Measuring impact of water management on ecological health of a river: Poudre River, Colorado, USA

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Abstract The Cache la Poudre River (Poudre River) has its upper watershed in the Rocky Mountains and its lower watershed in the transition zone between the mountains and the Great Plains to the east. The river flows through the City of Fort Collins where it is a significant riverine attribute. Streamflows in the Poudre River have been greatly modified by diversions to the river and from the river, and by storage reservoirs. Analysis of the ecological health of a river should start by creating an understanding of the links between the physical habitat and the streamflows and use this understanding to develop functions that transform the streamflows to an annual index that can be used to better understand how hydrological changes impact factors limiting the aquatic ecosystem. Indices considered here include: (1) changes in the river's capacity to maintain the river channel, (2) changes in flashiness of the river during the winter, (3) percent of annual flow required to remain in the river to significantly increase the health of the river, and (4) unnaturally high flows in October attributable to water accounting.

Key words rivers; water management; channel maintenance; hydraulic alteration; riverine ecological health; aquatic ecosystems; Cache la Poudre River

INTRODUCTION

The primary objective of this paper is to demonstrate how a riverine system analyst can formulate indices tailored to capture linkages between important parameters of the riverine ecosystem and the streamflows. The secondary objective is to present information on water management issues related to environmental flows in the Cache la Poudre River. Impacts of the water management on the streamflows in the Cache la Poudre River from the viewpoint of aquatic habitat concerns are used as an example of the process of developing the indices. A previous paper, Milhous & Bartholow (2010), presented a number of environmental flow issues associated with management of the water resources. Presented here is additional information on water management concerns associated with environmental flow needs.

The Cache la Poudre River (Poudre River) is in the Front Range area of Colorado, USA. The river has its upper watershed in the Rocky Mountains and its lower watershed in the transition zone between the mountains and the Great Plains to the east, and is a tributary of the South Platte River. Streamflows in the Poudre River have been significantly modified by diversions to the river and from the river, and by storage reservoirs. Water is diverted into the Poudre River watershed from adjacent watersheds in the upper basin and through Horsetooth Reservoir. Most water imported is from the Colorado River Basin. The water stored in Horsetooth Reservoir enters the Poudre River below a canyon just above the transition zone. Measured streamflows from two gauges are used in this paper. One is at the mouth of Poudre Canyon and the second is in the city of Fort Collins, Colorado. There are many diversions between the canyon mouth and Fort Collins. For additional information on the river see Bartholow (2010) and Milhous & Bartholow (2010). Maps of the river in the Fort Collins reach are in both of these papers.

An analysis of the ecological health of a river should start by creating links between the riverine ecosystem and the streamflows and use these links to develop functions that transform the streamflows to an annual index that shows the riverine impacts of hydrological changes. Classes of indices include indices that: (1) characterize the watershed and the streamflows, (2) characterize the movement of sediment and the maintenance of the channel, and (3) represent important aspects of the riverine habitat. Each of these three classes is discussed in the following sections.

Three time periods are used to investigate changes in streamflows on the riverine system of the Poudre River. The three periods are defined by the years a major reservoir was completed in the watershed. The first period is from 1885 through 1910 and ends with the completion of

Halligan Reservoir on the North Fork of the Poudre River in 1910. The second is from 1911 to 1943 and ends when Milton H Seaman Reservoir, also on the North Fork, was completed. The third period is from 1944 to 2012. The accounting year is from November to October.

CLASS 1. CHARACTERISTICS OF WATERSHED AND STREAMFLOWS

The Poudre watershed above the mouth of Poudre Canyon has three zones: an upper zone from about 3400 m to 2400 m where snow accumulates during the winter and spring runoff originates. The second zone is between 2400 m and 1500 m where there may be snow-melt in early spring but not always. The second zone is the zone where the water causing major floods may originate because of major rain-runoff events. (The largest was between 425 and 570 m^3/s and occurred on 20 May 1904.) The parameters used to characterize the streamflows were calculated using daily discharges and were selected to show how the streamflows vary and to characterize the size of the river. The skewness parameter is the difference between the mean and median divided by the median. The use of the 25 and 75 percentiles to characterize annual streamflows is based on discussions in Richter *et al*. (1997).

