BIOLOGY:

The Distribution of Bacterial Contaminants in Dammed Aquatic Systems

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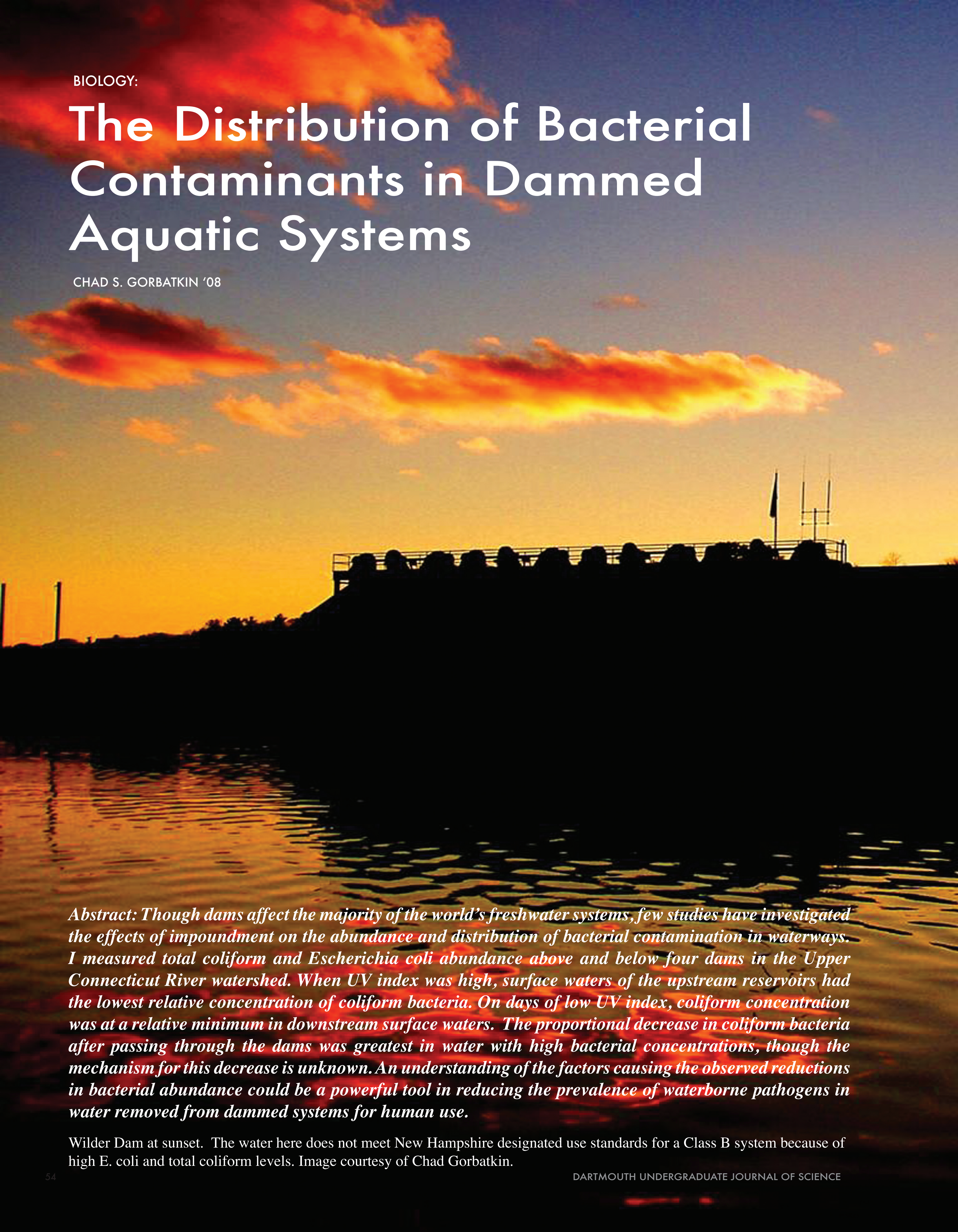
Abstract: Though dams affect the majority of the world's freshwater systems, few studies have investigated the effects of impoundment on the abundance and distribution of bacterial contamination in waterways. I measured total coliform and Escherichia coli abundance above and below four dams in the Upper Connecticut River watershed. When UV index was high, surface waters of the upstream reservoirs had the lowest relative concentration of coliform bacteria. On days of low UV index, coliform concentration was at a relative minimum in downstream surface waters. The proportional decrease in coliform bacteria after passing through the dams was greatest in water with high bacterial concentrations, though the mechanism for this decrease is unknown. An understanding of the factors causing the observed reductions in bacterial abundance could be a powerful tool in reducing the prevalence of waterborne pathogens in water removed from dammed systems for human use.



