Table of Contents **Page**

Objective

- ➢ To show that a pattern of careful selection has been used to produce diversion results from what appears to have been a predetermined outcome

- To show that current proposed solutions will offer little to zero long-term benefits, and that their actual environmental beneficial effects are over exaggerated

- That the main environmental issues in LRC are not being properly addressed

- That creating instream wetlands using native beavers or manmade beaver dam analogues will provide a more common-sense approach and offer better overall environmental benefits and should be an option for irrigators

- To use **Mainstream Environmental Science**
  (All documentation will be referenced and available online)

Topics of Discussion

- The natural flow regime
- Diversion numbers from the model
- Flow meter study
- Analysis from DNR Fisheries Department
- Effectiveness of proposed solutions (short-term verses long-term benefits)
- Minnesota Nutrient Reduction Strategy and pollution concerns
- Creation of instream wetlands with beavers and beaver dam analogues
- Physical Habitat Simulation Study
- Aquifer recharge analysis
- Trout and the law of unintended consequences
- Peer review from Dr. Gary Johnson
- Carbon footprint with importing water
- Fact check analysis

The Natural Flow Regime

A paradigm for river conservation and restoration

N. LeRoy Poff, J. David Allan, Mark B. Bain, James R. Karr, Karen L. Prestegaard, Brian D. Richter, Richard E. Sparks, and Julie C. Stromberg

Humans have long been fascinated by the dynamism of free-flowing waters. Yet we have expended great effort to tame rivers for transportation, water supply, flood control, agriculture, and power generation. It is now recognized that harnessing of streams and rivers comes at great cost: Many rivers no longer support socially valued native species or sustain healthy ecosystems that provide important goods and services (Naiman et al. 1995, NRC 1992).

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The ecological integrity of river ecosystems depends on their natural dynamic character

The extensive ecological degradation and loss of biological diversity resulting from river exploitation is eliciting widespread concern for conservation and restoration of healthy river ecosystems among scientists and the lay public alike (Allan and Flecker 1993, Hughes and Noss 1992, Karr et al. 1985, TNC 1996, Williams et al. 1996). Extirpation of species, closures of fisheries, groundwater depletion, declines in water quality and availability, and more frequent and intense flooding are increasingly recognized as consequences of current river management and development policies (Abramovitz 1996, Collier et al. 1996, Naiman et al. 1995). The broad social support in the United States for the Endangered Species Act, the recognition of the intrinsic value of noncommercial native species, and the proliferation of watershed councils and riverwatch teams are evidence of society's interest in maintaining the ecological integrity and self-sustaining productivity of free-flowing river systems.

Society's ability to maintain and restore the integrity of river ecosystems requires that conservation and management actions be firmly grounded in scientific understanding. However, current management approaches often fail to recognize the fundamental scientific principle that the integrity of flowing water systems depends largely on their natural dynamic character; as a result, these methods frequently prevent successful river conservation or restoration. Streamflow quantity and timing are critical components of water supply, water quality, and the ecological integrity of river systems. Indeed, streamflow, which is strongly correlated with many critical physicochemical characteristics of rivers, such as water temperature, channel geomorphology, and habitat diversity, can be considered a "master variable" that limits the distribution and abundance of riverine species (Power et al. 1995, Resh et al. 1988) and regulates the ecological integrity of flowing water systems (Figure 1). Until recently, however, the importance of natural streamflow variability in maintaining healthy aquatic ecosystems has been virtually ignored in a management context.

Historically, the "protection" of river ecosystems has been limited in scope, emphasizing water quality and only one aspect of water quantity: minimum flow. Water resources management has also suffered from the often incongruent perspectives and fragmented responsibility of agencies (for example, the US Army Corps of Engineers and Bureau of Reclamation are responsible for water supply and flood control, the US Environmental Protection Agency and state environmental agencies for water quality, and the US Fish &

Ecological Significance of Natural Flow Regimes

The natural flow paradigm springs from an understanding that aquatic and riparian organisms depend upon, or can tolerate, a range of flow conditions specific to each species. For example, certain fish species will move into floodplain areas during flood events to spawn, feed, or escape predation from other species occupying the main channel. If flooding occurs at the right time of the year, and lasts for the right amount of time, these fish populations will benefit from the flood event.

On the other hand, other species may be adversely affected by the same flood. For example, benthic (bottom-dwelling) macroinvertebrates may be scoured from the streambed or riparian trees may become stressed or die from prolonged flooding and associated oxygen deprivation. Also important is the rate at which flow levels change. If the river level rises too fast, it can trap animals such as amphibians and reptiles on the floodplain. Conversely, young plants such as cottonwoods taking root on the floodplain can die from moisture stress if their growing root systems cannot keep up with the dropping water table linked to falling river levels.

Natural low-flow conditions can be equally important. Prolonged natural droughts might help certain plants such as bald cypress trees become established on the floodplain, before river levels again rise up around their growing trunks. In the river channel, low flows will concentrate fish and other aquatic organisms, benefiting predators such as larger fish or wading birds. If low flows are too severe, or last for too long due to human influences, large numbers of individuals may perish and jeopardize the local populations of certain species.

Thus, rather than trying to prescribe a flow regime that benefits some species all of the time, a better approach is to restore or sustain a flow regime that benefits each species some of the time. The species that are found in each river have endured many trials of adverse flow conditions, exploited many occasions of favorable flow, and have managed to persist in their native rivers over long periods of time. Until very recently in evolutionary time, the variation in river flows has been dictated largely by natural climatic and environmental conditions. These natural river flows have influenced the development of behavioral (e.g., floodplain spawning), physiological (e.g., tolerance for oxygen deprivation), and morphological (e.g., body shape) traits in riverine species. Thus, perpetuation of the natural flow regime is the best approach for conserving the full richness of a river's biological diversity.

Flow regimes (explained in detail in Section 6) exert a strong influence on other ecosystem conditions as well. Water chemistry, temperature, nutrient cycling, oxygen availability, and the geomorphic processes that shape river channels and floodplains are often tightly coupled to streamflow variation. Natural flow regimes are therefore intimately linked to many different aspects of ecological integrity.

RIVER RESEARCH AND APPLICATIONS
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SHORT COMMUNICATION

A PRESUMPTIVE STANDARD FOR ENVIRONMENTAL FLOW PROTECTION

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[d] *The Nature Conservancy, Seattle, Washington, USA*

ABSTRACT

The vast majority of the world's rivers are now being tapped for their water supplies, yet only a tiny fraction of these rivers are protected by any sort of environmental flow standard. While important advances have been made in reducing the cost and time required to determine the environmental flow needs of both individual rivers and types of rivers in specific geographies, it is highly unlikely that such approaches will be applied to all, or even most, rivers within the forseeable future. As a result, the vast majority of the planet's rivers remain vulnerable to exploitation without limits. Clearly, there is great need for adoption of a "presumptive standard" that can fill this gap. In this paper we present such a presumptive standard, based on the Sustainability Boundary Approach of Richter (2009) which involves restricting hydrologic alterations to within a percentage-based range around natural or historic flow variability. We also discuss water management implications in applying our standard. Our presumptive standard is intended for application only where detailed scientific assessments of environmental flow needs cannot be undertaken in the near term. Copyright © 2011 John Wiley & Sons, Ltd.

KEY WORDS: environmental flow; sustainability; Sustainable Boundary Approach; river management; corporate water use; water stewardship; water allocation; water scarcity

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- "This approach recognizes the importance of natural flow variability and sets protection standards by using allowable departures from natural conditions, expressed as percentage alteration."
- "management can be facilitated by creating **computerized hydrological models** to evaluate what the likely disturbance to natural flows would be".

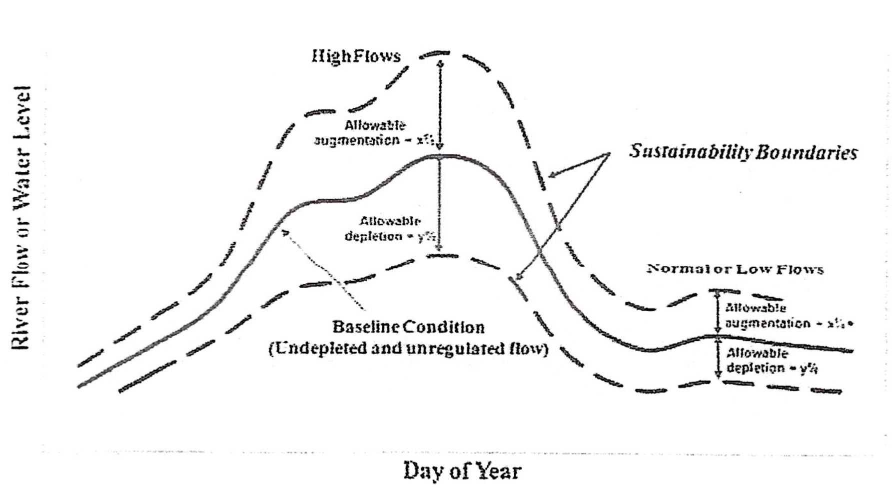


Figure 1. Illustration of the sustainability boundary approach from Richter (2009; reprinted with permission). The sustainability boundaries set limits on the degree to which natural flows can be altered, expressed as a percentage of natural flows.

The Natural Flow Regime – Analysis (pages 2-3)

How do we know what the proper flow level should be for any given stream?

In science the term "natural" means without human occupation. In grocery stores it can vary a lot.

All rivers flow levels vary immensely throughout the year, but also vary from upstream locations to downstream, this is especially true in small streams.

Different flow levels favor different species. Both high and low flow levels can be beneficial to certain species, even when the connection might not be direct, i.e. birds.

This is why biologist have developed the natural flow regime. The closer a stream can be restored to its natural state the better the overall benefits because all the species involved co-existed in that state for long periods of time, and nature will favor natural selection and select the best species for each location. Over time these species adapted to each other and many have symbiotic relationships to some degree.

The natural flow regime stresses the importance of flow rates throughout the year, but pays special attention to high and low flow rates. The five components of the natural flow regime are; magnitude, frequency, duration, timing, and rate of change. These components apply mostly to the extremes of river flow and their persistence to natural flows. Although all the in between flows are important, most of our attention needs to be focused on when extreme conditions prevail.

I would like to use this analogy that we are familiar with at our nursery. The trees and shrubs we plant do best when temperatures are in their normal ranges. A winter temperature of -30 degrees can kill some trees, whereas a temperature of -20 will have less potential for injury. The same can be said for the other extreme. A temperature of 105 degrees might damage some of our trees whereas a temperature of 95 degrees will do little damage. We are usually not concerned until temperatures reach extreme conditions. Whether a morning low temperature is -10 or -20 will likely have little effect, so changing the temperature in that range will likely not matter. Another concern we sometimes have is when temperatures change very rapidly. Whether the rapid change is from very warm to very cold, or vice versa, the rate of change is more critical then to overall amount of change, if that change occurs more gradually.

To understand why this is critical to this LRC project, and in prescribing a feasible working solution, we need to see the flow rates for LRC and how and when irrigation diversion is affecting them. This will be done in the "effectiveness of proposed solutions" section later in this presentation.

Richter Study (page 4)

The graft at the bottom of the page was displayed at one PAT meeting.

Two quotes from this report were used, and this report contains over 20 references to using natural flow.

There is another similar report to this referred to as the "Acreman Study".

The PHABSIM model also stresses the importance of subscribing to the natural flow regime.

Estimations from the LRC model

(DNR's main objection to estimating natural flow regime is that it would require a few more additional difficult estimations to replace estimations already being used).

Partial list of estimations in modelling LRC includes the following:

1). Estimating baseflow from streamflow (WHAT model)

2). Effects of tiling on LRC

3). ET rates to estimate cover crop used in the no-use scenario (WEPP model)

4). Variable rainfall rates in the LRC watershed

5). MODFLOW model requires numerous parameters (transmissivity)

6). Estimating direction of underground flow both vertically and horizontally (hydraulic conductivity)

7). GSSHA model (runoff and recharge from variable rainfall events)

8). Irrigation evaporation rates

9). Irrigation usage rates (20-25%)

10). Estimating the ET rates of crops under irrigation to determine recharge potential (peas, corn, potatoes, beans, alfalfa, etc.) (SWAT model)

11). Aquifer drawdown during and after pumping (overestimating from peer review analysis)

12). Estimating water amounts leaving or entering the watershed (e.g. Rice, Skunk, and Mud Lake area)

13). Estimations required to obtain stream flow levels (stream gauges)

14). Physical Habitat Simulation Study model, (PHABSIM), (to study fish habitats)

15). Instream Flow Incremental Methodology model (IFIM)

16). Domestic and city water well use

17). Estimating ET rates from various weather conditions (humidity, temperature, wind speeds)

Numbers Taken from the Executive Summary of the model

- For model calibration years 2006-2014, median diversion was **<u>24%</u>** and maximum diversion was **<u>35%.</u>**

  Alfalfa was chosen at this time after seeing the results from several options, thus the results now become a **subjective value**. This is not a standard scientific procedure. The cover crop should have been agreed upon and chosen beforehand, not after witnessing the results.

  Note; The no-use cover crop parameter makes a huge difference in diversion rates, as noted in the model.

Quote from Dr. Johnson peer review, "Use of non-irrigated alfalfa to replace irrigated conditions is unrealistic and provides little to no understanding of natural conditions in LRC. It is possible that the non-irrigated alfalfa simulation estimates more baseflow than naturally occurred in LRC, resulting in erroneously high estimates of baseflow diversion."

An analogy we can use is this; If we were trying to balance our checkbook and had all of our deposits and expenses but we did not know the starting balance, we would never know the current balance. In the same way we need to know what our starting flow level is so we can estimate diversion levels more accurately.

- For verification period 2015-2018, median diversion dropped to **<u>11%</u>** and maximum to **<u>27%.</u>**
  (Model was run in two stages. The calibration stage is where parameters are adjusted to match observed results, and the verification stage is run without adjustments to check for accuracy).

- Using the 20% reduction from flow meter results, median diversion dropped to **<u>7.4%</u>** and maximum to **<u>21%.</u>**
  (These numbers appear very close to being acceptable and are inside the margin-or-error, but were rejected).

DEPARTMENT OF NATURAL RESOURCES

Flow Meter Study

Double blind study of calculated and reported water use in the Little Rock Creek Area

3/4/2021

Table 1 - Data bounds for filtering each center pivot.

Data bounds	Reject if...	Reject if...	Reject if...
Irrigator	Speed of sound range	Water velocity	Pump rate
5015	x>1458	7>x>10	x>950
5016	x>1400	x<3	x>800
49041	x>1381	3>x>10	x>600
49042	x>1468	x<3	x>700
49043	x>1382	2.5>x>10	x>600
49044	x>1485	x<2	x>400
49045	x>1401	x<2	x>450
49046	x>1475	x<3	x>650
71043	x>1453	2.5>x>6	x>700

Table 2 - Irrigator and associated method of reporting water use.

Irrigator	Method of reporting
5015	Hour meter on pivot x flow rate
5016	Hour meter on pivot x flow rate
49041	Kilowatt hours x horse power it takes to make 1 kilowatt hour x flow rate x efficiency factor
49042	Hour meter on pivot x flow rate
49043	Timing device with hour meter x flow rate
49044	Kilowatt hrs x horse power it take to make 1 kilowatt hour x flow rate
49045	Timing device with hour meter x flow rate
49046	Timing device with hour meter x flow rate
71043	Hour meter on pivot x flow rate

Table 3 – Months of flow meter data omitted from comparison due to missing values

Irrigator	Months Omitted in 2018	Months Omitted in 2019
5015	July	May and June
5016	July and August	None
49041	July	None
49042	July	None
49043	July and August	None
49044	July	None
49045	All months	None
49046	July and August	None
71043	July and August	None

Table 4 - Comparisons of study participants for reported and measured annual water use totals.

2018 Measured Total (MG)	2018 *Reported Total (MG)	2018 % Diff	2018 Volume Diff (MG)	2019 Measured Total (MG)	2019 *Reported Total (MG)	2019 % Diff	2019 Volume Diff (MG)
22,103,908	23,149,800	5%	(1,045,892)	11,464,299	11,890,800	4%	(426,501)
6,796,168	9,855,000	45%	(3,058,832)	24,782,169	35,199,900	42%	(10,417,731)
10,850,796	14,134,500	30%	(3,283,704)	7,075,793	6,635,925	-6%	439,868
8,855,526	13,261,500	50%	(4,405,974)	7,202,562	8,694,000	21%	(1,491,438)
5,133,932	6,696,000	30%	(1,562,068)	19,233,869	25,020,000	30%	(5,786,131)
5,774,722	6,094,340	6%	(319,618)	5,747,859	6,090,725	6%	(342,866)
-	-	-	-	5,947,245	8,005,140	35%	(2,057,895)
2,641,686	2,793,600	6%	(151,914)	5,549,362	4,134,100	-26%	1,415,262
3,095,974	4,776,300	54%	(1,680,326)	15,783,680	23,185,500	47%	(7,401,820)
65,252,712	80,761,040	24%	(15,508,328)	102,786,838	128,856,090	25%	(26,069,252)

/as calculated

Potential reasoning for overreporting

- Pumps never over perform and wear down and lose performance with time (Sand and dissolved particles will wear down impeller blades)

- Hour meters used to report usage do not account for when valves or end guns are shutoff to account for square or irregular fields

- Well inlet screens can become plugged and limit water capacity (Galvanized verses stainless steel screens)

- Wells can become dysfunctional with time and lose volume potential

- Calcium carbonates can build up in nozzles limiting spray volume and can vary tremendously from well to well, is sometimes referred to as "limescale" buildup

- The only way to under report water usage would be to make an error

Questions:

If the test was initiated by the DNR, meters chosen and calibrated along with all other parameters of the study were determined by the DNR, end results were ascertained, compiled, and defined and by the DNR, and the volunteers demonstrated proper cooperation, why were the results then rejected?

If the test was to be deemed insufficient from the beginning, why invest the time and money to do it at all? In essence, they rejected their own study and deemed it of low quality. This has the appearance that the results were not in favor with expectations?

Why did the irrigators not have a seat in the room when the decision was made not to include the results? They are the experts in this field and maybe a roundtable discussion including them could resolve this.

Flow Meter - Analysis (page 12)

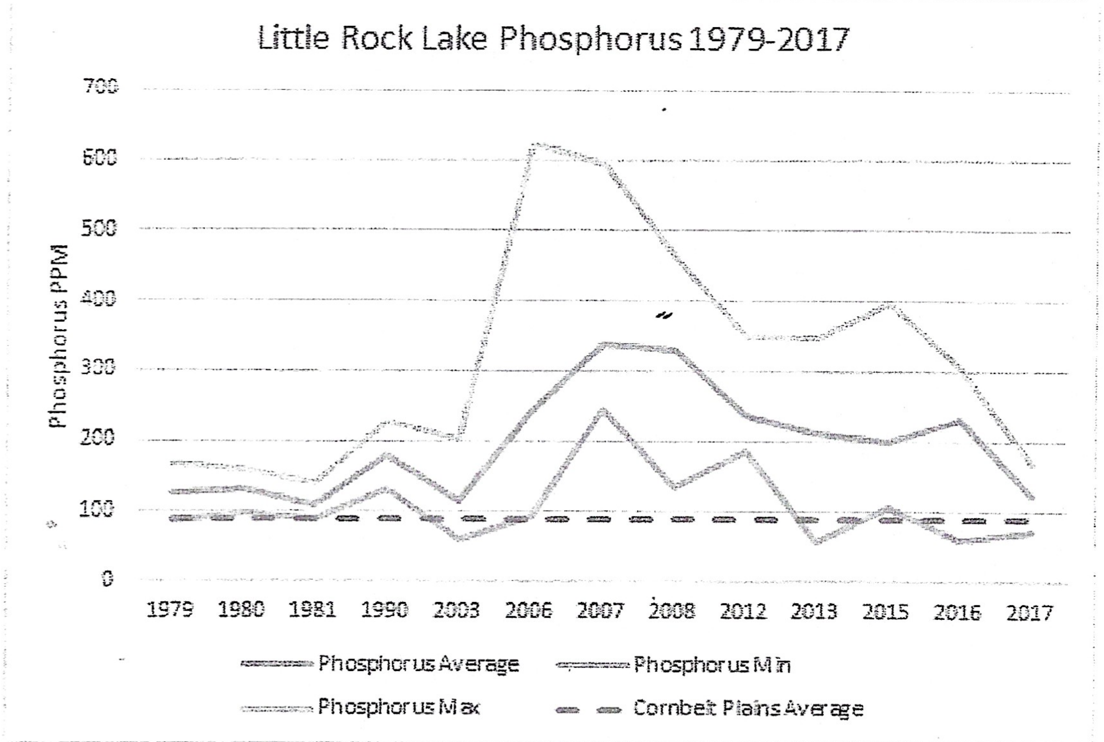
Flow meter study was a double-blind study meaning neither side new the other side results.

Most common method used is by using the irrigation pump run time multiplied by its projected flow rate. One volunteer used kilowatt hours, calibrated by the power company by a meter, multiplied by flow rate determined by estimating an efficiency factor of the pump.

First year some data was overwritten by later data. Those months were omitted and only months where data was recorded by the flow meter were used. Results of 24 and 25 % were consistent with each other but some variation was observed between irrigators, but this variation seemed to occur equally in both directions so results did not reflect much of a change.

OK Randy,

I am sending you some stuff to consider here. We have our easement area between CR 40 and the Min maint road. In that area there are several eroding banks that we made note of over the years for potential fixes. One of the things I wanted to know is how much erosion is actually taking place? Well, I can say unequivocally, there is quite a bit!!! The change in a couple seasons of monitoring equates to several hundred tons of sediment supplied to the stream channel. So how does this all factor in? Well, sediment changes habitat for all fish and invertebrates, not just trout, but all species of fish that have been present in the system. So, why is so much erosion occurring? That points directly at the altered hydrology in the watershed. What changed in the watershed? Land use, significantly since pre-settlement. Inclusion of fields over forest and shrub communities, ditching, tiling, pavement, lawns. All these add water faster, to a system that has relatively fragile structure due to the high sand content in the soils. The stream channel is highly erodible, without vegetation to stabilize the banks. This has obviously been going on for a long time. Stations we electrofish within the easement, have sand plumes soft enough, we feel like we are stepping in quick sand. This is not good for most all living critters. Yet this year we recorded the highest survival of our stocked Brown Trout. So the water quality and temperature still support the fish. On an interesting side note, I am also working on the drawdown project on the lake. Well Gerry Maceij and Benton SWCD have been super aggressive with funding BMP's in the watershed since 2012..... The lake phosphorus seems to be showing this too.... See graph below. What this suggests is the watershed loading seems to be decreasing, which is a good thing for the creek as well.



In any case attached are some older reports and pictures. I will send over the more recent fish data in a separate email...

Eric

Eric Altena
Area Fisheries Manager | Fish and Wildlife

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16543 Haven Road
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Cell: 320-293-2439

Gmail

Randy Klaphake <rdee4694@gmail.com>

LRC

2 messages

Randy Klaphake <rdee4694@gmail.com> Thu, Jan 16, 2025 at 12:43 PM
To: "eric.altena@state.mn.us" <eric.altena@state.mn.us>

Hi Eric,

I spoke to you about 5 years ago about the fish habitat conditions in LRC. Was wondering if you could assist me again in helping me to identify the cold water fish species that are currently living in LRC. Which of the following would you list as cold water species?

blacknose dace, brook stickleback, brown trout, central mudminnow, central stoneroller, common shiner, creek chub, fathead minnow, johnny darter, longnose dace, northern pike, and white sucker.

Thanks,
Randy Klaphake
320-232-8369

Altena, Eric (DNR) <eric.altena@state.mn.us> Thu, Jan 16, 2025 at 3:32 PM
To: Randy Klaphake <rdee4694@gmail.com>

Hello Randy,

I hope all is well and you have escaped getting the crud that seems to be going around. Unfortunately with my side work in hockey rinks, I Was not so lucky.. Ugh.

Anyway to address your question, water temperature is not the only criteria for sensitive fish species. Trout obviously require the coldest water, and to a lesser extent northern pike (prefer cool water), Longnose dace are a very intolerant species which require specific well oxygenated and unpolluted riffle habitats. To be honest all of the remaining species are relatively ubiquitous species being tolerant of many habitats and conditions and generally found in abundance in many warmwater streams. Since we last discussed the stream, we have been able to switch our annual stocking to Driftless strain brook trout. We have been stocking those for the last three years and have been seeing some good survival and growth. The largest component I have seen on LRC in my work term here, has been the degradation of habitat. Particularly as we get below the MMR area. There has been some sediment infusion from a couple of sources for sure, banks included that have converted the stream into a sand bed, with relatively featureless areas common. Obviously, there is not any fish species that does well in that environment.

Hopefully this is somewhat helpful. Please let me know if you have other questions and I will do my best to help you out.

Take care and have a great day!

Eric

Eric Altena

Area Fisheries Manager | Fish and Wildlife

Minnesota Department of Natural Resources

Randy Klaphake <rdee4694@gmail.com> Jan 20, 2025, 10:23 AM (21 hours ago)

to Eric

Another question occurred to me after reviewing my notes from our 2017 phone conversation. Do you monitor trout to see if numbers are increasing or declining? It would be interesting to see if the trout numbers increased during the wet period from 2014 through 2020. And compare that to the dryer period we are now in. And do we know sediment levels from this timeframe? Might that tell us something about how sediment and water levels affect trout?

Thanks again, Randy

Altena, Eric (DNR) 6:01 AM (2 hours ago)

to me

Hey Randy,
We do monitor the trout, although, it's really more for "general survival" and natural reproduction. We do single pass electrofishing once a year. If we were to actually do population estimate work, it would be by blocking off a section of stream and doing a two pass removal. That said, we do have confidence in our data with single pass electrofishing and can say the population is made up of xxx fish between 85 and 300 mm for example. Anecdotally, I can say we have not had the greatest survival in the last few years, although plenty of things can contribute to that, I can say with some level of certainty, that the habitat changes are affecting more than the lack of water or the temperature and quality of the water. You could have the best water quality and quantity, but if the stream morphology is goofy and only sand bed, there aren't very many fish that will like it. The best habitat in LRC for trout anyway, tends to be between 234 and the MMR. That same stretch also happens to be the area with the most gradient and coincidentally the best habitat.

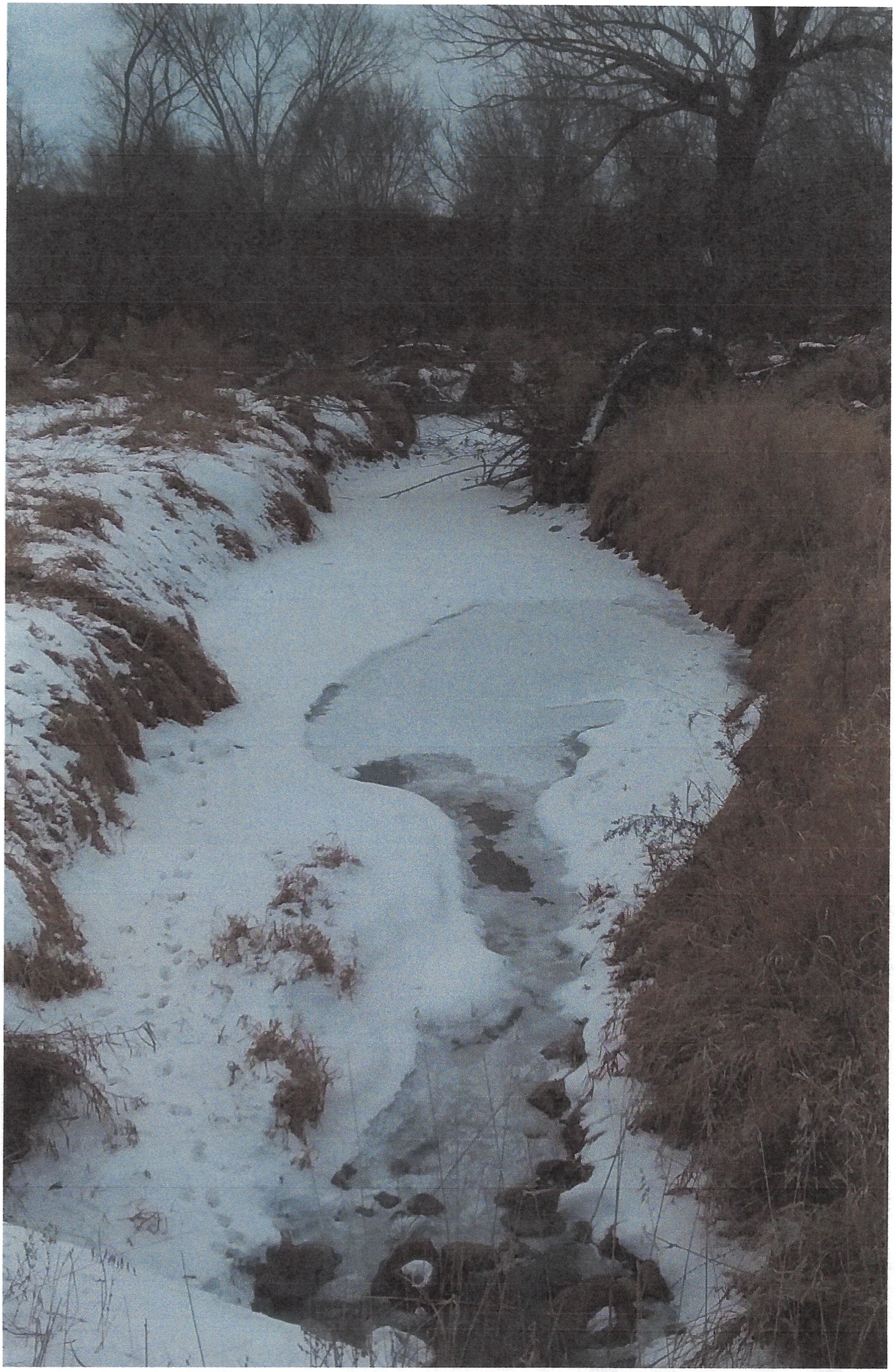
The MMR is the minimum Maintenance Road area, just upstream from CR 40 (40 hole). Sorry, I spit out acronyms without thinking at times. I have attached the 2022 report which explains a lot of how we do things and what we get from the data. We did sample this year and came up wit a fair amount of brook trout, which is encouraging. Still working on that report though.