Table 1 Annual parameters that characterize streamflows in the Cache la Poudre River, Colorado for three periods separated by the time of construction of a major reservoir in the basin.

Annual parameter	1885–1908	1911–1942	1943–2012
Median daily discharge, m^3/s	3.43	2.55	1.87
Mean daily discharge, m^3/s	11.92	11.25	9.04
Maximum daily discharge, m^3/s	144.42	213.79	169.05
Minimum daily discharge, m^3/s	0.85	0.09	0.05
Coefficient of variation	1.55	1.72	1.77
Skewness	2.48	3.42	3.84
25.0 percentile discharge, m^3/s	11.50	11.67	9.03
75.0 percentile discharge, m^3/s	2.15	1.25	0.93

CLASS 2. CAPACITY OF RIVER TO MAINTAIN ITS CHANNEL AND TO FLUSH SEDIMENT

The ecological health of a river is related to the characteristics of the river channel. An important consideration is the streamflow needed to maintain the channel and transport sediment through the channel. Only the streamflows needed to maintain the channel are considered here. A Channel Maintenance Capacity Index has been developed. The equation for the index is:

$$CMCI = \sum_{i=1,n} (Q_d(i)/Q_r)^{\beta} \text{ when } Q_d(i) > Q_{crit} \quad (1)$$

where Q_d is the daily discharge, Q_{crit} a critical discharge and Q_r a reference discharge. The summation is over the number of days Q_d is greater than Q_{crit}. The value of Q_{crit} is determined based on the shear stress required to move or disturb the bed material. The form of the equation is based on a relevant sediment transport equation. Other forms have been used in the analysis of different rivers.

Streamflows that initialize substrate movement have a dimensionless shear stress (β) of 0.021 (discharge of 50.1 m^3/s in the Poudre River) and for general movement of the substrate β is 0.035 (147.3 m^3/s); for details, see Milhous (2009). An example of the usual approach to determining streamflows for maintaining the stream channel is from Poff & Ward (1989). They accept the assumption that bankfull discharge is the “formative channel-modifying discharge” that causes significant substrate movement. They also concluded the effective discharge for moving substrate is generally less than or equal to bankfull discharge and a conservative estimate of bankfull discharge is the annual maximum daily discharge with a return period of 1 in 2 years. The annual maximum daily streamflow in the Poudre River with a return period of 1 in 2 years is 72.6 m^3/s (β = 0.024). The implied assumption in Poff and Ward is that only the "effective" discharge is important. In reality, all discharges are important and this concept is captured by the channel maintenance capacity index. The results of an analysis of channel maintenance capacity using equation (1) are presented in Fig. 1.

