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Sensitivity Analysis of Environmental Flow Rule Curves for Water Allocation Optimization: Case Study, the Upper Oldman River Basin, Alberta, Canada

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Abstract: Water allocation models use a set of decision rule curves to define constraints and priorities for optimal allocation of limited water supply to all water demands and requirements at the river basin scale. These rules are necessary to achieve optimal tradeoff between different river basin management goals (e.g. environment protection, urban development, agricultural expansion). However, many operating rules need to be modified as water demands and river basin priorities change over time due to socio-political forces and climate change. In particular, environmental flow criteria are of major interest; they can raise challenges for resource allocation, and represent an important interface between societal values and operational policy.

In this research, a sensitivity analysis of alternate environmental flow rule curves (EFRCs) is examined for different hydrologic regimes. EFRCs are developed using hydrologic methods including flow duration curves, baseflow separation, and Tessman methods. The Water Resources Management Model (WRMM), developed by Alberta Environment, is used in this research. The Upper Oldman River Basin, one of the headwaters of the trans-boundary South Saskatchewan River Basin (SSRB) in western Canada, is used as a case study. The main objective of this research is to develop different EFRCs to understand their sensitivities to alternative future scenarios. All three operational EFRCs are compared using a group of performance criteria: reliability, resilience, and vulnerability. Results show that water allocation performance is very sensitive to the different EFRCs. The Q90 rule curves are superior to the other rules in several respects, and provide optimal trade-off between different water demands including environmental flow and junior irrigation sectors. However, further work is required to evaluate their ecological impact for practical application.

Keywords: Water allocation, environmental flow, reliability, resilience, vulnerability.

1 INTRODUCTION

A natural flow regime supports native river ecosystems and ecologies of flora and fauna (Poff et al. 1997). Growing water shortages have increased competition among sectors and communities, between upstream and downstream users, and between human needs and those of the environment. Development poses heavy
demands on water resources, which could negatively affect the environment by decreasing environmental flows and degrading the water quality of river systems. Optimization models have been used as planning tools in complex flow networks (Labadie, 2004). They require a set of decision rule curves to define constraints and priorities for optimal allocation of limited water supply to all water demands and requirements at the river basin scale. However, operating rules need to be modified as water demands and river basin priorities may change over time due to socio-political forces and climate change. Consequently the operational policies and decision rules for water allocation plans need to be adjusted to respond to particular situations. Additionally, climate and societal uncertainties require development of a range of decision rules for water resources planning. Some studies have been conducted to incorporate environmental flow rule curves (EFRCs) into water allocation modeling, but few studies have assessed the sensitivity of the EFRCs in different hydrologic regimes considering competitive water demand sectors (Vogel et al. 2007; Shiau and Wu 2010; Snelder et al. 2011). Vogel et al. (2007) examined relationships among reservoir storage, instream flow, and water-supply yield for a range of reservoirs and operating rules. Various operating policies were developed based on the storage-instream flow relationship. Shiau and Wu (2010) presented an approach to devising the optimal reservoir operation rules to manage off-stream water supplies and maximizing environmental benefits. Snelder et al. (2011) developed a method to assess environmental flow rules and their consequences for protection of the ecosystem. They showed that the minimum flow rules had variable consequences for habitat requirements and supply reliability. This research developed EFRCs for different hydrologic regimes in the Upper Oldman River Basin, one of the headwaters of the trans-boundary SSRB in Canada using WRMM optimization model, developed by Alberta Environment. The EFRCs are defined using hydrologic methods (Tharme 2003), including flow duration curve (FDC) (Vogel et al. 2007), baseflow separation (Caissie and El-Jabi 1995; Smakhtin 2001), and Tessman method (modified Tennant’s method) (Tessman 1980). Water allocation performance is compared using reliability, resilience and vulnerability criteria (Hashimoto et al. 1982). The main objective of this study is to evaluate different rule curves under varying hydrologic conditions. Results can be used to highlight trade-offs between different water-demand sectors under future climate change conditions, including extreme droughts and floods.

2 METHODS AND MATERIALS

2.1 Study Area

We used the Upper Oldman River Basin in southwest of Alberta, Canada for this study. The Oldman River originates in the Rocky Mountains, having a catchment area of 303 km² (Fig. 1). Snowmelt is the major source of river flow; rainfall events contribute additional water. The highest elevation of the basin is 3,300 m above sea level at its headwater and the lowest at the confluence with the Bow River is about 700 m. Average rainfall is less than 700 mm. The average annual discharge of the basin at Oldman River near Brocket is about 37 m³/s. The City of Lethbridge is a major source of municipal water demand in downstream reaches of the study area. As used by Alberta Environment for planning studies, a 73-year (1928-29 to 2000-01) historical streamflow sequence, precipitation, evaporation and water demands and requirements for different water uses in the basin are considered for this research.