Thanks and let me know if there are additional questions.

Eric

DNR's Fisheries Analysis (pages 13-15)

Email exchange between DNR's Fisheries Manager and myself. One exchanged occurred in 2017 and the other in 2015. Both report similar situations and that LRC has severe erosion problems with sand inundating the riverbed that is affecting the fish more then any other reported stressor, including water flow and stream temperature. Sand is affecting trout spawning success since trifling and gravel are required even over temperature and flow rates. Since this analysis has been consistent, it is very likely to continue or probably get worse with time. A complete 2022 DNR Fisheries analysis is available if desired.



Stream Incision Analysis

Pictures of LRC at our nursery site. Stream channel incision can be obviously seen from either picture, which hardly does justice when witnessed in person. LRC is mostly in what geologist call an outwash plain, or deposits from the Mississippi River during glacial melting. This material is more erodible than glacial till, which covers most of Minnesota, and glacial till consist of a conglomerate of gravel, rock, and clay.

In glacial till regions, most riverbeds will have a rocky bottom protecting much of its riverbed from erosion. Stream structure is referred to as morphology, and when not properly in alignment, can have severe negative effects on aquatic lifeforms. For instance, amphibians need both land and water to complete their life style, and in situations like this are restricted from easy access in and out of the water. When one group of species is reduced from an ecosystem it can have a domino effect on other species which are now missing their main food source. And when they are missing, their predators will now also be reduced, and so on and so on. Beaver dams and BDA's have been shown to be an effective tool against this type of problem.

Another reason for the high level of erosion that is occurring in LRC comes from an increase of runoff compared to preindustrial age. When the native vegetation was removed to make room for modern agriculture, water runoff was increased. Since it is impossible to plant food crops without clearing the land, this situation has been ongoing for a long time. Improvements are slowly being implemented such as lessening of tillage practices, planting of cover crops, buffer zones, perennial erosion strips, underground tiling, and just a general shortening of the timeframe where soils are exposed to erosion.

Most of the high volume of runoff water coming through LRC originates in the non-irrigated eastern potions of the LRC watershed, as noted in the TMDL reports. Those soils are higher in water holding capacity and also have higher gradient or elevation relief compared to irrigated soils. Many irrigated fields that I have noticed are surrounded by roadways with no water exits or culverts to even allow for runoff to occur. Since our nursery is located upstream from where most of the irrigation is occurring, the high instream erosion noted in the pictures was likely produced from areas located upstream from us.

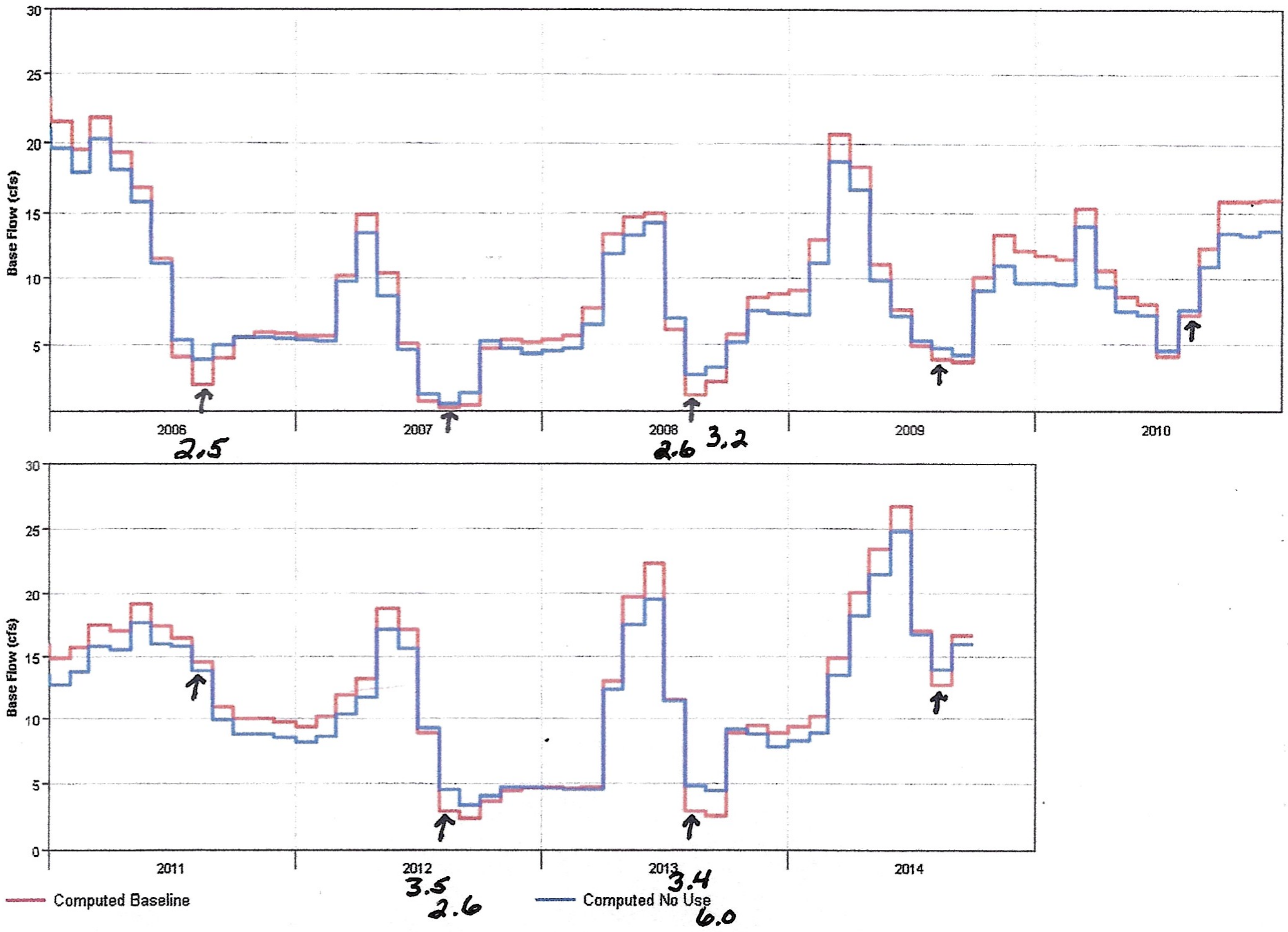


Figure 38 Computed base flow for the baseline and no-use scenarios at station 15029001 on Little Rock Creek.

- Chart is a good summary for the calibration years of 2006-2014
- Arrows indicate where August is and blue line is with no irrigation
- 9 out of every 12 months diversion is negative (adding water to the creek)
- Model shows that diversion exceeds the 15% SDL in **2006, 2008, 2012, 2013**
- Little to no diversion above the 5 cfs. mark (mostly confined between 2-4 cfs.)
- The current solutions being considered main intent is to move up the red line a bit
- 2007, the driest year had very little diversion and it is considered sustainable by the 15% SDL which **equates in volume to 1.1 cfs.** In other words, the method used here says the fish should be fine, but common rational arguments seem to tell a different story.

Questions: Could short-term benefits be lost when years similar to 2007 occur, and could they negate any lasting long-term benefits? Does the "percent of flow" method fail in small streams like LRC due to limited testing results, and could it perform better in larger streams?

Would retaining water, (creating wetlands) inside the creek provide a refuge for the fish for these dry periods when they will likely need it the most?

Year	Modeled Flow at 15029001 No Use Scenario (Mcfy)	Modeled Flow at 15029001 Baseline Scenario (Mcfy)	Modeled Flow at 15031001 No Use Scenario (Mcfy)	Modeled Flow at 15031001 Baseline Scenario (Mcfy)
2006	347.40	357.09	851.16	860.46
2007	170.16	176.65	501.45	503.82
2008	232.21	248.25	583.93	600.27
2009	300.39	335.49	714.01	765.69
2010	317.29	362.00	705.35	773.76
2011	411.54	451.59	896.81	966.76
2012	268.95	282.69	692.08	707.78
2013	301.59	310.76	721.38	722.81
2014*	371.36	396.30	769.32	804.53

Mcfy - Million cubic feet per year

* volume through September

Modeled (computed) baseflow from Figures 38 and 39 in Groundwater Flow and Groundwater/Stream Interaction in the Little Rock Creek Area (DNR, 2018)

Average annual flow rates from above in cfs

2006	11.02	11.32	26.99	27.29
2007	5.40	5.60	15.90	15.98
2008	7.36	7.87	18.52	19.03
2009	9.53	10.64	22.64	24.28
2010	10.06	11.48	22.37	24.54
2011	13.05	14.32	28.44	30.66
2012	8.53	8.96	21.95	22.44
2013	9.56	9.85	22.87	22.92
2014*	11.78	12.57	24.40	25.51

The accusation that irrigation in the LRC watershed is increasing the impairment of the creek by reducing the flow rates is simple false. The charts show that annual flow rates for the baseline, or irrigation condition, exceeds the flow rates for the no-use, or no irrigation conditions for all measured years.

This accusation was prompted by the MPCA in its 2009 TMDL release. When taking a further look at how they came to that conclusion, since they had no model to help discern flow rates, they used methods based on presumptions about how they thought the likelihood of water diversion could be happening and consequently ended with results being mostly just speculative.

But what if we used the results from August when diversion is at its peak? If we used the downstream gauge where volume amounts are at their highest, and used those numbers to ascertain diversion from LRL, what would those results indicate? The median August baseflow diversion at the downstream gauge is 2.3 cfs. This is equal to 5,961,600 cubic feet of water for the entire month of August. The volume of water in LRL is estimated by the 2009 TMDL report to be 10,084-acre feet. Using those numbers, we can now calculate that 1.35% of the volume of the lake would not be displaced, which is certainly not substantial when considering the overall effects this would have.

Another way to ascertain what these effects would have would be to look at how this diversion would affect total water residence time in LRL. That same TMDL report says water residence time in LRL is .3 - .5 years, or 150 days to use a round number. Using the diversion and volume numbers above we can then calculate that the resident time would be increased to 152 days, which again is not substantial. Actual number would be less than that because most of the year water flow rates are actually increased.

Effectiveness of Proposed Solutions – Analysis (page 20)

Graph is from the long-term gauge in LRC. There are 3 gauging stations in operation on LRC and this is the middle gauge. All 3 gauges are located in the downstream portions of the creek where flow levels are at their highest. This gauge was chosen because it represents LRC generally better than any other place on the creek. This location is also where most of the trout exist in LRC.

The horizontal axis is time divided into 9 years. Vertical axis is flow rate in cubic feet per second, cfs. In the graph, each horizontal line is one month, separated by a vertical line linking it to the next consecutive month, thus 12 horizontal markings per year. Arrow indicates where August is in each year. The red line indicates computed baseflow baseline, or with current irrigation, and the blue line indicates the computed baseflow for the no-use condition which is without irrigation. The difference between each line is diversion, which can be either positive or negative.

First note of interest is that on average 9 out of every 12 months, the red line, which indicates flow rate with irrigation, is above the blue line, which indicates flow rates with irrigation removed. This tells us that more water is in the creek with irrigation 9 out of every 12 months. Page 16 shows these results which John Oswald performed for us who was the first hydrologist we hired. Overall, more water is flowing into LRL with irrigation then what would be if irrigation was removed.

There are 4 years where diversion exceed the SDL. They are 2006, 2008, 2012, and 2013, and also indicative by noticing that the red line in these months is below the blue line. In all 4 of these years the baseflow level is between 2 and 4 cfs. When we move to about 5 cfs. or higher, most of the time the lines will reverse, indicating no diversion from irrigation. But this pattern is concerning since when the water levels get low below 5 cfs. more diversion from irrigation is occurring. If the flow meter study results of 20% overreporting were graphed, these two lines would be closer together. The intent of the solutions being offered is to move up slightly the red line in these 4 years to reduce diversion from irrigation.

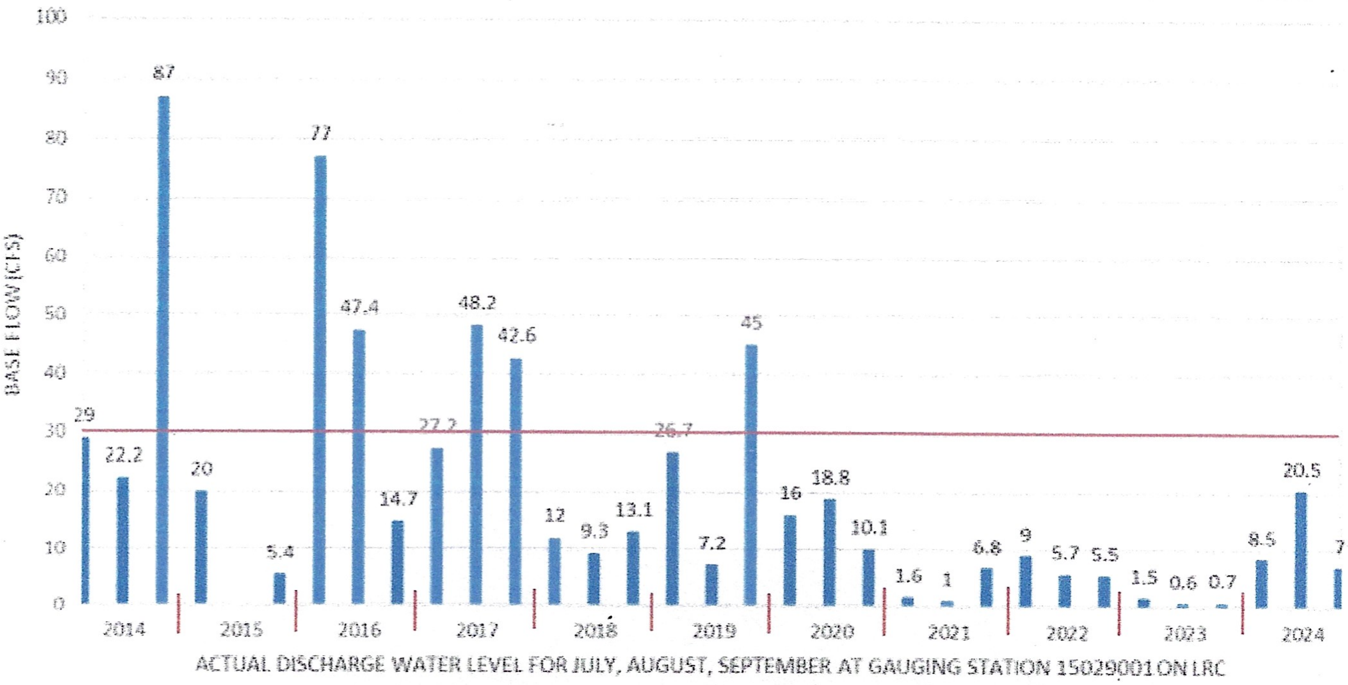
Now take a look at 2007, which is the driest year in this timeframe. A quote from the LRC model states this, "Diversion limits did not exceed limits at the upstream or long-term gauge in 2007 due to very low flows in the no-use model." So then, according to the model and using the percent of flow concept, diversion here is acceptable. But water flow levels in 2007 were lower than in the 4 years where diversion did exceed limits. If you trace the blue line, which is no irrigation, horizontally out, it is still below the red line in the 4 years where diversion is a problem, as noted by the model. It is possible that this model and concept may have performed slightly better in a larger river system.

So now we are faced with a strange dilemma. We either have to accept the classroom explanation using the model indicating no problem in 2007, or take a more common-sense approach and accept that the fish will be suffering more in 2007 then they will in any of the 4 years when diversion exceeded the SDL. This situation also reveals another unwanted phenomenon, that years like 2007 will erase any benefits that were acquired when in reducing diversion. In other words, there will be limited, or zero long-term benefits from the current proposed solutions. Interpretation of the model becomes very important now. We have to acknowledge its strengths and weaknesses and assess each for what it is. Without proper awareness of this phenomenon, we will not provide the best solution for the situation.

It looks as though nature has the final word and is still ultimately in charge if she decides to send a drought our way. With current proposed solutions we will be helpless to curb the impacts because we did not conserve any water when the levels were higher. So then, is there a way to avoid this? What if we could retain some of the water that flowed away during those high-water timeframes. The answer is we can, and by using a trick that nature has already has figured out, but which we have removed. What if we installed small dams inside the creek bed to conserve some of that water, or allowed beavers to do the work for us? Would this not give the fish a refuge during prolong drought periods. And would it not also allow some of that water to percolate into the streambed, which just might flow back into the creek when the water level receded.

Another aspect to consider here is the natural flow regime. We know the baseline, or red line, would be where it is. But the blue line is a variable dependent on the chosen cover crop in the no-use scenario. So where would the likelihood of that line be? Probably below the current no-use line since we know that native vegetation ET rates probably exceeded the no-use ET rates of alfalfa. The USGS estimates that a mature oak tree transpires approximately 40,000 gallons per year. So now, instead of having one high capacity well on a 160-acre parcel, in the native environment we would have probably thousands of smaller wells, disguised as oak trees, consuming more total water and lowering the stream flow level.

Another aspect of the natural flow regime, which was touched upon earlier, are the critical aspect of the high and low flows. Are the flow diversions between 2 and 4 cfs. really as critical as the low flow in 2007. ~~Should not our focus be on making sure the low flows don't exceed frequency and duration of when the~~ stream was in its natural state.



- Chart is actual flow levels taken from long-term stream gauge for July, August, and September for the 10-year period from 2014 through 2024

- Years 2015-2018 were the modeled verification period that shows no diversion issues

- Years 2019 and 2020 were wet years. We now have 7 consecutive years of no diversion above the 15% SDL (were any environmental improvements noticed inside or alongside the creek?)

- Years 2021 and 2013 reflect equivalence to 2007 where diversion was very low

- Total time where percentage of diversion exceeded the 15% SDL for years **2006-2024** is: (7 months out of 19 years or **minimum of 3%,** or 12 months of 19 years or **maximum of 5%)**

- Analysis shows that relieving diversion in the current manner will only produce temporary short-term benefits, with little or no long-term benefits

- Take note to the **high marks** also. Remember that those numbers reflect the average for that given month, and that actual spikes can easily be 3 to 4 times higher.

Effectiveness of Proposed Solutions – Additional Analysis (page 24)

So another question we need to ask is whether 2007 is just 50-to-100-year anomaly, or if it might occur more frequently? This chart is actual flow rates from the long-term gauging station that recorded streamflow there. The purpose of this graph is to extend the modelled period out to 2024. Increments on this graph are separated in 10 cfs., instead of 5 as in the previous graph. To simplify the chart we only graphed July, August, and September, where diversion could be expected. Years 2015 – 2018 were modelled and did not show diversion above set limits. 2019 and 2020 were relatively wet years and would unlikely produce diversion above set limits. So this now shows 7 years of no diversion above acceptable set limits, and the question can be asked if noticeable changes were seen in the creek. If they were, they likely got erased when looking at flow levels for 2021 and 2023, which show striking similarities to 2007.

In the previous chart we compared streamflow levels obtained from actual numbers from the long-term gauge against computed baseflow numbers and found that when under 5 cfs., they pretty much match since any runoff water would probably be long gone when streamflow falls to these levels. For this reason, we feel relatively confident that we can correlate critical low flow levels between charts and extend the timeframe another 6 years to look for patterns. We did not see another year like the 4 years where diversion fell below 5 cfs., but yet did not fall to far down where diversion would be reduced like in 2007.

Now using all the modelled years, along with the six extended years, we can extrapolate the amount of time that LRC existed above and below the SDL. This should be deemed important since if high cost and labor will be required to import water, along with high maintenance cost, we should try to determine the total effects from implementing that solution to determine justification. Judging from these graphs, and when including months in question, 9 months existed where diversion may have been greater than set limits. If 19 years can be used to extrapolate this from, then diversion in excess of set limits occurred about 4% of the time. Since some question remain in 2021 and 2013 as to which category those months fall into, most look to be comparable to 2007, but some months could be above set limits. We can now say with relative safety that diversion in excess of set limits would unlikely occur more then 5% of the time, and certainly not at levels where large changes in LRC and LRL could be expected, especially when considering that most these benefits will likely just be temporary.

Attention also needs to be turned to the high-water marks. Remember that Eric Altena, from the DNR Fisheries Department, noted that erosion from excessively high-water levels flowing through the creek was causing severe stream incision and causing much harm to stream habitat. Quote from the Natural Flow Regime, "In describing the ecological functions of a flow regime, we pay particular attention to high-and low-flow events, because they often serve as ecological "bottlenecks" that present critical stresses and opportunities for a wide array of riverine species." The numbers indicated on the graph only reflect the averages for those months, and that actual flow levels were at some cases almost 10 times higher, but existed in shorter timeframes. These excessive high flows might be hard to eliminate from fields when high rainfalls are experienced. To reduce these effects once in the creek, we once again could install instream barriers, or small beaver dams, to reduce these impacts. More information will be directed to this solution coming up later.

9/21/2024


Little Rock Creek
Little Rock Creek

Google Earth View of Our Nursery (page 26)

Picture of our nursery showing the huge storage capacity of LRC. Of our 80-acre plot, about 25 acres belongs to LRC, noted by the green vegetative ground cover. The current LRC can be seen dwarfed inside this huge reservoir winding and twisting around.

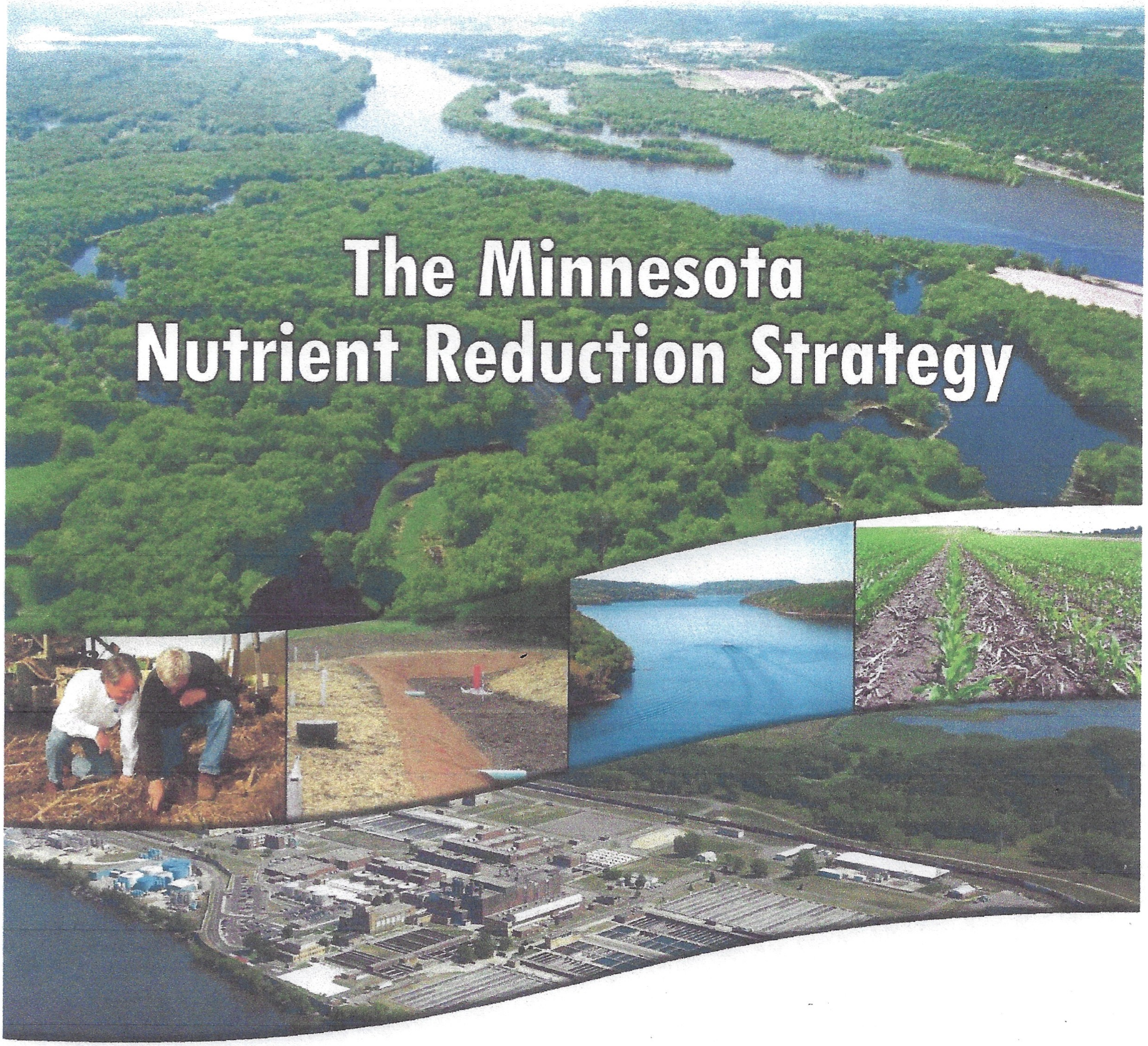
Google View of Our Nursery – Closer View (page 27)

A closer view of a portion of our nursery showing our footbridge, which is barely discernable, but also the position of a beaver dam in the lower right corner. Its exact location can be determined by where the green coloring is diminished, and right where the K is located in the word creek. The green coloring is not false imaging but is the actual view seen from space. So why is it green?

View of LRC from Our Footbridge (page 28)

A view standing on our footbridge looking at LRC. The heavy algae presence indicates high nutrient levels in the water. Once again, the best way to eliminate these contaminants is by the structure of small dams inside the creek to create wetlands. I have seen numerous articles where wetlands are referenced as being "nature's kidneys". Wetlands are very effective in removing contaminants, especially phosphorus and nitrates. Once again, we can import all the water used for irrigating, or shut off all the irrigators, neither one will make any difference in cleaning up this mess.

The Minnesota Nutrient Reduction Strategy



348 pages Total

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Minnesota Pollution Control Agency
MINNESOTA DEPARTMENT OF AGRICULTURE
Minnesota Board of Water & Soil Resources
NRCS
FSA FARM SERVICE AGENCY
Minnesota DEPARTMENT OF NATURAL RESOURCES
MINNESOTA MDH DEPARTMENT of HEALTH
PFA Minnesota Public Facilities Authority
UNIVERSITY OF MINNESOTA Driven to Discover
METROPOLITAN COUNCIL
USGS science for a changing world

Minnesota Nutrient Reduction Strategy – Analysis (pages 30-31)

The Minnesota Nutrient Reduction Strategy was implemented in 2014 in an effort to reduce hypoxia in the Gulf of Mexico. Eleven states agreed to this venture, along with Minnesota, with technical analysis suggesting that Minnesota remove 45% of levels measured in 2014, of nitrates and phosphorus exiting the state by 2040. Nowhere in this report does it suggest that reduction should be made by increasing flow levels. Contaminants leaving LRC will go into LRL, then into the Mississippi River, and then eventually pass through or along all eleven states before exiting in the Gulf of Mexico, where it creates a large dead zone in the ocean there. It disappointing to know that we have already poured millions of dollars into this project, and may pour millions more, and have no plan to remove any pollutants.

are stream beaver created wetlands considered the best ecosysten

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AI Overview

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Yes, stream beaver-created wetlands are often considered among the best ecosystems in the world due to their high biodiversity, ability to improve water quality, and role in supporting a wide variety of plant and animal life, making beavers "ecosystem engineers" who create highly productive habitats comparable to rainforests and coral reefs.

Key points about beaver wetlands:

High biodiversity:

Beaver ponds create diverse wetland environments with a wide range of plant and animal species, including fish, amphibians, birds, and insects.

Water quality improvement:

Beaver dams slow water flow, allowing sediment to settle and filter pollutants, resulting in cleaner downstream water.

Flood control:

By storing water in their ponds, beavers can help regulate water flow and mitigate flooding.

Drought mitigation:

Beaver ponds can also act as water reservoirs during dry periods.

Keystone species:

Beavers are considered a keystone species because their actions significantly impact the entire ecosystem around them.

- Estimates of beaver populations in North America is thought to be between 60 and 400 million (Pollock et al. 2003); Seton (1929). Fur trapping, which began in the 1700s to support the European fashion for pelt hats (Bryce 1990), resulted in massive declines in beaver populations.

