossing; (2) the flow reversal frequency; and (3) the streamflow standard deviation (one of the most common measures of variability generally).

[4] In this study, we first evaluate flow alteration induced by the implementation of the fixed flow and fractional flow permit programs by comparing flow crossing, flow reversal, and standard deviation. Second, for the fractional flow program only, we evaluate process control techniques in minimizing unstable flow fluctuations. Third, we explore the application of this control technique using a design procedure wherein the control parameter values are determined on the basis of the watershed response characteristics to a unit change of withdrawal rate. Additionally, tentative recommendations are made for uses of these alternative regulatory programs. We expect the results of this study to help water managers become aware of potential feedback instability problems and to suggest a usable approach to controlling stream withdrawal most effectively within a permit framework.

2. Overview of Analysis

2.1. Alternative Regulatory Withdrawal Programs

[5] The regulatory programs proposed by *Eheart* [2002] are based on the fixed or fractional flow withdrawal permit systems. Details of these permit programs are discussed by *An and Eheart* [2004]. Assuming once-daily streamflow observations at a gauging location, the maximum withdrawal allowance W_{it} for user i at day t under the two permit programs is expressed as

Fixed flow permit

$$W_{it} = \mathrm{FX}_i \times A_i, \ \text{if } Q_t > Q_s; \text{otherwise}, 0 \qquad (1)$$

Fractional flow permit

$$W_{it} = \mathit{ff}_i \times (Q_t - Q_s), \ \text{if } Q_t > Q_s; \text{otherwise}, \ 0, \qquad (2)$$

where FX_i = the maximum allowable fixed rate of user i (mm/day); ff_i = the maximum allowable fraction to user i which is calculated by FF × $(A_i/\sum A_i)$; FF = the maximum allowable fraction of streamflow at a nearby gauge allocated in aggregate to all users upstream of that location; A_i = the riparian area of user i; Q_t = the streamflow measured at a reference gauge at day t; Q_s = the minimum flow standard imposed at a reference gauge.

[6] Thus each user is allowed to withdraw up to a certain constant (fixed) rate of water, FX_i, or a certain fraction of the local flow, $\mathit{ff}_i \times (Q_t - Q_s)$, as long as water is physically available at the withdrawal site and the minimum streamflow standard at nearby gauging stations is met. For equity reasons, FX_i is uniformly normalized on the users' riparian area, and assumed to be the same across all potential riparian users, and ff_i is allocated in proportion to the riparian area of user i. Under both permit programs, the allowance of withdrawal is subject to the measured streamflow at a nearby gauge, which is often located downstream of the withdrawal point. If this occurs, this water regulatory process, as noted above, constitutes a feedback loop, because the gauge reading influences, and is influenced by, the users' water withdrawals. The time delay between water withdrawal action and streamflow measurement is the salient parameter in this feedback process, which can lead to unstable fluctuations of both streamflow and allowable withdrawal rates. Optimization of the allocation parameters might help control such fluctuation under both permit programs to some extent, but it would be beneficial if a usable alternative that is specifically designed to control such instability is available. In the next section, such an alternative is presented.

2.2. Modified Regulatory Withdrawal Programs: Applications of Process Control Techniques

[7] Many chemical and manufacturing processes have been bedeviled by unstably fluctuating process conditions (temperatures, pressures, flow rates, etc.) and product quality, induced by a delayed response (or dead time) of the output (process condition) to a change of the input (valve position, heat addition or removal, etc.). These fluctuations have been controlled by a variety of process control techniques [*Smith and Corripio*, 1985; *Morari and Zafiriou*, 1989; *Ogunnaike and Ray*, 1994; *Marlin*, 1995] that mediate control signals specifically to avoid such unstable fluctuations. It is the premise of the work presented here that those process control techniques might help reduce undesirable streamflow variation if applied to the design of water withdrawal permit programs. Two types of control techniques, namely, (1) first-order filter control and (2) proportional-integral-derivative control, are integrated into the fractional flow regulatory program. It is our contention that the fixed flow program, while administratively simpler than the fractional flow program, is less able to control such fluctuations, with or without the use of process control techniques, as well as low flow events. This is because the fixed withdrawal limitation of that program leaves it with so much less room to maneuver than the fractional system. Indeed, the very term "fixed flow system

with process control techniques" could be judged an oxymoron, because the control techniques would render it no longer a fixed system. Hence we confine our analysis to the fractional flow program.

2.2.1. A Fractional Flow Permit Program Incorporating First-Order Filter Control

[8] The first-order filter is one of the simplest and the most common techniques used for attenuating high-frequency component of a signal in a feedback process [*Marlin*, 1995]. Assuming ε to be an error signal (the deviation of the output value from the target output value), the current (filtered) signal ε'_t with the first-order filter is obtained by averaging the current raw signal, ε_t, with the past filtered signal, $\varepsilon'_{t\text{-}1}$, with a filter coefficient, β:

$$\varepsilon'_t = \beta\varepsilon'_{t-1} + (1-\beta)\varepsilon_t. \tag{3}$$

In this study, the deviation of the observed streamflow from the minimum flow standard is taken as the error signal $\varepsilon_t (= Q_t - Q_s)$ which is to be controlled by the first-order filter. By integrating this filtering technique into the simple fractional flow permit program, the modified formula to determine the maximum allowance of withdrawal is

$$W_{it} = \mathrm{FF} \times \frac{A_i}{\sum A_i} \times \varepsilon'_t. \tag{4}$$

Under this new definition, the maximum allowable withdrawal at a given location i, W_{it} is a prescribed fraction, FF, of the filtered streamflow of the previous and current days. The optimal value of the filter coefficient, β, that achieves the desired control performance, is sought within a range from zero to one. For equity reasons, the same β is assumed for all potential riparian users.

2.2.2. A Fractional Flow Permit Program Incorporating Proportional-Integral-Derivative Control

[9] Proportional-integral-derivative (PID) control is one of the most conventional and popular process control techniques. Compared to the first-order filter, PID control is more sophisticated, in that the manipulated variable is controlled with three actions, i.e., the proportional, integral, and derivative actions:

$$p(t) = K_C\left[\varepsilon(t) + \frac{1}{\tau_I}\int_0^t \varepsilon(t')dt' + \tau_D\frac{d\varepsilon(t)}{dt}\right] + p_s, \tag{5}$$

where p = the manipulated variable; p_s = the set point value of the manipulated variable; ε = the error signal (the deviation of the output from the target output value); K_c = the proportional gain; τ_I = the integral time constant; and τ_D = the derivative time constant. Under this control method, the error signal ε_t calculated by the difference between the output value and the target output value is transmitted to the PID controller that determines the manipulated variable value according to equation (5) [e.g., *Ogunnaike and Ray*, 1994].