Wilder Dam at sunset. The water here does not meet New Hampshire designated use standards for a Class B system because of high E. coli and total coliform levels. Image courtesy of Chad Gorbatkin.

Introduction

Dam building has quickly become a dominant industry in countries wishing to develop energy security and control over water resources (1,2,3). By placing a physical barrier on a flowing body of water, a dam alters physical, chemical, and biological processes of watersheds (4,5). These transformations in ecological dynamics are compounded by normal human inputs and by changes in human inputs that result directly from the placement of dams, including changes in the degree of urbanization and sanitation systems (6,7).

Dams may alter the species composition and population dynamics of microbial communities, which comprise a large portion of the energy flow within many ecosystems (8,9). Microbial abundance directly relates to the prevalence of infectious waterborne disease, and therefore any effect of dams on microbial community composition has immediate implications for human health (10,11). An understanding of the growth, mortality, and distribution of these organisms in aquatic systems could therefore facilitate efforts to control the prevalence of waterborne disease (12,13). A metric of particular interest is the abundance of total coliform (TC), a bacterial group associated with the digestive tracts of warm-blooded mammals. This group includes Escherichia coli (E. coli), which is linked to fecal contamination (12). Coliform subgroups, and specifically fecal coliform such as E. coli, not only cause disease but also serve as bioindicators for the extent of fecal contamination, which can be linked to the presence of pathogens such as Cryptosporidium oocysts and Giardia cysts (7).

In this study, I tested the hypothesis that dams have significant and predictable effects on coliform concentration in surrounding water by altering the water's exposure to UV radiation. Specifically, I predicted that, in an impounded waterway, surface locations with lower velocity and more direct UV light radiation would have lower concentrations of bacterial contaminants than locations exposed to less direct UV radiation (14). Furthermore, I predicted that movement through or over a dam would not significantly change bacterial concentrations, because the reduction in bacterial abundance due to UV radiation in the upstream reservoir would be so dramatic that the maximum effect of movement over the dam would be very low.

Methods

Study Sites

This study was conducted at four dam sites in the Upper Connecticut River watershed. The two smaller dam sites on Connecticut tributaries include the Waits Dam along Waits River in Bradford, VT and Adams Paper Mill Dam along Wells River in Wells River, VT. Waits Dam is approximately 9 m in height and 23 m in length. Waits River approaches Bradford from a relatively undisturbed area higher in the watershed, and enters the city limits 500 m upstream of the dam. Adams Paper Mill Dam is approximately 5 m in height and 12 m in length. This entire section of Wells River is upstream of major urban pollution and fecal contamination. Both dams are top-spilling.

Comerford Dam in Northern New Hampshire Image Courtesy of Chad Gorbatkin

The two larger dams on the Connecticut River mainstream are the Comerford Dam near Littleton, NH and the Wilder Dam near Hanover, NH. The Comerford Dam is approximately 57 m in height and 733 m in length. The area surrounding Comerford Dam is constituted, in part, by farmland, but the reservoir itself is a New Hampshire Designated Use (DU) Class B freshwater system. The DU Class B status designates a freshwater system suitable for all recreational purposes. Wilder Dam is approximately 13 m in height and 200 m in length, and is downstream of the Town of Hanover sewage plant discharge. Water collecting above the dam fails to meet DU standards for a Class B freshwater system based on *E. coli* and TC sampling by the US EPA. Both dams are operated and maintained by Trans Canada Pipelines Limited, and water from both of these dams is drawn from low in the water column prior to spilling.

Bacterial Sampling

Samples were taken from the center of the rivers at a depth of 0-1 m when possible, except for sites of high current near dam outputs. At each dam, one sample was taken at the shortest distance from the dam where water velocity was not influenced by the impoundment. This sampling was performed either by lowering a Van Dorn sampler from a bridge or by wading to the center. Distance from the dam at which sampling was performed was approximately 400 m for Waits Dam, 1000 m for Adams Paper Mill, and 3000 m for the Wilder and Comerford Dams. A second sample was taken with a Van Dorn bottle immediately upstream of each dam. This sampling was performed from bridges above Wilder Dam, Comerford Dam, and Waits Dam. One set of surface water samples was taken at Wilder on a day of moderate UV index (UVI 3) and high temperature (11 oC) from 12-4 pm. Another set of samples was taken at Waits, Adams Paper Mill, Comerford, and Wilder over two days of low UVI (UVI 1) and low temperature (0-2 oC) from 12-4 pm. Vertical sampling was also performed at Wilder Dam, immediately upstream of the impoundment, on a day of UVI 1 and 2 oC. Downstream sampling was performed from the stream bank at each dam, due to extreme mixing and high water velocity at the dam outputs.