Figure 1. Location of the Upper Oldman River Basin in Alberta, Canada.
2.2 Environmental Flow Assessment

The environmental flow requirement for a river is defined simply as an estimate of how much of a river’s natural flow regime must be preserved to maintain ecosystem health (Poff et al. 1997; Tharme 2003). In this research, three hydrologic environmental flow assessment methods are used to develop EFRCs for the WRMM optimization model. As Tharme (2003) reported, hydrologic methods are a widely used approach for environmental flow assessment in many countries. For example, 10% and 2.5-5% mean annual riverflow (MAR) is used to set environmental flow in Spain and Portugal, respectively. Locke and Paul (2011) developed a desktop method to estimate environmental flow in Alberta, Canada, based on the greater of either a 15% reduction from natural flow or the 80% exceedance natural flow. They recommended this method where site specific instream flow data are not available. Various exceedence percentiles derived from flow duration curve (FDC) analysis often used as minimum flow recommendation include Q95 in the UK, Bulgaria, Taiwan and Australia; Q90 in Canada, Brazil and the UK (Tharme 2003). The FDC is an expression of frequency of occurrence, which is constructed from gauged river flow data. Flows are ranked by size and plotted as a function of exceedence probability. Various exceedence percentiles display the relationship between discharge and the percentage of time that it is equaled or exceeded. Commonly the Q90 index (the flow that is equaled or exceeded for 90% of the time) is used as a minimum flow recommendation in this research. Monthly FDCs are developed, as annual indices mask the impact of seasonal variability of streamflow (Vogel et al 2007). It enables us to incorporate some aspects of streamflow timing into rule curves. A recursive digital filter method, as an automated baseflow identification technique is used to extract long-term average weekly baseflow as an environmental flow threshold. Baseflow is used as indicator of sustainable minimum flow to protect ecosystem (Smakhtin 2001). A recursive digital filter with the parameter value of 0.925 is used to separate baseflow from total river flow, following the suggestions of previous studies (Nathan and McMahon 1990; Arnold and Allen 1999; Ghanbarpour et al. 2008). Monthly environmental flow using the Tessman method is calculated based on an evaluation of the MAR and mean monthly riverflow (MMR) (Table 1) (Tessman 1980). Monthly flows are then transformed into weekly flows to be used in WRMM optimization.

<table>
<thead>
<tr>
<th>Riverflow conditions</th>
<th>Monthly environmental flow</th>
</tr>
</thead>
<tbody>
<tr>
<td>MMR &lt; 0.4 MAR</td>
<td>MMR</td>
</tr>
<tr>
<td>MMR &gt; 0.4 MAR and MMR &lt; 0.4 MAR</td>
<td>0.4 MAR</td>
</tr>
<tr>
<td>0.4 MMR &gt; 0.4 MAR</td>
<td>0.4 MMR</td>
</tr>
</tbody>
</table>

2.3 Water Allocation Optimization

Alberta Environment uses a network flow optimization technique for water allocation and reservoir simulation to allocate water supply to the water users and requirements. (AENV 2002; Ilich et al. 2000) The WRMM is a steady state, surface water allocation optimization model. It optimizes allocation of water resources over a set of time intervals, considering the physical setting of the water distribution system, water supply and demands, operational policy rule curves, and penalty functions. Water allocation priorities are defined by penalty functions (costs) and the objective function expressed in minimum cost network flow using a linear programming form can be defined as:

\[
\text{Maximize } \sum_{(i,j) \in A} C_{ij} X_{ij} \quad \forall i, j \in N
\]

where \(X_{ij}\) and \(C_{ij}\) are flow and penalty value per unit of flow along an arc \((i,j)\), respectively in arcs \(A\) and a total of \(N\) nodes. The aim of a minimum cost flow is to
maximize supply to all users according to their priorities. Alternative operational policies and decision rule curves could be accommodated in WRMM optimization model. Then frequency, duration, and magnitude of water deficit from optimization results could be assessed using three performance evaluation criteria: reliability, resilience, and vulnerability (Hashimoto et al. 1982). Reliability is the probability of supply deficit in water allocation system. This criterion is calculated as the number of time intervals (weeks) with satisfied demand divided by the total number of time intervals in the simulation. Reliability varies from 0 (100% probability of deficit) to 1 (no risk of deficit). Resilience is defined as the probability of satisfactory state after a deficit has occurred. This measure shows how quickly the water allocation system recovers from deficit. Resilience is mathematically defined as the frequency of consecutive time intervals that allocation failed to meet water demand over total duration of failures. It varies from more than 0 to 1. When resilience is equal to 1, system is fully resilient; no more than one deficit occurs (McMahon et al. 2006). Vulnerability shows the significance of the supply deficit to the system and varies from 0 to 1. It is operationally defined as the fraction of demand that cannot be met with available supplies.

