



Water Soluble Polymers as a Means to Increase Flow Capacity: Field Experiment of Drag Reduction by Polymer Additives in an Irrigation Canal

Walid Bouchenafa¹; Benjamin Dewals²; Arnaud Lefevre³; and Emmanuel Mignot⁴

Abstract: A drag reduction method by polymer additives was tested for the first time in a large scale open-channel watercourse. Ten and a half tons of a water soluble polymer were injected during 15 consecutive hours in the upstream section of an irrigation canal in steady state, leading to a 20 ppm concentration of polymer in the water. The evolution of the water depth was measured every 10 min for 18 h along ten sections further downstream, up to a distance of 26.3 km from the injection section. The water depth at all sections remained constant until the arrival of the polymer, at which time it strongly decreased, sometimes with a slight water-depth increase beforehand; the depth then remained constant as long as the polymer injection remained. A maximum water depth reduction of 26 cm (i.e., 17%) was measured at the first cross section (2 km downstream from injection). The water depth reduction decreased to 10% and 3% at 10 and 20 km downstream from the injection, respectively. However, further downstream, at a distance of 26.3 km, the water depth increased by 5%. This paper also discusses the environmental impacts of polymer injection through analysis of samples taken from the water and bed material before and during the experiments. DOI: [10.1061/\(ASCE\)HY.1943-7900.0001904](https://doi.org/10.1061/(ASCE)HY.1943-7900.0001904). © 2021 American Society of Civil Engineers.

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Introduction

Flow conveyance is a key design criterion for constructed open channels such as irrigation channels or water transfer works. Techniques to enhance the flow conveyance of such channels are of high engineering relevance. Similarly, flow conveyance of natural water courses is a critical parameter in flood hazard evaluation. One possible approach for increasing the discharge capacity of open channels is the use of drag reduction techniques.

Several drag reduction methods exist. Drag reduction due to flow aeration has been studied both from a fundamental (Pang et al. 2014) and a more applied (Chanson 1994) perspective. Chanson (1994) notably reviewed measurements of flow aeration in spillways in which the friction factor could be divided by up to 10 when aeration took place. Another drag reduction method involves the use of sediment-laden flows. Best and Leeder (1993) reported a 32% reduction in shear velocity with a kaolinite and illite concentration of 2.2 g/L added to sea water. Wang et al. (1998) measured friction factors decreasing by up to 50% for clay concentrations of 8% in flows over rough beds, Li and Gust (2000) obtained up to a

60% reduction in shear velocity, and Amos et al. (1992) and Wang et al. (1998) reported reduced friction coefficients for field studies in rivers and deltas, respectively. A third available method for drag reduction consists of modifying the surface texture of the bed by adding riblets, Bechert et al. (1997) measured the effect of surface texture/Garcia-Mayoral and Jimenez (2011) computed it, reaching drag reductions up to 10%. So-called “drag reduction” by addition of polymers to a fluid is a fourth method, effective in reducing the friction head losses of a turbulent flow. This method was first pointed out by Toms (1949); dedicated research works have been regularly reviewed by Virk (1975), Graham (2004), White and Mungal (2008), and more recently by Xi (2019). The following brief literature review is only a short summary of the available knowledge related to the present application. For more details, readers can refer to the review by Xi (2019).

Drag reduction by addition of polymers is used in a variety of applications, as listed by Brostow (2008): oil pipeline conduits, oil well operations, flood water disposal, firefighting, field irrigation, transport of suspensions and slurries, sewer systems, water heating and cooling systems, airplane tank filling, marine systems, and bio-medical systems (including blood flow). The drag reduction is not based on any chemical reaction but is rather a consequence of mechanical interactions between the polymer and turbulent flow structures. When the solution is dilute enough, the chains of polymers are so far apart that their interactions can be neglected (Xi 2019); the flow remains Newtonian, and its viscosity is hardly affected. The onset of drag reduction appears with a sufficient amount of added polymers (typically a few ppm). Drag reduction reaches 80% under optimum conditions; this is referred to as maximum drag reduction. The interactions between the polymer chains and the flow result in a weakening of turbulent vortices, a reduction of turbulent stresses, and a modification of the mean velocity profile in the vicinity of the walls. Warholic et al. (1999) revealed that the buffer layer exhibits a higher slope and extends further away from the wall than it does under the classical law of the wall without polymers. Xi (2019) stated that the log layer follows the same slope but with a higher

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intercept. To summarize, the addition of polymers does not affect the viscous shear stress at the wall but rather reduces the turbulent Reynolds stresses, resulting in a global reduction of total stresses.