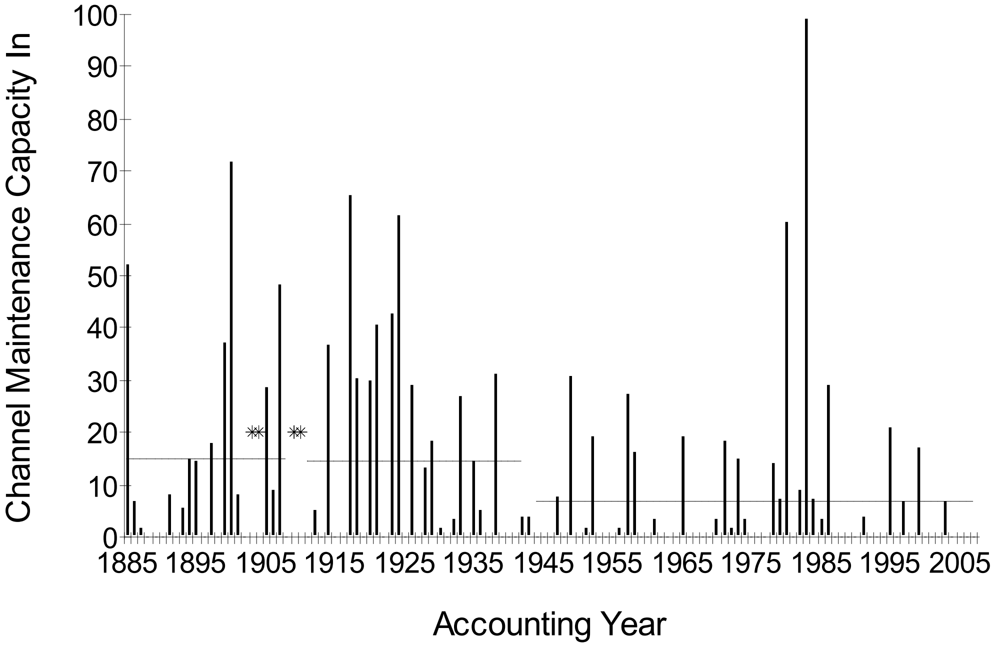

Fig. 1 Channel maintenance capacity index for each year. The solid lines are the averages for the three periods defined by construction of major reservoirs in the watershed. The * indicates a year with out data. The horizontal lines are the average for the period with the line.

CLASS 3. LINKING STREAMFLOWS AND THE RIVERINE ECOSYSTEM

In this section, three indices are presented based on links between daily streamflows and important components of the riverine ecosystem of the Poudre River. Others links are possible, some of these are presented in Milhous & Bartholow (2010). The development of the indices should be specific to the environmental flow issues and river being investigated.

Winter Richards-Baker Index

The Richards-Baker Index (R-BI) (Baker, 2004), is an index to changes in the streamflow and rate-of-change of the streamflows (flashiness). An increase in flashiness in a river could have a significant impact on organisms adapted to more stable high- or low-flow periods. The equation for the Richards-Baker Index (R-BI) for a year is:

$$R - BI = \sum_{i=2,n} abs[Q_d(i) - Q_d(i-1)] \Big/ \sum_{i=1,n} Q_d(i) \tag{2}$$

where $Q_d(i)$ is the daily discharge on day i, and n is the number of days in the period. The *R-BI* for the winter (December–March) at the mouth of Poudre Canyon is shown in Fig. 2. The average for the first period is not shown because of the quality of the winter data. Another index to flashiness (TQmean) has been applied in the analysis of environmental flows for the Poudre River and is presented in Milhous & Bartholow (2010).

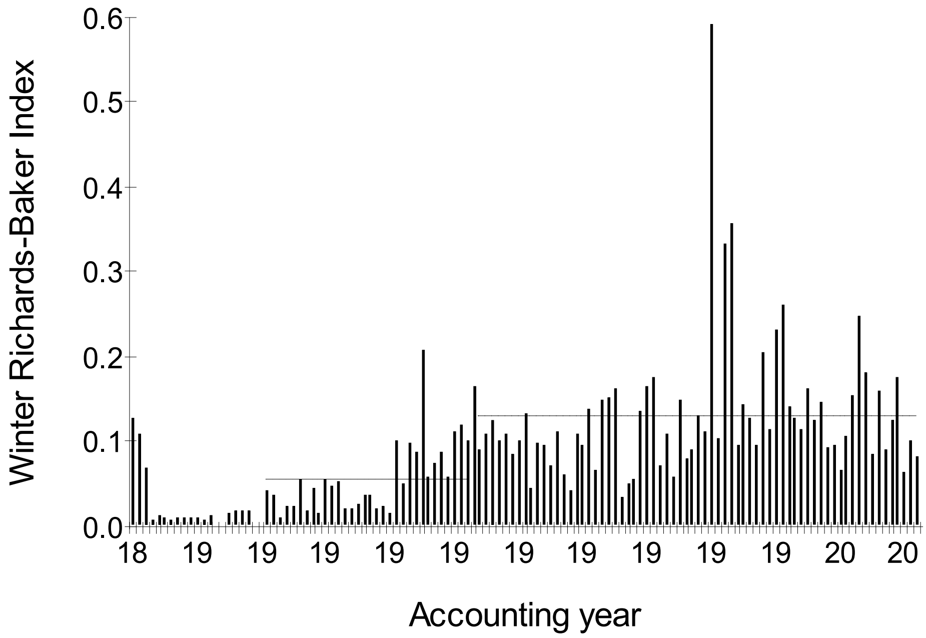

Fig. 2 Winter Richards-Baker Index for the Poudre River at the mouth of Poudre Canyon. The horizontal lines are the averages for the three periods defined by construction of major reservoirs in the watershed.