Instream Wetland – Analysis (page 33)

The AI response on my computer to a question that I asked of it. To compare beaver dams or instream wetlands to coral reefs and rainforest is quite remarkable. To understand this, we must realize what is happening behind a beave dam. First, all living species need water for survival at different stages of life. This water is unlike swamp or bog water because it constantly refreshes itself by the continue flow of the creek. A few species need moving water, but a great majority prefer shallow undisturbed water. The water behind a dammed river will provide many preferred criteria for this to happen. Usually when biodiversity is increased, which is usually considered the benchmark for ecosystem health, numbers and specie diversity are increased, which brings in even more species looking for food, and then more species, and etc. This is why biologist have given the label "keystone species" to beavers. This also means that most creek ecosystems we currently witness have been diminished from their former capacity, which is a fact unknown to most people.

The Beaver Restoration Guidebook

Working with Beaver to Restore Streams, Wetlands, and Floodplains

Version 2.02, March 23, 2023

Photo credit: Worth A Dam Foundation (martinezbeavers.org)

Prepared by

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Funded by

North Pacific Landscape Conservation Cooperative

Version 2.02. Get the latest version at: https://www.fws.gov/media/beaver-restoration-guidebook

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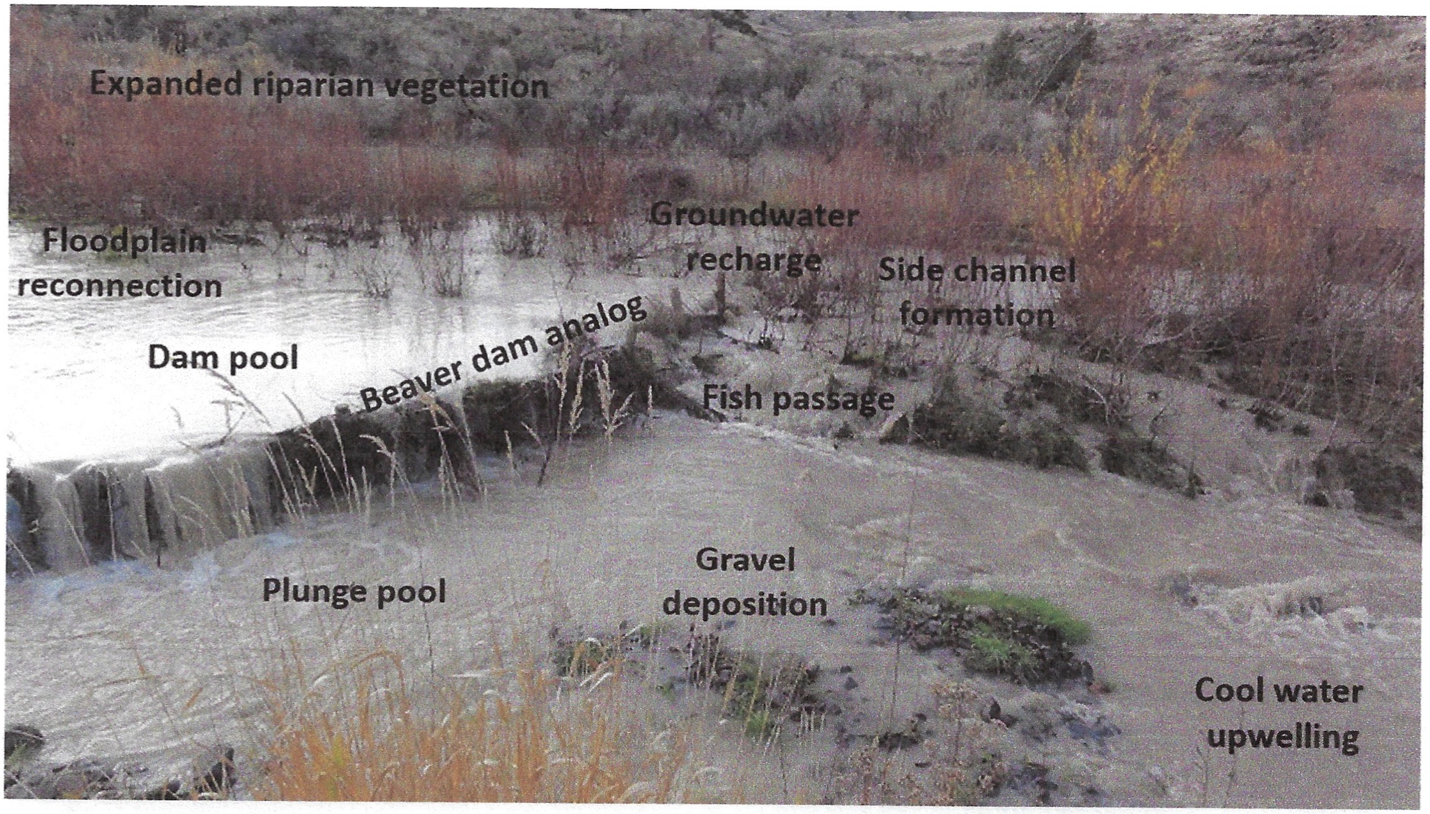
scientific reports

Figure 3

From: Ecosystem experiment reveals benefits of natural and simulated beaver dams to a threatened population of steelhead (*Oncorhynchus mykiss*)



Example of a beaver dam analog (BDA) annotated with some of the expected responses.

Back to article page >

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- Increased Water Retention **(conserves and stores water)** (Finley 1937, Wilen et al. 1975).
- Increases Base Flows **(hyporheic exchange by creating hydrostatic pressure, 24-7)** Dalke 1947, Pollock et al. 2003, Majerova et al. 2015, Naiman et al. 1986, Syphard and Garcia 2001, Cunningham et al. 2006, Westbrook et al. 2006, Hood and Bayley 2008, Lowry 1993, Rosemond and Anderson 2003, Lawler 2009).
- Decreases Peak Flows **(1). slows down erosion, 2). Increases sediment deposition 3). Decreases channel incision** (Pollack et al. 2003, Li and Shen 1973, Woo and Waddington 1990, Dunaway et al. 1994, Scheffer 1938, Smith 1950, Naiman et al. 1986).
- Expansion of Habitat Area and Complexity **(increases connectivity)** (Naiman et al. 1988b, Martell et al. 2006, Pollock et al. 2007, Hood and Bayley 2008,
- Increases Wetland Area (Westbrook et al. 2006, Hood and Bayley 2008, Cunningham et al. 2006, Syphard and Garcia 2001, in Minnesota Johnson and Naiman 1990a).
- Increases Groundwater Recharge (Workman and Serrano 1999, Girard et al. 2003, Westbrook et al. 2006, Lowry and Beschta 1994, Lautz et al. 2006, Pollock et al. 2003 & 2007, Weber et al. 2017).
- Water Quality and Sediment Retention (Naiman et al. 1986, Butler and Malanson 1995, Pollock et al. 2007, Green and Westbrook 2009, Devito and Dillon 1993, Ringer 1994, Reiner 1983, Scheffer 1938, Ives 1942, Johnson and Naiman 1987, Westbrook et al. 2011).
- Temperature Moderation **(both winter and summer)** (Kaushal et al. 2010, Hoffman and Recht 2013, White and Rahel 2008, Weber et al. 2017, McRae and Edwards 1994, Chesney et al. 2010, Munir and Westbrook 2021).

- Contaminants **(chemicals and manure)** (Balodis 1994, Muller-Schwarze and Sun 2003, Muskopf 2007, Collen and Gibson 2000, Francis et al. 1985, McDowell and Naiman 1986).
- Fish **(increases in abundance and size)** (Pollock et al. 2003, Hanson and Campbell 1963, Keast and Fox 1990, Gard 1961, Murphy et al. 1989, Leidholt Bruner et al. 1992, Schlosser 1995, Sigourney et al. 2006, Silloway and Beesley 2011, Bell et al. 2001, Brakensiek and Hankin 2007, Ransom 2007, Wallace and Allen 2007, Hillemeier et al. 2009, Chesney et al. 2010, Wallace 2010 Swales et al. 1988, Cunjak 1996, Sommer et al. 2001, Limm and Marchetti 2009).
- Amphibians **(amphibians are often used as ecological markers when water and land are in conjunction)** (Muller-Schwarze 2011, Gill 1978, Karraker and Gibbs 2009, Stevens et al. 2006, Anderson et al. 2014, Pearl and Hayes 2004, Cushman and Pearl 2007, Russell et al. 1999, Skelly and Freidenburg 2000, Quail 2001, Crisafulli et al. 2005, Stevens et al. 2007).
- Reptiles **(mostly turtles)** (Russell et al. 1999, Metts et al. 2001).
- Birds and waterfowl (to many species to list but mallard ducks are the most common)
- Geomorphology **(This is what Eric Altena alluded to. This refers to form and structure and is usually compromised by stream incision and results in less connectivity).** (Scheffer 1938, Butler and Malanson 1995, McCullough et al. 2005, Pollock et al. 2007, Polvi and Wohl 2012, Naiman et al. 1988b, Pollock et al. 2014, Cluer and Thorne 2014, Beechie et al. 2008, Demmer and Beschta 2008).

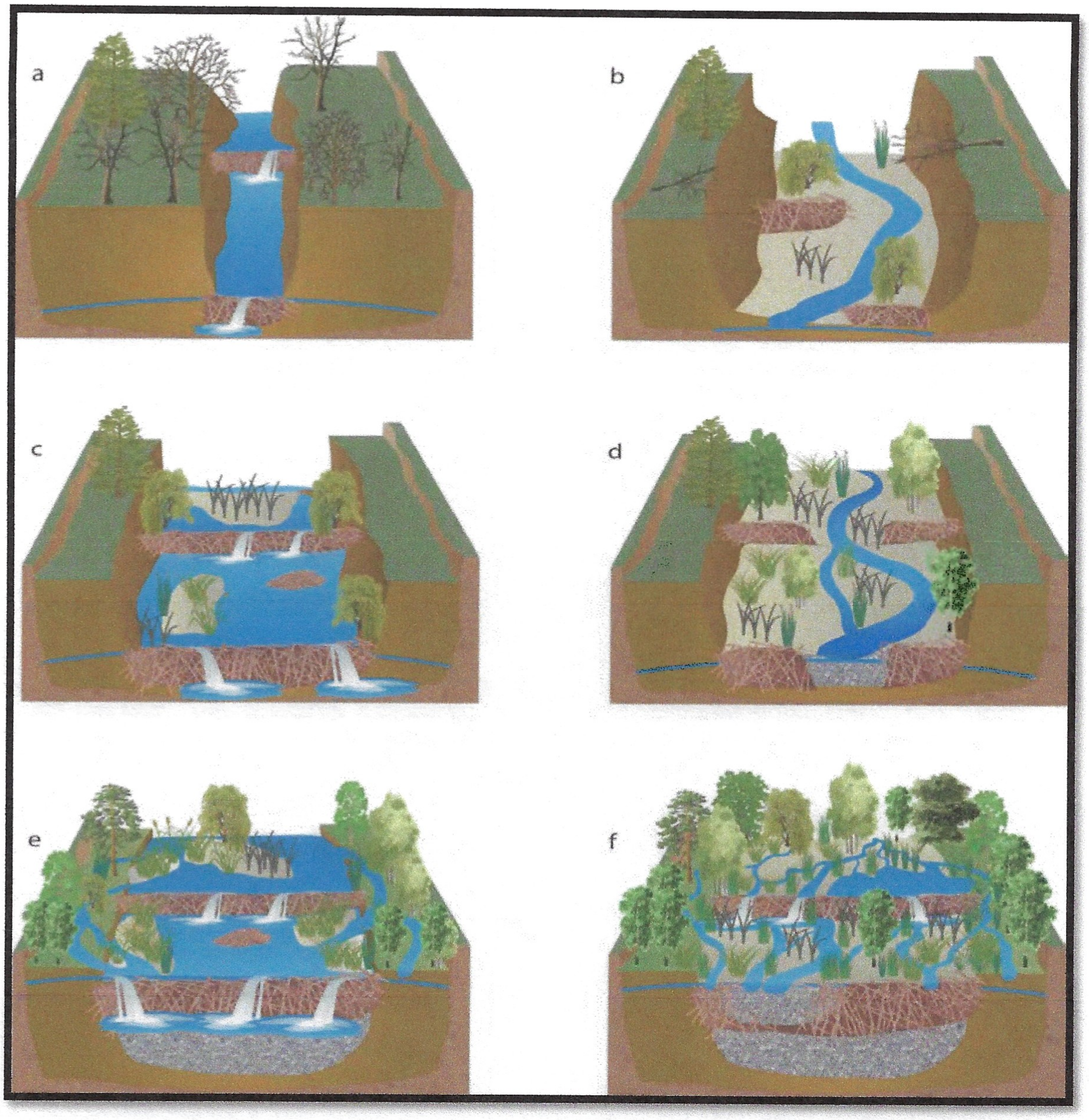

Figure 2: Conceptual model illustrating how beaver dams affect the development of incised streams; (a) beaver attempting to build dams within narrow incision trenches where high stream power often results in blowouts or end cuts that help to widen the incision trench, as illustrated in (b), allowing an inset floodplain to form. The widened incision trench results in lower stream power which enables beaver to build wider, more stable dams (c). Because of high sediment loads, the beaver ponds rapidly fill up with sediment and are temporarily abandoned, but the accumulated sediment facilitates the growth of riparian vegetation (d). This process repeats itself until the beaver dams raise the water table sufficient to reconnect the stream to its former floodplain (e). Eventually (f), the stream ecosystem develops a high level of complexity as beaver dams, live vegetation and dead wood slow the flow of water and raise groundwater levels such that multithread channels are formed, often connected to offchannel wetlands such that the entire valley bottom is saturated, as described elsewhere (Sedell and Frogatt 1983, Walter and Merritts 2008). Figure from Pollock et al. 2014.

The Beaver Restoration Guidebook and Contributors (35-36)

The Beaver Restoration Guidebook was just recently published in 2023, making it about as current as is possible. Probably its largest attribute is realized when you look at all the contributors. It is a very broad and extensive list, which suggest to me that it constitutes mainstream science. It will be the focus of our next section and is easily available to access online.

Beaver Dam Analogue Display (page 37)

Because biologist have realized the value that beaver dams bring in restoring small streams, and because the biggest deterrent to doing so is people, ecologist have designed a manmade beaver dam called a beaver dam analogue, BDA. These are very simple structures to build and can be built in areas where chosen. They can be built to chosen form and height and can incorporate needed structures, for instance fish passages, as shown in this picture. The downside with a BDA is that they will not repair themselves, as a live beaver dam usually will.

Benefits of Creating Small Instream Wetlands with Dams (pages 38-39)

Listing the many ecological advantages of incorporating instream wetlands in small creeks. This extensive list was all taken from The Beaver Restoration Handbook.

Stream Incision Repair with Small Beaver Dams (page 40)

Also taken from the same handbook, this conceptual model displays a possible progression when beaver dams are incorporated into a stream. Illustration a, shows an incised stream similar in character to LRC. Each proceeding illustration shows a slow progression of what can happen when small dams are inserted into an incised creek. Eventually deposition occurs behind the dam lifting up the riverbed and slowly connecting it with the riverbank, known as connectivity. Illustrations e and f are much healthier ecosystems when compared to what the riverbed looked like in illustration a.

Beavers support freshwater conservation and ecosystem stability

January 4, 2022

One of the most comprehensive studies conducted on beavers has conclusively demonstrated that beavers are essential for freshwater conservation and ecosystem stability by creating and preserving aquatic and wetland environments in Minnesota. This new research from the Natural Resources Research Institute (https://www.nrri.umn.edu/)(NRRI) at the University of Minnesota Duluth was recently published in the journal Ecography (https://onlinelibrary.wiley.com/doi/10.1111/ecog.05814).

"Although there are many studies on how beavers change ecosystems, the scale of this study—spanning 70 years across five different watersheds—is really unprecedented and, as a result, gave us the unique opportunity to understand how beavers transform and engineer ecosystems over long time periods and large spatial scales," said Tom Gable, coauthor of the study and a postdoctoral researcher in the University of Minnesota Department of Fisheries, Wildlife and Conservation Biology. "We think this work will be of value to many conservationists, scientists and citizens who want to understand how reintroduced or recovering beaver populations can positively affect their ecosystems."

Understanding how ecosystems become more resilient is a key goal for ecologists because it can provide insights into how ecosystems may respond to human impacts and climate change. This study suggests beavers, as ecosystem engineers, can be a biological tool that helps buffer ecosystems against disturbances and alterations.

Ecosystem engineers are ecologically important species that benefit other species by physically altering their environment. Although ecosystem engineers are relatively uncommon, they are not rare: they exist in most major ecosystems.

Most previous research on ecosystem engineers has suggested that their ecological impact does not vary across time or space. However, this research team led by Sean Johnson-Bice—who studied beavers for his master's degree at the University of Minnesota Duluth—determined that how beavers impact ecosystems can vary depending on the scale at which they are studied. In other words, beavers' ecological role varies between local and regional perspectives.

"In combination with other recent research we conducted on beaver population dynamics in northern Minnesota, our study demonstrates the resilience and stability that beaver populations have within landscapes," said Johnson-Bice, lead author of the study who is currently a PhD student at the University of Manitoba. "Their populations at a landscape scale appear relatively unaffected by environmental conditions and, as such, they can be key drivers of freshwater habitat diversity and promoting ecosystem stability."

The Helms Deep beaver dam/NPS

"There is one dam we called Helm's Deep, which measured 12 feet tall," notes Windels. "Beavers are crafty engineers. They're pretty smart for a dumb animal; they impound the most amount of water with the smallest dams. Beavers cover about 13 percent of the landscape. What we see now is what we would have seen pre-settlement. It's a window into the past."

But wolves and moose are also dependent upon the beavers. The moose population was as low as 200 in 2006, a function of disease and habitat quality. They do like the aquatic vegetation that grows in beaver ponds.

"There are 40 to 50 moose in the park now," Windels says.

Bridge Creek Study

Article | Open access | Published: 04 July 2016

Ecosystem experiment reveals benefits of natural and simulated beaver dams to a threatened population of steelhead (*Oncorhynchus mykiss*)

Nicolaas Bouwes, Nicholas Weber, Chris E. Jordan, W. Carl Saunders, Ian A. Tattam, Carol Volk, Joseph M. Wheaton & Michael M. Pollock

Scientific Reports **6**, Article number: 28581 (2016) | Cite this article

A Corrigendum to this article was published on 05 June 2018

Abstract

Beaver have been referred to as ecosystem engineers because of the large impacts their dam building activities have on the landscape; however, the benefits they may provide to fluvial fish species has been debated. We conducted a watershed-scale experiment to test how increasing beaver dam and colony persistence in a highly degraded incised stream affects the freshwater production of steelhead (*Oncorhynchus mykiss*). Following the installation of beaver dam analogs (BDAs), we observed significant increases in the density, survival and production of juvenile steelhead without impacting upstream and downstream migrations. The steelhead response occurred as the quantity and complexity of their habitat increased. This study is the first large-scale experiment to quantify the benefits of beavers and BDAs to a fish population and its habitat. Beaver mediated restoration may be a viable and efficient strategy to recover ecosystem function of previously incised streams and to increase the production of imperiled fish populations.

Introduction

Beaver in Eurasia and North America were once abundant and ubiquitous[1]. Their dense and barbed fur has great felting properties and as early as the 1500s, intense trapping to provide pelts mainly for making hats occurred throughout Eurasia[2]. By the early 1700s, beaver were nearly extirpated in Eurasia and North America became the new source of pelts for international commerce. The exploration, settlement and many territorial claims of North America by several European countries were driven mainly by the search for beaver-trapping opportunities[2].

Beavers save Czech government €1.2 million by building planned dam

Officials say beavers accomplished in days what humans couldn't in years due to bureaucracy.

By JERUSALEM POST STAFF
FEBRUARY 10, 2025 14:25

Wild European beaver, Castor fiber, sitting on felled tree in water and gnawing bark from branches.
(photo credit: Vaclav Matous. Via Shutterstock)

In the Czech Republic, a family of beavers saved the government approximately 30 million Czech crowns (1.2 million euros) by building a dam that local authorities had been planning since 2018. According to Blic, the

In the Czech Republic, a family of beavers saved the government approximately 30 million Czech crowns (1.2 million euros) by building a dam that local authorities had been planning since 2018. According to Blic, the beavers began constructing the dam without any human intervention, effectively accomplishing a project that had been delayed due to bureaucracy and outstanding approvals.

The beavers chose to build their dam in a drainage canal created by the military on a former training ground in the Brdy region. This area had been causing headaches for local environmentalists due to its artificial drainage system, which they had been attempting to reverse. As reported by Izvestia, the beavers' activity contributed to the restoration efforts in the region.

"A beaver can build a dam in one or two nights," said local zoologist Jiří Vlček, according to Blic. "While humans have to obtain building permits, approve projects, and find funding, beavers simply act instinctively and quickly."

Authorities in the Czech Republic expressed their admiration for the beavers' work. "Beavers always know best," said Jaroslav Obermajer from the Nature Conservation Authority, as reported by Metro. "The places where they build dams are always chosen just right—better than when we design it on paper."

The beavers' dam successfully waterlogged the local floodplain, creating new wetlands vital for the river's habitat. According to Bild, the wetland provides favorable conditions for swamp inhabitants, including rare stone crayfish, frogs, and other endangered species.

"The beavers have done exactly what we had planned in tedious bureaucracy. And they did it for free," said Bohumil Fišer, head of the Administration for Protected Areas of the Czech Hills.

The dam project was part of the Czech Republic's plan to revitalize an area of the Brdy region that was once damaged by the erection of a military base. The authorities were planning the construction since 2018 but faced delays due to necessary permits and outstanding approvals. The local water management was negotiating projects and land ownership related to the river revitalization, facing challenges including unclear land ownership.

for the whole model period (2006 through water year 2018) at the two gaging stations with measurements that span most of the model period (long-term gauge and downstream gauge). The results indicate an adequate fit of modeled base flows during summer low flow periods, the focus of evaluations that use the model.

We went further by conducting an inter-watershed comparison as an independent line of evidence on the relationship between groundwater-use rates and summer base flow. We compared the stream flow calculated by the Little Rock Creek model to a nearby watershed that had fewer irrigation systems and we found that there was a high level of agreement between the two.

We also heard from stakeholders that the estimated water use volumes reported by irrigators may well be higher than actual volumes used. The suggestion was that if the DNR used volumes that more accurately reflected water use it would show a lower impact to stream flow from irrigation. Irrigators and the DNR collaborated on a two-year water use calibration study of nine irrigation systems and found that it was common to report irrigation volumes that are more than 10 percent greater than actual pumping volumes. This study cannot be relied upon as being representative of all water users in the area as it only included 9 wells out of over 300 permitted wells in the area. However, to understand how much of difference over-reporting may affect the analysis, the DNR developed a model run with groundwater uses modified to 80 percent of the reported volumes. The result was a computed reduction in the median baseflow diversion of 0.27 cfs at station 15029001 as compared to the reference median baseflow at this station of 7.2 cfs. With this information the DNR modeled sustainable diversion limit used the actual reported volumes.

11. Respondents did not agree with the proposed solutions to avoid negative impacts to Little Rock Creek. They believe that piping water from a distance is too expensive, complicated, and unnecessary in years where rainfall is high.
    DNR Response: *The feasibility of this potential action has not yet been evaluated. The RFP that DNR will be issuing will provide more context on potential solutions. The evaluation of this and other potential actions from proposed water users will be considered as part of the water use conflict resolution.*

12. Respondents believed that beaver dams could increase recharge and that DNR has not shown why this approach would not work.
    DNR Response: *Beaver will build dams on streams to impound water. In the past, beaver have been active at the site of the Sartell Wildlife Management Area, creating a pool. The DNR installed a permanent structure to increase assurances that a pool would persist for waterfowl habitat. As described in the Findings of Fact, this has increased the temperature of Little Rock Creek, contributing to the high temperature impairment below the Sartell WMA. Our in-stream analysis confirms this and is consistent with the findings in the Little Rock Total Maximum Daily Load (TMDL). We have temporarily removed the dam to promote colder downstream temperatures and are monitoring the temperatures below the dam. Any impoundments on the stream, whether constructed by people or beaver, will carry the risk of increasing both temperatures and the likelihood of negative impacts to ecosystems.*

Supporting Documents of Beaver Dam Restoration Projects (page 42-46)

These are supporting documents in using beavers and BDA's in stream restoration. The first is a 70-year study done by the University of Minnesota Duluth using 5 watersheds in the Lake Superior region. The second is from Voyageurs National Park in northern Minnesota where the reintroduction of beavers has contributed to the overall improvement of their ecosystem. The third comes from Oregon and is considered to most extensive study ever done on the relationship between trout fish habitats, stream temperatures, effects of BDA's and live beavers, and the usage of a control plots where observed comparisons could be made. The last two pages come from Europe where a military base was erected causing harm to a local stream. After more than 5 years of planning and disputes as to how to fix the problem, in two nights live beavers came to the rescue and solved the problem for free.

DNR's Commissioner's Response to Using Beaver Dams (page 47)

This comes from the DNR's Commissioner's response to stakeholders in the LRC project where using beavers to restore LRC was proposed. This response indicates how far removed from mainstream science they really are, or how policy driven everything is towards a predetermined purpose. It seems that the term "negative impacts" is used whenever some ideas counter opposes their purpose. It is so easy to assign that terminology to almost anything because everything actually negatively impacts something. Yes, there may be negative impacts to using beaver dams, but what about considering the overall effects to the numerous problems associated with LRC, and what is referred to as common sense.

DEPARTMENT OF NATURAL RESOURCES

Assessment of instream temperatures in Little Rock Creek near Sartell Wildlife Management Area

1/26/2021

Challenges

- In regards to the pond crated behind the impoundment, there is no indication that any attempt was made to measure temperature gradients inside the pond, or if the present of a thermocline existed at the bottom of the pond, or at the lower portions inside the creek bed.

- Since LRC is listed by the TMDL as being impaired for excess nutrient load of phosphorus and nitrates, the nutrient load entering the pond, verses exiting the pond, was never monitored. Wetlands of this nature have been cited to be excellent removers of phosphorus through sedimentation, and nitrates through anaerobic processes. References are often made referring to wetlands as "natures kidneys", in comparison to their similar functions. The potential now exists that the impairment of LRC, and the consequential nutrient loading of LRL, may have been accidentally increased.

- When considering the numerous inter and intra annual variations that LRC goes through, can one test on one pond be used to accurately determine all warming possibilities? What about pond sizes? Could a smaller pond possible produce different results? This particular impoundment had been in place for around 50 years, and evidence suggest that age could be a deterrent to producing baseflow. Another factor not considered is the substrate below the pond. Does it accurately match substrate in all other locations?

Thermal Characteristics of a Beaver Dam Analogues Equipped Spring-Fed Creek in the Canadian Rockies

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(This article belongs to the Special Issue **Ecosystem Functioning in Rivers and Riparian Zones**)

Abstract

Beaver dam analogues (BDAs) are becoming an increasingly popular stream restoration technique. One ecological function BDAs might help restore is suitable habitat conditions for fish in streams where loss of beaver dams and channel incision has led to their decline. A critical physical characteristic for fish is stream temperature. We examined the thermal regime of a spring-fed Canadian Rocky Mountain stream in relation to different numbers of BDAs installed in series over three study periods (April–October; 2017–2019). While all BDA configurations significantly influenced stream and pond temperatures, single- and double-configuration BDAs incrementally increased stream temperatures. Single and double configuration BDAs warmed the downstream waters of mean maxima of 9.9, 9.3 °C by respective mean maxima of 0.9 and 1.0 °C. Higher pond and stream temperatures occurred when ponding and discharge decreased, and vice versa. In 2019, variation in stream temperature below double-configuration BDAs was lower than the single-configuration BDA. The triple-configuration BDA, in contrast, cooled the stream, although the mean maximum stream temperature was the highest below these structures. Ponding upstream of BDAs increased discharge and resulted in cooling of the stream. Rainfall events sharply and transiently reduced stream temperatures, leading to a three-way interaction between BDA configuration, rainfall and stream discharge as factors co-influencing the stream temperature regime. Our results have implications for optimal growth of regionally important and threatened bull and cutthroat trout fish species.

LRC Solution Comparative
(which solution offers the best results based on mainstream science, opinion)

No Benefit (left blank)   Some Benefit X   Moderate Benefit XX   Good Benefit XXX

Issue and (Where Referenced)	Importing Water	Beaver Dams and BDA's
High phosphorus and sediment load (TMDL)		X X X
High Nitrogen levels (TMDL)		X X
Stream Temperature (TMDL)	X	X?
Dissolved Oxygen Levels (TMDL)	X	X
Increasing Critical Low Flow Levels (TMDL)	X	X X
Stream and Riverbank Connectivity (TMDL)		X X
Predation (TMDL)	?	?
Reducing Stream Incision (DNR Fisheries Dept.)		X X
Economic Value (Minnesota Tax Payers)		X
Increase Biodiversity (Overall Stream health)	X	X X X

Picture of a Beaver Dam at our Nursery (page 51)

This is a picture of the live dam that was present at our nursery for several years. This was the second dam that they had built within a few years. The first dam was further downstream and had interfered with monthly gauging that DNR personnel were taking. Some trapping occurred there, and the beavers decided to move their dam upstream a little to this location. Notice the narrow width of the dam indicating the narrowness of the stream in this location, and showing once again the incision that is occurring. Our footbridge, located slightly further upstream, is actually connected to a short-raised walkway that we used to shorten the total length of the footbridge. We later discovered, after digging in some wire, that this raised pathway is actually an extinct beaver dam. The width of that dam, and when extrapolating the current width of the stream, the dam had to have been over 100 feet in length, indicating to us that this stream had not always been incised to this degree.