Virk (1971) observed that the level of drag reduction efficiency depends greatly on the size of the wall roughness. Using the non-dimensional roughness height $k_s^+ = k_s u_* / \nu$, where k_s is the equivalent sand roughness height, $u_* = \sqrt{\tau_w / \rho}$ is the friction velocity, τ_w is the shear stress at the wall, ρ is the fluid density, and ν is the fluid kinematic viscosity, Virk (1971) showed that for $k_s^+ > 50$, drag reduction efficiency decreases compared to a flow over a smooth surface (for the same concentration of polymer). This holds true up to the experimental limit of k_s^+ of approximately 150. Mignot et al. (2019) recently confirmed this reduced efficiency of polymers over a rough surface with k_s^+ in the range of 100–135.

Nevertheless, the addition of polymers to open-channel flows has received relatively little attention. However, it has been applied under specific circumstances in sewer systems, such as during the 2010 Winter Olympic games; the high number of fans visiting the city of Whistler led to unusually large quantities of waste water (Hart et al. 2011). Including polymer additives in the waste water decreased the water depth and increased flow velocity, leading to an increased discharge capacity of the sewers. The authorization for releasing polymers in sewer flows was based on a materials safety data sheet (MSDS) that indicated that the chemicals were nontoxic at limited dose concentrations (Hart et al. 2011). Taking a more fundamental approach, Mignot et al. (2019) measured the efficiency of polymer addition to one-dimensional (1D) open-channel flows in smooth and rough prismatic channels at the laboratory scale, with and without large-scale emerging obstacles. They concluded that by adding a limited concentration of polymer (approximately 20 ppm) to a steady flow without obstacles, the Darcy-Weisbach friction coefficient decreased by a factor of 2 in a flow over a smooth surface and by a factor of 1.5 in a flow over a rough surface; however, the friction coefficient was unaffected when flow resistance was dominated by emerging obstacles. These results were fully in agreement with the observations of Janosi et al. (2004) of dam-break flows without and with polymers: “drag reduction is more efficient when the turbulence is homogeneous (smooth boundary layer excitation) and less efficient when it is strongly heterogeneous with wave breaking, bubbling, foaming, etc. (inertial excitation).”

This literature review suggests that this method may have some potential for increasing the bank-full discharge in watercourses. A main advantage of polymer inclusion compared to alternative drag reduction methods is its relatively simple implementation at a given site by simply delivering into the water polymers stored outside the watercourse. However, while adding polymers to a flow has become a common approach in engineering for reducing friction head losses for pressurized flows (Brostow 2008), it has hardly been tested in open-channel flow conditions and, to the best of the authors’ knowledge, never at large scale (over tens of kilometers).

The aim of the present study was to assess the possibility of substantially decreasing friction resistance and thereby increasing the discharge capacity of a large-scale watercourse by adding polymers. As a proof of concept, the present study was based on a single experiment; however, it was highly demanding in terms of the quantity of injected polymer and in terms of flow monitoring over a very large area (26.3 km) during a long experiment (18 h).

The paper is organized as follows. Next section presents the study site, the polymer injection process, and the water depth monitoring strategy. Following section then presents the time evolution of measured water level along the canal and the corresponding friction coefficients. Discussions on environmental issues and conclusions are finally provided regarding the increased discharge capacity of the watercourse.