Water Deficiency Index

Low flows are considered to be a limit on the quality of the Poudre River aquatic ecosystem. An index, the Water Deficiency Index (*WDI*) has been developed to give water managers information on the quantity of additional water that may be required in rivers in order to make the river healthy. The equation for the index *WDI* is:

$$WDI = \sum_{i=1,n} (Q_d(i) - Q_l)/Q_r \quad \text{when } Q_d(i) < Q_l \tag{3}$$

where Q_d is the daily discharge, Q_l is a limit based on habitat considerations, and Q_r is a reference discharge. An application of the index to determine the water needed to meet the aquatic needs in the Fort Collins reach of the Poudre River is presented here (Fig. 3). The assumption made is that the aquatic needs will be met if daily streamflows at the Fort Collins gauge are equal to, or larger than, the annual minimum 7-day discharge exceeded in 9 out of 10 years (0.28 m^3/s) at the mouth of Poudre Canyon. Using the mean annual discharge at the canyon mouth as the reference discharge means that *WDI* is the percent of annual discharge that would need to be left (i.e. not diverted) in the river to meet aquatic ecosystem needs.

High streamflows in October attributable to water accounting

Starting in 2004 there was a change in water management of the Poudre River. The Northern Colorado Water Conservation District (Northern Water) started releasing water from Horsetooth Reservoir in the last month of the accounting year (October). The water flowed down the Poudre River to the South Platte River and was diverted to off-river reservoirs. Some of the habitat impacts of this change in water management have been presented in Milhous & Bartholow (2010). The release from one reservoir to another is made for water accounting purposes (from the account of Northern Water to the account of some other organization). The impact of this water management change is investigated by looking at the time pattern of changes in the 7-day maximum streamflows in the 16 September–31 October period as compared to the 7-day minimum streamflows for the same period. The purpose of this comparison is to show that important changes in streamflows can be used to identify the link between habitat and streamflows. Brown trout

(*Salmo trutta*) are an important fish species in the Poudre River. Brown trout spawn in the autumn and rapid changes in streamflows are considered to be detrimental to spawning. The range between the maximum and minimum 7-day streamflows, as compared to the base flow (the 7-day minimum), gives some idea as to the stability of the spawning streamflows. Figure 4 demonstrates the significant change in the range of streamflows in some years (e.g. 2004) compared to previous years and suggests the next step in deciding the best water management practice would be to investigate the spawning habitat changes. Some information on the habitat changes is given in Milhous & Bartholow (2010).

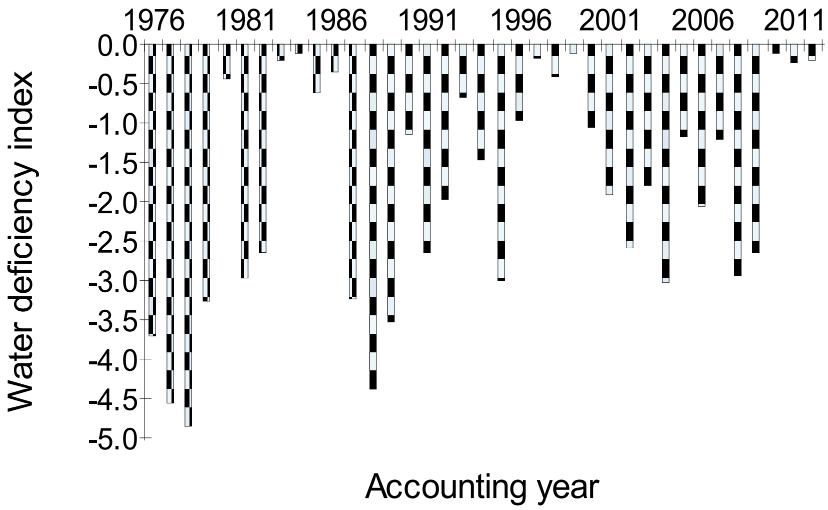

Fig. 3 Water deficiency index for the Fort Collins reach of the Poudre River calculated using data for the Fort Collins gauge.