[10] Assuming that the error signal, ε_t is the deviation of the observed streamflow from the minimum flow standard $(= Q_t - Q_s)$, and the manipulated variable is the water withdrawal rate at each ungauged withdrawal site, equation (5) can be rewritten for the maximum allowable withdrawal W_{it} based on PID control at that withdrawal site i at day t as

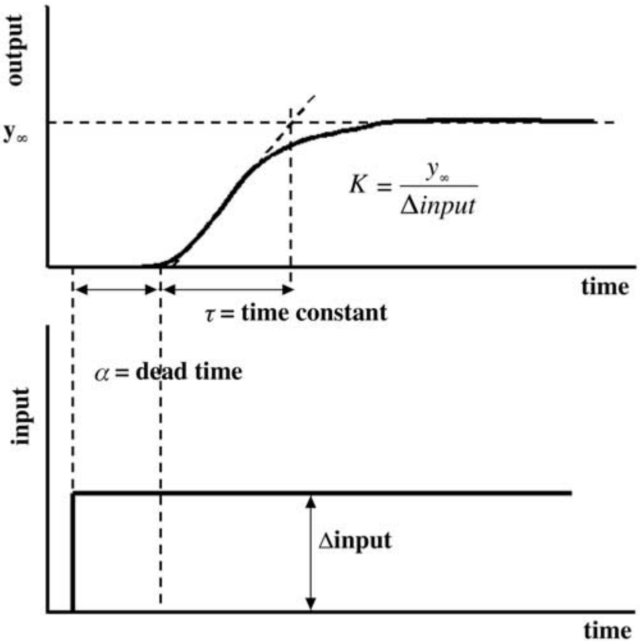

Figure 1. FOPDT model approximation in determining process parameters K, τ, and α.

$$W_{it} = K_{C_i}\left[(Q_t - Q_s) + \frac{1}{\tau_{I_i}}\sum_{t=0}^{k}(Q_t - Q_s) + \tau_{D_i}\frac{Q_t - Q_{t-1}}{1}\right]. \tag{6}$$

[11] Note that the discrete formula (6) approaches the continuous PID algorithm (5) as the time step approaches zero. The integral and derivative terms are approximated by a simple rectangular approximation and a backward difference, respectively.

[12] This formula expresses the notion that withdrawal based on PID control is a linear function of the streamflow deviation from the minimum flow standard. Thus the PID approach may be thought of as the fractional flow program with the integral and derivative actions simply added for more sophisticated withdrawal control. Accordingly, we allow that proportional gain K_{C_i} can be replaced with the maximum allowable fraction, ff_i (= FF × $(A_i/\sum A_i)$).

[13] Under PID control, three unknown parameters, K_c, τ_I, and τ_D in equation (6) have to be specified for each withdrawal-streamflow response process. In this study, however, each of the three parameters is assumed to be uniform across users to ensure equitable allocation of water. across the users.

[14] In chemical process control, a variety of tuning rules have been suggested for specification of the PID control parameters, including the IMC tuning rule [*Rivera et al.*, 1986] in Table 1, which is used here. This tuning rule requires information on characteristics of the process model, which are the process gain K, time constant τ, and time delay α (note that, despite the superficial similarity, these process parameters are different from the three PID control parameters, K_c, τ_I, and τ_D), in a first-order-plus-dead-time

Table 1. IMC Controller Tuning Rule[a]

Controller Type	K_c	τ_I	τ_D	Recommended Choice of λ
PID	$\frac{2\tau+\alpha}{2K(\lambda+\alpha)}$	$\tau+\frac{\alpha}{2}$	$\frac{\tau\alpha}{2\tau+\alpha}$	$\frac{\lambda}{\alpha} > 0.25$

[a] From *Rivera et al.* [1986].

(FOPDT) model [*Cohen and Coon*, 1953; *Smith*, 2002]. Because the process dealt with here is the relationship between water withdrawals at an upstream point and streamflow responses at a downstream point, the process gain K can be obtained from a ratio of the streamflow change to a step increase of a withdrawal rate. The time constant τ is estimated from the time required for the streamflow to reach steady state, and the time delay α is estimated as the dead time between the streamflow response to a step increase in a withdrawal rate. By analyzing streamflow responses to unit changes of withdrawal at each potential withdrawal site, sets of three process parameters are estimated for each withdrawal–streamflow response process. Figure 1 shows the FOPDT model approximation to identify such process characteristics by analyzing output response to a step change in input.

[15] According to the assumption of uniformity of control parameters, however, these sets of process parameter values are selected as the most pessimistic (e.g., largest time delay) set of values: $K = 0.69$, $\tau = 10$ days and $\alpha = 0.7$ day. This operation worsens streamflow variability, but avoids the inequity issue. On the basis of these K, τ, and α values, values of the control parameters, K_c, τ_I, and τ_D are estimated according to the IMC rule. However, because the given *ff* value substitutes for K_c in PID control, we, in fact, apply the IMC tuning rule for τ_I, and τ_D only, which results in 10.35 days and 0.34 days, respectively. By simulating combinations of these two parameters and given *ff* values, optimal values of the control parameters are sought.

2.3. Description of Simulation Framework

[16] For modeling regulatory programs in practice as realistically as possible, the SWAT (Soil and Water Assessment Tool) model is adopted. SWAT is a sophisticated river basin and watershed scale model that predicts the impact of land management practices on water, sediment, and agricultural yields in large complex watersheds with varying soils, land use, and management conditions over long periods of time [*Arnold et al.*, 1998; *Neitsch et al.*, 2001] (see http://www.brc.tamus.edu/swat). A number of climate, hydrology, nutrients, erosion, crop growth, main channel processes, and water routing models are incorporated in SWAT to simulate hydrologic and agricultural processes accurately. For modeling purposes, a watershed is partitioned into a number of subwatersheds or subbasins according to drainage topology, and then each subwatershed is divided into hydrologic response units (HRUs) that comprise unique land use, soil, and management combinations. This feature enables SWAT users to simulate user-specified restrictions on stream water withdrawal at different sites realistically. The most recent version of SWAT has been incorporated into BASINS (Better Assessment Science