Presentation of the Field Campaign

Study Site

Following the authorization of polyacrylamide (PAM) release given by the Nebraska Farmer Irrigation District Office (FIDO), the field campaign was conducted by SNF SA on April 10, 2019, in a 50-km reach of the Tri-State Canal (Figs. 1 and 2), an irrigation channel maintained by FIDO in Scottsbluff, Nebraska. It is a prismatic trapezoidal meandering canal with a bottom width of 17 m and oblique banks with a 1:1 slope. The canal exhibits a mild slope S_0 of approximately 10^{-4} . The banks are mostly covered with clay, while the bottom of the channel is covered with a mix of alluvium, fine gravels, and medium gravels with diameters of 8–13 mm (Fig. 1). The Manning friction coefficient is about $n = 0.017$ [or $n_g = 0.05 \text{ m}^{1/6}$ following Yen’s (1992) notation]. The discharge was kept constant



(a)



(b)

Fig. 1. (a) The Tri-State Canal at Scottsbluff; and (b) sediment taken from the bed.

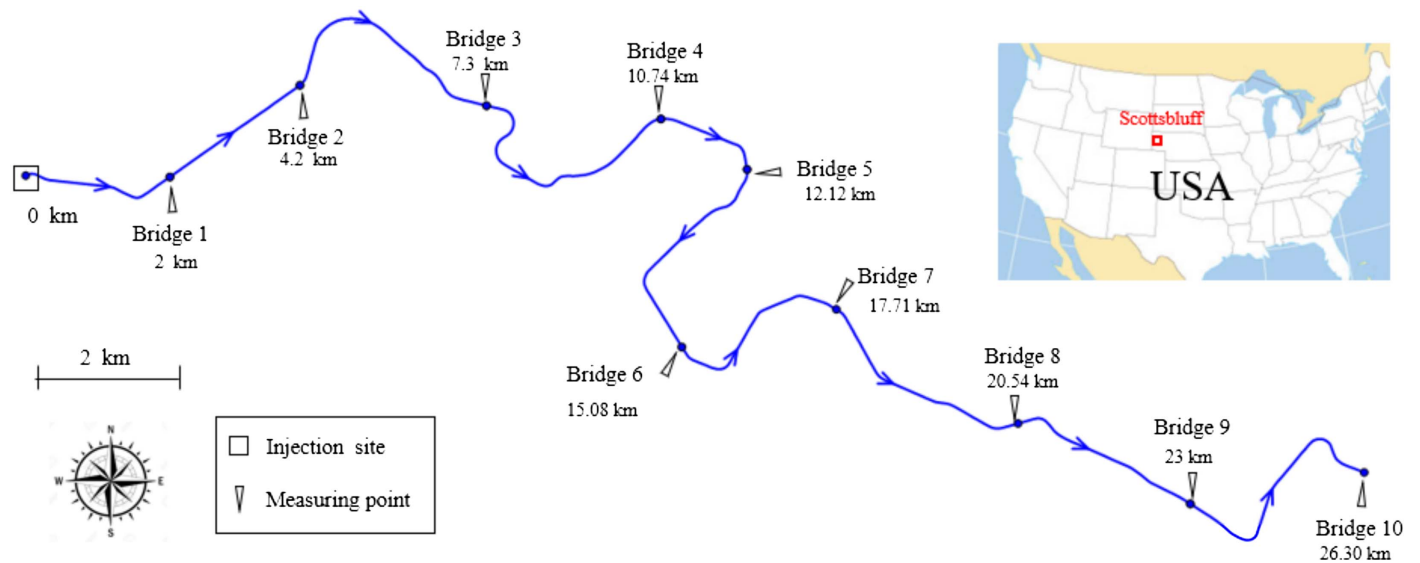


Fig. 2. Study site and identification of monitoring points.

during the whole day at $Q_{\text{water}} = 9.653 \text{ m}^3/\text{s}$ by a mobile dam located 34 km upstream from the study site, and no rain took place during the campaign. The outside temperature was about 12°C . Before the injection of polymers, water depth h and the corresponding width of the free surface b were spatially varied along the canal from $h = 0.85\text{--}1.50 \text{ m}$ and $b = 18.7\text{--}21 \text{ m}$, resulting in cross-sectional averaged velocity ranging between 0.35 and 0.64 m/s. The resulting flow regime was steady, gradually varied, subcritical (with a limited Froude number of 0.1–0.2), and turbulent (with a Reynolds number of $1.8 \times 10^6\text{--}2 \times 10^6$).