3 RESULTS AND DISCUSSIONS

Three hydrologic methods were used to define environmental flow threshold and construct EFRCs for headwater river reaches of the Upper Oldman River Basin in the SSRB (Fig. 1). First, FDC Q90 rule curves are developed based on observed 90% exceedance natural flow in three reaches upstream of Oldman Reservoir (Fig. 1). Figure 2 shows three sample FDCs extracted in the reach 1. Q90 values for January, May and August are 1.53, 11, 4.59 m$^3$/s, respectively (Fig 2). Second, the average baseflow (ABF) rule curves are developed based on long-term average baseflow, extracted using recursive digital filter with the parameter value of 0.925. Figure 3 shows base flow separation for two sample water years in the reach 1. The third type of EFRCs are developed using Tessman method (Table 1).

![Figure 2. Monthly FDCs to determine Q90 in the reach 1.](image-url)

![Figure 3. Baseflow separation using recursive digital filter in the reach 1.](image-url)
Three different EFRCs in Figures 4 show observed river flow in a wet (1974) and a dry (1983) year. The Q90 rule would be in deficit in early high flow season in a dry year (Week 17 through Week 19). The ABF rule curve shows large water deficit during dry year and low flow seasons (Fig. 4). As a result, more supply deficit could be expected for other competitive water demand sectors like junior irrigation in downstream. The ABF rule curve could be expected to be more efficient during wet years and high flow seasons, especially for supporting instream flow needs. However, the Q90 rule curve could release supply to the other water demand sectors more efficiently including senior and junior irrigation sectors, especially during low flow seasons. A few weeks' supply deficit also could be seen in the early high flow season, considering the Tessman rule (Fig 4). As a result, the Tessman rule provides more instream flow than Q90, and less than ABF. The WRMM optimization modeling results were examined considering three EFRCs and three simulation periods including 73 years of record between 1926 and 2000, a wet year in 1974, and a dry year in 1983 (Table 2).

![Figure 4. EFRCs and observed river flow in two wet and dry years in the reach 1.](image-url)
Table 2 shows network performance based on reliability, resilience, and vulnerability criteria. Water allocation performance in all water demand sectors is very sensitive to the different EFRCs. A particular water demand sector with a higher penalty function will be satisfied first (Ilich 2009). Therefore, performances of the municipal and senior irrigation sectors are similar in a particular simulation time horizon because they have higher penalty functions than other sectors. For example, reliability of the senior irrigation sector, considering three different EFRCs, is equal (0.89) in 73 years simulation period (Table 2). On the other hand, there are substantial changes in performance criteria for junior irrigators and environmental flows, as they have lower penalty functions. Supply deficit first occurs in the sectors with lower penalty functions (AENV 2002; Ilich 2009).

Table 2. Comparison of EFRCs using reliability, resilience and vulnerability criteria.

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Water demand sectors</th>
<th>Q90</th>
<th>ABF</th>
<th>Tessman</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>(1)</td>
<td>(2)</td>
<td>(3)</td>
</tr>
<tr>
<td>Reliability</td>
<td>Municipal &amp; industry</td>
<td>0.64</td>
<td>0.64</td>
<td>0.49</td>
</tr>
<tr>
<td></td>
<td>Senior Irrigation</td>
<td>0.89</td>
<td>1</td>
<td>0.97</td>
</tr>
<tr>
<td></td>
<td>Junior Irrigation</td>
<td>0.71</td>
<td>0.98</td>
<td>0.90</td>
</tr>
<tr>
<td></td>
<td>Environmental flow</td>
<td>0.88</td>
<td>0.92</td>
<td>0.85</td>
</tr>
<tr>
<td></td>
<td>All sectors</td>
<td>0.78</td>
<td>0.88</td>
<td>0.80</td>
</tr>
<tr>
<td>Resilience</td>
<td>Municipal &amp; industry</td>
<td>0.13</td>
<td>0.17</td>
<td>0.16</td>
</tr>
<tr>
<td></td>
<td>Senior Irrigation</td>
<td>0.20</td>
<td>1</td>
<td>0.75</td>
</tr>
<tr>
<td></td>
<td>Junior Irrigation</td>
<td>0.16</td>
<td>0.84</td>
<td>0.27</td>
</tr>
<tr>
<td></td>
<td>Environmental flow</td>
<td>0.36</td>
<td>0.59</td>
<td>0.59</td>
</tr>
<tr>
<td></td>
<td>All sectors</td>
<td>0.21</td>
<td>0.65</td>
<td>0.44</td>
</tr>
<tr>
<td>Vulnerability</td>
<td>Municipal &amp; industry</td>
<td>0.34</td>
<td>0.33</td>
<td>0.46</td>
</tr>
<tr>
<td></td>
<td>Senior Irrigation</td>
<td>0.12</td>
<td>0</td>
<td>0.08</td>
</tr>
<tr>
<td></td>
<td>Junior Irrigation</td>
<td>0.32</td>
<td>0.04</td>
<td>0.28</td>
</tr>
<tr>
<td></td>
<td>Environmental flow</td>
<td>0.02</td>
<td>0.01</td>
<td>0.02</td>
</tr>
<tr>
<td></td>
<td>All sectors</td>
<td>0.20</td>
<td>0.09</td>
<td>0.21</td>
</tr>
</tbody>
</table>