Bacterial Processing

EPA-Approved Method 10029 and the membrane filtration technique using m-ColiBlue24 Broth were used to count TC and E. coli. Samples were filtered through 0.45 um filter paper and then incubated at 37 oC for 24 hours. Rather than using a 5-fold dilution factor for a standard 100 ml solution as prescribed by Method 10029, I filtered 20 ml of water for all samples.

Data Analysis

I combined the TC counts from above and below the dams taken on the day of low radiation and used dams as replicates in the statistical analyses. A paired two-sample t-test was used with log-transformed TC counts to assess whether there were differences between the above-dam and below-dam sites. To compare bacterial contamination between two sampling locations (laterally or vertically distinguished), log-transformed TC and E. coli counts were analyzed using two-sample t-tests. One-tailed tests were used in all cases to test for specific directional change in bacterial concentrations. Two-tailed tests were not used because the direction of change was hypothesized a priori.

Results

Surface Waters Approaching Dam

The incoming water far above Wilder Dam had the maximum microbial concentrations of all surface locations sampled, with 731 TC/100 mL and 89 E. coli/100 mL. In UVI 3 conditions, Wilder Dam had significantly less TC and E. coli in the reservoir 100 m above the dam than 3000 m upstream ($t_{1,2} = 3.07$, $p = 0.046$ for TC; $t_{1,1} = 5.21$, $p = 0.060$ for E. coli; Fig. 1). The magnitude of the change was 40% for TC and 56% for E. coli. In UVI 1 conditions, Waits Dam had significantly more TC and E. coli in the reservoir surface water directly above the dam than in the approaching surface water ($t_{1,1} = 13.27$, $p = 0.024$ for TC; $t_{1,1} = 7.84$, $p = 0.040$ for E. coli; Fig. 1). The magnitude of the change was 266% for TC and 1000% for E. coli. Adams Paper Mill Dam (in UV1 conditions), Comerford Dam (in UVI 1 conditions), and Wilder Dam (in UVI 1 conditions) did not show significant changes in bacterial concentrations between the immediate upstream and far upstream sites (two-sample t-tests, $p>0.30$).

Bacterial Stratification in Wilder Reservoir

At Wilder dam, there was no change in temperature (~7.5oC) and no change in dissolved oxygen (DO; ~11.2 mg/L) from the surface to the reservoir bottom. There was no correlation between depth and TC or E. coli concentration. However, the surface water layer (0-1 m) contained significantly fewer TC and E. coli colonies than the deeper water (2-8 m; $t_{1,3} = 2.08$, $p = 0.064$ for TC; $t_{1,4} = 2.69$, $p = 0.027$ for E. coli). The surface layer contained 71% more TC and 55% more E. coli than the deeper layers contained. However, the ratio of E. coli:TC was 0.18 in the top layer (0-1 m) and increased 128% to 0.23 in deeper water (2-8 m).

Dam encounter

For data taken on days with low a low UV index (UVI 1) the surface water immediately above dams had significantly more TC and E. coli than immediately below the dams ($t_{1,3} = 1.81$, $p = 0.084$ for TC; $t_{1,3} = 1.70$, $p = 0.094$ for E. coli; Fig. 2). Waits Dam had the largest change in bacterial concentration with 66% reduction in TC and 70% reduction in E. coli ($t_{1,1} = 3.85$, $p = 0.081$ for TC; $t_{1,1} = 5.84$, $p = 0.053$ for E. coli). Wilder Dam in UVI 1 conditions had the largest ratio of E. coli:TC both above and below the dam. However, the proportion increased from 0.16 to 0.23 (144%) after water spilled over the dam. For Wilder Dam in UVI 3 conditions, the surface water immediately above the dam had significantly less TC than surface water immediately below ($t_{1,2} = 2.88$, $p = 0.051$). The above-dam water at Wilder in UVI 3 conditions had 69% of the TC that was in the below-dam surface water. The rivers with the highest bacterial concentrations in the reservoir above the dam, the Waits and Connecticut, showed the greatest magnitude of change in bacterial concentration after water had flowed through or over the dam (Fig. 2). For the four dams at UVI 1, the higher pre-reservoir TC corresponded to a greater percent decrease in TC from pre-reservoir to post-dam (Table 1).