Polymer Injection Process

The polymer considered herein was a soluble anionic PAM of very high molecular weight ($20 \times 10^6 \text{ Da}$) in powder form. Tests carried out by Mignot et al. (2019) showed that drag reduction did not increase for polymer concentrations exceeding 20–30 ppm, probably corresponding to the maximum drag reduction asymptote. The polymer concentration of the solution introduced into the canal was set to $c = 20 \text{ ppm}$ by adjusting the mass rate of polymer powder to the flow rate of the canal: $Q_{m\text{-polymer}} = c\rho_{\text{water}}Q_{\text{water}} = 696 \text{ kg/h}$, with $\rho_{\text{water}} = 1,000 \text{ kg/m}^3$. For an injection lasting 15 consecutive hours, the supplied quantity of water-soluble polymer reached 10.5 t.

Before injecting the polymer into the canal, the powder was first hydrated. The hydration installation comprised (Fig. 3) a hopper for continuous feeding of the polymer powder, a metering device for polymer dilution, and a polymer wetting cone connected to a water inlet circuit fed with water from the canal using a pumping loop. The wetting cone was also connected to a second adjustable flow rate volumetric pump, ensuring the transfer of the dissolved polymer solution in a hose with three connections for the supply of polymer solution to the canal. The three injection points were placed regularly across the section at the center of the canal and 1.5 m away from each bank (Fig. 3).

The polymer solution was continuously injected into the Tri Sate Canal at the upstream section from 6:00 a.m. until 9:00 p.m. using a hose laid through the canal width, firmly attached to the end of the hose so as not to be taken away by the hydrodynamic forces of the flow. To estimate the length required for homogenization of the polymer, we applied the Rutherford (1994) method based on the 5% criteria, assuming that the polymer would behave as a passive tracer and considering the three injection points (Fig. 3).

Using a dimensionless transverse mixing coefficient $\varepsilon_y/hu^* = 0.17$ (where u^* is the friction velocity) and a ratio $U/u^* = 10$ (where U is the sectional-averaged velocity), the length for perfect mixing equals about 1.1 km, that is, about half the distance from injection to Bridge #1.

Water Depth Measurements

Over the studied domain, the canal is crossed by ten bridges (Fig. 2); the bridges were used in this study as monitoring points for their easy access to the centerline of the canal. A set of ten ultrasonic sensors attached to the ten bridges measured the time evolution of the water depth every 10 min. Three measurements were taken one after the other over a few seconds and the averaged value was recorded with an uncertainty estimated at about 0.5 cm. In addition, a time-lapse camera was installed in front of a ruler to record the time evolution of the water depth in the canal at 15 km downstream from the injection point (video available at SNF-Group 2016).

Measurement Results

The time evolution of the water depth variation at the ten bridges is depicted in Fig. 4. For the sake of efficiency, measurements started late at the most downstream sections, and all measurements were stopped a few hours after the end of the water depth variation. Because the polymer injection was maintained at a constant value during the whole measurement campaign, the present data permits the effect of the arrival of the polymer cloud at the ten monitoring sections and the steady flow with polymer addition to be analyzed but not the back-to-normal conditions.

Fig. 4 confirms previous experiments in laboratory conditions, that adding polymers to a large-scale watercourse reduces water depth. As the polymer arrived at a cross section, water depth decreased quite linearly with time and eventually reached a lower plateau of maximum drag reduction with a constant reduced water depth. However, at several sections a slight water depth increase was observed just before the decreasing depth tendency; this can presumably be attributed to the propagation of gravity waves following polymer injection.