One deterrent to having live beavers is the fact that beavers need trees for food and to build dams with. One of their favorites trees is Aspen, which is the white bark trees with black blotches on the bark. Aspen trees are very common along creeks since they are very shallow rooted and prefer wet soils. Aspen trees are not commonly sold by nurseries because they are very susceptible to fungal diseases. It is very rare to see a one-foot diameter aspen tree in the wild because it usually succumbs to diseases before they grow to that size. Beavers however usually remove them when they are still healthy, but aspen trees have a unique feature that allows them sucker up, or to resprout from the roots, if removed before they die. This seems to be a symbiotic relationship between the beavers and aspen trees where both benefit from the other. At our nursery where the aspen trees were removed, now once where we had hundreds of aspens, we now have thousands. They recover very fast since their root system is still 100% functional and it is not uncommon for them to grow 5 or more feet in the first year of removal.

Instream Flows for Riverine Resource Stewardship

Tom Annear, *Wyoming Game and Fish Department*

Ian Chisholm, *Minnesota Department of Natural Resources*

Hal Beecher, *Washington Department of Fish and Wildlife*

Allan Locke, *Alberta Sustainable Resource Development*

Peter Aarrestad, *Connecticut Department of Environmental Protection*

Nina Burkhart, *U.S. Geological Survey, Fort Collins, Colorado*

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Christopher Estes, *Alaska Department of Fish and Game*

Joel Hunt, *Manitoba Conservation*

Rick Jacobson, *Connecticut Department of Environmental Protection*

Gerrit Jobsis, *South Carolina Department Natural Resources*

John Kauffman, *Virginia Department of Game and Inland Fisheries*

John Marshall, *Ohio Department of Natural Resources*

Kevin Mayes, *Texas Parks and Wildlife Department*

Clair Stalnaker, *U.S. Geological Survey, Emeritus*

Rod Wentworth, *Vermont Department of Fish and Wildlife*

IFC Riverine Resource Stewardship Policy Statement: All streams and rivers should have instream flows that maintain or restore, to the greatest extent possible, ecological functions and processes similar to those exhibited in their natural or unaltered state.

SETTING PROGRAM GOALS AND OBJECTIVES

Instream flow programs should incorporate a broad ecosystem perspective that allows aquatic resource goals and objectives to be designed according to the unique characteristics of each instream flow issue. Knowledge of state and provincial water allocation policies can guide managers in defining realistic goals and objectives for specific stream segments. Managers can then identify the technical approaches to be used and plan studies to gather the information necessary to set appropriate flow regimes, evaluate the potential effects of proposed development schemes, or develop restoration plans. A comprehensive ecosystem approach can also facilitate communication between natural resource agencies, stakeholders, and the public by keeping interested parties informed about the status of the stream's resources, threats from development, opportunities for improvement, and restoration plans.

It is essential to know what outcomes are expected before embarking on a course of action. Once these goals are stated, objectives can be identified to best secure instream flows. In the initial stages of an emerging instream flow program, particularly in situations where extensive water use and over-allocation is the norm, the agency's objective may be to attain a permanent instream flow where dewatering had been prevalent or to set a water use limit to halt continuing decline. Although obtaining a single value minimum flow may be a positive step forward, the IFC promotes establishing or expanding program opportunities that move beyond the simple watering of dry stream channels toward sustaining healthy resource needs for managing fishery resources. Biologists began to include more practical, equitable, and scientifically based considerations into their endeavors. In the past 50 years, they have produced more than three-dozen various methods—29 of which are presented in this text.

Instream Flows for Riverine Resource Stewardship is by far the best and most comprehensive treatise on the subject of instream flows to date. The material represents an exhaustive treatment of a very complex and highly technical subject. It frequently, and appropriately, stresses the importance of addressing five riverine components (i.e., hydrology, biology, geomorphology, water quality, and connectivity) when developing, commenting on, or designing instream flow programs and recommending instream flow prescriptions. There is adequate warning and justification against the use of single-flow recommendations, like $7Q_{10}$, for fishery and riverine management. In addition to the riverine components, the authors stress the need to incorporate legal, institutional, and public involvement components in efforts to preserve fishery and wildlife resources. Because the science of instream flow is necessarily multidisciplinary, the authors emphasize that riverine management is most effective when all eight ecosystem components are integrated.

Ample consideration is given to water law in general (including the eastern riparian doctrine versus the western prior appropriation doctrine) as well as to agency rights and responsibilities; public trust and public interest philosophies; the importance of public participation and effective communication; streamflow measurements and U.S. Geological Survey data records, which are the basis of many methodologies; and macro-, meso-, and micro-habitat. Also emphasized is the need to mimic and preserve natural flow regimes and understand the effects of channelization, stream straightening, riprap, bank armoring, and in-channel and riparian mining. The authors underscore the vital key of protecting all aquatic habitats, including the riparian-floodplain zones, and argue for a drought policy by which water shortages would be

TABLE 3.

Summary of instream flow assessment tools and a general description of their application.

Instream Flow Assessment Tool	Type of Technique	Level of Effort	Resource Component
Indicators of Hydrologic Alteration (IHA)	Monitoring/Diagnostic	Low, but can be difficult (office)	Hydrology
Range of Variability Approach	Monitoring/Diagnostic	Low (office)	Hydrology
Two-Dimensional Models	Incremental	High (field)	Biology
Aquatic Base Flow (ABF)	Standard Setting	Low (office)	Biology
Biological Response Correlations	Incremental	High (field)	Biology
Feeding Station	Incremental	High (field)	Biology
Flow Duration Curve Methods	Standard Setting	Low (office)	Biology
Index of Biotic Integrity (IBI)	Monitoring/Diagnostic	High (field)	Biology
Physical Habitat Simulation (PHABSIM) System	Incremental	High (field)	Biology
Plunge Pool	Incremental	High (field)	Biology
Riverine Community Habitat and Restoration Concept (RCHARC)	Incremental	Moderate (field)	Biology
Single Transect	Standard Setting	Moderate (field)	Biology
Tennant	Standard Setting	Low (office) Moderate (field)	Biology
Toe-of-Bank Width (Toe Width)	Standard Setting	Moderate (field)	Biology
Wetted Perimeter	Standard Setting	Moderate (field)	Biology
Channel Maintenance Flows	Standard Setting	High (field)	Geomorphology
Flushing Flow (Empirical, Sediment Transport Modeling, and Office Based Hydrologic Models)	Standard Setting	High (field); Low (office)	Geomorphology
Geomorphic Stream ClassificationSystem	Monitoring/Diagnostic	High (field)	Geomorphology
Hydraulic Engineering Center—6 Model (HEC-6)	Incremental	High (field)	Geomorphology
Hydraulic Engineering Center—River Analysis System (HEC-RAS)	Incremental	High (field)	Geomorphology
Enhanced Stream Water Quality (QUAL2E)	Monitoring/Diagnostic	High (field)	Water Quality
Stream Network Temperature (SNTEMP) Stream Segment Temperature (SSTEMP)	Monitoring/Diagnostic	High (field) Low (field)	Water Quality
Seven-Day, Ten-Year Low Flow ($7Q_{10}$)	Monitoring/Diagnostic	Low (office)	Water Quality
Floodplain Inundation	Incremental	High (field)	Connectivity
Migration Cue	Standard Setting	Low (office)	Connectivity
Salmon Barrier	Incremental	Moderate (field)	Connectivity
Tidal Distributary/Estuary	Incremental	High (field)	Connectivity
Demonstration Flow Assessment (DFA)	Standard Setting	Moderate (field)	Multiple Components
Instream Flow Incremental Methodology (IFIM)	Incremental	High (field)	Multiple Components

Critical Opinion: The PHABSIM is best used as a decision-making tool for evaluations of alternative discharges to quantify the proportions of suitable and unsuitable areas of stream reaches and segments subject to regulation or flow management. Practitioners should place emphasis on developing habitat suitability criteria that closely describe the actual behavior of the species of interest.

Output must be measured against what is known to occur for the species of interest. Reach mapping is a critical component of applying this method and can help to ensure against mistakes in applying the habitat suitability criteria. For example, fish that typically spawn or rear along river channel margins and floodplains may select for slow, shallow habitat that the model may indicate occurs at very low discharges in the center of the channel. In reality, only overbank flows provide spawning and rearing habitat for this species, and correct interpretation of the results and subsequent recommendations must reflect this biological phenomena. To avoid such mistakes, the modeler must eliminate (set channel index to zero) in-channel areas from consideration as spawning and rearing habitat.

When used, the PHABSIM model must be placed in proper context as to the relative importance and likely change in the other ecosystem components. It does not provide information about the full range of ecosystem components but is useful for helping describe the biological component by assessing hydraulic habitat. Additional analysis, separate from PHABSIM, must be completed to adequately address instream flow needs for hydrologic variability (inter- and intra-annual), geomorphology, water quality, and connectivity. Practitioners should not prescribe a minimum instream flow standard by recommending the maximum habitat value from the weighted usable area/discharge graph for a single life stage of a single species; doing so can result in unrealistically high recommendations that damage the credibility of the entire study and the study team. Rather, output from the model should

Limitations and Constraints: The PHABSIM provides a habitat/flow function that is limited to the hydraulic attributes of depth and velocity within fixed channel indexes. Further, it evaluates only the spatial aspects of the hydraulic attributes within stream reaches and requires a well designed stratified sampling procedure for extrapolation to segments and linkage with hydrologic time series to describe the temporal aspect of the habitat hydraulics. Because the habitat-based instream flow models rely on empirical measurements of the stream channel as inputs, adequate understanding of sediment transport and channel dynamics must be incorporated into any simulation for unobserved flow conditions.

The model does not predict the effects of flow on channel change. If a channel is not in dynamic equilibrium, the model users may have to hedge on simulations of future (therefore unobservable) discharge conditions and call for periodic adjustments, with empirical measurements at regular intervals. Likewise, water quality is not incorporated in PHABSIM. Any significant alteration of the flow regime by flow regulation has been shown also to result in alteration of the temperature regime. Small changes in temperature can have very significant effects on egg maturation, incubation, and time of hatching and growth, depending on the species. Stream temperature can also affect the suitability of some habitat types for some species and life stages of organisms. In addition, PHABSIM cannot provide meaningful information on the effects of rapidly varying flow.

Inappropriate selection and use of models, ignoring model assumptions, and failure to validate model output can lead to serious errors in application. First-order habitat requirements are well known for only a few high-profile species. Basic habitat requirements are not known for many rare or widely dispersed species, or those that inhabit streams and habitat types that are difficult to sample. Second-order habitat requirements (e.g., proximity to food sources or refugia) are largely unknown for many aquatic species.

Calibration and Validation: Calibration and validation procedures are described by Milhous et al. (1989) for the hydraulic models and by Thomas and Bovee (1993) for the habitat suitability models. Careful calibration and validation of both aspects of PHABSIM are necessary to establish scientific credibility.

The Physical Habitat Simulation Study – Analysis (pages 53-58)

The Physical Habitat Simulation Study, PHABSIM, was used to determine the sustainable diversion limit on LRC. This portion of the model has never been peer reviewed up to this point, mainly because it requires a biologist, not just a hydrologist. In an effort to review this process on my own, I purchased the 'Instream Flows for Riverine Resource Stewardship' manual, which was intended to be used for purposes such as what exist in LRC, or a study college manual. This manual also emphasizes the "need to mimic and preserve natural flow regimes." It also "stresses the importance of addressing five riverine components (i.e., hydrology, biology, geomorphology, water quality, and connectivity)."

On page 42, I included a page from this manual that list 29 different models to choose from when addressing stream ecology. Note that the PHABSIM study addresses the component of biology only. Other models are available for addressing geomorphology, water quality, and connectivity. In the next two pages, I highlighted excerpts from this manual that indicate quite clearly that the PHABSIM model must include the other components when adequately assessing the extent of variability that exist in any stream. Analyzing one component only will give very limited information on total stream health.

In another stark reminder of the limiting focus of this study, we only have to be reminded of what Eric Altena said about LRC in the location of where this study occurred. He said that severe streambed erosion was happening in the minimum maintenance road area, which corresponds with the focus area of the PHABSIM study. When considering that only the biological aspects were accounted for in this study, and that the study area had other rather severe limiting components of connectivity, water quality, and geomorphology, resulting from severe erosion, one has to wonder whether the results of just using one component can accurately describe the complex ecology of LRC. Why were the other components not looked at when they represent the bulk of the problem in LRC?

Recharge Analysis:

Quote from the model:

- "Crop irrigation increases groundwater recharge relative to the reference land cover of non-irrigated alfalfa because irrigation increases soil moisture. Enhanced recharge occurs after large summer rainfall events, in the fall as evapotranspiration rates decrease, and even when the following spring if there is a winter soil-moisture deficit for non-irrigated alfalfa".

- In the simulations handout from the 08/08/2022 model release, **20 wells** had to be removed to get below the SDL, or **9 wells** were replaced with importing water to equal the 20 wells to get below the SDL. This indicates that recharge, or baseflow, increases with well removal, but that recharge is more than twice that rate where irrigation is occurring.

- Aquifer recharge is the result of excess rainwater that neither runs off nor is lost to evaporation

- In all fields the recharge surface area will always exceed the area being irrigated. Usually corners or adjacent non-irrigated areas will add to the recharge. Or stated another way, nowhere currently does a single well irrigate a field larger than its recharge surface area. Most of the water lost from irrigation comes from extra transpiration of the crops being grown, or from extra evaporation while irrigating, not from removing water from the recharge area. Removing additional water off a given site could result in aquifer decline in that area.

- We also do not know how close we are with some wells to the "edge", where well interference or drawdown past the top of the intake screen could occur. And we also don't know where that "edge" will be in the future if prolong droughts should occur. My well monitoring of 20 wells in the LRC zone of influence has reviewed that some wells do fluctuate more than others.

- For these reasons, if import wells are to become part of our future, some early warning system should be installed in areas where the extra water is being withdrawn.

CHARR III | Published: 29 July 2019

Projected changes in Brook Trout and Brown Trout distribution in Wisconsin streams in the mid-twenty-first century in response to climate change

Matthew G. Mitro, John D. Lyons, Jana S. Stewart, Paul K. Cunningham & Joanna D. T. Griffin

Hydrobiologia **840**, 215–226 (2019)

Abstract

Climate warming is a threat to the survival of fishes adapted to cold water. Brook Trout *Salvelinus fontinalis* and Brown Trout *Salmo trutta* are two cold-water species occurring in streams in Wisconsin, where climate change may make these species particularly vulnerable. Vulnerable trout populations need to be identified to aid in the development of adaptation strategies. We used web-based stream temperature and fish-distribution models in FishVis to predict current (late twentieth century) and project future (mid-twenty-first century) distributions of Brook Trout and Brown Trout. The models predict the suitability of habitat for trout in individual reaches using environmental variables in a geographic information system, including adjacent and upstream channel characteristics, surficial geology, landcover, and climate. Future projections of air temperature and precipitation were obtained from 13 general circulation models downscaled for Wisconsin. Currently, 34,251 km of streams are suitable for Brook Trout and 20,011 km for Brown Trout. The models project a decline of 68% (10,995 km) in stream habitat for Brook Trout and a decline of 32% (13,668 km) for Brown Trout. These projected declines, while substantial, were lower than earlier estimates because our models account for projected increased precipitation that may enhance groundwater inputs and partially offset higher air temperatures.

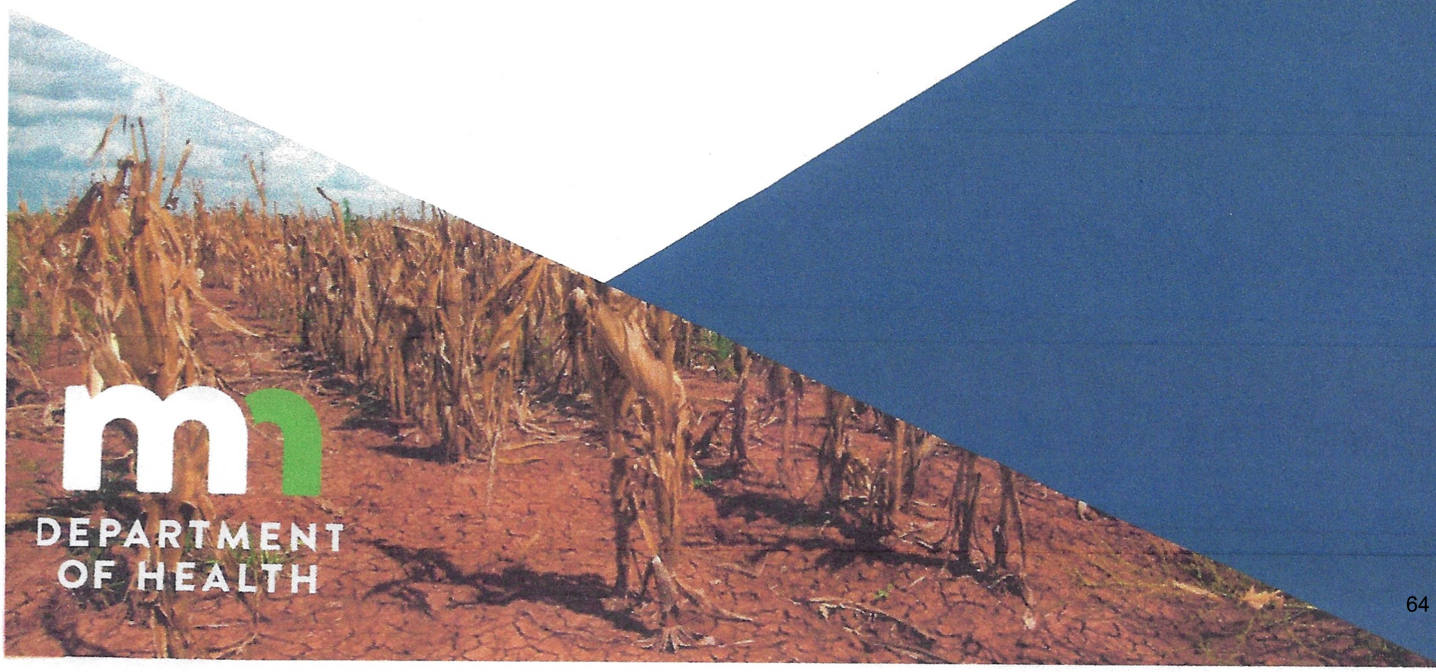
1980	40.42	1970-1979
1981	42.5	39.96
1982	39.19	
1983	41.6	
1984	41.61	
1985	39.07	41.26
1986	41.7	
1987	45.65	
1988	41.69	
1989	39.23	
1990	42.64	
1991	42	
1992	41.31	
1993	39.25	
1994	41.14	41.53
1995	40.5	
1996	38.04	
1997	40.92	
1998	45.36	
1999	44.14	
2000	42.09	
2001	43.36	
2002	42.33	
2003	41.91	
2004	41.66	
2005	43.64	42.32
2006	45.01	
2007	43.09	
2008	39.75	
2009	40.41	
2010	43.54	
2011	42.54	
2012	45.59	
2013	39.59	
2014	39.02	
2015	43.81	42.18
2016	44.67	
2017	42.67	
2018	40.8	
2019	39.58	
2020	42.95	
2021	44.57	43.68
2022	40.49	
2023	44.37	
2024	46.05	

Baseflow Temp. will reflect air temp.

Planning for Climate & Health Impacts in West Central Minnesota

Emergency Management Considerations for HSEM Region 4

Published by the Minnesota Climate & Health Program in August 2018



DEPARTMENT OF HEALTH

REGION 4 CLIMATE PROFILE

Use the following information on temperature, precipitation, and vulnerable populations to help plan for future weather-related incidents.

TEMPERATURE

There has been an increase in winter and summer temperatures. Our average winter lows are rising rapidly, and our coldest days of winter are now warmer than we have ever recorded. In fact, Minnesota winters are warming nearly 13 times faster than our summers. The continued rise in winter temperatures will result in less snow pack, which will increase chances for grassland/wildfires as well as drought. The warmer winter temperatures will also have major consequences for our ecosystems, including native and invasive species, whose growth, migration, and reproduction are tied to climate cues. The increase in Lyme disease across Minnesota is also likely influenced in part by the loss of our historical winters, due to a longer life-cycle period for ticks. Freeze-thaw cycles are likely to increase as well, damaging roads, power lines and infrastructure, and causing hazardous travel conditions. By mid-century our average summer highs will also see a substantial rise, coupled with an increase in more severe, prolonged heat waves that can contribute to drought and wildfires and pose a serious health threat, particularly to children and seniors. Here are temperature trends for HSEM Region 4:

Average Summer Maximum Temperature for HSEM Region 4		
1981-2010	2050-2075	Change
80.7 °F	88.3 °F	+7.6 °F

Average Winter Minimum Temperature for HSEM Region 4		
1981-2010	2050-2075	Change
4.5 °F	14.3 °F	+9.8 °F

PRECIPITATION

There has been an increase in total average as well as heavy precipitation events, with longer periods of intervening dry spells. Our historical rainfall patterns have changed substantially, giving rise to larger, more frequent heavy downpours. Minnesota's high-density rain gauge network has captured a nearly four-fold increase in "mega-rain" events just since the year 2000, compared to the previous three decades. Extreme rainfall events increase the probability of disaster-level flooding. However, there is also an increased probability that by mid-century heavy downpours will be separated in time by longer dry spells, particularly during the late growing season. Over the past century, the Midwest hasn't experienced a significant change in drought duration. However, the average number of days without precipitation is projected to increase in the future, leading Minnesota climate experts to state with moderate-to-high confidence that drought severity, coverage, and duration are likely to increase in the state. Modeling future precipitation amounts and patterns is less straight-forward compared to temperature. Some climate models do a better job than others representing rainfall for the Midwest, and available data sources only provide average estimates on a monthly scale, masking the spikes in extremes that trigger flood and drought disasters. Trend data provided here for HSEM Region 4 are summarized for early summer, when historically Minnesota receives most of its rainfall, and for early fall when rainfall scarcity may threaten crop harvests and local agricultural economies:

Average Early Summer Precipitation for HSEM Region 4		
1981-2010	2050-2075	Change
3.9"	4.4"	+0.5"

Average Early Fall Precipitation for HSEM Region 4		
1981-2010	2050-2075	Change
2.5"	2.3"	-0.2"

[illegible] minute supply. This ability to prey on different size fish enables it to dominate many habitats and have a catastrophic effect on the many species it encounters as it moves from area to area in search of food. The introduction of the Nile perch into Lake Victoria has had a catastrophic effect on the ecosystem. Hundreds of fish native to the lake have become extinct, by the 1980's, 300 of these fish were nonexistent."

Imagine having a lake rich with hundreds of different species of fish, and within a couple decades, the majority of them are gone and only the Nile perch dominates. The effect is overwhelming and extends to the shore. The fish is fattier than the native fish species, so rather than drying it in the sun, fishermen have to smoke their catch. This requires a good deal of firewood, resulting in the widespread loss of surrounding forest that was already under pressure — and the likely the decline of species reliant on the forest. The cascading disastrous effects have placed it firmly on the list of one of the 100 worst invasive species in the world.

Brown trout

The brown trout is a freshwater fish, but it can adapt to salt water. (Photo: IDAK/Shutterstock)

This trout species may be a favorite among fishermen, but it's not necessarily a favorite among other fish. Brown trout are originally native to Europe, North Africa and western Asia but today can be found all over the world. It was part of an aquaculture trend that started in the mid-1800s in Europe and has been moved around the world ever since as a popular fish for farming and fishing. However, its impact on native fish species can be problematic.

Not only does the brown trout compete — and usually win — against native trout species such as brook trout and golden trout, but it also out-competes other fish species. Where it doesn't out-compete other trout species, there's evidence that it breeds with them. This has conservationists worried about the genetic make-up of native species. Conservation measures, including restricting the introduction or stocking of brown trout, are important steps in battling this invasive species, and in some cases, it's working.

Rainbow trout

Below is a list of current research projects, with additional links, that are currently being conducted in Minnesota in connection with effects of brown trout to native species.

Current Fisheries Research Projects

These projects are currently being conducted by the Lake City Fisheries Research staff as lead or co-investigators:

- Project 677 - The Effects of Removing Brown Trout from a Driftless Area Stream in Southeastern Minnesota
- Objectives - This study will identify whether removal of brown trout allows a headwater brook trout population in SE Minnesota to expand in abundance. Results will quantify changes in growth and survival relative to a control reach, revealing extents of interspecific interactions and longer-term compensatory responses. Finally, the study will measure the effectiveness of the fish barrier to upstream movement of brown trout, the timing and extent of movement, thus informing managers about the frequency and intensity of brown trout control efforts needed to maintain brook trout within the lower stream reaches.
- Demographic Responses of Brook Trout to Removal of Brown Trout from a Driftless Area Stream in Minnesota PDF

- Project 675 - Characterization of Driftless Area Brook Trout Populations in Southeastern Minnesota: Distribution, Population Dynamics, Movement, and Effects of Sympatry with Brown Trout

- Objectives - To characterize brook trout populations in southeastern Minnesota, determine if population characteristics differ between presumed native and eastern origin populations, and estimate movement, growth, and mortality of brook trout in sympatry with brown trout.

- Spatial Distribution of Apparent Native Brook Trout Populations and their Characteristics in Southeastern Minnesota Streams PDF

- Application of Mixture Models for Estimating Age and Growth of Stream Dwelling Brook Trout PDF

- Seasonal Movement, Growth, and Mortality of Brook Trout in Sympatry with Brown Trout in Headwater Streams in Southeast Minnesota PDF

- Project 674 - Movement, growth and mortality of brown trout in southeast Minnesota streams.

- Objective - Quantify spatial and seasonal patterns of survival and movement of brown trout, evaluate the relative importance of survival and movement on brown trout populations, and assess the influence of habitat quality and trout density on spatial and seasonal patterns.

- Project 659 - Effects of trout density and other factors upon the growth of brown trout in southeast Minnesota streams.
- Objectives - Quantify amount of variation in brown trout growth that is due to year-to year changes in environmental conditions versus stream-to-stream differences and assess the effects of trout density and other environmental factors on these year-to-year and stream-to-stream differences in growth.

- Project 603 - Review of brown trout ecology in Driftless Area streams and elsewhere with application to management.

what trout species was responsible for the

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AI Overview

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Lake trout, brown trout, and rainbow trout are all species of trout that contributed to the extinction of the Titicaca orestias, a fish native to Lake Titicaca. These trout were introduced to the lake in the 1930s and 1940s, outcompeting the native fish.

Explanation

- The trout were introduced to the lake in the form of eggs sent by the United States.
- The trout became the top predator in the lake, eating smaller fish like the carachi.
- The trout also competed with the native fish for food.
- The trout transformed local fishing practices, with the trout becoming a popular catch.

Other factors that contributed to the extinction of the Titicaca orestias include:

Pollution

Runoff from fertilizers and pesticides, as well as metals like zinc and copper, contaminated the water

Habitat loss

The introduction of the trout and silverside disrupted the lake's ecosystem

Titicaca orestias - Wikipedia

The Titicaca orestias became extinct due to competition by introduced trout like the lake trout, brown trout, or the rainbow trout...

Wikipedia

Lake Titicaca Orestias - Extinction

Extinction.photo by Marc Schlossman

Titicaca Orestias - SHOAL Conservation

ARTICLE • YELLOWSTONE SCIENCE - VOLUME 25 ISSUE 1: NATIVE FISH CONSERVATION

Non-native Lake Trout Induce Cascading Changes in the Yellowstone Lake

Yellowstone National Park

> **"Yellowstone Lake and connecting streams and rivers lie within the heart of YNP and, as such, are among the most pristine waters remaining on Earth."**
>
> *—from Koel et al. 2017*

Yellowstone Lake, located at the heart of the Greater Yellowstone Ecosystem, is the largest lake above 2,100 m (7,000 ft.) elevation in North America.
NPS PHOTO - N. Herbert

ɔm Yellowstone Science 25(1)

/ Todd M. Koel, Jeffery L. Arnold, Lisa A. Baril, Kerry A. Gunther, Douglas W. Smith, John M. ɣslo, & Lusha M. Tronstad

e mountainous region within and bordering southeastern Yellowstone National Park (YNP) is among the most remote in ' contiguous United States. Lying completely within wilderness, the watershed of the upper Yellowstone River is pristine. ɔwmelt waters feed numerous tributaries to the Yellowstone River, which ultimately winds northward to Yellowstone

Richard Conniff is an award-winning science writer for magazines and a contributing opinion writer for the *New York Times*. His books include *House of Lost Worlds* (Yale University Press, 2016) and *The Species Seekers* (W. W. Norton, 2010).

IT'S ONE OF THE FEW GOVERNMENT PROGRAMS MOST TAXPAYERS love. Stocking America's waterways with fish for anglers has a persistent Norman Rockwell kind of appeal, based on the idea that, with a little help, any lake or stream can be a place where your average kid (or grown-up) can toss out a line and just maybe reel in dinner.

Fish stocking is also the basis for a recreational fishing economy worth $25.7 billion a year, according to a 2011 survey by federal agencies. Hence, it has been government policy since the late 1800s to haul juvenile fish from hatcheries to local lakes and since the 1950s to airlift and release them by the thousands into remote lakes everywhere.