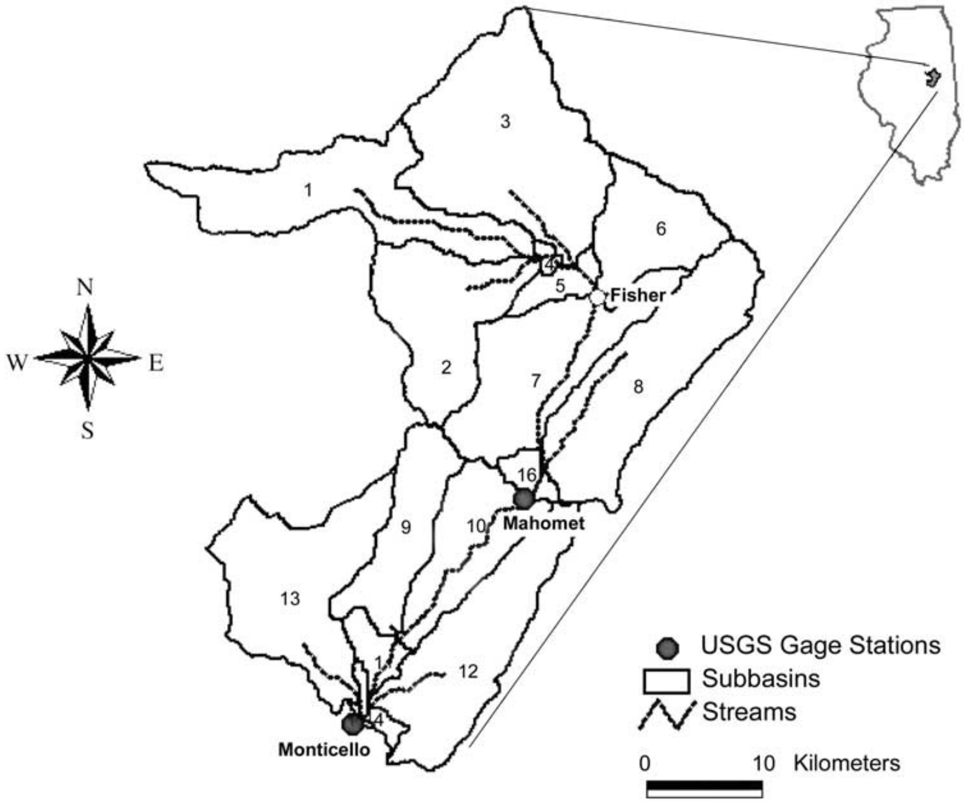

Figure 2. Upper Sangamon River watershed.

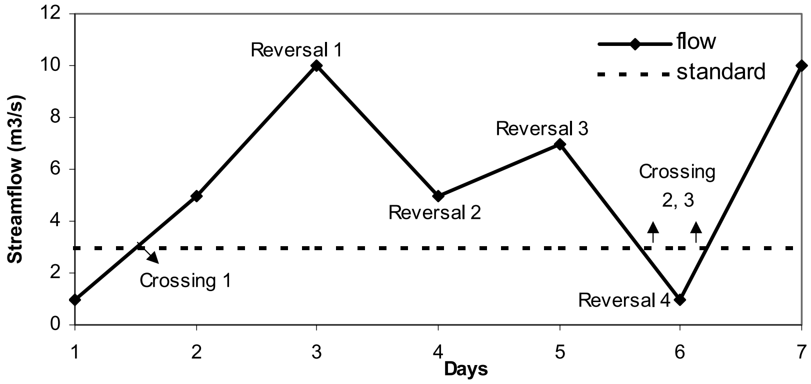

Figure 3. Computations of flow crossing and flow reversal illustrated by a hypothetical hydrograph. Flow crossing and reversal are analyzed on a daily basis within a period of simulation.

Integrating Point and Nonpoint Sources) version 3.0 which operates within the Arcview Geographic Information System (GIS). BASINS provides GIS-based watershed database, i.e., the digital elevation map (DEM), land use and land cover (LULC), soil distribution data (STATSGO), and delineation tools that enhance the accuracy of the watershed delineation (U.S. Environmental Protection Agency, unpublished manuscript, 2003) (see http://www.epa.gov/waterscience/basins/b3webdwn.htm).

[17] To simulate the alternative regulatory water withdrawal permit programs shown in equations (1), (2), (4), and (6), we make a special modification to the subroutines of the SWAT model related to water use and irrigation practices. Then the SWAT model is calibrated with annual crop yields and historical daily streamflows. The simulation of water withdrawal permit programs is undertaken for an agriculturally dominated watershed in central Illinois, the Upper Sangamon River basin (USGS Cataloging unit: 07130006 upstream of Monticello, IL: Figure 2). The watershed drains 1441 km^2 (550 square miles) and more than 95% of the total area is in agricultural use, primarily in corn (Zea Mays L.). For modeling purposes, the watershed is subdivided into 16 subbasins and 20 HRUs.

[18] For simplicity in simulation, the following assumptions are made; first, withdrawal allocation parameters under each of alternative programs are set to vary from 0 to 20 mm/day for FX and 0 to 300% for FF, which are reasonable ranges to reflect typical irrigation exercises. Second, water withdrawal from streams is assumed utilized only for irrigation on riparian land. Although water withdrawal for nonriparian use is allowed under RRMWC, we assume riparian use to be dominant in this type of agriculturally oriented watershed. Third, we assume that water withdrawal is allowed only from streams having nonzero 7Q10 (downstream of Fisher), and that riparian land is defined as the area, at a maximum, within 1.6 km (1 mile) from the stream. Therefore the total riparian area for surface water withdrawal and application is estimated at 149.4 km^2, which is approximately 10.4% of the total drainage area. In allocating water withdrawal permits over riparian users, we assume that each riparian subbasin (subbasins 7, 16, 10, 11, 14, and 15 in Figure 2) represents a potential withdrawal location of water users.

[19] In the modeling exercise, water withdrawal for irrigation is initiated by the root zone moisture deficit (RZD) in soil layers such that a user starts withdrawal when RZD reaches a prescribed trigger value and ceases when that soil moisture reaches field capacity, which is where RZD becomes zero. Through preliminary experiment, profit-optimal trigger values are estimated for each potential withdrawal location.

[20] One, and the only currently active, USGS stream gauging station (station number: 05572000) located at the outlet of the basin near Monticello, is chosen as a reference gauging station where the minimum streamflow standard is imposed. Using the historic streamflow record at the Monticello gauging station, the minimum streamflow standards corresponding to the 10% Tennant method [*Tennant*, 1976] are estimated for various streamflow record periods as: 0.870 m^3/s (1930–1940), 1.260 m^3/s (1960–2000), and, for the 7Q10 method [*Singh and Stall*, 1973] as: 0.048 m^3/s (1963–1992). By applying each of these estimates to simulation exercises, we would be able to examine the effectiveness of the regulatory programs over a wide range of minimum flow standard.

[21] In this evaluation, we choose the 9 year period 1932–1940 as a simulation period, using data from the Urbana, IL weather station. Because this period is recorded as the driest in eastern U.S. history, we expect this weather to reflect an increase in potential water demands under more frequent droughts in traditionally humid regions (K. Kunkel, personal communication, 2003). The 9 year period is also within the range of recommendations by RWR and RRMWC for the duration of permits. Using the output from the SWAT simulation, the streamflow variability indices, i.e., flow crossing (CROS), flow reversal (REV), and standard deviation of flow (STD) are calculated for each regulatory withdrawal program.