Water depth was reduced by up to 26 cm at Bridge #1; this represents 17% of the initial water depth. However, the magnitude of

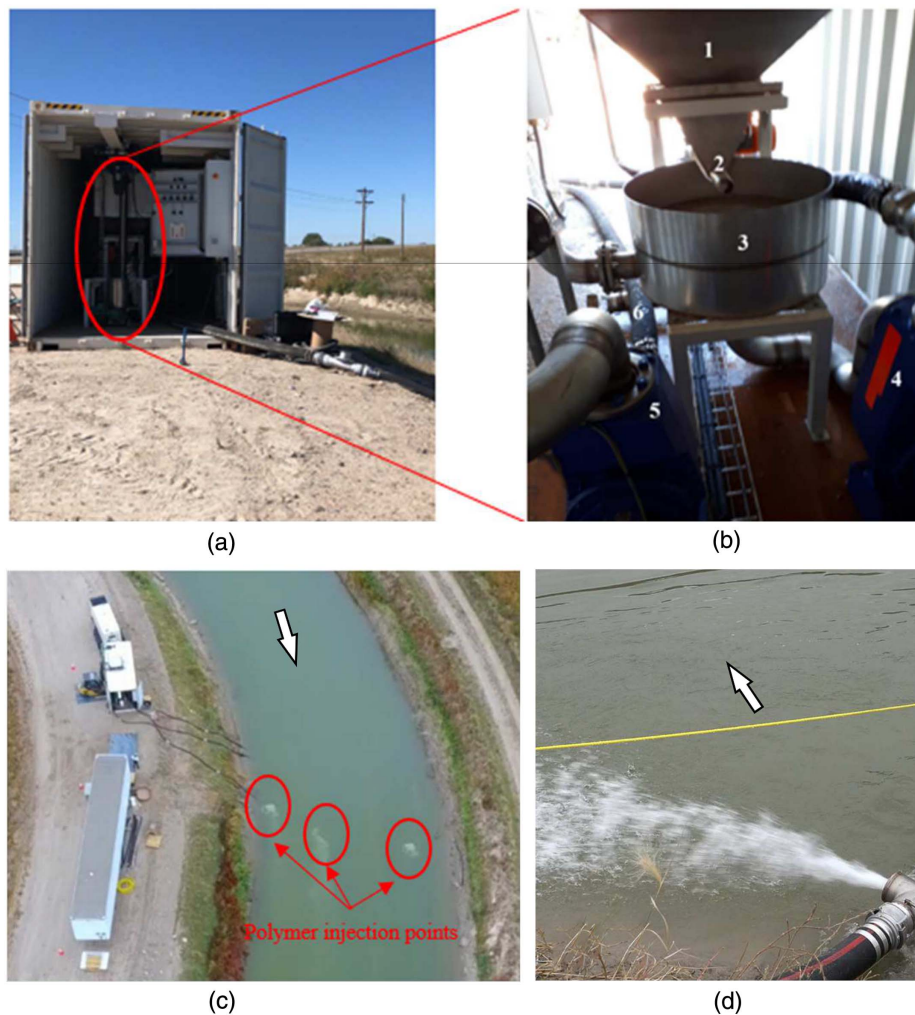


Fig. 3. (a) Polymer dispersion device located in a container installed next to the canal; (b) close-up view of the dispersion device, including hopper, metering device, wetting cone, pumping loop, flow rate volumetric pump, and hose with three connections; (c) the three injection points; and (d) close-up view of an injection point.