But indiscriminate fish stocking is increasingly looking as if it might just be one of the dumber things people have ever done to the environment, because the introduced fish tend to displace native species. "Think about it," says Julian D. Olden, a University of Washington ecologist working on nonnative fish issues. "The fish we stock are those that grow rapidly, are highly fecund and are great on the end of the hook," he says, referring to the trout, bass, northern pike and other game fish that are commonly introduced to U.S. lakes and rivers. That is, we select for aggressive predators. "It shouldn't be too surprising that the same attributes we love as anglers are also responsible for the high impacts we are witnessing on native species and ecosystems," Olden says.

Fish stocking has, of course, sometimes helped rebuild threatened native species—for instance, lake trout in the Great Lakes and brook trout in Great Smoky Mountains National Park. But until recently, hatcheries and fish stocking also made it easier to sacrifice rivers and lakes to development, observes Rick Williams, a fisheries biologist who advises Fly Fishers International. "[Development proponents] would say, 'We're going to put this dam into this rivershed, and it's going to create all these benefits,'" he explains. The proponents would admit that there might be some negative effects on native salmon or steelhead trout, for example, but then they would gloss over those consequences, saying, "Don't worry, we're going to put in a hatchery." Eventually, after the habitat was damaged beyond repair, people gradually realized that "hatchery fish are not wild fish." The adaptations that let fish thrive in crowded hatchery conditions do not easily translate into survival or reproductive success in the wild. After just a single generation in captivity, hatchery steelhead already differed from their wild counterparts in the expression of hundreds of genes, according to a 2016 study.

State and federal officials, together with some anglers, have thus begun to rethink our long infatuation with fish stocking, and in some cases they are working to unwind its destructive effects. In August 2016 the National Park Service approved a plan to remove stocked fish from 85 high-elevation lakes in California's Sequoia and Kings Canyon National Parks. Also last year, Oregon removed limits on how many bass, walleye and other introduced game fish anglers can take in three rivers where those fish interfere with native species. In addition, a proposed nationwide network of native fish refuges moved toward becoming reality in 2015, when North Carolina, Georgia and Tennessee designated the Little Tennessee River basin the nation's first Native Fish Conservation Area.

TROUBLED WATERS

CONCERNS ABOUT the inadvertent effects of fish stocking have been around almost from the start. In Europe, people began to experiment with rearing fish fry in captivity to restock streams in the

IN BRIEF

Stocking waterways with trout, northern pike, bass and other species for sport fishing is a popular and time-honored tradition.

But introducing these game fish in places where they do not occur naturally can have devastating consequences for native species and ecosystems.

Recently officials and conservation-minded anglers have begun work to mitigate the damage. Not everyone supports such efforts, however.

Table 5. Fish species-life stage and number observed.

Species – common name	Species – scientific name	Life Stage	Number Caught
blacknose dace	Rhinichthys atratulus	adult	122
blacknose dace	Rhinichthys atratulus	young-of-year	1
brook stickleback	Culaea inconstans	adult	2
brook stickleback	Culaea inconstans	young-of-year	3
brown trout	Salmo trutta	adult	8
brown trout	Salmo trutta	juvenile	40
brown trout	Salmo trutta	young-of-year	74
central mudminnow	Umbra limi	adult	14
central mudminnow	Umbra limi	young-of-year	3
central stoneroller	Campostoma anomalum	adult	1
common shiner	Luxilus cornutus	adult	1
creek chub	Semotilus atromaculatus	adult	51
creek chub	Semotilus atromaculatus	juvenile	11
creek chub	Semotilus atromaculatus	young-of-year	15
fathead minnow	Pimephales promelas	adult	1
Johnny darter	Etheostoma nigrum	adult	2
Johnny darter	Etheostoma nigrum	young-of-year	46
longnose dace	Rhinichthys cataractae	adult	5
northern pike	Esox lucius	adult	1
white sucker	Catostomus commersonii	juvenile	54
white sucker	Catostomus commersonii	young-of-year	28

122 Trout
25%

Fish captured on Little Rock Creek from two sites with PAS sampling from 2017 to 2019.

Listing of creeks in Minnesota that have been delisted as trout streams

1). Barbour Creek
2). Beaver Creek
3). Briggs Creek
4). Bruce Creek
5). Pancake Creek
6). Warba Creek
7). Bungo Creek
8). Carey Creek
9). Cottonwood Creek
10). Cullen Brook
11). East Swan River
12). Faun Creek
13). Finn Creek
14). Hay Creek
15). Holmstad Creek
16). Kinzer Creek
17). Libby Brook
18). Meadow Creek
19). Michaud Brook
20). Hay Creek
21). Mosquito Creek
22). Mud Creek
23). Nelson Hay Creek
24). O' Brien Creek
25). Peter's Creek
26). Pokety Creek
27). Poplar Creek
28). Martin Creek
29). Prairie River
30). Rush Lake Creek
31). Sisseebakwet Creek
32). Snake River
33). Spring Creek
34). Spring Lake Creek
35). Shine Creek
36). Three Mile Creek
37). Trout Brook
38). Van Sickle Brook
39). Venning Creek
40). Willow Creek
41). Cedar Lake

Evaluation and Feasibility of Stocking Trout in LRC – Analysis (pages 61-71)

Page 61 includes the front page of a study from Wisconsin where trout decline is expected to happen in relationship to our warming climate. Numerous studies could have been used to demonstrate this, but Wisconsin's weather and climate are very similar to ours so it was chosen by location.

Page 62 is actual weather data taken from the DNR's website looking at weather changes in the past 5 decades, for exclusively just central Minnesota. The left column lists the year, and the right column expresses average annual temperature for that given year. For the decade from 1970-1979, not shown, average annual temperature was 39.96 degrees Fahrenheit. Temperatures have slowly inched upward with the coldest year being 1996, and the warmest year being 2024. Climatologist have concluded the most of Minnesota has warmed 3 degrees since 1980. This is about twice as fast as the worldly average, probably due to the fact that we are located far from any moderating large body of water. Temperature records also show that this warming trend worldwide is not linear, but is accelerating.

Pages 63 and 64 is a climate study released from the Minnesota Department of Health for exclusively our region of west central Minnesota, and was published in 2018. The average summer maximum temperature is expected to increase 7.6 degrees from the time period from 1981-2010, to 2050-2075. The average winter minimum temperature is expected to increase 9.8 degrees for the same time period. Predictions like this were very uncommon 20 years ago because climatologist at that time were much less sure of the numerous feedback loops involved in climate predictions. As more results have been obtained, the bolder the predictions have become, as seen with this one. Our now borderline designated trout streams will unlikely survive much into this timeframe.

Page 65 shows brown trout as being listed in the top 10 most invasive fish species in the world as by the environmental group Mother Nature Network. Page 66 shows 5 projects where the MN DNR is involved with, where brown trout is being investigated for displacing native brook trout, mostly in southeastern Minnesota. Page 67 list 3 trout species that were major contributors in the extinction of a native fish species in South America. Page 68 is the front page of a study in Yellowstone National Park where researchers have found many cascading negative effects due to trout stocking. Page 69 is the front page of an article that Scientific American ran in their November 2017 issue. Scientific American has been in circulation for about 150 years and has a very high reputation to excellence. They condemn the stocking of any trout species into lakes or streams where they are not native to. They list the biggest deterrent to stopping the stocking is people being unaware of the dangers associated with distributing non-native trout species. Page 70 is from the PHABSIM study listing the fish caught in the electroshocking procedure to count fish. At this site 25% of all fish were non-native trout, and one has to wonder which one of these other native species got displaced. Page 71 is a list of trout streams in Minnesota that have been delisted over the years.

Johnson, Gary S. Ph.D.; University of Idaho Professor of Hydrogeology: 1990-2012; Present: Professor Emeritus of Hydrogeology

Link to groundwater modeling articles: http://onlinelibrary.wiley.com/doi/10.1111/j.1745-6584.1997.tb00061.x/full; http://imnh.isu.edu/digitalatlas/hydr/addinfo.MODFL098.html

National Groundwater Association Program Committee member: http://www.ngwa.org/Events-Education/conferences/Pages/5029sep16.aspx

Forecast of Natural Aquifer Discharge Using Data-Driven, Statistical Approach
November 2013 - Kevin G. Boggs, Rob Van Kirk, Gary S. Johnson, Jerry P. Fairley

Forecasting Natural Aquifer Discharge Using a Numerical Model and Convolution
August 2013 – Kevin G Boggs, Gary S Johnson, Rob Van Kirk, Jerry P Fairley

System Dynamics to Sustainable Water Resources Management in the Eastern Snake Plain Aquifer Under Water Supply Uncertainty
December 2012 – Jae Hyeon Ryu, Bryce A. Contor, Gary Johnson, John Tracy

Evaluation of Validity of Response Functions in a Thick Unconfined Aquifer
April 2010 – Gary S. Johnson

The Role of Uncertainty in the Use of Groundwater Models for Administration of Water Rights
September 2008 – Donna M. Cosgrove, Gary S. Johnson, David Tuthill

Efficient and Practical Approaches to Ground-Water Right Transfers Under the Prior Appropriation Doctrine and the Snake River Example 1
January 2008 – Gary S. Johnson, Bryce A. Contor, Donna M. Cosgrove

Regional Scale Modeling of Surface and Ground Water Interaction in the Snake River Basin
Scott A. Miller, Gary S. Johnson, Donna M. Cosgrove, Roger Larson

Transient Response Functions for Conjunctive Water Management in the Snake River Plain, Idaho
June 2007 – Donna M. Cosgrove, Gary S. Johnson

Recharge of the Snake River Plain Aquifer: Transitioning from Incidental to Managed
June 2007 – Gary S. Johnson, Walter H. Sullivan, Donna M. Cosgrove, Robert D. Schmidt

Modeling groundwater flow and contaminant transport in the Snake River Plain aquifer: A stochastic approach
January 2002 – Edith Gego, Gary S. Johnson, Matthew R. Hankin, John Andrew Welhan

Forecast of Natural Aquifer Discharge Using a Data-Drive, Statistical Approach
November 2013 – Kevin G. Boggs, Rob Van Kirk, Gary S. Johnson, Jerry P. Fairley

Recharge of the Snake River Plain Aquifer
January 1999 – Gary S. Johnson, Walter H. Sullivan, Donna M. Cosgrove, Robert D. Schmidt

Aquifer Management Zones Based on Simulated Surface-Water Response Functions
March 2005 – Donna M. Cosgrove, Gary S. Johnson

Description of the IDWR/UI Snake River Plain Aquifer Model
January 1999 – Donna M. Cosgrove, Gary S. Johnson, Sherry Laney

EVALUATION OF THE MINNESOTA DEPARTMENT OF NATURAL RESOURCES GROUNDWATER FLOW MODELING FOR DETERMINING BASEFLOW DIVERSIONS IN THE LITTLE ROCK CREEK AREA

By
Gary S. Johnson PhD
Emeritus Professor of Hydrogeology
University of Idaho

For

Irrigation Association of Minnesota

May 14, 2023

REPORT PURPOSE

The purpose of this report is to provide an independent evaluation of methods and conclusions associated with the Minnesota Department of Natural Resources (DNR) recommendation for managing water resources of the Little Rock Creek (LRC) area. The recommendation relies heavily on intensive computer modeling that is unfamiliar to the vested water interests. Implementation of DNR's recommendation would have a major impact to the livelihood of irrigators and other residents in the area.

This report focuses on development of groundwater flow modeling efforts and their use to develop recommendations for limits on irrigation pumping. The report findings are based on two recent DNR publications on modeling in the LRC area identified in the References. Analysis of stream habitat considerations is outside of my area of expertise and beyond the scope of this report.

OVERALL PERSPECTIVE ON DNR'S GROUNDWATER MODEL DEVELOPMENT AND APPLICATION IN THE LRC AREA

Effective water management at a basin scale requires understanding the interactions between surface and groundwater. Consumptive use of groundwater (e.g., evaporation and transpiration) can result in depletion of surface water resources and should be considered, preferably, prior to development of a basin's water resources.

Methods to confidently determine the quantitative impacts of irrigation pumping on surface water are obscured by the complexity of the geologic and hydrologic environments. This includes confounding effects of many aquifer recharge and discharge mechanisms and the largely hidden spatial variations in geologic properties that control the timing and magnitude of aquifer pumping effects on surface water. Hydrogeologists are typically faced with the prospect of either using highly simplified techniques that are compromised by intensive assumptions to "simplify" the complex environment or apply technically sophisticated and data intensive models to incorporate our limited understanding of the complex hydrogeologic system into the quantitative evaluation. Unfortunately, these models are representing systems that we don't fully understand, and there is often insufficient data to construct and populate a model that is reliable for predictions. The DNR has followed the later path of using multiple models to attempt to, not only understand the system, but forecast the quantitative impacts of irrigation groundwater pumping on surface water in the LRC area.

The DNR has invested substantial effort into the development and application of a groundwater model in the LRC area. Based on my experience and review of the primary documentation, it appears that DNR technical staff has used current and accepted practices and all available data to build and apply the model. I was impressed by their work. However, all models are approximations of reality and are developed using uncertain estimates of processes and nearly all properties, parameters, and inputs. Consequently, **a rigorous model development effort does not necessarily mean the model is reliable for making quantitative predictions.** This is especially concerning when the outcome of the process has a major impact on the citizens in the area.

DESCRIPTION OF SPECIFIC CONCERNS

The following are areas where I believe there is reason to have concerns about model application to develop quantitative rules constraining irrigation pumping. Justification of the individual concerns are described in the respectively labeled appendices to this report.

A. HIGH UNCERTAINTY IN SIMULATED BASEFLOWS RELATIVE TO DNR RECOMMENDED BASEFLOW DIVERSION LIMITS

All models are approximations of reality and uncertainties in model parameters and inputs affect the accuracy of predictions made by the models. DNR has depended almost entirely on models constrained by our limited understanding of highly variable subsurface properties and aquifer recharge and discharge to develop recommended limits to groundwater use for irrigation. The extended model period from 2015 through 2018 (I will refer to as a verification period) may be considered as a test of model predictive accuracy. During this period, for multiple reasons, the model did "not meet the goals" for accuracy (DNR, 2021). During this verification period errors (differences between model simulated and stream gauge estimated) baseflows were several times larger than the recommended August baseflow diversion limits. This was partially a result of difficulties in determining the baseflows estimated from the stream gauges. However, large uncertainties in what the "true" values of the most critical model output (baseflow) also adversely impact model development and consequently its predictive accuracy. Further justification for this point of concern is provided in Appendix A.

B. SELECTION OF NON-IRRIGATED ALFALFA INSTEAD OF NATIVE VEGETATION AS A REFERENCE CONDITION

The DNR determined baseflow diversions as the difference in baseflows resulting from two simulations: 1) a simulation where all irrigated acreage was converted to non-irrigated alfalfa (called the reference or no-use condition), and 2) a simulation representing actual irrigation conditions. Results of the non-irrigated or reference simulation were used to determine estimates of baseflow and streamflow rates in the absence of irrigation. Use of non-irrigated alfalfa to replace irrigated conditions is unrealistic and provides little to no understanding of

Peer Review Summary of Appendix A:

- Baseflow estimations produce by direct measurements using the W.H.A.T. model do not always match well with computer estimates of baseflow; (low flows are slightly better matched).

- The computed estimated drawdown from pumping in observation wells is showing more drawdown than the direct actual measurement from the observation wells shows, thus exaggerating diversion amounts.

Peer Review Summary of Appendix B:

- Direct quote: "The DNR should have more interest in returning LRC to a near natural flow condition than to an arbitrary and unrealistic representation of non-irrigated alfalfa substituted for irrigated crops." (See Richter attachments).

  Fact: The chosen cover in the no-use condition has the highest degree of influence on diversion than any other parameter in the model.

  1). A predetermined **standard** should be used in this situation because diversion cannot ever be directly measured, and without a standard, wide variations will be possible. The standard in the Richter study was intended to be from "natural or historic flow", which is repeated over 20 times in that report. The term "natural" in scientific circles always means, without human interference.

  2). The cover crop was chosen from two selections after the diversion numbers were known. In this manner, the amount of diversion can actually be selected, and now becomes a subjected value. How can this be considered mainstream science when no other field of science is allowed to do this. In other words, diversion by this method is a chosen value, and consequently by science standards holds very little value. The cover crop, at the very least, should have been predetermined before results were seen.

Peer Review Summary of Appendix C:

- In regards to the flow meter study this was stated: "The sensitivity of this critical simulation results to uncertainty in irrigation pumping rates warrants further investigation".

Model review was presented in two parts. The part submitted to the Commissioners Order contained 13 pages, and the part intended and presented to irrigators contained 36 pages, (much effort went into this)

Debatable issue:

- Why was Dr. Johnson never consulted on his peer review analysis? No rebuttal or discussion was ever allowed on issues of concern.

Randy Klaphake <rdee4694@gmail.com> Sun, Dec 22, 2024 at 7:07 PM
To: "Johnson, Gary (garyj@uidaho.edu)" <garyj@uidaho.edu>

Hi Gary,

I am considering doing a presentation at the next Kimley-Horn/DNR meeting in February and have another question to ask you. After you did the peer review on the LRC model that was submitted to the DNR before the Commissioner's Order, did the DNR consult with you on your submission, and was it a productive exchange of ideas?

Thanks, Randy
[Quoted text hidden]

Johnson, Gary (garyj@uidaho.edu) <garyj@uidaho.edu> Sun, Dec 22, 2024 at 7:58 PM
To: Randy Klaphake <rdee4694@gmail.com>

Hi Randy. No. I never received any communication from the DNR.

Good luck with these efforts, and hope you have a great Christmas.

Gary

From: Randy Klaphake <rdee4694@gmail.com>
Sent: Sunday, December 22, 2024 5:07 PM
To: Johnson, Gary (garyj@uidaho.edu) <garyj@uidaho.edu>
Subject: Re: LRC model

[Quoted text hidden]

Randy Klaphake <rdee4694@gmail.com> Thu, Dec 26, 2024 at 9:59 AM
To: "Johnson, Gary (garyj@uidaho.edu)" <garyj@uidaho.edu>

Hi Gary,

This is the first time that I have been witness to a scientific peer review action setting. I was expecting more of a joint effort in resolving items in question. Is this normal procedure and are you satisfied with their response? In case you haven't seen the entire DNR's stakeholders response, I will attach it here.

Thanks, Randy
[Quoted text hidden]

Johnson, Gary (garyj@uidaho.edu) <garyj@uidaho.edu> Fri, Dec 27, 2024 at 1:37 PM
To: Randy Klaphake <rdee4694@gmail.com>

Hi Randy. To me it isn't a peer review. This is constituents objecting to an agencies evaluation, and the agency defending what it has determined. I think a process with engaged stakeholders is more beneficial, but a more tedious process for the agency. It would mean groups like IAMs having a seat at the table throughout the "research" process. Seems to me that the train has left the station.

Gary

From: Randy Klaphake <rdee4694@gmail.com>
Sent: Thursday, December 26, 2024 7:59 AM
To: Johnson, Gary (garyj@uidaho.edu) <garyj@uidaho.edu>
Subject: Re: LRC model

[Quoted text hidden]

Peer Review from Dr. Gary Johnson – Analysis (pages 73-77)

This is a summary of peer review done by Dr. Gary Johnson. Page 73 is part of his resume. Page 74 and 75 are two actual transcripts of his peer review analysis. Page 76 is the summary analysis of that review. And page 77 is a copy of an email exchange I had with Dr. Johnson discussing how the peer review correspondence went with the MN DNR. He told me there was no correspondence. This is not the complete analysis but it can be easily obtained for further review if so desired.

Email quote: "I read something from April 2024 that may have been to the commissioners. It appeared to me to be defensive of their position rather than an open-minded consideration of alternatives, especially in response to the expansion of beaver dams and impoundments to increase recharge. Hopefully the new consultant will be easier to work with."

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Assessment of carbon emission potential of polyvinyl chloride plastics

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Abstract. Plastic pollution has become a global concern, and research has shown that carbon emissions during the lifecycle of plastics are rapidly consuming global carbon credits. This study focuses on the effective assessment of carbon emissions from polyvinyl chloride (PVC) plastics using a life cycle assessment (LCA) method during the production and recycling stages. The greenhouse gas emission potential is evaluated using 1kg PVC plastic as a functional unit. Research has shown that the total carbon emissions during the production stage of PVC plastic are 7.83kg $CO_{2\text{-eq}}$. The carbon emissions during the production stage of hydrochloric acid, acetylene, electricity, and water vapor are 2.340 kg $CO_{2\text{-eq}}$, 4.900 kg $CO_{2\text{-eq}}$, 0.117 kg $CO_{2\text{-eq}}$, and 0.468 kg $CO_{2\text{-eq}}$, respectively. During the recycling phase, the carbon emissions from the power consumption zone are 0.184 kg $CO_{2\text{-eq}}$, followed by 0.156 kg $CO_{2\text{-eq}}$ from natural gas. Research has shown that fossil materials contribute the largest carbon emissions during the production stage of PVC plastics. Therefore, how to effectively reduce the use of fossil fuels or seek alternative raw materials can effectively reduce carbon emissions.

1 Ton PVC will emit 7.83 Tons of CO_2

1. Introduction

Plastics are multifunctional, durable, and cost-effective materials used in a wide range of strategic fields, including packaging, construction, automotive manufacturing, electronics, and agricultural production [1].Over the past 70 years, plastic production has continued to grow, from 1.5 million tons in the 1950s to 359 million tons in 2018 [2].Due to the difficulty of natural decomposition of plastics, they have accumulated in land, freshwater, and oceans for decades. In 2010 alone, an estimated 4 million to 12 million tons of plastic waste generated on land entered the marine environment [3],There are also increasing reports of pollution in freshwater systems and terrestrial habitats, as well as the pollution of synthetic fibers to the environment [4].After physical, chemical, and/or biological interactions, large blocks of plastic will be decomposed into microplastics (MP) (1–5 mm) or nanoplastics (NPs) (< 1000 nm)[5].

At present, there are more than 300 types of plastics produced, of which more than 60 are commonly used and can be divided into ordinary plastics and engineering plastics according to their uses. Polyethylene (PE), polypropylene (PP), polyvinyl chloride (PVC), polystyrene (PS), polyurethane (PU), and phenolic resin are the main general-purpose plastics, among which PP and PE are the most commonly used polymers in daily plastic products. In Europe, 40% of plastic is used for packaging. The large-scale production of plastics will inevitably lead to a large amount of waste generation. Currently, the main disposal methods include incineration, landfill, and recycling, among which recycling can minimize environmental pollution. At present, the biggest difficulty faced by plastic recycling is that the cost of collection and treatment is lower than the value of secondary materials. Unfortunately, the economic benefits of plastic recycling are poor. Landfill is the lowest cost method of all treatments, with most waste plastics directly entering the landfill site.

When microplastics enter the marine environment, marine organisms will ingest a certain amount of microplastics and enter higher-level organisms along the biological chain, posing unpredictable hazards. The harm caused by plastics to aquatic organisms mainly includes plastic additives, physical blockages caused by ingestion, and other issues. Plastic additives and pollutants can cause behavioral changes, metabolic processes, and endocrine disruptions. The types of harm caused by ingestion include internal damage to aquatic organisms, suffocation and entanglement, reduced growth and photosynthesis of primary producers in the food chain such as algae, and their impact on the reproduction and development of crustacean.

All plastics used before, including resins, fibers, and additives, were processed from fossil fuels. The molecules or monomers used to manufacture plastics, such as ethylene and propylene, also come from fossil fuels. Plastics require a large amount of resources and energy input during the production stage, which can only be used in plastic production after being processed. The energy and material input during the processing further exacerbates the carbon emissions brought by the plastic

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Additional Carbon Footprint of Importing Water – Analysis (page 79)

When considering importing water, we must also consider the impacts to the environment that this could have. This is the front page of a study done on CO2 emissions during the production of PVC plastic pipe commonly used in transporting underground water. Plastics have come under scrutiny recently because of their nondegradable tendencies and their high energy consumption during production. In the production stages alone, for each pound of PVC pipe produced, it will emit 7.83 pounds of CO2. This does not include the fossil fuels used in extraction, transportation, refinement, or any of the energy requirements involved in installment such as digging trenches, dewatering, and covering and additional transportation energy consumption. This also does not consider the fact that the production of PVC pipe also produces the highest amount of leftover toxic compounds from manufacturing that need to be properly disposed of.

PVC pipe has the highest energy consumption, or CO2 emissions, of all the plastic products. But its largest advantage point is the fact that it can be recycled using less energy than most of its counter products. But when buried underground, that will negate that attribute. Importing water will create a huge carbon footprint where none was before and that should be considered into the final solution plan.

Fact Check - What We Know and What We Don't Know

- We know that LRC is a severely incised stream with much instream erosion occurring and that the incision is likely to continue, unless acted upon

- We know that LRC is listed as an impaired stream with a high nutrient load (TMDL)

- We know that the model shows diversion above the SDL around 5% of the time

- We know that irrigation is not causing impairment of LRL by flow reduction

- We know that LRC was altered at least 5 times since European occupation. However, each alteration is unlikely to be equal. The first two probably produced more changes than what the last three will.
  1). When native beavers were removed by fur traders
  2). When agriculture removed the native vegetation

  3). When nonindigenous trout were stocked in LRC
  4). When modern irrigation started using groundwater
  5). When underground tiling was installed to drain and reduce saturated soils

- We know that indigenous trout were not part of the LRC ecosystem after European occupation

- We know that native beaver occupation in LRC was almost inevitable throughout most of its history

- We know that temperatures and rainfall have increased over the past four decades

- We know that mainstream science favors creating instream wetlands by the installation of small dams, whether it be natural or manmade

What We Don't Know

- We don't know the natural flow regime of LRC

- We don't know the potential effects that any additional groundwater pumping will have on existing aquifers, which will be required when conforming with current proposed solutions, (importing, or to lesser degree augmenting)

- We don't know the ecological effects of the introduced nonindigenous trout

- We don't know yet what we don't know

The Natural Flow Regime

A paradigm for river conservation and restoration

N. LeRoy Poff, J. David Allan, Mark B. Bain, James R. Karr, Karen L. Prestegaard, Brian D. Richter, Richard E. Sparks, and Julie C. Stromberg

Humans have long been fascinated by the dynamism of free-flowing waters. Yet we have expended great effort to tame rivers for transportation, water supply, flood control, agriculture, and power generation. It is now recognized that harnessing of streams and rivers comes at great cost: Many rivers no longer support socially valued native species or sustain healthy ecosystems that provide important goods and services (Naiman et al. 1995, NRC 1992).

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The ecological integrity of river ecosystems depends on their natural dynamic character

The extensive ecological degradation and loss of biological diversity resulting from river exploitation is eliciting widespread concern for conservation and restoration of healthy river ecosystems among scientists and the lay public alike (Allan and Flecker 1993, Hughes and Noss 1992, Karr et al. 1985, TNC 1996, Williams et al. 1996). Extirpation of species, closures of fisheries, groundwater depletion, declines in water quality and availability, and more frequent and intense flooding are increasingly recognized as consequences of current river management and development policies (Abramovitz 1996, Collier et al. 1996, Naiman et al. 1995). The broad social support in the United States for the Endangered Species Act, the recognition of the intrinsic value of noncommercial native species, and the proliferation of watershed councils and riverwatch teams are evidence of society's interest in maintaining the ecological integrity and self-sustaining productivity of free-flowing river systems.

Society's ability to maintain and restore the integrity of river ecosystems requires that conservation and management actions be firmly grounded in scientific understanding. However, current management approaches often fail to recognize the fundamental scientific principle that the integrity of flowing water systems depends largely on their natural dynamic character; as a result, these methods frequently prevent successful river conservation or restoration. Streamflow quantity and timing are critical components of water supply, water quality, and the ecological integrity of river systems. Indeed, streamflow, which is strongly correlated with many critical physicochemical characteristics of rivers, such as water temperature, channel geomorphology, and habitat diversity, can be considered a "master variable" that limits the distribution and abundance of riverine species (Power et al. 1995, Resh et al. 1988) and regulates the ecological integrity of flowing water systems (Figure 1). Until recently, however, the importance of natural streamflow variability in maintaining healthy aquatic ecosystems has been virtually ignored in a management context.

Historically, the "protection" of river ecosystems has been limited in scope, emphasizing water quality and only one aspect of water quantity: minimum flow. Water resources management has also suffered from the often incongruent perspectives and fragmented responsibility of agencies (for example, the US Army Corps of Engineers and Bureau of Reclamation are responsible for water supply and flood control, the US Environmental Protection Agency and state environmental agencies for water quality, and the US Fish &

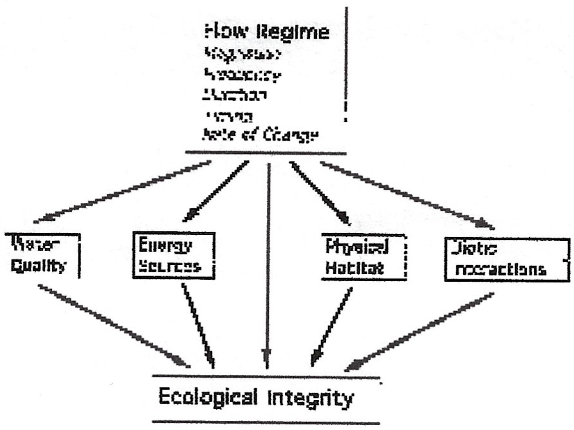

Figure 1. Flow regime is of central importance in sustaining the ecological integrity of flowing water systems. The five components of the flow regime—magnitude, frequency, duration, timing, and rate of change—influence integrity both directly and indirectly, through their effects on other primary regulators of integrity. Modification of flow thus has cascading effects on the ecological integrity of rivers. After Karr 1991.