[22] Streamflow crossing is defined as the number of times flow passes through the minimum flow standard:

$$\mathrm{CROS} = \sum_t \mathrm{CROS}_t, \tag{7}$$

where $\mathrm{CROS}_t = 0$ or 1, 1 if $\mathrm{Index}_t - \mathrm{Index}_{t\text{-}1} \neq 0$, 0 otherwise; $\mathrm{Index}_t = -1$ or 1, 1 if $Q_t - Q_s > 0$, -1 if $Q_t - Q_s < 0$. This measure was called the withdrawal interruption frequency (WIF) in the previous work [*An and Eheart*, 2004] to represent ease of implementation of the regulatory water withdrawal programs. Flow crossing focuses on flow

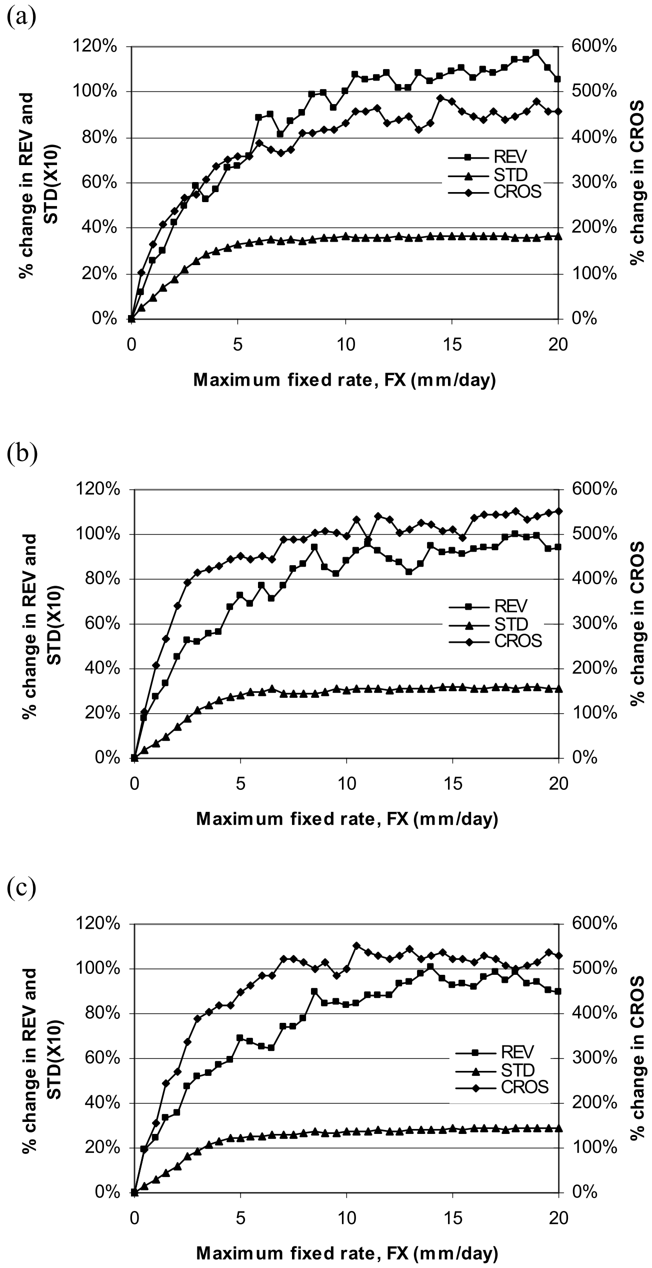

Figure 4. Percent change in streamflow variability indices (CROS, flow crossing; REV, flow reversal; STD, standard deviation) under the fixed flow permit program with change of maximum allowable fixed rate, FX, at varying levels of minimum streamflow standards.

alteration near the minimum flow standard, and is related to the frequency of withdrawal interruption.

[23] The streamflow reversal is defined as the number of times in a given period there is a transition between streamflow rising and falling:

$$\mathrm{REV} = \sum_{t} \mathrm{REV}_t, \tag{8}$$

where $\mathrm{REV}_t = 0$ or 1, 1 if $\mathrm{change}_t \times \mathrm{change}_{t\text{-}1} = -1$, 0 otherwise; $\mathrm{change}_t = -1$ or 1, 1 if $Q_t - Q_{t\text{-}1} > 0$, -1 if $Q_t - Q_{t\text{-}1} < 0$. Thus any one pair of consecutive changes in the sign of the time derivative of the hydrograph is considered to be one reversal regardless of its duration or proximity to the low flow standard. By comparing the frequency of flow reversals in the hydrograph, we can assess the abruptness and the number of intra-annual cycles in environmental variations under the given flow regulation. The computations of flow crossing and flow reversal are presented in Figure 3.

[24] The standard deviation is one of the most common statistical parameters to measure overall dispersion (variation) of data. The standard deviation of streamflow is the third measure of streamflow variability:

$$\mathrm{STD} = \sqrt{\frac{\sum_{t=1}^{n} Q_t^2 - \frac{\left(\sum_{t=1}^{n} Q_t\right)^2}{n}}{n-1}}, \tag{9}$$

where n is number of days over simulation periods.

3. Results

[25] Since there is some natural variation in streamflow, all results presented below are expressed relative to the "zero withdrawal" case. In theory, withdrawals from the stream could cause either an increase or a decrease in streamflow variability, but in the model results presented here, usually, although not always, result in an increase. The results are presented in Figures 4–7; the standard deviation is multiplied by 10 for scaling purposes.

3.1. Streamflow Variability Under Fixed Flow and Fractional Flow Withdrawal Permit Programs

[26] Streamflow variation caused by flow regulation stemming from the fixed flow and fractional flow withdrawal programs is estimated, as noted above, by flow crossing frequency, flow reversal frequency, and standard deviation. Figures 4 and 5 show the percent change in these three variability indices under the fixed flow and fractional flow withdrawal programs. Three levels of minimum streamflow standard are simulated, i.e., 0.048 m^3/s, 0.870 m^3/s, and 1.260 m^3/s.