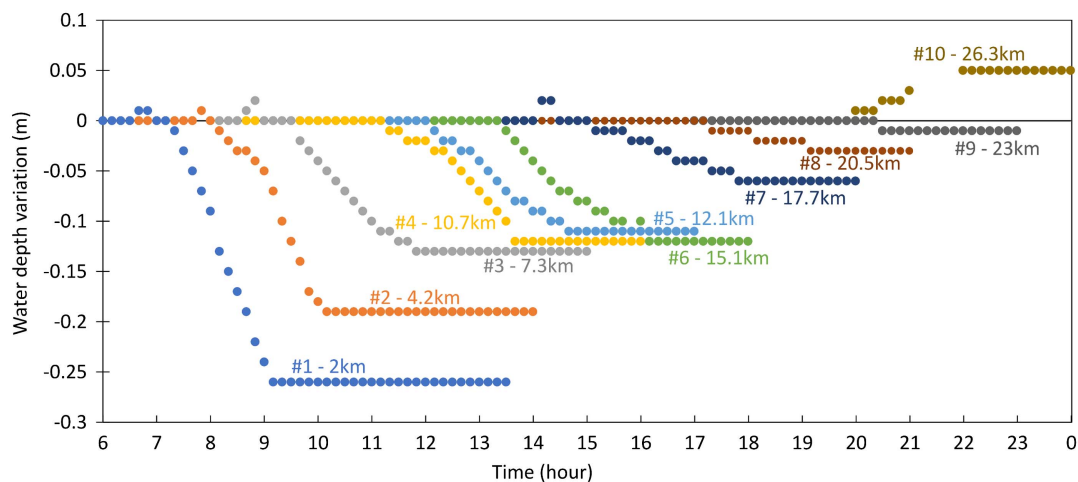


Fig. 4. Time evolution of water depth variation for monitoring Bridges #1 to #10. Water depth reduction at Bridge #6 exceeded that at Bridge #5 due to a higher initial local water depth (1.17 m at Bridge #6 compared to 1.01 m at Bridge #5). Note that the measurement device did not work from 9:00 p.m. to 10:00 p.m. at Bridge #10.

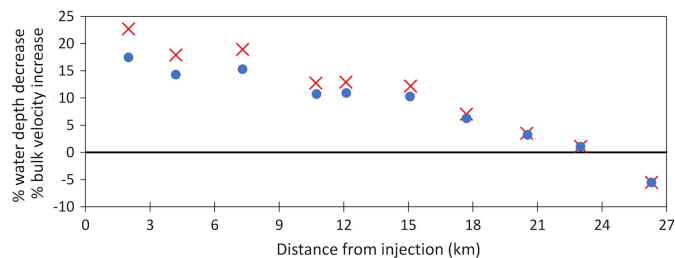


Fig. 5. Relative maximum water depth reduction (circles) and cross-sectional averaged velocity increase (crosses) as a function of distance from injection.

water depth reduction and the efficiency of drag reduction decreased heading downstream (Figs. 4 and 5). The relative water depth reduction decreased almost linearly with distance from the injection point and vanished at a distance of about 25 km downstream, at which the water depth was hardly affected by the polymer addition. However, for the measurement section farthest downstream at Bridge #10, the water depth increased after the arrival of the polymer front and reached a constant plateau of increased water depth 5.5% higher than the initial depth (see discussion in the following).

The time interval from the beginning of injection (6:00 a.m.) until the beginning of water depth reduction (full circle) is plotted in Fig. 6 for all measurement points. This graph confirms that the polymer front traveled from the injection point to the monitoring sections at the cross-sectional averaged velocity. The square symbols in Fig. 6 correspond to the time required to reach the maximum drag reduction. The time difference between the arrival of the polymer front and maximum drag reduction increased from 1.8 h at Bridge #1 to 3 h at Bridge #9. This result was in fair agreement with the well-known longitudinal dispersion process of a scalar cloud (El Kadi Abderrezak et al. 2015): the further downstream from the injection point, the wider the curve of concentration versus time at a given point in a watercourse.

Fig. 5 reveals that the increased sectional-averaged velocity reached 23% at Bridge #1, and this increase in velocity decreased approximately linearly to a value of zero at Bridge #9; velocity decreased at Bridge #10. The resulting sectional-averaged velocity ranged between 0.43 and 0.76 m/s. These velocities can be compared to the critical velocity at which bed erosion is expected to take place. Critical velocity computed using the Zanke (1977) formula (cited, for example, by Dey and Papanicolaou 2008) was

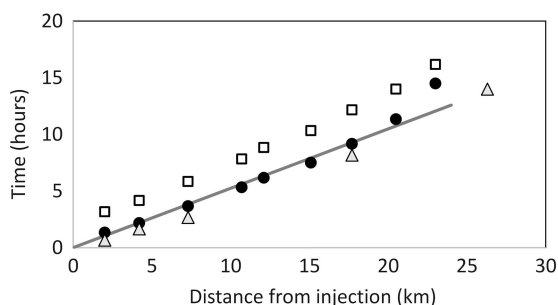


Fig. 6. Time required for initiation of water depth increase (when available, triangles), initiation of water depth decrease (full circles), and initiation of maximum drag reduction (open squares) as a function of distance from injection point. Plain line represents the theoretical arrival time of flow based on mean cross-sectional averaged velocity.