Wildlife Service for water-dependent species of sporting, commercial, or conservation value), making it difficult, if not impossible, to manage the entire river ecosystem (Karr 1991). However, environmental dynamism is now recognized as central to sustaining and conserving native species diversity and ecological integrity in rivers and other ecosystems (Holling and Meffe 1996, Hughes 1994, Pickett et al. 1992, Stanford et al. 1996), and coordinated actions are therefore necessary to protect and restore a river's natural flow variability.

In this article, we synthesize existing scientific knowledge to argue that the natural flow regime plays a critical role in sustaining native biodiversity and ecosystem integrity in rivers. Decades of observation of the effects of human alteration of natural flow regimes have resulted in a well-grounded scientific perspective on why altering hydrologic variability in rivers is ecologically harmful (e.g., Arthington et al. 1991, Castleberry et al. 1996, Hill et al. 1991, Johnson et al. 1976, Richter et al. 1997, Sparks 1995, Stanford et al. 1996, Toth 1995, Tyus 1990). Current pressing demands on water use and the continuing alteration of watersheds require scientists to help develop management protocols that can accommodate economic uses while protecting ecosystem functions. For humans to continue to rely on river ecosystems for sustainable food production, power production, waste assimilation, and flood control, a new, holistic, ecological perspective on water management is needed to guide society's interactions with rivers.

The natural flow regime

The natural flow of a river varies on time scales of hours, days, seasons, years, and longer. Many years of observation from a streamflow gauge are generally needed to describe the characteristic pattern of a river's flow quantity, timing, and variability—that is, its natural flow regime. Components of a natural flow regime can be characterized using various time series (e.g., Fourier and wavelet) and probability analyses of, for example, extremely high or low flows, or of the entire range of flows expressed as average daily discharge (Dunne and Leopold 1978). In watersheds lacking long-term streamflow data, analyses can be extended statistically from gauged streams in the same geographic area. The frequency of large-magnitude floods can be estimated by paleohydrologic studies of debris left by floods and by studies of historical damage to living trees (Hupp and Osterkamp 1985, Knox 1972). These historical techniques can be used to extend existing hydrologic records or to provide estimates of flood flows for ungauged sites.

River flow regimes show regional patterns that are determined largely by river size and by geographic variation in climate, geology, topography, and vegetative cover. For example, some streams in regions with little seasonality in precipitation exhibit relatively stable hydrographs due to high groundwater inputs (Figure 2a), whereas other streams can fluctuate greatly at virtually any time of year (Figure 2b). In regions with seasonal precipitation, some streams are dominated by snowmelt, resulting in pronounced, predictable runoff patterns (Figure 2c), and others lack snow accumulation and exhibit more variable runoff patterns during the rainy season, with peaks occurring after each substantial storm event (Figure 2d).

Five critical components of the flow regime regulate ecological processes in river ecosystems: the magnitude, frequency, duration, timing, and rate of change of hydrologic conditions (Poff and Ward 1989, Richter et al. 1996, Walker et al. 1995). These components can be used to characterize the entire range of flows and specific hydrologic phenomena, such as floods or low flows, that are critical to the integrity of river ecosystems. Furthermore, by defining flow regimes in these terms, the ecological consequences of particular human activities that modify one or more components of the flow regime can be considered explicitly.

- The *magnitude* of discharge[1] at any given time interval is simply the amount of water moving past a fixed location per unit time. Magnitude can refer either to absolute or to relative discharge (e.g., the amount of water that inundates a floodplain). Maximum and minimum magnitudes of flow vary with climate and watershed size both within and among river systems.
- The *frequency* of occurrence refers to how often a flow above a given magnitude recurs over some specified time interval. Frequency of occurrence is inversely related to flow magnitude. For example, a 100-year flood is equaled or exceeded on average once every 100 years (i.e., a chance of 0.01 of occurring in any given year). The average (median)

[1]Discharge (also known as streamflow, flow, or flow rate) is always expressed in dimensions of volume per time. However, a great variety of units are used to describe flow, depending on custom and purpose of characterization: Flows can be expressed in near-instantaneous terms (e.g., ft^3/s and m^3/s) or over long time intervals (e.g., acre-ft/yr).

flow is determined from a data series of discharges defined over a specific time interval, and it has a frequency of occurrence of 0.5 (a 50% probability).

•The *duration* is the period of time associated with a specific flow condition. Duration can be defined relative to a particular flow event (e.g., a floodplain may be inundated for a specific number of days by a ten-year flood), or it can be a defined as a composite expressed over a specified time period (e.g., the number of days in a year when flow exceeds some value).

•The *timing*, or *predictability*, of flows of defined magnitude refers to the regularity with which they occur. This regularity can be defined formally or informally and with reference to different time scales (Poff 1996). For example, annual peak flows may occur with low seasonal predictability (Figure 2b) or with high seasonal predictability (Figure 2c).

•The *rate of change*, or *flashiness*, refers to how quickly flow changes from one magnitude to another. At the extremes, "flashy" streams have rapid rates of change (Figure 2b), whereas "stable" streams have slow rates of change (Figure 2a).

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Figure 2. Flow histories based on long-term, daily mean discharge records. These histories show within- and among-year variation for **(a)** Augusta Creek, MI, **(b)** Satilla River, GA, **(c)** upper Colorado River, CO, and **(d)** South Fork of the McKenzie River, OR. Each water year begins on October 1 and ends on September 30. Adapted from Poff and Ward 1990.

Hydrologic processes and the flow regime. All river flow derives ultimately from precipitation, but in any given time and place a river's flow is derived from some combination of surface water, soil water, and groundwater. Climate, geology, topography, soils, and vegetation help to determine both the supply of water and the pathways by which precipitation reaches the channel. The water movement pathways depicted in Figure 3a illustrate why rivers in different settings have different flow regimes and why flow is variable in virtually all rivers. Collectively, overland and shallow subsurface flow pathways create hydrograph peaks, which are the river's response to storm events. By contrast, deeper groundwater pathways are responsible for baseflow, the form of delivery during periods of little rainfall.

Variability in intensity, timing, and duration of precipitation (as rain or as snow) and in the effects of terrain, soil texture, and plant evapotranspiration on the hydrologic cycle combine to create local and regional flow patterns. For example, high flows due to rainstorms may occur over periods of hours (for permeable soils) or even minutes (for impermeable soils), whereas snow will melt over a period of days or weeks, which slowly builds the peak snowmelt flood. As one proceeds downstream within a watershed, river flow reflects the sum of flow generation and routing processes operating in multiple small tributary watersheds. The travel time of flow down the river system, combined with nonsynchronous tributary inputs and larger downstream channel and floodplain storage capacities, act to attenuate and to dampen flow peaks. Consequently, annual hydrographs in large streams typically show peaks created by widespread storms or snowmelt events and broad seasonal influences that affect many tributaries together (Dunne and Leopold 1978).

The natural flow regime organizes and defines river ecosystems. In rivers, the physical structure of the environment and, thus, of the habitat, is defined largely by physical processes, especially the movement of water and sediment within the channel and between the channel and floodplain. To understand the biodiversity, production, and sustainability of river ecosystems, it is necessary to appreciate the central organizing role played by a dynamically varying physical environment.

The physical habitat of a river includes sediment size and heterogeneity, channel and floodplain morphology, and other geomorphic features. These features form as the available sediment, woody debris, and other transportable materials are moved and deposited by flow. Thus, habitat conditions associated with channels and floodplains vary among

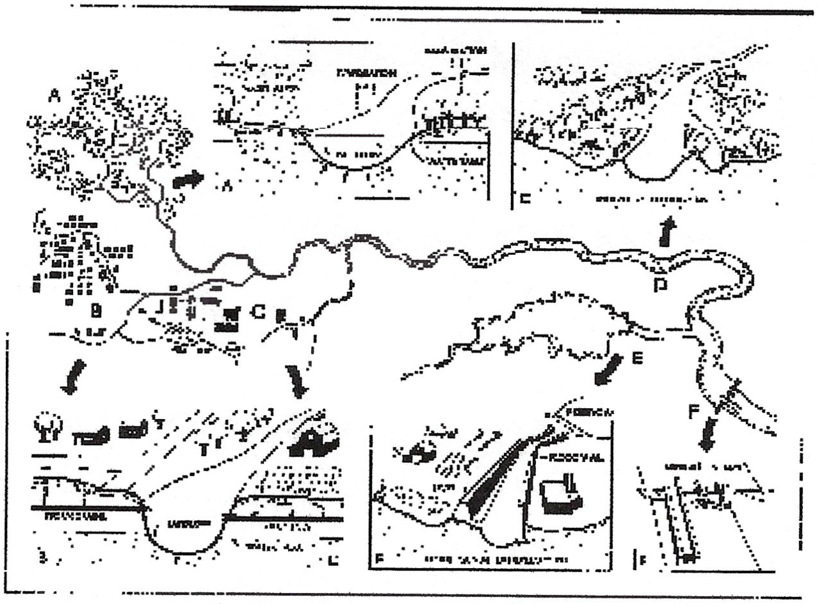

Figure 3. Stream valley cross-sections at various locations in a watershed illustrate basic principles about natural pathways of water moving downhill and human influences on hydrology. Runoff, which occurs when precipitation exceeds losses due to evaporation and plant transpiration, can be divided into four components (**a**): overland flow (1) occurs when precipitation exceeds the infiltration capacity of the soil; shallow subsurface stormflow (2) represents water that infiltrates the soil but is routed relatively quickly to the stream channel; saturated overland flow (3) occurs where the water table is close to the surface, such as adjacent to the stream channel, upstream of first-order tributaries, and in soils saturated by prior precipitation; and groundwater flow (4) represents relatively deep and slow pathways of water movement and provides water to the stream channel even during periods of little or no precipitation. Collectively, overland and shallow subsurface flow pathways create the peaks in the hydrograph that are a river's response to storm events, whereas deeper groundwater pathways are responsible for baseflow. Urbanized (**b**) and agricultural (**c**) land uses increase surface flow by increasing the extent of impermeable surfaces, reducing vegetation cover, and installing drainage systems. Relative to the unaltered state, channels often are scoured to greater depth by unnaturally high flood crests and water tables are lowered, causing baseflow to drop. Side-channels, wetlands, and episodically flooded lowlands comprise the diverse floodplain habitats of unmodified river ecosystems (**d**). Levees or flood walls (**e**) constructed along the banks retain flood waters in the main channel and lead to a loss of floodplain habitat diversity and function. Dams impede the downstream movement of water and can greatly modify a river's flow regime, depending on whether they are operated for storage (**e**) or as "run-of-river," such as for navigation (**f**).

rivers in accordance with both flow characteristics and the type and the availability of transportable materials.

Within a river, different habitat features are created and maintained by a wide range of flows. For example, many channel and floodplain features, such as river bars and riffle-pool sequences, are formed and maintained by dominant, or bankfull, discharges. These discharges are flows that can move significant quantities of bed or bank sediment and that occur frequently enough (e.g., every several years) to continually modify the channel (Wolman and Miller 1960). In many streams and rivers with a small range of flood flows, bankfull flow can build and maintain the active floodplain through stream migration (Leopold et al. 1964). However, the concept of a dominant discharge may not be applicable in all flow regimes (Wolman and Gerson 1978). Furthermore, in some flow regimes, the flows that build the channel may differ from those that build the floodplain. For example, in rivers with a wide range of flood flows, floodplains may exhibit major bar deposits, such as berms of boulders along the channel, or other features that are left by infrequent high-magnitude floods (e.g., Miller 1990).

Over periods of years to decades, a single river can consistently provide ephemeral, seasonal, and persistent types of habitat that range from free-flowing, to standing, to no water. This predictable diversity of in-channel and floodplain habitat types has promoted the evolution of species that exploit the habitat mosaic created and maintained by hydrologic variability. For many riverine species, completion of the life cycle requires an array of different habitat types, whose availability over time is regulated by the flow regime (e.g., Greenberg et al. 1996, Reeves et al. 1996, Sparks 1995). Indeed, adaptation to this environmental dynamism allows aquatic and floodplain species to persist in the face of seemingly harsh conditions, such as floods and droughts, that regularly destroy and re-create habitat elements.

From an evolutionary perspective, the pattern of spatial and temporal habitat dynamics influences the relative success of a species in a particular environmental setting. This habitat template (Southwood 1977), which is dictated largely by flow regime, creates both subtle and profound differences in the natural histories of species in different segments of their ranges. It also influences species distribution and abundance, as well as ecosystem function (Poff and Allan 1995, Schlosser 1990, Sparks 1992, Stanford et al. 1996). Human alteration of flow regime changes the established pattern of natural hydrologic variation and disturbance, thereby altering habitat dynamics and creating new conditions to which the native biota may be poorly adapted.

Human alteration of flow regimes

Human modification of natural hydrologic processes disrupts the dynamic equilibrium between the movement of water and the movement of sediment that exists in free-flowing rivers (Dunne and Leopold 1978). This disruption alters both gross- and fine-scale geomorphic features that constitute habitat for aquatic and riparian species (Table 1). After

Table 1. Physical responses to altered flow regimes.

Source(s) of alteration	Hydrologic change(s)	Geomorphic response(s)	Reference(s)
Dam	Capture sediment moving downstream	Downstream channel erosion and tributary headcutting	Chien 1985, Petts 1984, 1985, Williams and Wolman 1984
		Bed armoring (coarsening)	Chien 1985
Dam, diversion	Reduce magnitude and frequency of high flows	Deposition of fines in gravel	Sear 1995, Stevens et al. 1995
		Channel stabilization and narrowing	Johnson 1994, Williams and Wolman 1984
		Reduced formation of point bars, secondary channels, oxbows, and changes in channel planform	Chien 1985, Copp 1989, Fenner et al. 1985
Urbanization, tiling, drainage	Increase magnitude and frequency of high flows	Bank erosion and channel widening	Hammer 1972
		Downward incision and floodplain disconnection	Prestegaard 1988
	Reduced infiltration into soil	Reduced baseflows	Leopold 1968
Levees and channelization	Reduce overbank flows	Channel restriction causing downcutting	Daniels 1960, Prestegaard et al. 1994
		Floodplain deposition and erosion prevented	Sparks 1992
		Reduced channel migration and formation of secondary channels	Shankman and Drake 1990
Groundwater pumping	Lowered water table levels	Streambank erosion and channel downcutting after loss of vegetation stability	Kondolf and Curry 1986

such a disruption, it may take centuries for a new dynamic equilibrium to be attained by channel and floodplain adjustments to the new flow regime (Petts 1985); in some cases, a new equilibrium is never attained, and the channel remains in a state of continuous recovery from the most recent flood event (Wolman and Gerson 1978). These channel and floodplain adjustments are sometimes overlooked because they can be confounded with long-term responses of the channel to changing climates (e.g., Knox 1972). Recognition of human-caused physical changes and associated biological consequences may require many years, and physical restoration of the river ecosystem may call for dramatic action (see box on the Grand Canyon flood, page 774).

Dams, which are the most obvious direct modifiers of river flow, capture both low and high flows for flood control, electrical power generation, irrigation and municipal water needs, maintenance of recreational reservoir levels, and navigation. More than 85% of the inland waterways within the continental United States are now artificially controlled (NRC 1992), including nearly 1 million km of rivers that are affected by dams (Echeverria et al. 1989). Dams capture all but the finest sediments moving down a river, with many severe downstream consequences. For example, sediment-depleted water released from dams can erode finer sediments from the receiving channel. The coarsening of the streambed can, in turn, reduce habitat availability for the many aquatic species living in or using interstitial spaces. In addition, channels may erode, or downcut, triggering rejuvenation of tributaries, which themselves begin eroding and migrating headward (Chien 1985, Petts 1984). Fine sediments that are contributed by tributaries downstream of a dam may be deposited between the coarse particles of the streambed (e.g., Sear 1995). In the absence of high flushing flows, species with life stages that are sensitive to sedimentation, such as the eggs and larvae of many invertebrates and fish, can suffer high mortality rates.

For many rivers, it is land-use activities, including timber harvest, livestock grazing, agriculture, and urbanization, rather than dams, that are the primary causes of altered flow regimes. For example, logging and the associated building of roads have contributed greatly to degradation of salmon streams in the Pacific Northwest, mainly through effects on runoff and sediment delivery (NRC 1996). Converting forest or prairie lands to agricultural lands generally decreases soil infiltration and results in increased overland flow, channel incision, floodplain isolation, and headward erosion of stream channels (Prestegaard 1988). Many agricultural areas were drained by the construction of ditches or tile-and-drain systems, with the result that many channels have become entrenched (Brookes 1988).

These land-use practices, combined with extensive draining of wetlands or overgrazing, reduce retention of water in watersheds and,

A controlled flood in the Grand Canyon

Since the Glen Canyon dam first began to store water in 1963, creating Lake Powell, some 430 km (270 miles) of the Colorado River, including Grand Canyon National Park, have been virtually bereft of seasonal floods. Before 1963, melting snow in the upper basin produced an average peak discharge exceeding 2400 m^3/s; after the dam was constructed, releases were generally maintained at less than 500 m^3/s. The building of the dam also trapped more than 95% of the sediment moving down the Colorado River in Lake Powell (Collier et al. 1996).

This dramatic change in flow regime produced drastic alterations in the dynamic nature of the historically sediment-laden Colorado River. The annual cycle of scour and fill had maintained large sandbars along the river banks, prevented encroachment of vegetation onto these bars, and limited bouldery debris deposits from constricting the river at the mouths of tributaries (Collier et al. 1997). When flows were reduced, the limited amount of sand accumulated in the channel rather than in bars farther up the river banks, and shallow low-velocity habitat in eddies used by juvenile fishes declined. Flow regulation allowed for increased cover of wetland and riparian vegetation, which expanded into sites that were regularly scoured by floods in the constrained fluvial canyon of the Colorado River; however, much of the woody vegetation that established after the dam's construction is composed of an exotic tree, salt cedar (*Tamarix* sp.; Stevens et al. 1995). Restoration of flood flows clearly would help to steer the aquatic and riparian ecosystem toward its former state and decrease the area of wetland and riparian vegetation, but precisely how the system would respond to an artificial flood could not be predicted.

In an example of adaptive management (i.e., a planned experiment to guide further actions), a controlled, seven-day flood of 1274 m^3/s was released through the Glen Canyon dam in late March 1996. This flow, roughly 35% of the pre-dam average for a spring flood (and far less than some large historical floods), was the maximum flow that could pass through the power plant turbines plus four steel drainpipes, and it cost approximately $2 million in lost hydropower revenues (Collier et al. 1997). The immediate result was significant beach building: Over 53% of the beaches increased in size, and just 10% decreased in size. Full documentation of the effects will continue to be monitored by measuring channel cross-sections and studying riparian vegetation and fish populations.

instead, route it quickly downstream, increasing the size and frequency of floods and reducing baseflow levels during dry periods (Figure 3b; Leopold 1968). Over time, these practices degrade in-channel habitat for aquatic species. They may also isolate the floodplain from overbank flows, thereby degrading habitat for riparian species. Similarly, urbanization and suburbanization associated with human population expansion across the landscape create impermeable surfaces that direct water away from subsurface pathways to overland flow (and often into storm drains). Consequently, floods increase in frequency and intensity (Beven 1986), banks erode, and channels widen (Hammer 1972), and baseflow declines during dry periods (Figure 3c).

Whereas dams and diversions affect rivers of virtually all sizes, and land-use impacts are particularly evident in headwaters, lowland rivers are greatly influenced by efforts to sever channel–floodplain linkages. Flood control projects have shortened, narrowed, straightened, and leveed many river systems and cut the main channels off from their floodplains (NRC 1992). For example, channelization of the Kissimmee River above Lake Okeechobee, Florida, by the US Army Corps of Engineers transformed a historical 166 km meandering river with a 1.5 to 3 km wide floodplain into a 90 km long canal flowing through a series of five impoundments, resulting in great loss of river channel habitat and adjacent floodplain wetlands (Toth 1995). Because levees are designed to prevent increases in the width of flow, rivers respond by cutting deeper channels, reaching higher velocities, or both.

Channelization and wetland drainage can actually increase the magnitude of extreme floods, because reduction in upstream storage capacity results in accelerated water delivery downstream. Much of the damage caused by the extensive flooding along the Mississippi River in 1993 resulted from levee failure as the river reestablished historic connections to the floodplain. Thus, although elaborate storage dam and levee systems can "reclaim" the floodplain for agriculture and human settlement in most years, the occasional but inevitable large floods will impose increasingly high disaster costs to society (Faber 1996). The severing of floodplains from rivers also stops the processes of sediment erosion and deposition that regulate the topographic diversity of floodplains. This diversity is essential for maintaining species diversity on floodplains, where relatively small differences in land elevation result in large differences in annual inundation and soil moisture regimes, which regulate plant distribution and abundance (Sparks 1992).

Ecological functions of the natural flow regime

Naturally variable flows create and maintain the dynamics of in-channel and floodplain conditions and habitats that are essential to aquatic and riparian species, as shown schematically in Figure 4. For purposes of illustration, we treat the components of a flow regime individually, although in reality they interact in complex ways to regulate geomorphic and ecological processes. In describing the ecological functions associated with the components of a flow regime, we pay particular attention to high- and low-flow events, because they often serve as ecological "bottlenecks" that present critical stresses and opportunities for a wide array of riverine species (Poff and Ward 1989).

The magnitude and frequency of high and low flows regulate numerous ecological processes. Frequent, moderately high flows effectively transport sediment through the channel (Leopold et al. 1964). This sediment movement, combined with the force of moving water, exports organic resources, such as detritus and attached algae, rejuvenating the biological community and allowing many species with fast life cycles and good colonizing ability to reestablish (Fisher 1983). Consequently, the composition and relative abundance of species that are present in a stream or river often reflect the frequency and intensity of high flows (Meffe and Minckley 1987, Schlosser 1985).

High flows provide further ecological benefits by maintaining ecosystem productivity and diversity. For example, high flows remove and transport fine sediments that would otherwise fill the interstitial spaces in productive gravel habitats (Beschta and Jackson 1979). Floods import woody debris into the channel (Keller and Swanson 1979), where it creates new, high-quality habitat (Figure 4; Moore and Gregory 1988, Wallace and Benke 1984). By connecting the channel to the floodplain, high overbank flows also maintain broader productivity and diversity. Floodplain wetlands provide important nursery grounds for fish and export organic matter and organisms back into the main channel (Junk et al. 1989, Sparks 1995, Welcomme 1992). The scouring of floodplain soils rejuvenates habitat for plant species that germinate only on barren, wetted surfaces that are free of competition (Scott et al. 1996) or that require access to shallow water tables (Stromberg et al. 1997). Flood-resistant, disturbance-adapted riparian communities are maintained by flooding along river corridors, even in river sections that have steep banks and lack floodplains (Hupp and Osterkamp 1985).

Flows of low magnitude also provide ecological benefits. Periods of low flow may present recruitment opportunities for riparian plant species in regions where floodplains are frequently inundated (Wharton et al. 1981). Streams that dry temporarily, generally in arid regions, have aquatic (Williams and Hynes 1977) and riparian (Nilsen et al. 1984) species with special behavioral or physiological adaptations that suit them to these harsh conditions.

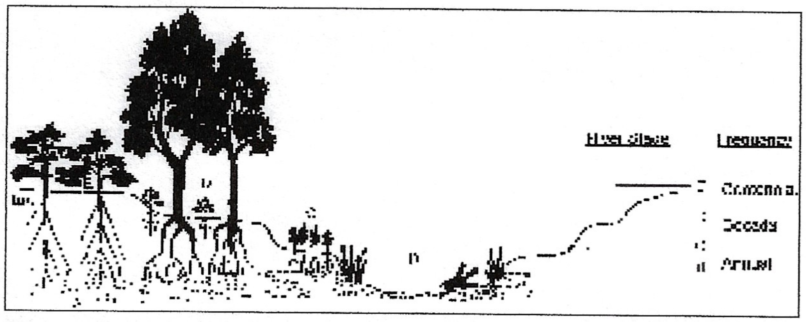

Figure 4. Geomorphic and ecological functions provided by different levels of flow. Water tables that sustain riparian vegetation and that delineate in-channel baseflow habitat are maintained by groundwater inflow and flood recharge (A). Floods of varying size and timing are needed to maintain a diversity of riparian plant species and aquatic habitat. Small floods occur frequently and transport fine sediments, maintaining high benthic productivity and creating spawning habitat for fishes (B). Intermediate-size floods inundate low-lying floodplains and deposit entrained sediment, allowing for the establishment of pioneer species (C). These floods also import accumulated organic material into the channel and help to maintain the characteristic form of the active stream channel. Larger floods that recur on the order of decades inundate the aggraded floodplain terraces, where later successional species establish (D). Rare, large floods can uproot mature riparian trees and deposit them in the channel, creating high-quality habitat for many aquatic species (E).

The duration of a specific flow condition often determines its ecological significance. For example, differences in tolerance to prolonged flooding in riparian plants (Chapman et al. 1982) and to prolonged low flow in aquatic invertebrates (Williams and Hynes 1977) and fishes (Closs and Lake 1996) allow these species to persist in locations from which they might otherwise be displaced by dominant, but less tolerant, species.

The timing, or predictability, of flow events is critical ecologically because the life cycles of many aquatic and riparian species are timed to either avoid or exploit flows of variable magnitudes. For example, the natural timing of high or low streamflows provides environmental cues for initiating life cycle transitions in fish, such as spawning (Montgomery et al. 1983, Nesler et al. 1988), egg hatching (Næsje et al. 1995), rearing (Seegrist and Gard 1978), movement onto the floodplain for feeding or reproduction (Junk et al. 1989, Sparks 1995, Welcomme 1992), or migration upstream or downstream (Trépanier et al. 1996). Natural seasonal variation in flow conditions can prevent the successful establishment of nonnative species with flow-dependent spawning and egg incubation requirements, such as striped bass (*Morone saxatilis*; Turner and Chadwick 1972) and brown trout (*Salmo trutta*; Moyle and Light 1996, Strange et al. 1992).

Seasonal access to floodplain wetlands is essential for the survival of certain river fishes, and such access can directly link high wetland productivity with fish production in the stream channel (Copp 1989, Welcomme 1979). Studies of the effects on stream fishes of both extensive and limited floodplain inundation (Finger and Stewart 1987, Ross and Baker 1983) indicate that some fishes are adapted to exploiting floodplain habitats, and these species decline in abundance when floodplain use is restricted. Models indicate that catch rates and biomass of fish are influenced by both maximum and minimum wetland area (Power et al. 1995, Welcomme and Hagborg 1977), and empirical work shows that the area of floodplain water bodies during nonflood periods influences the species richness of those wetland habitats (Halyk and Balon 1983). The timing of floodplain inundation is important for some fish because migratory and reproductive behaviors must coincide with access to and avail-

Table 2. Ecological responses to alterations in components of natural flow regime.[a]

Flow component	Specific alteration	Ecological response	Reference(s)
Magnitude and frequency	Increased variation	Wash-out and/or stranding	Cushman 1985, Petts 1984
		Loss of sensitive species	Gehrke et al. 1995, Kingsolving and Bain 1993, Travnichek et al. 1995
		Increased algal scour and wash-out of organic matter	Petts 1984
		Life cycle disruption	Scheidegger and Bain 1995
		Altered energy flow	Valentin et al. 1995
	Flow stabilization	Invasion or establishment of exotic species, leading to:	
		Local extinction	Kupferberg 1996, Meffe 1984
		Threat to native commercial species	Stanford et al. 1996
		Altered communities	Busch and Smith 1995, Moyle 1986, Ward and Stanford 1979
		Reduced water and nutrients to floodplain plant species, causing:	
		Seedling desiccation	Duncan 1993
		Ineffective seed dispersal	Nilsson 1982
		Loss of scoured habitat patches and secondary channels needed for plant establishment	Fenner et al. 1985, Rood et al. 1995, Scott et al. 1997, Shankman and Drake 1990
		Encroachment of vegetation into channels	Johnson 1994, Nilsson 1982
Timing	Loss of seasonal flow peaks	Disrupt cues for fish:	
		Spawning	Fausch and Bestgen 1997, Montgomery et al. 1993, Nesler et al. 1988
		Egg hatching	Næsje et al. 1995
		Migration	Williams 1996
		Loss of fish access to wetlands or backwaters	Junk et al. 1989, Sparks 1995
		Modification of aquatic food web structure	Power 1992, Wootton et al. 1996
		Reduction or elimination of riparian plant recruitment	Fenner et al. 1985
		Invasion of exotic riparian species	Horton 1977
		Reduced plant growth rates	Reily and Johnson 1982
Duration	Prolonged low flows	Concentration of aquatic organisms	Cushman 1985, Petts 1984
		Reduction or elimination of plant cover	Taylor 1982
		Diminished plant species diversity	Taylor 1982
		Desertification of riparian species composition	Busch and Smith 1995, Stromberg et al. 1996
		Physiological stress leading to reduced plant growth rate, morphological change, or mortality	Kondolf and Curry 1986, Perkins et al. 1984, Reily and Johnson 1982, Rood et al. 1995, Stromberg et al. 1992
	Prolonged baseflow "spikes"	Downstream loss of floating eggs	Robertson 1997
	Altered inundation duration	Altered plant cover types	Auble et al. 1994
	Prolonged inundation	Change in vegetation functional type	Bren 1992, Connor et al. 1981
		Tree mortality	Harms et al. 1980
		Loss of riffle habitat for aquatic species	Bogan 1993
Rate of change	Rapid changes in river stage	Wash-out and stranding of aquatic species	Cushman 1985, Petts 1984
	Accelerated flood recession	Failure of seedling establishment	Rood et al. 1995

[a]Only representative studies are listed here. Additional references are located on the Web at http://lamar.colostate.edu/~poff/natflow.html.

ability of floodplain habitats (Welcomme 1979). The match of reproductive period and wetland access also explains some of the yearly variation in stream fish community composition (Finger and Stewart 1987).