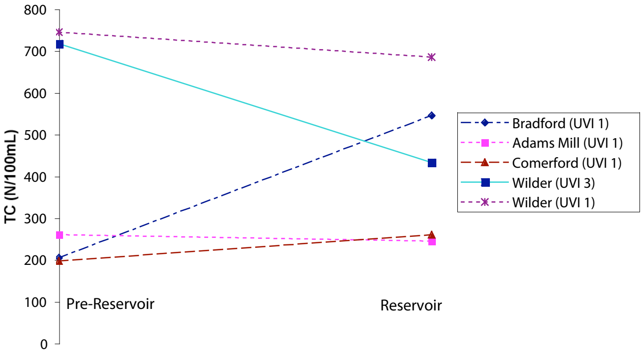


Figure 1. Total coliform concentration in surface waters upstream of the reservoir (i.e., pre-reservoir) and surface waters in the reservoir for four impounded waterways in October-November 2005. Change in TC between the two sampling locations is not integrable, because it is not scaled to distance. Ultraviolet Index (UVI) is the index developed by the Environmental Protection Agency and National Weather Service and is scaled 1-16 for predicted ground-level ultraviolet intensity.

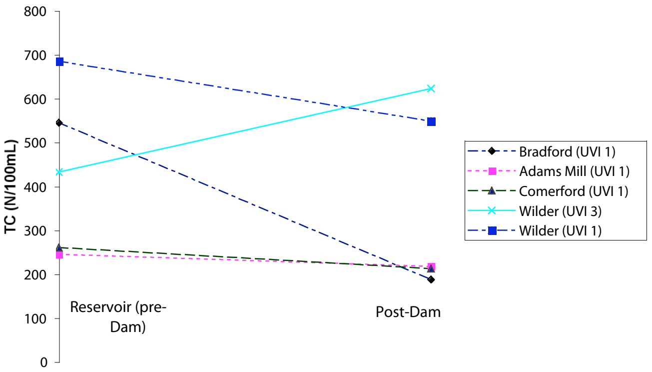


Figure 2. Surface water total coliform immediately above four dams (left) and immediately downstream of dams (right) in October-November 2005. The change is not integrable because it is not scaled to distance.

Discussion

As surface water approached and flowed through or over each of the four dams, TC and E. coli showed significant fluctuations. For each of the dams, the sampling location with the lowest concentration of TC was that with the highest presumed UV exposure. Other studies have also documented the dominant effects of UV radiation on bacterial abundance (15,16,17). On days of low UV radiation, the surface water TC minima were determined by the currently unknown physical effects of flowing through or over the dam.

For surface water approaching the dam on days of UVI 1, Waits River was the only system that showed a significant increase in TC and E. coli from high above to immediately above the impoundment. The increase could be due to the top-spilling dam preventing heavier organic particles from exiting the shallow reservoir (18), but this would not account for a 379% increase in the E. coli: TC ratio. This change in the E. coli:TC ratio would more likely result from a change in the nature of inputs. When Waits River approaches the dam, it flows directly through the town of Bradford. Various non-point sources of fecal contamination are therefore the most likely causes of this increase (7). I strongly suggest further study of point and non-point fecal inputs into this section of Waits River, because this sudden overloading of bacterial contaminants could cause eutrophication and shifts in normal species interactions.

The Connecticut River showed a substantial decrease in the E. coli and TC present in surface water approaching Wilder Dam (i.e., from high above to immediately above the impoundment) at UVI 3. I attribute this to the fact that reservoir water mixes less thoroughly than upstream water, enabling reservoir surface waters to receive a higher proportion of UV radiation than upstream surface waters (15). The reduction in TC and E. coli concentration in the reservoir due to UV suggests concomitant reduction in the abundance of human pathogens, including infectious bacteria and protozoan parasites, for which UV is also lethal (19,20). These results have important implications for minimizing waterborne disease in areas of the world that regularly receive UVI 5-10, as these systems may experience more extreme microbial reductions in upstream reservoirs.