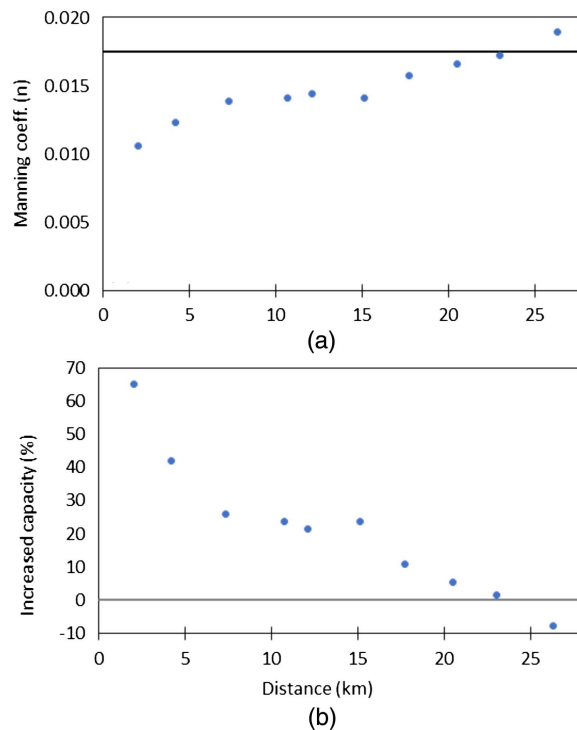


Fig. 7. (a): Manning friction coefficient n computed for all measurement sections once maximum drag reduction was reached (dots) along with initial Manning coefficient (plain line); and (b) increase in discharge capacity at maximum drag reduction.

about 1.1 m/s, higher than the cross-sectional averaged velocities at all monitored sections both before and during polymer injection. No major erosion was expected, therefore; this was confirmed by an on-site survey a few days after the experiments, when the canal was emptied for the winter season, and by areal images taken from a drone before and during the polymer injection. No major changes in turbidity in the water column and, therefore, no major changes in sediment discharge were evident (not shown here).

Based on the water depth decrease for a fixed discharge, the effect of the polymer can be seen as a reduced Manning friction coefficient. Fig. 7(a) plots the equivalent Manning coefficient computed at the maximum drag reduction plateau for each measurement section. As expected, the Manning coefficient reduction was greatest in the upstream-most monitored sections and decreased heading downstream. At Bridge #1, the Manning coefficient was reduced by 40%. The discharge capacity of the canal (bank-full discharge) was increased by more than 60% near the injection point, but this enhanced capacity decreased heading downstream [Fig. 7(b)]. At Bridge #9 the Manning coefficient was hardly affected by the polymer inclusion, in agreement with previous observations that water depth hardly evolved with time at this location. Finally, at the downstream-most measurement section (Bridge #10), the equivalent Manning coefficient seemed to increase [Fig. 7(a)] and the discharge capacity was reduced [Fig. 7(b)].

From the present data set, the reason for the increase in water depth at Bridge #10 remains unclear. We examined two hypotheses to explain such an increase but without a satisfactory conclusion. On the one hand, the flow disturbance induced by the reduction in water depth in the upstream part of the canal was likely to induce the propagation of gravity waves. However, this would lead to a behavior similar to the water depth augmentations recorded at Bridges #1, #2, #3, and #7—that is, a temporary increase followed

by a reduction in water depth, not a plateau as measured at Bridge #10. On the other hand, based on a mass balance consideration, the transient water depth decrease in the upstream part of the studied area (Bridges #1 to #9) should be balanced by a temporary increase in flow discharge further downstream. Again, this should lead to a temporary water depth increase further downstream, not to a plateau. Consequently, no clear explanation for the water depth evolution at Bridge #10 is available so far based on the current data set. This effect requires further attention in subsequent field campaigns and could possibly be better understood based on a validated computational model of the canal.