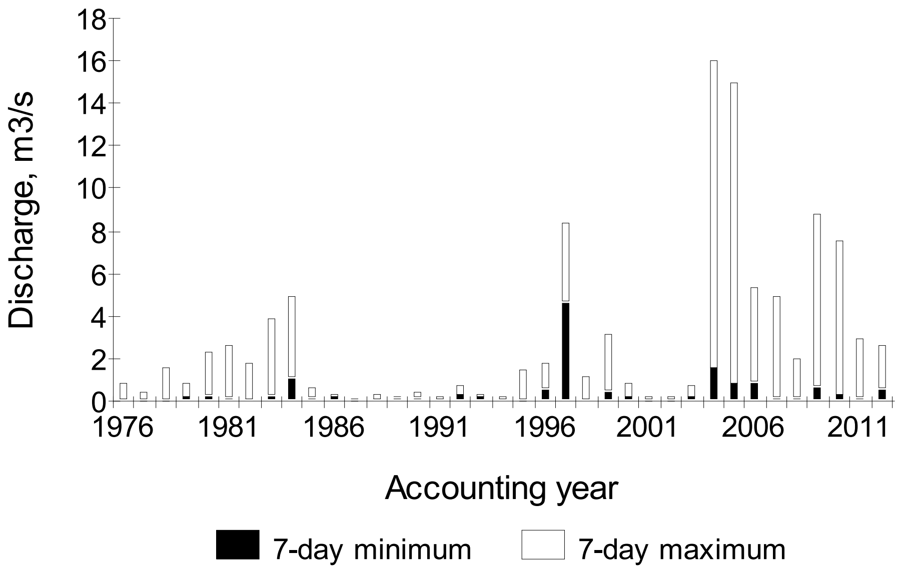

Fig. 4 Changes in the 7-day maximum discharge as compared to the 7-day minimum discharge for 16 September–31 October.

DISCUSSION

In this paper the primary objective is to show that indices are important in evaluating the impact of water management on ecological health of a river and can be created by linking habitat and streamflow. Three classes of indices and four examples were presented.

The first class is a set of characteristics of the streamflow in the river that are important in understanding the river. It is important to determine these characteristics but they should not be the main focus of streamflow analysis as an element of river ecological health evaluations.

The second class is the evaluation of the sedimentation characteristics of the river. An evaluation of channel maintenance should be an element in all river health studies. The example presented was one of channel maintenance – other studies could include an evaluation of the streamflows needed to flush fine sediment, scour encroaching vegetation, and transport of slugs of sediment that may be transported to the river by tributaries.

The third class is a set of indices that link physical habitat considerations to the streamflows. Three examples were presented. Many others are possible and the number is only limited by knowledge of the riverine ecosystem. The link in the first example, the Richards-Baker Index to flashiness, comes from the knowledge that rapid changes in streamflows can have negative impacts on the ecological health of the river. The link in the second is that low flows can limit the aquatic ecosystem and a water manager needs to know the quantity of water required to make the river healthy. The third example is from knowledge that excessively high flows during the spawning period of some fish may limit spawning success for some important fish species.

This paper illustrates the use of streamflow data for water management when we think in terms of aquatic habitat objectives. In many cases an analysis should not stop with just the streamflow–habitat links (of the type illustrated in this paper) but proceed with a true habitat analysis with as much information on the biology as possible. This paper demonstrates that it is possible to determine changes in riverine health with just streamflow data and that this information can help in water management. The two important ideas are: firstly, think about the maintenance of the channel; and secondly, think about how the streamflow conditions limit the health of the riverine ecosystem.

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