(1) 73 years simulation, (2) wet year of 1974, and (3) dry year of 1983

The results have shown that the Q90 ENFRCs are superior to other rules, in terms of reliability, resilience, and vulnerability (Table 2). The Q90 rule curves increased the performance of the flow network in wet and dry years, and over the whole 73 years simulation, in terms of reliability, resilience, and vulnerability. The Q90 provides less instream flow release and more allocated supply for water consumption in other sectors such as junior and senior irrigation sectors than other two competitive EFRCs. Although, Q90 rules were improved water allocation performance in different water demand sectors, but their efficiency regarding ecological effects on the aquatic environments need to be investigated. To show a better picture of consequence of different EFRCs, a trade-off analysis between different sectors and different performance criteria was conducted. Figure 5 shows some examples of trade-offs analysis. The Q90 rules show the highest level of reliability in junior irrigation and environmental flow sectors during a dry and wet year simulations (Fig. 5 (A) and (B)). The Tessman rules are very competitive with Q90, in terms of junior irrigation reliability. However, the Tessman rules are not optimal considering environmental flow reliability. The ABF rules are least preferred EFRCs in both wet and dry year simulations, in terms of reliability. As a result, Q90 rule curve can provide an optimal trade-offs between junior irrigation and environmental flow sectors, in terms of reliability, resilience, and vulnerability, as
junior irrigation and environmental flow are two competitive water demands sectors in this river basin (Table 2 and Fig. 5). In other word, Q90 rules provide a win-win operational policy for water allocation practice in study area. Comparison between environmental flow vulnerability and resilience is shown in Figure 5, to show a possible trade-offs analysis between different performance criteria within one particular water demand sector. The Q90 rules have shown the highest resilience and the lowest vulnerability in comparison with other two EFRCs in dry year in 1983 (Fig. 5 (C)).

Figure 5. Comparison of EFRCs using trade-offs between reliability, resilience, and vulnerability for junior irrigation and environmental flow sectors. (A) and (C) Dry year in 1983; (B) Wet year in 1974.

4 CONCLUSIONS

River regulation and increasing irrigation and municipal water demands could have adverse consequences for aquatic ecology. Such changes can lead to significant loss of fisheries, decline in vegetation cover, and environmental degradation, especially during low flow hydrologic regimes. Different EFRCs have variable consequences, in terms of water allocation performance and ecosystem health (Snelder et al 2011). This research has shown that three different EFRCs could affect reliability, resilience, and vulnerability of water allocation system under different climatic conditions. Developing a variety of decision rule curves and incorporating them into WRMM optimization technique could facilitate a study of the trade-offs between competitive water demand sectors at the river basin scale. It was shown here that the Q90 rule curves could improve allocation performance of the flow network. The Q90 rule curves points to a potential trade-offs between environmental flows and junior irrigation water demands. The Q90 rules may be useful for drought management, as they provide minimum environmental flows to the natural river while maintaining water for senior and junior irrigation water demands. However, their efficiency in terms of possible effects on the aquatic environments should be evaluated using ecologic-based approaches (Poff et al. 2009). This research has shown that water allocation performance is very sensitive to the different EFRCs. Application of a particular EFRC requires policy and science to balance human water demands and ecosystem water requirements. In fact, the definition and application of environmental flow is a major constraint for water allocation practice. Therefore, incorporating optimal EFRCs into water allocation models can be conducted based on an adaptive management approach (Richter et al. 2006), as environmental flow target levels reflect societal values and choices, in addition to the ecosystem health.

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REFERENCES