[27] Under the fixed flow permit program, it is observed that the percent change in flow crossing and flow reversal monotonically increase up to 485% and 117%, respectively, at the minimum flow standard of 0.048 m^3/s as the maximum allowable fixed rate FX increases from 0 mm/day (zero withdrawal) to 20 mm/day (see Figure 4a). However, the change in the standard deviation of streamflow remains at a very low percentage, a maximum of 3.7%. Such a low change in the standard deviation means that the annual streamflow variance under withdrawal regulation is not very different from that under the zero withdrawal case. This is because the standard deviation gives more weight to high streamflows than to low ones. However, it seems obvious that water withdrawal does change the daily streamflow variation during low flow periods. As the minimum flow standard increases, the maximum value of flow crossing increases up to 580% while the flow reversal slightly decreases to a maximum (over all FX) of 100% (see Figure 4). This is because the streamflow violates the standard more frequently at higher minimum flow standards,

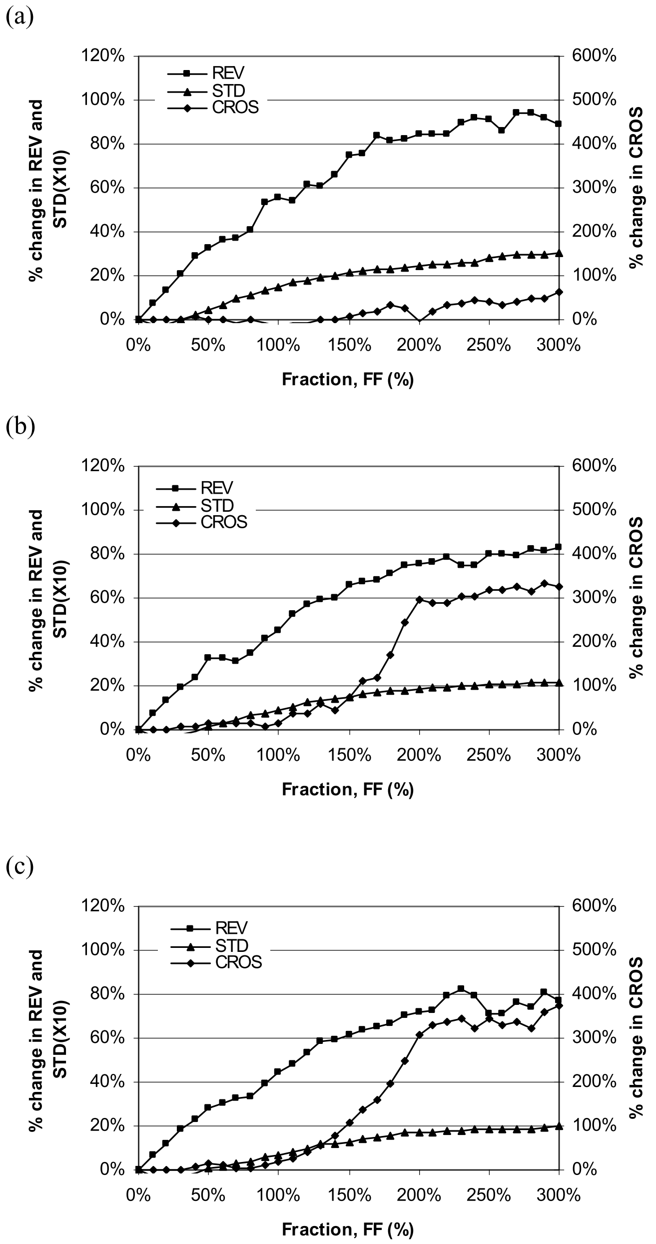

Figure 5. Percent change in streamflow variability indices (CROS, flow crossing; REV, flow reversal; STD, standard deviation) under the fractional flow permit program with change of maximum allowable fraction, FF, at varying levels of minimum streamflow standards.

but does not oscillate often at a lower level than the standard. Restricting the maximum fixed rate, FX, to values lower than 5 mm/day reduces the flow crossing and flow reversal to a certain extent, i.e., 360% and 67% with the minimum flow standard of 0.048 m^3/s (these values become higher at higher standards), but not to an insignificant level.

[28] Under the fractional flow withdrawal permit program, the streamflow is again shown to have a low standard deviation, less than 2~3%, regardless of the minimum flow standard or maximum fraction (see Figure 5). At the minimum flow standard of 0.048 m^3/s, increases in the flow crossing and flow reversal are observed as a maximum 63%, and 94%, respectively (see Figure 5a). Of particular note is that the maximum increase in flow crossing is much lower under the fractional flow than the fixed flow permit program. However, as the standard increases, the flow crossing is shown to suddenly increase with an inflection point at about FF = 120~180%. Apparently, severe flow variation is inevitable at high flow standards, especially under the over-allocated situation (FF higher than 100%). As with fixed flow permits, restricting the allocation parameter FF lower than 100% restricts the flow crossing to less than 20%, which represents a fairly low streamflow variability. Flow reversal is also controlled to less than 50% at FF lower than 100%.

[29] It would be beneficial if the streamflow variability could be controlled even with *FF* higher than 100%. Such over-allocation is not intended under the precepts of the program, but is physically possible and might be desirable in cases where the incremental economic benefit is large and environmental cost is small. In such a situation, streamflow fluctuation is hardly avoidable with the existing form of the fractional withdrawal permit system. In the next section, we simulate modifications of the existing fractional flow withdrawal program to ensure a better control of streamflow variability even under the over-allocated situation.

3.2. Streamflow Variability Under Modified Withdrawal Permit Programs

[30] In this section, we evaluate streamflow variability by the same set of criteria for cases where the permit programs are modified to reduce instability. These modifications are the process control methods introduced above.

3.2.1. First-Order Filter Control

[31] Under first-order filter control, the control parameter β has to be properly specified to achieve desired control performance. Since there is no analytic tuning method for the first-order filter, a trial and error approach is used. The maximum allowable fraction FF is set to vary from 100 to 300% in order to reflect overallocation, and the filter coefficient β is set to vary from zero to one. Figure 6 shows the percent change in the streamflow variability characterized by the flow crossing and flow reversal as a function of the filter coefficient β at given values of FF = 100%, 150%, 200%, and 300% for minimum flow standards of 0.048 m^3/s, 0.870 m^3/s, and 1.260 m^3/s. The standard deviation of the streamflow is not plotted because of its insensitivity to the water withdrawal allowed by both fixed and fractional programs, as noted in the previous section.

[32] For the minimum streamflow standard of 0.048 m^3/s (see Figure 6a), which is the lowest standard in this study, the flow crossing has the lowest value at β = 0 for FF = 100%, 0.05 or 0.35 for FF = 150%, 0 for FF = 200%, and 0.05 or 0.45 for FF = 300%. A zero value of β means no filtering action (see equations (3) and (4)), resulting in the exactly same withdrawal regulation as the original fractional flow permit. It seems that filtering action under first-order filter control does not reduce the streamflow variation as represented by flow crossing when the minimum flow standard is low. As the maximum fraction allocated to the users increases up to 300%, the minimum value of flow crossing is still found at a β value close to zero. The minimum value of flow reversal is found near β = 0.5~0.6 for FF higher than or equal to 150%, which is different from the value that minimizes flow crossing. It