Many riparian plants also have life cycles that are adapted to the seasonal timing components of natural flow regimes through their "emergence phenologies"—the seasonal sequence of flowering, seed dispersal, germination, and seedling growth. The interaction of emergence phenologies with temporally varying environmental stress from flooding or drought helps to maintain high species diversity in, for example, southern floodplain forests (Streng et al. 1989). Productivity of riparian forests is also influenced by flow timing and can increase when short-duration flooding occurs in the growing season (Mitsch and Rust 1984, Molles et al. 1995).

The rate of change, or flashiness, in flow conditions can influence species persistence and coexistence. In many streams and rivers, particularly in arid areas, flow can change dramatically over a period of hours due to heavy storms. Non-native fishes generally lack the behavioral adaptations to avoid being displaced downstream by sudden floods (Minckley and Deacon 1991). In a dramatic example of how floods can benefit native species, Meffe (1984) documented that a native fish, the Gila topminnow (*Poeciliopsis occidentalis*), was locally extirpated by the introduced predatory mosquitofish (*Gambusia affinis*) in locations where natural flash floods were regulated by upstream dams, but the native species persisted in naturally flashy streams.

Rapid flow increases in streams of the central and southwestern United States often serve as spawning cues for native minnow species, whose rapidly developing eggs are either broadcast into the water column or attached to submerged structures as floodwaters recede (Fausch and Bestgen 1997, Robertson in press). More gradual, seasonal rates of change in flow conditions also regulate the persistence of many aquatic and riparian species. Cottonwoods (*Populus* spp.), for example, are disturbance species that establish after winter–spring flood flows, during a narrow "window of opportunity" when competition-free alluvial substrates and wet soils are available for germination. A certain rate of floodwater recession is critical to seedling germination because seedling roots must remain connected to a receding water table as they grow downward (Rood and Mahoney 1990).

Ecological responses to altered flow regimes

Modification of the natural flow regime dramatically affects both aquatic and riparian species in streams and rivers worldwide. Ecological responses to altered flow regimes in a specific stream or river depend on how the components of flow have changed relative to the natural flow regime for that particular stream or river (Poff and Ward 1990) and how specific geomorphic and ecological processes will respond to this relative change. As a result of variation in flow regime within and among rivers (Figure 2), the same human activity in different locations may cause different degrees of change relative to unaltered conditions and, therefore, have different ecological consequences.

Flow alteration commonly changes the magnitude and frequency of high and low flows, often reducing variability but sometimes enhancing the range. For example, the extreme daily variations below peaking power hydroelectric dams have no natural analogue in freshwater systems and represent, in an evolutionary sense, an extremely harsh environment of frequent, unpredictable flow disturbance. Many aquatic populations living in these environments suffer high mortality from physiological stress, from wash-out during high flows, and from stranding during rapid dewatering (Cushman 1985, Petts 1984). Especially in shallow shoreline habitats, frequent atmospheric exposure for even brief periods can result in massive mortality of bottom-dwelling organisms and subsequent severe reductions in biological productivity (Weisberg et al. 1990). Moreover, the rearing and refuge functions of shallow shoreline or backwater areas, where many small fish species and the young of large species are found (Greenberg et al. 1996, Moore and Gregory 1988), are severely impaired by frequent flow fluctuations (Bain et al. 1988, Stanford 1994). In these artificially fluctuating environments, specialized stream or river species are typically replaced by generalist species that tolerate frequent and large variations in flow. Furthermore, life cycles of many species are often disrupted and energy flow through the ecosystem is greatly modified (Table 2). Short-term flow modifications clearly lead to a reduction in both the natural diversity and abundance of many native fish and invertebrates.

At the opposite hydrologic extreme, flow stabilization below certain types of dams, such as water supply reservoirs, results in artificially constant environments that lack natural extremes. Although production of a few species may increase greatly, it is usually at the expense of other native species and of systemwide species diversity (Ward and Stanford 1979). Many lake fish species have successfully invaded (or been intentionally established in) flow-stabilized river environments (Moyle 1986, Moyle and Light 1996). Often top predators, these introduced fish can devastate native river fish and threaten commercially valuable stocks (Stanford et al. 1996). In the southwestern United States, virtually the entire native river fish fauna is listed as threatened under the Endangered Species Act, largely as a consequence of water withdrawal, flow stabilization, and exotic species proliferation. The last remaining strongholds of native river fishes are all in dynamic, free-flowing rivers, where exotic fishes are periodically reduced by natural flash floods (Minckley and Deacon 1991, Minckley and Meffe 1987).

Flow stabilization also reduces the magnitude and frequency of overbank flows, affecting riparian plant species and communities. In rivers with constrained canyon reaches or multiple shallow channels, loss of high flows results in increased cover of plant species that would otherwise be removed by flood scour (Ligon et al. 1995, Williams and Wolman 1984). Moreover, due to other related effects of flow regulation, including increased water salinity, non-native vegetation often dominates, such as the salt cedar (*Tamarix* sp.) in the semiarid western United States (Busch and Smith 1995). In alluvial valleys, the loss of overbank flows can greatly modify riparian communities by causing plant desiccation, reduced growth, competitive exclusion, ineffective seed dispersal, or failure of seedling establishment (Table 2).

The elimination of flooding may also affect animal species that depend on terrestrial habitats. For example, in the flow-stabilized Platte River of the United States Great Plains, the channel has narrowed dramatically (up to 85%) over a period of decades (Johnson 1994). This narrowing has been facilitated by vegetative colonization of sandbars that formerly provided nesting habitat for the threatened piping plover (*Charadius melodius*) and endangered least tern (*Sterna antillarum*; Sidle et al. 1992). Sand-hill cranes (*Grus canadensis*), which made the Platte River famous, have abandoned river segments that have narrowed the most (Krapu et al. 1984).

Changes in the duration of flow conditions also have significant biological consequences. Riparian plant species respond dramatically to channel dewatering, which occurs frequently in arid regions due to surface water diversion and groundwater pumping. These biological and ecological responses range from altered leaf morphology to total loss of riparian vegetation cover (Table 2). Changes in duration of inundation, independent of changes in annual volume of flow, can alter the abundance of plant cover types (Auble et al. 1994). For example, increased duration of inundation has contributed to the conversion of grassland to forest along a regulated Australian river (Bren 1992). For aquatic species, prolonged flows of particular levels can also be damaging. In the regulated Pecos River of New Mexico, artificially prolonged high summer flows for irrigation displace the floating eggs of the threatened Pecos bluntnose shiner (*Notropis sinius pecosensis*) into unfavorable habitat, where none survive (Robertson in press).

Modification of natural flow timing, or predictability, can affect aquatic organisms both directly and indirectly. For example, some native fishes in Norway use seasonal flow peaks as a cue for egg hatching, and river regulation that eliminates these peaks can directly reduce local population sizes of these species (Næsje et al. 1995). Furthermore, entire food webs, not just single species, may be modified by altered flow timing. In regulated rivers of northern California, the seasonal shifting of scouring flows from winter to summer indirectly reduces the growth rate of juvenile steelhead trout (*Oncorhyncus mykiss*) by increasing the relative abundance of predator-resistant invertebrates that divert energy away from the food chain leading to trout (Wootton et al. 1996). In unregulated rivers, high winter flows reduce these predator-resistant insects and favor species that are more palatable to fish.

Riparian plant species are also strongly affected by altered flow timing (Table 2). A shift in timing of peak flows from spring to summer, as often occurs when reservoirs are managed to supply irrigation water, has prevented reestablishment of the Fremont cottonwood (*Populus fremontii*), the dominant plant species in Arizona, because flow peaks now occur after, rather than before, its germination period (Fenner et al. 1985). Non-native plant species with less specific germination requirements may benefit from changes in flood timing. For example, salt cedar's (*Tamarix* sp.) long seed dispersal period allows it to establish after floods occurring any time during the growing season, contributing to its abundance on floodplains of the western United States (Horton 1977).

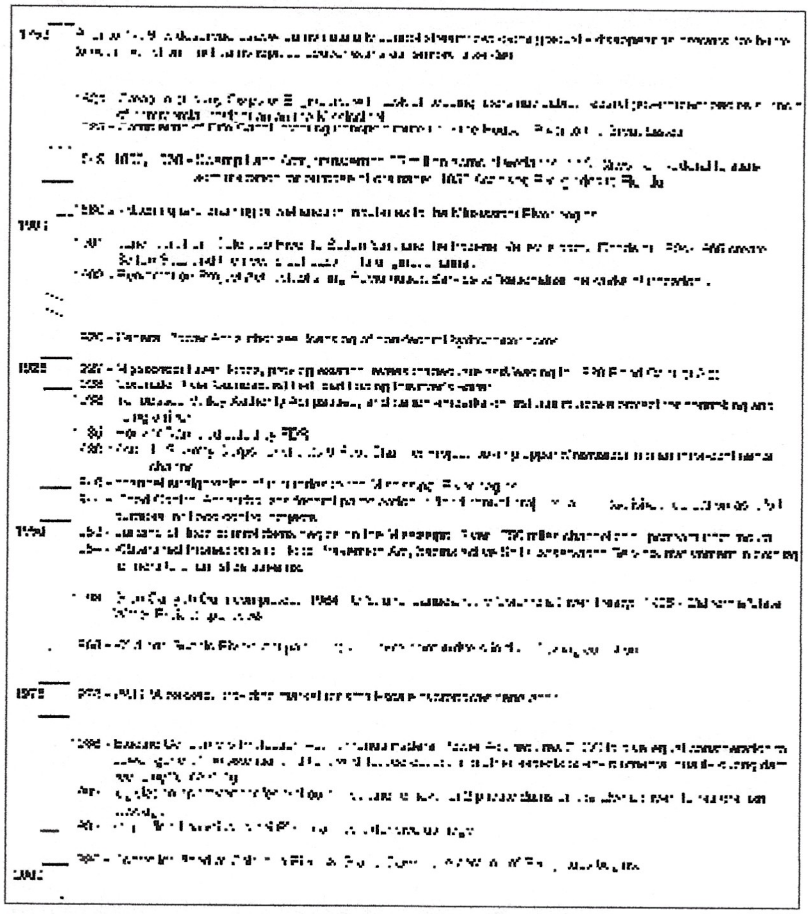

Figure 5. A brief history of flow alteration in the United States.

Altering the rate of change in flow can negatively affect both aquatic and riparian species. As mentioned above, loss of natural flashiness threatens most of the native fish fauna of the American Southwest (Minckley and Deacon 1991), and artificially increased rates of change caused by peaking power hydroelectric dams on historically less flashy rivers creates numerous ecological problems (Table 2; Petts 1984). A modified rate of change can devastate riparian species, such as cottonwoods, whose successful seedling growth depends on the rate of groundwater recession following floodplain inundation. In the St. Mary River in Alberta, Canada, for example, rapid drawdowns of river stage during spring have prevented the recruitment of young trees (Rood and Mahoney 1990). Such effects can be reversed, however. Restoration of the spring flood and its natural, slow recession in the Truckee River in California has allowed the successful establishment of a new generation of cotton-

Table 3. Recent projects in which restoration of some component(s) of natural flow regimes has occurred or been proposed for specific ecological benefits.

Location	Flow component(s)	Ecological purpose(s)	Reference
Trinity River, CA	Mimic timing and magnitude of peak flow	Rejuvenate in-channel gravel habitats; restore early riparian succession; provide migration flows for juvenile salmon	Barinaga 1996[a]
Truckee River, CA	Mimic timing, magnitude, and duration of peak flow, and its rate of change during recession	Restore riparian trees, especially cottonwoods	Klotz and Swanson 1997
Owens River, CA	Increase base flows; partially restore overbank flows	Restore riparian vegetation and habitat for native fishes and non-native brown trout	Hill and Platts in press
Rush Creek, CA (and other tributaries to Mono Lake)	Increase minimum flows	Restore riparian vegetation and habitat for waterfowl and non-native fishes	LADWP 1995
Oldman River and tributaries, southern Alberta, Canada	Increase summer flows; reduce rates of postflood stage decline; mimic natural flows in wet years	Restore riparian vegetation (cottonwoods) and cold-water (trout) fisheries	Rood et al. 1995
Green River, UT	Mimic timing and duration of peak flow and duration and timing of nonpeak flows; reduce rapid baseflow fluctuations from hydropower generation	Recovery of endangered fish species; enhance other native fishes	Stanford 1994
San Juan River, UT/NM	Mimic magnitude, timing, and duration of peak flow; restore low winter baseflows	Recovery of endangered fish species	—[b]
Gunnison River, CO	Mimic magnitude, timing, and duration of peak flow; mimic duration and timing of nonpeak flows	Recovery of endangered fish species	—[b]
Rio Grande River, NM	Mimic timing and duration of floodplain inundation	Ecosystem processes (e.g., nitrogen flux, microbial activity, litter decomposition)	Molles et al. 1995
Pecos River, NM	Regulate duration and magnitude of summer irrigation releases to mimic spawning flow "spikes"; maintain minimum flows	Determine spawning and habitat needs for threatened fish species	Robertson 1997
Colorado River, AZ	Mimic magnitude and timing	Restore habitat for endangered fish species and scour riparian zone	Collier et al. 1997
Bill Williams River, AZ (proposed)	Mimic natural flood peak timing and duration	Promote establishment of native trees	USCOE 1996
Pemigewasset River, NH	Reduce frequency (i.e., to no more than natural frequency) of high flows during summer low-flow season; reduce rate of change between low and high flows during hydropower cycles	Enhance native Atlantic salmon recovery	FERC 1995
Roanoke River, VA	Restore more natural patterning of monthly flows in spring; reduce rate of change between low and high flows during hydropower cycles	Increased reproduction of striped bass	Rulifson and Manooch 1993
Kissimmee River, FL	Mimic magnitude, duration, rate of change, and timing of high- and low-flow periods	Restore floodplain inundation to recover wetland functions; reestablish in-channel habitats for fish and other aquatic species	Toth 1995

[a]J. Polos, 1997, personal communication. US Fish & Wildlife Service, Arcata, CA.
[b]F. Pfeifer, 1997, personal communication. US Fish & Wildlife Service, Grand Junction, CO.

wood trees (Klotz and Swanson 1997).

Recent approaches to streamflow management

Methods to estimate environmental flow requirements for rivers focus primarily on one or a few species that live in the wetted river channel. Most of these methods have the narrow intent of establishing minimum allowable flows. The simplest make use of easily analyzed flow data, of assumptions about the regional similarity of rivers, and of professional opinions of the minimal flow needs for certain fish species (e.g., Larson 1981).

A more sophisticated assessment of how changes in river flow affect aquatic habitat is provided by the Instream Flow Incremental Methodology (IFIM; Bovee and Milhous

1978). IFIM combines two models, a biological one that describes the physical habitat preferences of fishes (and occasionally macroinvertebrates) in terms of depth, velocity, and substrate, and a hydraulic one that estimates how the availability of habitat for fish varies with discharge. IFIM has been widely used as an organizational framework for formulating and evaluating alternative water management options related to production of one or a few fish species (Stalnaker et al. 1995).

As a predictive tool for ecological management, the IFIM modeling approach has been criticized both in terms of the statistical validity of its physical habitat characterizations (Williams 1996) and the limited realism of its biological assumptions (Castleberry et al. 1996). Field tests of its predictions have yielded mixed results (Morehardt 1986). Although this approach continues to evolve, both by adding biological realism (Van Winkle et al. 1993) and by expanding the range of habitats modeled (Stalnaker et al. 1995), in practice it is often used only to establish minimum flows for "important" (i.e., game or imperiled) fish species. But current understanding of river ecology clearly indicates that fish and other aquatic organisms require habitat features that cannot be maintained by minimum flows alone (see Stalnaker 1990). A range of flows is necessary to scour and revitalize gravel beds, to import wood and organic matter from the floodplain, and to provide access to productive riparian wetlands (Figure 4). Interannual variation in these flow peaks is also critical for maintaining channel and riparian dynamics. For example, imposition of only a fixed high-flow level each year would simply result in the equilibration of in-channel and floodplain habitats to these constant peak flows.

Moreover, a focus on one or a few species and on minimum flows fails to recognize that what is "good" for the ecosystem may not consistently benefit individual species, and that what is good for individual species may not be of benefit to the ecosystem. Long-term studies of naturally variable systems show that some species do best in wet years, that other species do best in dry years, and that overall biological diversity and ecosystem function benefit from these variations in species success (Tilman et al. 1994). Indeed, experience in river restoration clearly shows the impossibility of simultaneously engineering optimal conditions for all species (Sparks 1992, 1995, Toth 1995). A holistic view that attempts to restore natural variability in ecological processes and species success (and that acknowledges the tremendous uncertainty that is inherent in attempting to mechanistically model all species in the ecosystem) is necessary for ecosystem management and restoration (Franklin 1993).

Managing toward a natural flow regime

The first step toward better incorporating flow regime into the management of river ecosystems is to recognize that extensive human alteration of river flow has resulted in widespread geomorphic and ecological changes in these ecosystems. The history of river use is also a history of flow alteration (Figure 5). The early establishment of the US Army Corps of Engineers is testimony to the importance that the nation gave to developing navigable water routes and to controlling recurrent large floods. However, growing understanding of the ecological impacts of flow alteration has led to a shift toward an appreciation of the merits of free-flowing rivers. For example, the Wild and Scenic Rivers Act of 1968 recognized that the flow of certain rivers should be protected as a national resource, and the recent blossoming of natural flow restoration projects (Table 3) may herald the beginning of efforts to undo some of the damage of past flow alterations. The next century holds promise as an era for renegotiating human relationships with rivers, in which lessons from past experience are used to direct wise and informed action in the future.

A large body of evidence has shown that the natural flow regime of virtually all rivers is inherently variable, and that this variability is critical to ecosystem function and native biodiversity. As we have already discussed, rivers with highly altered and regulated flows lose their ability to support natural processes and native species. Thus, to protect pristine or nearly pristine systems, it is necessary to preserve the natural hydrologic cycle by safeguarding against upstream river development and damaging land uses that modify runoff and sediment supply in the watershed.

Most rivers are highly modified, of course, and so the greatest challenges lie in managing and restoring rivers that are also used to satisfy human needs. Can reestablishing the natural flow regime serve as a useful management and restoration goal? We believe that it can, although to varying degrees, depending on the present extent of human intervention and flow alteration affecting a particular river. Recognizing the natural variability of river flow and explicitly incorporating the five components of the natural flow regime (i.e., magnitude, frequency, duration, timing, and rate of change) into a broader framework for ecosystem management would constitute a major advance over most present management, which focuses on minimum flows and on just a few species. Such recognition would also contribute to the developing science of stream restoration in heavily altered watersheds, where, all too often, physical channel features (e.g., bars and woody debris) are re-created without regard to restoring the flow regime that will help to maintain these re-created features.

Just as rivers have been incrementally modified, they can be incrementally restored, with resulting improvements to many physical and biological processes. A list of recent efforts to restore various components of a natural flow regime (that is, to "naturalize" river flow) demonstrates the scope for success (Table 3). Many of the projects summarized in Table 3 represent only partial steps toward full flow restoration, but they have had demonstrable ecological benefits. For example, high flood flows followed by mimicked natural rates of flow decline in the Oldman River of Alberta, Canada, resulted in a massive cottonwood recruitment that extended for more than 500 km downstream from the Oldman Dam. Dampening of the unnatural flow fluctuations caused by hydroelectric generation on the Roanoke River in

Virginia has increased juvenile abundances of native striped bass. Mimicking short-duration flow spikes that are historically caused by summer thunderstorms in the regulated Pecos River of New Mexico has benefited the reproductive success of the Pecos bluntnose shiner.

We also recognize that there are scientific limits to how precisely the natural flow regime for a particular river can be defined. It is possible to have only an approximate knowledge of the historic condition of a river, both because some human activities may have preceded the installation of flow gauges, and because climate conditions may have changed over the past century or more. Furthermore, in many rivers, year-to-year differences in the timing and quantity of flow result in substantial variability around any average flow condition. Accordingly, managing for the "average" condition can be misguided. For example, in human-altered rivers that are managed for incremental improvements, restoring a flow pattern that is simply proportional to the natural hydrograph in years with little runoff may provide few if any ecological benefits, because many geomorphic and ecological processes show nonlinear responses to flow. Clearly, half of the peak discharge will not move half of the sediment, half of a migration-motivational flow will not motivate half of the fish, and half of an overbank flow will not inundate half of the floodplain. In such rivers, more ecological benefits would accrue from capitalizing on the natural between-year variability in flow. For example, in years with above-average flow, "surplus" water could be used to exceed flow thresholds that drive critical geomorphic and ecological processes.

If full flow restoration is impossible, mimicking certain geomorphic processes may provide some ecological benefits. Well-timed irrigation could stimulate recruitment of valued riparian trees such as cottonwoods (Friedman et al. 1995). Strategically clearing vegetation from river banks could provide new sources of gravel for sediment-starved regulated rivers with reduced peak flows (e.g., Ligon et al. 1995). In all situations, managers will be required to make judgments about specific restoration goals and to work with appropriate components of the natural flow regime to achieve those goals. Recognition of the natural flow variability and careful identification of key processes that are linked to various components of the flow regime are critical to making these judgments.

Setting specific goals to restore a more natural regime in rivers with altered flows (or, equally important, to preserve unaltered flows in pristine rivers) should ideally be a cooperative process involving river scientists, resource managers, and appropriate stakeholders. The details of this process will vary depending on the specific objectives for the river in question, the degree to which its flow regime and other environmental variables (e.g., thermal regime, sediment supply) have been altered, and the social and economic constraints that are in play. Establishing specific criteria for flow restoration will be challenging because our understanding of the interactions of individual flow components with geomorphic and ecological processes is incomplete. However, quantitative, river-specific standards can, in principle, be developed based on the reconstruction of the natural flow regime (e.g., Richter et al. 1997). Restoration actions based on such guidelines should be viewed as experiments to be monitored and evaluated—that is, adaptive management—to provide critical new knowledge for creative management of natural ecosystem variability (Table 3).

To manage rivers from this new perspective, some policy changes are needed. The narrow regulatory focus on minimum flows and single species impedes enlightened river management and restoration, as do the often conflicting mandates of the many agencies and organizations that are involved in the process. Revisions of laws and regulations, and redefinition of societal goals and policies, are essential to enable managers to use the best science to develop appropriate management programs.

Using science to guide ecosystem management requires that basic and applied research address difficult questions in complex, real-world settings, in which experimental controls and statistical replication are often impossible. Too little attention and too few resources have been devoted to clarifying how restoring specific components of the flow regime will benefit the entire ecosystem. Nevertheless, it is clear that, whenever possible, the natural river system should be allowed to repair and maintain itself. This approach is likely to be the most successful and the least expensive way to restore and maintain the ecological integrity of flow-altered rivers (Stanford et al. 1996). Although the most effective mix of human-aided and natural recovery methods will vary with the river, we believe that existing knowledge makes a strong case that restoring natural flows should be a cornerstone of our management approach to river ecosystems.

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SHORT COMMUNICATION

A PRESUMPTIVE STANDARD FOR ENVIRONMENTAL FLOW PROTECTION

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ABSTRACT

The vast majority of the world's rivers are now being tapped for their water supplies, yet only a tiny fraction of these rivers are protected by any sort of environmental flow standard. While important advances have been made in reducing the cost and time required to determine the environmental flow needs of both individual rivers and types of rivers in specific geographies, it is highly unlikely that such approaches will be applied to all, or even most, rivers within the forseeable future. As a result, the vast majority of the planet's rivers remain vulnerable to exploitation without limits. Clearly, there is great need for adoption of a "presumptive standard" that can fill this gap. In this paper we present such a presumptive standard, based on the Sustainability Boundary Approach of Richter (2009) which involves restricting hydrologic alterations to within a percentage-based range around natural or historic flow variability. We also discuss water management implications in applying our standard. Our presumptive standard is intended for application only where detailed scientific assessments of environmental flow needs cannot be undertaken in the near term. Copyright © 2011 John Wiley & Sons, Ltd.

KEY WORDS: environmental flow; sustainability; Sustainable Boundary Approach; river management; corporate water use; water stewardship; water allocation; water scarcity

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Available freshwater supplies are being increasingly strained by growing human demands for water, particularly for irrigated agriculture and urban uses. The global population is growing by 80 million people each year, and if consumption patterns evolve as expected, two-thirds of the world's population will live in water-stressed areas by 2025 (WWAP, 2009). Whereas differing patterns of population growth, lifestyle changes and climate change will pose different scenarios on each continent, water managers and planners are challenged to meet growing water needs virtually everywhere.

At the same time, societies around the world are increasingly demanding that water managers also protect the natural freshwater ecosystems that are being tapped for water supplies. The need to protect 'environmental flows'—defined as the quantity, timing and quality of water flows required to sustain freshwater and estuarine ecosystems and the human livelihoods and well-being that depend on these ecosystems (Brisbane Declaration, 2007)—is now being addressed in many governmental water allocation policies, dam development plans and urban water supply plans. The stimuli for protecting environmental flows are varied and many, including the desire to protect biodiversity, ecosystem services (especially fisheries production), water-based tourism or recreation, economic activities such as hydropower generation and other cultural or spiritual values (Postel and Richter, 2003).

However, many good intentions to protect environmental flows have stalled upon encountering confusing and conflicting information about which method for environmental flow assessment is appropriate or 'best' and perceptions that the more credible and sophisticated methods require considerable investment of time, expertise and money to apply. These real and perceived hurdles have too often resulted in doing nothing to protect environmental flows, leaving the vast majority of rivers on the planet vulnerable to over-exploitation (Richter, 2009).

The environmental flow science community has long been attuned and responsive to the need for more cost-efficient and time-efficient approaches to determining environmental flow needs. Beginning in the 1970s with the Tennant (1976) method and continuing with the recent publication of the 'Ecological Limits of Hydrologic Alteration' (ELOHA; Poff *et al.*, 2010), a long series of efforts have been put forth by scientists to streamline and expedite environmental flow assessment while maintaining scientific credibility. However, widespread environmental flow protection across the planet's river networks has yet to be attained.

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Of particular concern and relevance to this paper is the fact that it is proving difficult to implement ELOHA in some jurisdictions even though the approach was explicitly designed to address the issues that have prevented other methods from being applied widely. The four co-authors of this paper have been actively encouraging government entities to apply the ELOHA framework; the difficulties we have experienced in these efforts have provided strong motivation for writing this paper. As we explain later in this paper, we continue to believe that ELOHA provides the best available balance between scientific rigor and cost of application for setting environmental flow standards for many rivers simultaneously. The ELOHA framework is currently being applied in various jurisdictions around the world. However, we are finding that many government entities are unable (or unwilling) to afford the cost of applying ELOHA (generally ranging from \$100k to \$2M), especially in situations where existing biological data and hydrologic models have poor spatial coverage. Time constraints are an even more frequent hindrance to the implementation of the ELOHA framework, particularly for jurisdictions embroiled in politically challenging situations such as responding to extreme droughts, legislative mandates or lawsuits. We suggest that until ELOHA or some variation can be applied everywhere, a presumptive, risk-based environmental flow standard is needed to provide interim protection for all rivers.

Another strong motivation for putting forth a presumptive standard at this time is the fact that many large water-using corporations are now looking for environmental indicators that can help them screen their operations and supply chains for water-related risks (e.g. SABMiller and WWF-UK, 2009). These corporations are increasingly coming to understand that, when environmental flows are not adequately protected, freshwater ecosystems will be stressed, jeopardizing ecosystem services valued by many people for their livelihoods and well-being. This can lead to conflicts that can ultimately endanger a company's 'social licence to operate' (Orr *et al.*, 2009). Presently, many corporations are using estimates for environmental flow requirements put forth by Smakhtin *et al.* (2004); these estimates range globally from 20% to 50% of the mean annual river flow in each basin. We agree with Arthington *et al.* (2006) that such a low level of protection as suggested by Smakhtin 'would almost certainly cause profound ecological degradation, based on current scientific knowledge'. We hope that the presumptive standard we offer in this paper will replace corporate use of the Smakhtin estimates for water risk screening.

The presumptive standard for environmental flow protection put forth in this paper is intended for use only in situations where the application of ELOHA or site-specific environmental flow determinations (e.g. Richter *et al.*, 2006) cannot be applied in the near future; in other words, it is intended for use as a default placeholder. This presumptive standard is derived from the sustainability boundary approach (SBA) described by Richter (2009), which involves maintaining flows within a certain percentage-based range around natural flows (i.e. flows in the absence of dam regulation or water withdrawals).