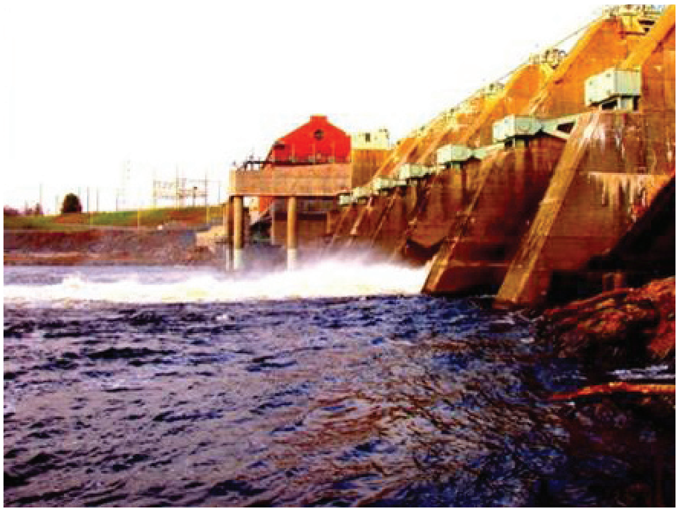
Immediately upstream of Wilder Dam, the top layer of water in the reservoir had considerably fewer bacteria than deeper waters. I attribute this decrease to UV decay of surface bacteria and to the sinking of dense organic particles on which bacteria feed. Because the increase in bacterial abundance occurred below the first meter of water, even extremely small (1-5 m) natural or human obstructions could have implications for bacterial distribution. Whether the water flows through the dam from the top of the water column or the bottom could have a large effect on the bacterial load of downstream water.

Although I predicted that there would be no difference in bacterial abundance between above- and below-dam sites, below-dam sites had significantly lower bacterial concentrations than above-dam sites on days with low UV index. Much of the current research on reducing the pathogen content of drinking water is directed at post-removal filtration, chemical treatment (including photocatalyzed sterilization), and solar inactivation (16,21). In this study, when UV radiation was low, the physical encounter with a dam removed between 11 and 66% of coliform. The two dams with the highest initial TC and E. coli showed the largest proportional decrease. Further research is necessary to determine if the magnitude of the decrease is related to the level of contamination, or properties of the dams.

	Connecticut at Wilder Dam	Wells River at Adams Paper Mill	Waits River at Waits Dam	Connecticut at Comerford Dam
TC rank	1	2	3	3
TC (N/100mL)	745	745	205	198
E. coli/TC	0.131	0.067	0.024	0.025
% D (TC)	-26	-16	-9	7
Drainage area (km2)	10594.7	255.7	50	6844
Q (m3/sec)	245.73	5.5	1.02	168.71
Top-spilling	no	yes	yes	no

Table 1. Characteristics of the four study systems in the Upper Connecticut watershed, USA in UV Index 1 conditions in October-November 2005. TC rank ranks sites according to pre-impoundment total coliform levels from highest to lowest. % d(TC) indicates percentage change in total coliform from pre-reservoir to post-dam sampling locations. DA indicates drainage area and Q indicates annual mean discharge for 2004.

The major problem with relying on UV to reduce the abundance of pathogens in surface waters is that UV fluctuates considerably (22). While post-dam water contained fewer bacteria at UVI 1 conditions, the same pattern was not observed at Wilder Dam in UVI 3 conditions. The site of lowest pathogen abundance in a given region may not be constant seasonally or even between days. This consistency will tend to be higher in equatorial regions, which may maintain greater evenness of moderate-to-high UV radiation between days and seasons (23). In these areas, the upstream reservoir may consistently have lower pathogen densities. Further research on the dynamics of high levels of bacterial contamination and high UV radiation is necessary, as these characteristics define a large number of dam systems in developing countries. A system-specific model predicting abundance of bacteria as a function of dam type, UVI, flow, and other parameters could compliment other cost-efficient pathogen reduction techniques to reduce waterborne disease in regions without formal sanitation or water processing stations.



Water gushes forth from the Wilder Dam.
Image courtesy of Chad Gorbatkin.

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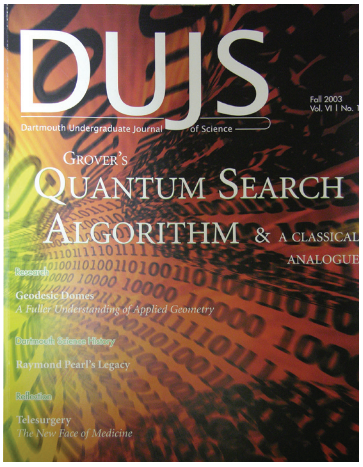

DUJS
Dartmouth Undergraduate Journal of Science
Fall 2003
Vol. VI | No. 1

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