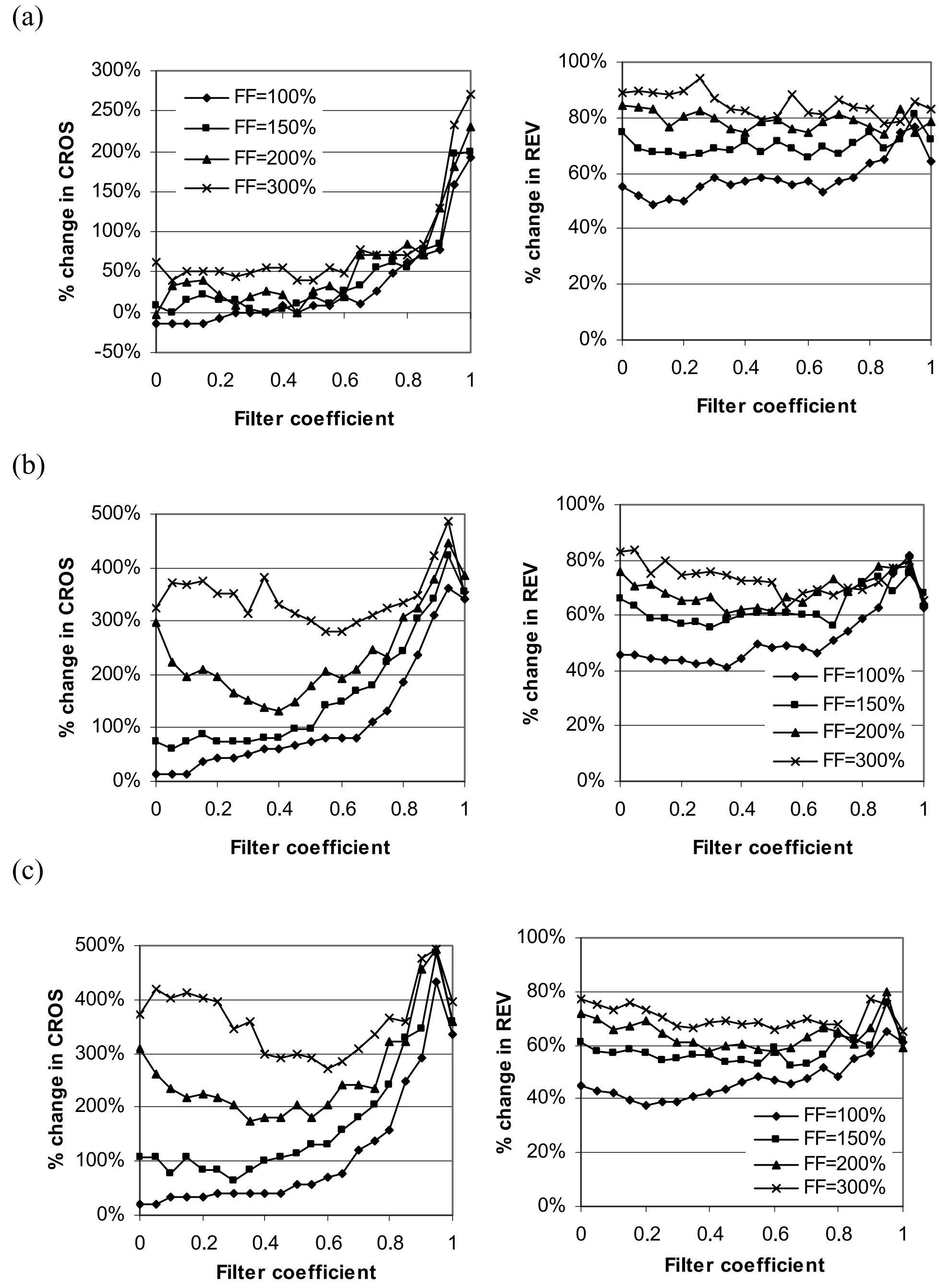

Figure 6. Percent change in flow crossing and reversal under the modified regulatory program based on the first-order filter control at varying filter coefficient.

also shows that the decrement in the flow reversal with such settings of β is not significant enough to justify adding first-order filter control to the fractional flow program. There is not much room for this additional filter to reduce streamflow variability at very low settings of the minimum flow standard.

[33] As the minimum streamflow standard increases, an increase in the ability of the first-order filter control to reduce the streamflow variation is observed. As shown in Figures 6b and 6c, for the minimum streamflow standards of 0.870 m^3/s and 1.260 m^3/s, the streamflow is found to fluctuate less for nonzero β, with significant reduction in the flow crossing and reversal, especially at FF values higher than about 200%. At a moderate level of overallocation, FF = 150%, the minimum value of flow crossing found at $\beta = 0.05$ is similar to the flow crossing value at $\beta = 0$ for the minimum flow standard of 0.870 m^3/s (see Figure 6b), indicating indifference between the simple fractional flow withdrawal program and the first-order filter withdrawal program in terms of streamflow variability. However, under the higher FF values of 200% and 300%, flow crossing is reduced significantly with the first-order filter at $\beta = 0.4$ and 0.6 for the low flow standard of 0.870 m^3/s, and 0.35 and 0.6 for the standard of 1.260 m^3/s (see Figures 6bc). This