Before discussing our proposed presumptive standard in greater detail, we provide a short discussion of the advantages of 'per cent-of-flow' (POF) approaches such as the SBA for expressing environmental flow requirements. We then summarize efforts around the world to apply flow protection standards based on POF expressions. Finally, we propose a specific presumptive standard using risk bands placed around natural flow variability and conclude with management implications in applying this presumptive standard.

APPROACHES FOR SETTING FLOW PROTECTION STANDARDS

A primary challenge in setting flow protection standards is to employ a practical method that limits water withdrawals and dam operations in such a way as to protect essential flow variability. As described by Richter (2009), a large body of scientific literature supports the 'natural flow paradigm' as an important ecological objective to guide river management (Richter *et al.*, 1997; Poff *et al.*, 1997; Bunn and Arthington, 2002; Postel and Richter, 2003; Arthington *et al.*, 2006). Stated simply, the key premises of the natural flow paradigm are that maintaining some semblance of natural flow regimes is essential to sustaining the health of river ecosystems and that health is placed at increasing risk with increasing alteration of natural flows (Richter *et al.*, 2003; Richter, 2009).

Three basic approaches have been employed for setting environmental flow standards across broad geographies such as states or nations: minimum flow thresholds, statistically based standards and POF approaches. The most commonly applied approach to date has been to set a minimum flow level that must be maintained. For example, the most widely used minimum flow standard in the USA is the annual 7Q10, which is defined as the lowest flow for seven consecutive days that occurs every 10 years on average. Whereas the original intent of the annual 7Q10 flow standard was to protect water quality under the federal Clean Water Act of 1972, it has become either explicitly in rule or by default the minimum flow threshold in many states (Gillilan and Brown, 1997; IFC, 2001). The growing recognition that this threshold was not sufficiently protective of aquatic habitats led in the 1980s and 1990s to several states setting higher flow thresholds, such as by setting the minimum level at 30% of the mean annual flow (MAF) or by setting thresholds that vary seasonally, such as at the

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level of 60% of MAF in winter, 30% of MAF in summer and 40% of MAF in spring and fall (Gillilan and Brown, 1997; IFC, 2001).

More recently, statistically based standards have been used to maintain certain characteristics of the flow regime. For example, such a standard may call for protecting a high flow of a specified magnitude, with specified duration, to occur with a specified inter-annual frequency. The application of a statistically based standard in regulating water use generally involves using computerized hydrologic models to simulate the cumulative effects of licenced or proposed water withdrawals and dam operations on the flow regime; hydrologic changes are allowed to accumulate until the statistical standards would be violated by further withdrawals or dam effects.

Flow standards set in the USA, the European Union and elsewhere in the past decade have increasingly been based on a POF approach (see case studies later in this paper). This approach explicitly recognizes the importance of natural flow variability and sets protection standards by using allowable departures from natural conditions, expressed as percentage alteration. The POF approach has several strong advantages over other approaches. For instance, the POF approach is considerably more protective of flow variability than the minimum threshold standards. Minimum-threshold-based standards can allow flow variability to become 'flat-lined' as water allocation pressure increases and reservoir operations are designed only to meet minimum release requirements. Statistically based standards, although usually more protective of flow regimes than minimum thresholds, can be confusing to non-technical stakeholders, and complex statistical targets have proven difficult for water managers to implement (Richter, 2009). By comparison, POF approaches are conceptually simple, can provide a very high degree of protection for natural flow variability and can also be relatively simple to implement (i.e. a dam operator simply releases the prescribed percentage of inflow, or cumulative water withdrawals must not reduce flow by more than the prescribed percentage).

Sustainability boundary approach

Recognizing that human-induced flow alterations can both deplete and unnaturally augment natural flows to the detriment of ecological health, Richter (2009) expanded upon the POF approach by suggesting that bands of allowable alteration called 'sustainability boundaries' could be placed around natural flow conditions as a means of expressing environmental flow needs, as depicted in Figure 1.

To apply the SBA, the natural flow conditions for any point of interest along a river are estimated on a daily basis, representing the flows that would have existed in the absence of reservoir regulation, water withdrawals and return flows (Richter, 2009). Limits of flow alteration, referred to as sustainability boundaries, are then set on the basis of allowable perturbations from the natural condition, expressed as percentage-based deviations from natural flows. Those withdrawing water or operating dams are then required to maintain downstream river flows within sustainability boundaries. Whereas maintaining flows within the targeted range may be infeasible on a real-time basis in many cases, such management can be facilitated by creating computerized hydrologic models to evaluate what the likely perturbation to natural flows would be under existing or proposed scenarios of water withdrawal and dam operations and by licencing such water uses accordingly.

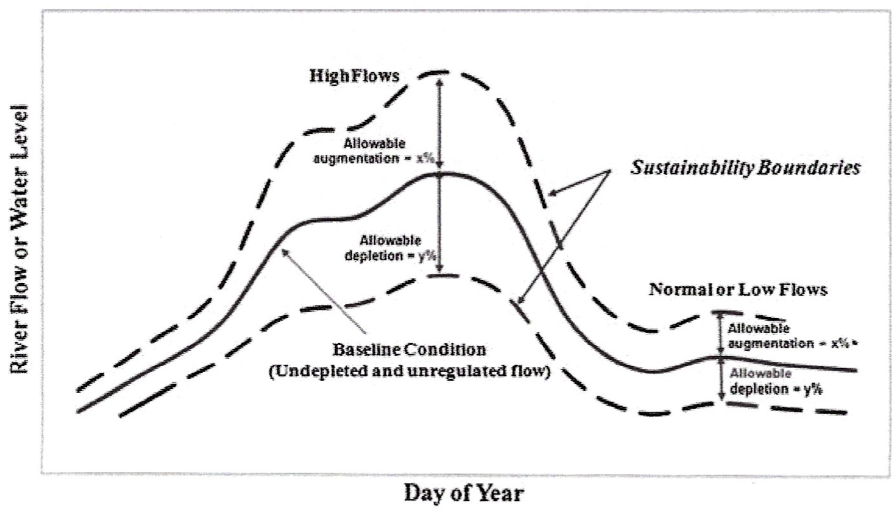

Figure 1. Illustration of the sustainability boundary approach from Richter (2009; reprinted with permission). The sustainability boundaries set limits on the degree to which natural flows can be altered, expressed as a percentage of natural flows.

The allowable degree of alteration from the natural condition can differ from one point to another along the same river. This determination for any point of interest along a river requires a negotiation or optimization between the following: (i) the desired consumption or dam regulation of water upstream, which might either deplete or unnaturally augment river flows; (ii) the desired uses of water downstream; and (iii) the desired ecological condition and ecosystem services to be maintained. As such, the SBA forces an explicit integration of environmental flow objectives with water withdrawals and dam operations. We recognize and emphasize that this is a socio-political decision-making process as much as it is a scientific one. As suggested by Richter (2009), the application of the SBA in setting river flow management goals requires transparent, inclusive and well-informed stakeholder engagement.

The basic challenge confronting environmental flow proponents is the difficulty of determining how much alteration from natural flows can be tolerated without compromising ecological health and ecosystem services to an undesirable degree. In the absence of such an understanding, water managers and governmental regulators have focused solely on water withdrawals and dam operations, providing only minimum flow protection or neglecting ecosystem considerations altogether. This highly undesirable situation calls for the adoption of a precautionary approach to fill the gap, until more detailed and regionally tailored studies of environmental flow needs can be completed and used to set flow protection standards.

We believe that sufficient scientific evidence and knowledge now exist to propose an SBA-based presumptive standard that can serve as initial guidance for regulating water withdrawals and dam operations in rivers. In designing the presumptive standard recommended later in this paper, we reviewed numerous other efforts to set environmental flow standards that apply across broad regions and many different rivers.

CASE STUDY REVIEW

The following case studies represent environmental flow policies and management guidelines that are being applied in the USA and Europe to limit flow alteration and to achieve relatively high levels of ecological protection, while allowing for carefully managed water development to proceed. Whereas not all of these cases can be characterized as pure POF approaches, we believe that these case studies illustrate useful and progressive water management policies that fulfill the intent of the SBA. They are described here to demonstrate the feasibility of applying standards in a manner consistent with the SBA and to support our recommendations for the presumptive standard described later in this paper.

Example #1—Southwest Florida Water Management District

Under the Florida state law, the state's five water management districts must determine 'minimum flows and levels' (MFLs) for priority water bodies of the state. Methods to determine MFLs differ among the five districts. The Southwest Florida Water Management District (SWFWMD) uses a POF-based approach that includes use of multiple environmental flow assessment methods, including the Instream Flow Incremental Methodology and the Wetted Perimeter approach (see IFC, 2001 for descriptions of these methods), to inform the setting of percentage alteration limits. The intent of the resulting MFLs is to limit water withdrawals such that physical habitat losses do not exceed 15% (Flannery *et al.*, 2002, 2008). The allowable flow reduction, which is referenced to as previous-day flows at a specified river gauge, can vary with season and with magnitude of flow and includes a 'hands-off' low flow threshold, meaning that all withdrawals are curtailed once the flow threshold is reached (see Rules of the Southwest Florida Water Management District, Chapter 40D-8, Water Levels and Rates of Flow, Section 40D-8.041 Minimum Flows at www.swfwmd.state.fl.us).

These MFLs are used in water management planning and incorporated as water withdrawal permit conditions. The percentage of allowable depletion has been set by SWFWMD for five non-tidal rivers in the district, ranging from 8% to 15% during high flows and 10% to 19% during low flows. Allowable depletions tend to be larger for freshwater flows into estuaries. For example, the lower Alafia River can be depleted up to 19% as it enters its estuary, based on limiting fish habitat loss caused by changes in salinity and dissolved oxygen to no more than 15%. No withdrawals are allowed when flows fall below 120 ft^3/s, based on chlorophyll residence time in the estuary, fish, dissolved oxygen and comb jellyfish. The proposed MFL for the Lower Peace River and its estuary limits withdrawals to flows above 130 ft^3/s, with allowable 16% reduction of daily flow up to a flow rate of 625 ft^3/s, 29% flow reductions in fall/winter and 38% flow reductions in summer above 625 ft^3/s (Flannery *et al.*, 2002, 2008).

Example #2—Michigan's Water Withdrawal Assessment Tool Approach

The Great Lakes–St Lawrence River Water Resources Compact and related state law require limits on water withdrawals to prevent 'adverse resource impact', defined as the point when 'a stream's ability to support characteristic fish populations is functionally impaired'. Zorn *et al.* (2008) documented the work of the Michigan Department of Natural Resources to develop a predictive model of how

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fish assemblages in different types of Michigan streams would change in response to decreased summer base flows, using habitat suitability information for over 40 Michigan fish species. The approach involved classification of all river segments in the state based on size and temperature regime and the development of a fish response curve that relates assemblage richness to an index flow (median August streamflow) for each of the 11 river classes. This index flow serves as a surrogate for withdrawals as a POF.

Across the majority of river types in Michigan, 'baseline or existing' ecological conditions are predicted to be maintained with cumulative withdrawals less than 6–15% of the index flow, depending on the stream type (Seelbach *et al.*, 2009). This is roughly equivalent to maintaining excellent ecological condition for many rivers, but some rivers that have historically been degraded would only be maintained in their current condition (Paul Seelbach, personal communication, University of Michigan, Ann Arbor). Adverse resource impacts are predicted to occur on most types of rivers with withdrawals greater than 17–25% of index flow. Rivers classified as 'transitional' between cold and cool rivers are very sensitive to withdrawals and are limited to withdrawals of 2–4% index flows before adverse resource impact is predicted to occur.

The Michigan Water Withdrawal Assessment Tool (WWAT) allows estimation of the likely impact of a water withdrawal on nearby streams and rivers using these threshold values. Use of the WWAT is required of anyone proposing to make a (large) new or increased withdrawal from the waters of the state, including all groundwater and surface water sources, prior to beginning the withdrawal. The WWAT is online at http://www.miwwat.org/.

Unlike Florida's POF approach, which references allowable depletions to a percentage of the previous day's flow, the Michigan approach references its withdrawal limits only to the August median flow. Because August is typically the lowest flow month in Michigan and Michigan flow regimes are fairly predictable, it is unlikely that cumulative withdrawals beyond the adverse resource impact level would frequently exceed the percentage guideline in other months. However, in very dry summers, one would expect the adverse resource impact percentage to be exceeded for a portion of the summer.

Example #3—UK Application of the European Union Water Framework Directive

The European Union (EU) Water Framework Directive, passed in 2000, was designed to protect and restore aquatic ecosystems by setting common ecological objectives across EU member states. The Water Framework Directive requires member states to achieve a 'Good Ecological Status' in all surface waters and groundwaters that are not determined to already be 'heavily modified'(Acreman *et al.*, 2006). It is assumed that meeting the Good Ecological Status requires protecting or restoring ecologically appropriate hydrological regimes, but the Water Framework Directive itself does not define environmental flow standards for any country in the EU (Acreman and Ferguson, 2010).

In the UK, a Technical Advisory Group worked with conservation agencies and academics to begin defining environmental standards for physio-chemical and hydro-morphological conditions necessary to meet different levels of ecological status (Acreman *et al.*, 2006). A key part of this work was defining thresholds of allowable water withdrawal as a percentage of natural flow. To achieve this, a literature review was prepared, and numerous expert workshops were convened. Each river in the UK was assigned to one of 10 classes, based on physical watershed characteristics, to facilitate application of withdrawal thresholds (Acreman and Ferguson, 2010).

Withdrawal standards were based on professional knowledge and discussion of the flow needs of various plant and animal communities—primarily macrophytes, macroinvertebrates and fish. Quantitative standards for achieving Good Ecological Status were specified for four groupings of river types, two seasons and four tiers of withdrawal standards based on annual flow characteristics (Table I). The allowable abstraction values in Table I are intended to be restrictions on cumulative withdrawals, applicable to any point on a river of that type.

The withdrawal standards in Table I were derived from an expert consensus workshop approach by using the precautionary principle to deal with considerable uncertainty. Different tolerances to flow alteration were recognized across taxa groups, but a 10% flow alteration was generally seen by experts as likely to have negligible impact for most taxa, stream types and hydrologic conditions (Acreman and Ferguson, 2010). The workgroup also generally agreed upon a Q95 (i.e. fifth percentile) flow as being 'hands-off', meaning that at that flow withdrawal would either stop or be significantly reduced. The recommended allowable withdrawal levels increase with magnitude of flow and in cooler months. Thus, permissible alterations range from 7.5% to 20% in warm months at lower flows (below Q70) and from 20% to 35% during cooler months at higher flows (Acreman *et al.*, 2006).

Example #4—Maine sustainable water use rule

In 2001, the Maine State Legislature passed a law requiring 'water use standards for maintaining instream flows...lake or pond water levels...protective of aquatic life and other uses...based on the natural variation of flows'. The resulting environmental flow and water level protection rule, finalized in 2007, establishes a set of tiered flow protection criteria

Table I. Standards for UK river types/subtypes for achieving Good Ecological Status, given as per cent allowable abstraction of natural flow (thresholds are for annual flow statistics)

Type or subtype	Season	Flow >Q60	Flow >Q70	Flow >Q95	Flow <Q95
A1	Apr–Oct	30	25	20	15
	Nov–Mar	35	30	25	20
A2 (downstream), B1, B2, C1, D1	Apr–Oct	25	20	15	10
	Nov–Mar	30	25	20	15
A2 (headwaters)	Apr–Oct	20	15	10	7.5
C2, D2	Nov–Mar	25	20	15	10
Salmonid spawning and nursery areas	Jun–Sep	25	20	15	10
	Oct–May	20	15	Flow >Q80	Flow <Q80

From Acreman and Ferguson (2010).

linked to different stream condition classes (Maine DEP, 2010a). The environmental flow standards may be established by one of two methods: a standard allowable alteration of flow or a site-specific flow assessment. The standard allowable alteration is based on the natural flow regime theory (Poff *et al.*, 1997; Richter *et al.*, 1997) and was informed by considerable scientific research on environmental flow requirements for the eastern USA (e.g. Freeman and Marcinek, 2006).

For all streams falling into the state's best-condition class (class AA), 90% of the total natural flow must be maintained when the flow exceeds the spring or early winter 'aquatic base flow' (Maine DEP, 2010b). This aquatic base flow is defined as the median monthly flow of the central month of each season (Maine DEP, 2006). In other seasons, withdrawals of up to 10% of daily flow can only occur when daily flows exceed 1.1 to 1.5 times the seasonal aquatic baseflow. No flow alteration is allowed in any season when flows are below aquatic base flow levels. In addition, all rivers and streams that flow into class AA waters must meet the POF standard.

Although used only for those waters with the highest ecological condition goals, which make up approximately 6% of state waters, the Maine standard provides a good example of use of a hands-off flow level combined with a POF approach.

Summary of case study findings

The case studies summarized here have much in common (Table II). In each case, standards were developed with a general intent to avoid ecological degradation of riverine ecosystems. The specifics of management goals vary from case study to case study, but common among them is the desire to maintain ecological conditions that are good to excellent or to avoid ecological harm. Each of these efforts to set standards has utilized the best available science for their region, and each has engaged large numbers of scientists familiar with flow–ecology science, using expert-based decision-making processes.

We found the recommendations for flow protection emerging from these expert groups to be quite consistent, typically resulting in a range of allowable cumulative

Table II. Summary of per cent-of-flow environmental flow standards from case studies

Location	Ecological goal	Cumulative allowable depletion	Considerations	Decision process
Florida (SWFWMD)	Avoid significant ecological harm (max. 15% habitat loss)	8–19% of daily flow	Seasonally variable extraction limit; 'hands-off' flow	Scientific peer review of site-specific studies
Michigan	Maintain baseline or existing condition	6–15% of August median flow	Single extraction limit for all flow levels	Stakeholders with scientific support
Maine	Protect class AA: 'outstanding natural resources'	10% of daily flow	Single extraction limit for all flow levels above a 'hands-off' flow level	Expert derived
European Union	Maintain good ecological condition	7.5–20% of daily flow	Lower flow; warmer months; 'hands-off' flow	Expert derived
		20–35% of daily flow	Higher flow; cooler months	

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depletion of 6% to 20% of normal to low flows, but with occasional allowance for greater depletion in seasons or flow levels during which aquatic species are thought to be less sensitive (Table II). These results suggest a consensus that modest alteration of water flows can be allowed with minimal to no harm to aquatic ecosystems and species.

A PROPOSED PRESUMPTIVE STANDARD

Our review of the case studies described above suggests that an appropriate presumptive standard for environmental flow protection can be proposed at this time, subject to some important caveats.

We suggest that a high level of ecological protection will be provided when daily flow alterations are no greater than 10%; a high level of protection means that the natural structure and function of the riverine ecosystem will be maintained with minimal changes. A moderate level of protection is provided when flows are altered by 11–20%; a moderate level of protection means that there may be measurable changes in structure and minimal changes in ecosystem functions. Alterations greater than 20% will likely result in moderate to major changes in natural structure and ecosystem functions, with greater risk associated with greater levels of alteration in daily flows. These thresholds are well supported by our case study review, as well as from our experiences in conducting environmental flow assessments for individual rivers (e.g. Richter *et al.*, 2003, 2006; Esselman and Opperman, 2010). This level of protection is also generally consistent with findings from regional analyses such as the 'benchmarking' study in Queensland, Australia, by Brizga *et al.* (2002) and by a national (US) analysis of hydrologic alteration which documented that biological impairment was observed in some sites with hydrologic alteration of 0–25% (the lowest class of alteration assessed) and in an increasing percentage of sites beyond 25% hydrologic alteration (Carlisle *et al.*, 2010).

This presumptive standard can be represented graphically as shown in Figure 2, using the convention of the SBA (Richter, 2009), with risk bands bracketing the daily natural flow conditions. When a single threshold value or standard is needed, such as for corporate risk screening or water supply planning purposes, we suggest that protecting 80% of daily flows will maintain ecological integrity in most rivers. A higher percentage of flow (90%) may be needed to protect rivers with at-risk species and exceptional biodiversity.

Whereas we believe that such a presumptive standard of limiting daily flow alterations to 20% or less is conservative and precautionary, we also caution that it may be insufficient to fully protect ecological values in certain types of rivers, particularly smaller or intermittent streams. Seasonal adjustments of the per cent of allowable depletion may be advisable. Several of our case studies utilized 'hands-off' flow thresholds to limit impacts to the frequency and duration of low-flow events. This may be an additional consideration where fish passage, water quality or other conditions are impaired by low flows. Also, when applying this presumptive standard to rivers affected by hydropower dams, imposing our suggested limits on daily flow averages may be insufficient to protect ecological integrity because of the propensity for peaking power operations to cause river flows to fluctuate considerably within each day. In such cases, our presumptive standard may need to be applied on an hourly, rather than daily, basis. Adjustments to our suggested values

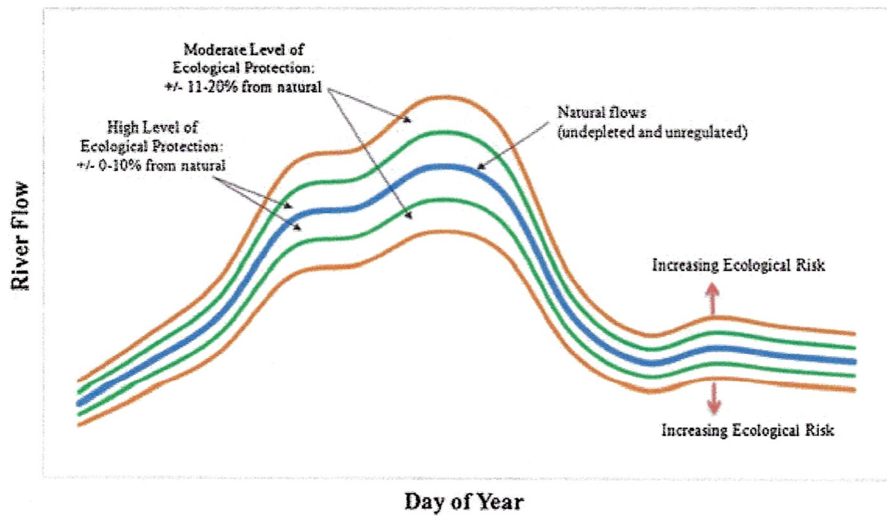

Figure 2. Presumptive standards are suggested for providing moderate to high levels of ecological protection. The greater the departure from natural flow conditions, the greater is the ecological risk to be expected. This figure is available in colour online at wileyonlinelibrary.com/journal/rra.

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should be considered when local or regional ecological knowledge indicates that narrower bands of allowable alteration are needed.

Most importantly, continued investment in detailed, site-specific or regional environmental flow assessment is urgently needed. Such research must continue to inform our understanding of flow–ecology relations and refine our presumptions about the adequacy of protecting different percentages of natural flows.

MANAGEMENT IMPLICATIONS

To properly apply our presumptive standard, water managers and other water stakeholders, such as corporations concerned about the sustainability of water use in particular river basins, will need to be able to do three basic things:

- Develop modelling tool(s) to estimate natural (unregulated and undepleted) flows on a daily basis; this provides the natural or 'baseline' flow data illustrated in Figure 1;
- Use the modelling tool(s) to evaluate whether *proposed* withdrawals, dam operations or other changes—when added to already-existing water uses—would cause the presumptive standard to be violated;
- Monitor daily flows at key locations, such as upstream and downstream of major water withdrawals and return flows, and at points of inflow to reservoirs, as a means for verifying and refining the modelling results and for regulatory enforcement purposes.

The capability to evaluate proposed hydrologic changes (second bullet in the above list) enables water managers to avoid issuing water use permits that would cause hydrologic variations to deviate outside of the sustainability boundaries set by the presumptive standard (±20%). Obviously, if a particular river's flow regime has already been altered more than ±20% during part or all of the time, water managers and stakeholders would need to decide whether to restore flows to a level consistent with the presumptive standard or adopt some other standard.

Application in over-allocated basins

Ongoing efforts to develop sustainable approaches to water management in the Murray-Darling river basin in Australia offer a highly relevant and useful example of re-balancing environmental and economic goals in a previously over-allocated basin. In response to considerable ecological degradation, heavy competition among water users, prolonged drought and climate change projections, the Commonwealth Parliament in 2007 passed a national water act calling for the development of a basin plan that would provide for integrated and sustainable management of water resources (MDBA, 2009). The Basin Plan is required to set enforceable limits on the quantities of surface water and groundwater that can be taken from the basin's water resources. These limits must be set at a level that the Murray-Darling Basin Authority, using the best available scientific knowledge, determines to be environmentally sustainable. This is defined as the level at which water in the basin can be taken from a water source without compromising the key environmental assets, the key ecosystem functions, the productive base or the key environmental outcomes of the water source. Considerable scientific analysis is being undertaken to determine environmental water requirements that will inform the determination of 'sustainable diversion limits'. Recent appropriations of federal funding to enable the buyback of historical entitlements can be used to reduce water usage to levels compatible with these diversion limits (Garrick *et al.*, 2009). The scientific assessment and decision-making being undertaken in the Murray-Darling basin exemplifies a situation in which our presumptive standard would have been violated by past water allocations, yet water managers and stakeholders are now striving to restore a level of ecological health and water use sustainability similar to the goals of our presumptive standard.

Technology requirements

The technology and capacity to manage water in this manner exist in many parts of the world, but we acknowledge that many water management institutions and corporations have not yet developed hydrologic modelling tools with the required level of temporal resolution (i.e. daily) to implement our presumptive standard. Similarly, few countries have been able to install and maintain daily flow monitoring networks with adequate spatial distribution to facilitate data collection and regulation of water uses in the manner we suggest. However, recent and ongoing advances in modelling approaches and technologies, as well as improvements in flow monitoring instrumentation, are driving down the expense of implementing this type of water monitoring and modelling programme. Given growing water scarcity and its economic implications, investment in this level of water management capacity should be given high priority by governments at all levels.

We recognize that many water planners continue to use hydrologic models that operate on a monthly time step. We can offer some guidance and caution. Although it is consistent with our presumptive standard to assume for planning purposes that 20% of the natural monthly mean flow can be allocated for consumptive use, this does not mean that a volume of water equivalent to 20% of the monthly mean can be allocated on a fixed basis without violating our presumptive standard. We illustrate this point

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with a simple hypothetical example. Let us say that the mean monthly flow in July is 100 m^3/s. You allocate a sum total of 20 m^3/s (20% of mean) for that month. Our presumptive standard will be violated each day in July that natural daily flows (recorded upstream or modeled) drop below100 m^3/s, which will be the case during the majority of the time for most river types. Therefore, the only way to be assured that our presumptive standard will not be violated given a monthly allocation will be to subsequently model the system at a daily time step to check for compatibility with the standard under the range of flows typically experienced by the river. Once such compatibility is assured, the water authority can confidently grant water use permits based on fixed amounts (i.e. monthly allocations or continuous rates of use) that provide the water user with desirable certainty.

Utility for water planning

Although implementation of our presumptive standard will require considerable investment in adequate technology and expertise as outlined previously in this paper, we want to emphasize that our presumptive standard will also be quite useful for initial water planning purposes that require less technological investment. As discussed in our introduction, many large corporations have become quite concerned about their water-related business risk and are interested in approaches that can help them screen for such risk across many facilities and parts of their supply chains. We suggest that our presumptive standard will be highly appropriate in risk screening, wherein estimates of water availability and use are available for river basins of interest. Our presumptive standard can be used to identify river basins in which water flows appear to have been altered by more than 20%, thereby posing considerable potential risk. In this sense, we are pleased to see the incorporation of a variation of our presumptive standard in the *Water Footprint Assessment Manual* (Hoekstra *et al.*, 2011), which is already being used by many corporations.

Implications for water supply and storage

We recognize that in most hydrologic settings, storage will be required to enable full utilization of up to 20% of the available daily flow for consumptive use. Creating such storage can lead to ecological impacts (such as impediments to fish migrations or blocking sediment transport) that can undo the ecological benefits that our presumptive flow standard is trying to protect. Therefore, we strongly urge water managers and engineers to employ innovative options for water storage—such as off-stream reservoirs or groundwater storage—that do not involve on-stream reservoirs. Alternatively, in systems in which storage reservoirs already exist, enlarging the capacity of those existing facilities will in most cases be far preferable to building new reservoirs.

Some water managers will feel excessively constrained by having to operate within the constraints of the presumptive sustainability boundaries suggested here. However, managing water sustainably necessarily implies living within limits (Richter *et al.*, 2003; Postel and Richter, 2003; Richter, 2009). We suggest that a strong social imperative has emerged that calls for setting those limits at a level that avoids damaging natural systems and the benefits they provide, at least as a default presumption. Where other socio-economic priorities suggest the need for relaxation of the presumptive sustainability boundaries we suggest here, we strongly encourage governments and local communities to invest in thorough assessments of flow–ecology relationships (Richter *et al.*, 2006; Poff *et al.*, 2010), so that decision-making can be informed with scientific assessment of the ecological values that would likely be compromised when lesser degrees of flow protection are adopted.

In our experiences in working with water and dam managers, we have found that a remarkable degree of creativity and innovation emerges when engineers and planners are challenged to meet targeted or forecasted water demands with the least disruption to natural flow patterns. Solving the water equation will require new thinking about how and where to store water, conjunctive use of surface water and groundwater, sizing diversion structures or pumps to enable extraction of more water when more is available during high flows, sizing hydropower turbines such that maximum power can be generated across a fuller range of flows, and other innovations. When such creativity is applied as widespread common practice, human impacts on freshwater ecosystems will most certainly be reduced substantially.

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