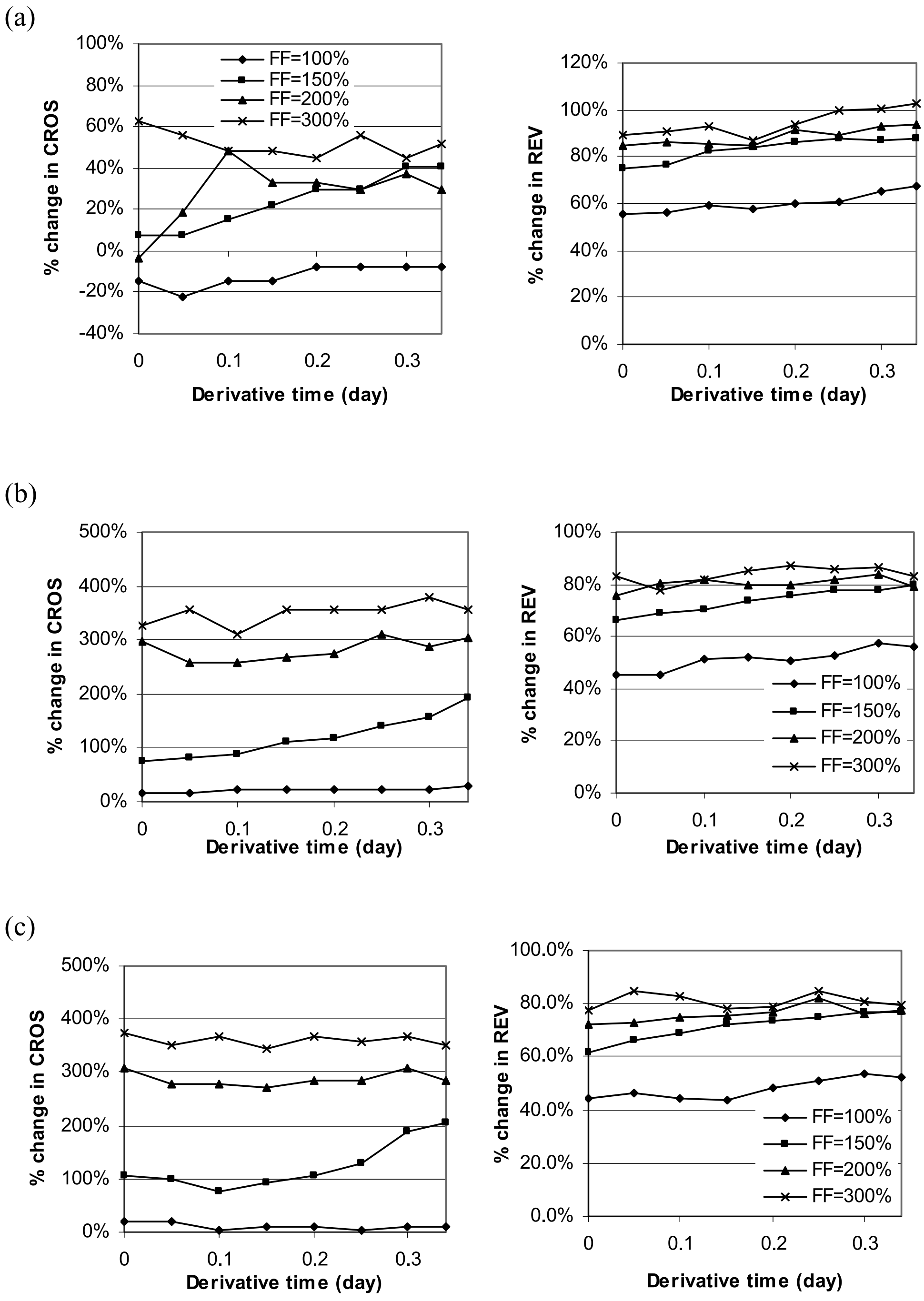

Figure 7. Percent change in flow crossing and reversal under the modified regulatory program based on the PID control at varying derivative times.

reduction in flow crossing varies from 50% to a maximum of 150%, indicating better performance in control of streamflow variability. For flow reversal, it is apparent that first-order filter control always helps reduce the streamflow variability by yielding minimum reversals at nonzero β; in fact, the same β values as the ones minimizing flow crossing also minimize flow reversal, particularly for FF = 200% or 300%.

[34] Incorporating information from recent streamflows into the decision of the current maximum allowable withdrawal (W_{it}) using first-order filtering seems to impart a smoothing effect on both withdrawals and streamflow, leading to less impact on streamflow variation, in comparison with a simple fractional flow approach.

3.2.2. PID Control

[35] According to the IMC tuning rule (see Table 1), which approximates the water withdrawal process with the FOPDT model, optimal τ_I and τ_D values are suggested as 10.35 and 0.34. On the basis of these values, we first conduct a simulation of the PID-control-based withdrawal program for the FF values tested for first-order filter control, i.e., 100%, 150%, 200%, and 300%. For τ_I ranging from 0.33 to 100 (1/30 to 10 times the suggested τ_I = 10.35), flow crossing and reversal are found to be rather large

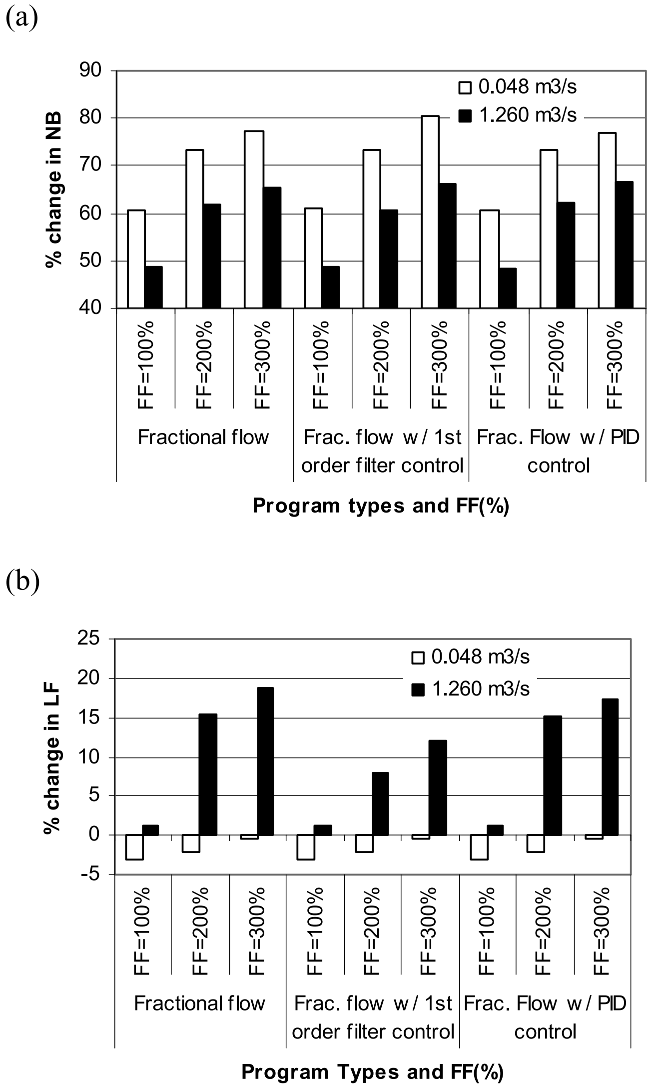

Figure 8. Percent change in net benefit (NB) and low flow frequency (LF) under the fractional flow and modified regulatory withdrawal programs.

compared to those under the simple fractional flow program. It seems that including the integral term in the calculation of maximum withdrawal allows W_{it} to be very large, resulting in the actual withdrawal not being controlled by the maximum withdrawal based on PID control. To keep W_{it} as a binding constraint on actual withdrawal, τ_I is set to infinity, resulting in the proportional and derivative terms alone being active.

[36] Figure 7 shows the percent change in streamflow variability characterized by flow crossing and flow reversal as a function of varying derivative time τ_D at constant FF values of 100%, 150%, 200%, and 300% for minimum flow standards of 0.048 m^3/s, 0.870 m^3/s, and 1.260 m^3/s. The value for τ_D is set to vary from 0 to a maximum of 0.34; values larger than that result in the derivative action reacting too sensitively to streamflow change.

[37] For the minimum streamflow standard of 0.048 m^3/s, which is the lowest in this study (see Figure 7a), flow crossing is found to have its lowest value at τ_D = 0.05 for FF = 100%, 0 for FF = 150%, 0 for FF = 200%, and 0.2 for FF = 300%. Because zero derivative time with an integral time of infinity means neither derivative nor integral actions are used in controlling withdrawal (see equation (6)), this result can be interpreted that PID control provides no better performance than the fractional flow program for the minimum streamflow standard of 0.048 m^3/s, except for FF = 300%. For the same standard, flow reversal is shown to increase with PID control for any given FF values, indicating that PID control does not improve variability by this measure under any circumstances.

[38] For the minimum flow standard of 0.870 m^3/s and 1.260 m^3/s, flow crossing is found to have its minimum value at a nonzero value of derivative time for most high FF values (Figure 7b and 7c). The reduction in flow crossing for such cases varies from 15% to a maximum of 40%. Reduction in the flow reversal is observed for FF values of 100% and 300%. However, reduction of streamflow variability as characterized by either flow crossing or reversal is not as significant as observed for first-order filter control. In fact, PID control is reduced to PD control by setting τ_I to infinity in equation (7), ultimately allowing withdrawal proportional to the maximum fraction of current available flow and the difference between the past and current streamflows, i.e., $ff \times (Q_t - Q_s + \tau_D(Q_t - Q_{t-1}))$ Despite its capability to incorporate process dynamics in specifying its control parameters through the FOPDT model approximation, PID control is not as effective in reducing streamflow variability, defined either by flow crossing or reversal, as the first-order filter. The results further suggest that the more sophisticated PID control involves unnecessary complexity and thus requires an unnecessarily greater tuning effort if all three actions are incorporated.

3.3. Comparison of Modified Withdrawal Programs to Simple Withdrawal Programs

[39] This section presents a comparison of the first-order filter, PID control programs, and the simple fractional flow withdrawal programs. The comparison is on the basis of net benefit and low flow frequency, the two most commonly considered objectives in water resources management. In this study, net benefit is defined as the collective water users' profit from crop production when water withdrawal is allowed according to the regulatory program. Low flow frequency is defined as the fraction of the time streamflow violates the minimum in-stream flow standard. For calculations of percent change, a zero withdrawal case is used as a basis. More details concerning this calculation are provided by *An and Eheart* [2004].

[40] Figure 8 shows percent change in net benefit (NB), and low flow frequency (LF) under each permit modification and FF level for the regulatory withdrawal programs for the minimum flow standards of 0.048 m^3/s and 1.260 m^3/s, the lowest and highest standards in this study. Net benefit and low flow frequency shown in Figure 8 correspond to the optimally chosen control parameter values (i.e., the value of the filter coefficient for the first-order filter control or derivative time for the PID control) that achieve minimum flow crossing or reversal at a given FF.

[41] It is shown that the modified programs, which are effective in reducing streamflow variability, are able to ensure the optimal level of net benefit and low flow frequency observed under the simple fractional flow program. In fact, at a high value of FF = 300%, net benefit

under the modification with the first-order filter is even higher than that under the simple fractional program, indicating the ability of the modified program in improving net benefit as well as stability (Figure 8a). Similarly, low flow frequency under both modifications is equal to or lower than those of the simple fractional flow program (Figure 8b).

[42] On the basis of these findings, we recommend water managers consider using the fractional flow withdrawal program alone for the normal situation where demands for withdrawal permits are less than or equal to available water. Adopting the modification of first-order filter control would be beneficial in cases where over allocation is inevitable.

4. Conclusions

[43] This paper has investigated potential streamflow variability problems that would attend withdrawal permit programs based on water sharing indexed to a downstream gauge. It is observed that some regulatory programs may cause or exacerbate severe fluctuations in daily streamflows, even while overall variation in the annual hydrograph as characterized by the standard deviation is insignificantly changed. To counteract this effect, process control techniques, i.e., the first-order filter and PID control, are introduced, and the modified regulatory programs that embed such techniques are evaluated through a modeling exercise on a typical watershed in a riparian state. These modified programs show successful control of streamflow variability, especially in an overallocated situation. The streamflow under the optimally tuned PID control demonstrates less variability than under the original fixed or fractional flow withdrawal programs at high FF, but improvements in variability by PID control are not as significant as those under the first-order filter control.

[44] Like those of any modeling exercise, the findings presented here are dependent on the data used. In this study, evaluation of the simple and modified regulatory programs is conducted for a relatively small watershed in central Illinois, but we believe that the general evaluation framework and findings are applicable to other watersheds where a regulated riparian water withdrawal permit program is considered. The key characteristic in extending these findings is the average time lag in the channel between changes in withdrawal by a user and those changes showing up as changes in the streamflow at the indexing gauge. Previous work [*An and Eheart*, 2004] showed that the fractional permit program has superior properties of withdrawal interruption and low flow frequency, with only a small sacrifice in economic efficiency compared to the fixed flow program. Thus the primary conclusions for agencies considering establishing water withdrawal permit programs, that seem to be robust to the alternative data sets considered here, are that (1) the fractional flow program generally achieves a better compromise among policy objectives than the fixed flow program, (2) if excessive streamflow oscillation caused by feedback loops is present, the first-order filter achieves more favorable performance than PID control, but that (3) neither modification is likely to be necessary in the absence of overallocation of fractional flow permits.

[45] Therefore we suggest that water managers operating under the authority of a law like the ASCE regulated riparian model water code adopt the fractional flow withdrawal program as a fundamental algorithm for allocation of permits for a “normal” situation, i.e., one in which low streamflow standards are rarely breached. They should then consider adoption of the first-order filter withdrawal algorithm for cases where overallocation or other factors are likely to result in excessive steamflow oscillation caused by feedback.

[46] Agencies that consider adopting such programs are advised to embark on an evaluation procedure similar to that demonstrated here, to determine the form of regulatory withdrawal program that achieves the most acceptable compromise of the water management goals. Current regulatory systems operated by state agencies, if they exist at all, are unlikely to have approached the level of complexity represented by a feedback control system. However, we expect that the additional levels of sophistication embodied in fractional flow permits or first-order filters will become attractive if the problems of streamflow oscillation discussed in this study are manifested. Undoubtedly, more discussions and mutual agreements among water managers, users, and researchers will be required prior to regulatory permit programs being implemented. We expect this study to open the door to such investigations and discussions.

Notation

A_i	riparian area of user *i*.
ff_i	maximum allowable fraction to each user *i*.
FF	maximum allowable fraction of streamflow at a reference gauge allocated in aggregate to all users upstream of that location.
FX_i	maximum allowable fixed rate of user *i*.
i	index of water user locations.
K	process gain.
K_c	proportional gain.
n	number of days over simulation period.
p	manipulated variable.
p_s	set point value of the manipulated variable.
Q_m	average mean flow.
Q_s	minimum flow standard.
Q_t	streamflow measured at a reference gauge at time *t*.
t	time.
W_{it}	withdrawal determined by permit program for user *i* at time *t*.
α	time delay.
β	filter coefficient.
ε	error signal.
ε'	first-order filtered signal.
τ	time constant.
τ_I	integral time constant.
τ_D	derivative time constant.

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