Discussion: Amount of Injected Polyacrylamide and Its Short and Long-Term Fates

During the test, for an injection lasting 15 consecutive hours, the supplied quantity of PAM water-soluble polymer reached 10.5 t. The European Commission (2002) reported that in the European Union 100,000 t of PAM are used each year; about half of this quantity is devoted to the water industry for water clarification, waterworks sludge treatment, and sewage sludge thickening. PAM is considered relatively nontoxic to humans, animals, fish, or plants, but this is not the case for acrylamide (AMD, monomer) (Joshi and Abed 2017), which is classified as a toxic compound for terrestrial and aquatic organisms. Residual AMD content in PAM is strictly regulated in Europe. The anionic polyacrylamide produced by SNF and used in the present work, contains less than 1,000 mg/kg (0.1% in mass) of residual AMD (HES SNF 2017), thereby satisfying European regulations (Guezennec et al. 2015). In addition, because the concentration of PAM in the water was 20 ppm (about 20 mg/L), a maximum AMD concentration of 2.10^{-2} mg/L was delivered to the environment during the 15 h of the present test.

The impact of polyacrylamide and acrylamide on living organisms and their fate in the environment have been studied by authors such as Caulfield et al. (2002), USEPA (2007), and Harford et al. (2011). The European Commission (2002) reported results from dedicated tests and reviews from the literature regarding acute toxicity to a selection of fishes (in their Table 3.13), to aquatic invertebrates (Table 3.14), and to plants, microorganisms, amphibians, and other fauna/flora. This report summarized the available 24-, 48-, and 96-h median lethal concentration (LC_{50}) and no-observed-effect concentration (NOEC) of acrylamide. For instance, the report indicated that Petersen et al. (1985) measured a 24-h LC_{50} for rainbow trout (*Oncorhynchus mykiss*) of 300 mg/L of acrylamide and a 48-h NOEC for *Daphnia magna* of 60 mg/L of acrylamide; these concentrations vary from one species to another depending on parameters such as the size or age of the organisms or the water temperature. Other authors have reported lethal concentrations of PAM itself (not AMD). For instance, De Rosemond and Liber (2004) reported a 48-h LC_{50} for *Ceriodaphnia dubia* equal to 218 mg/L of PAM. Harford et al. (2011) reported much smaller values—an inhibitory concentration of 10 mg/L for cladocerans—indicating that LC_{50} can be attributed also to modifications of the physical properties of water or food by the polymer. Petersen et al. (1985) reported a half-life elimination from the trout metabolism of several days.

To study the midterm fate of PAM, in situ samples were collected from the water and the bed sediment. Water samples were taken (1) the day before, (2) at 8:00 p.m. on the day of injection—that is, 14 h after the beginning of polymer injection—at each of the ten monitoring points, and (3) the day after the experiment. Samples were then analyzed by the SNF laboratory in France to

Table 1. Characteristics of canal water taken at Bridge #3 collected the day before trial, at 5:30 p.m. during the trial, and the day after injection

Time	Dynamic viscosity (10^{-3} Pa · s)	Turbidity (NTU)	pH	Electrical conductivity ($S \cdot m^{-1}$)
Before injection	1.01	3.20	6.8	0.045
During injection	1.06	3.27	6.8	0.045
After injection	1.03	3.25	6.8	0.045

evaluate the PAM concentrations and assess the impact of the PAM injection on the physicochemical properties, acrylamide concentration, and flocculation tendency of the water; the results are listed in the following. Table 1 reveals that the water samples taken before and after polymer injection had the same physicochemical properties. Second, the analysis of the water samples taken at the ten measurement points during polymer injection did not permit any AMD detection, because the AMD concentrations were below the detectable limits of quantification of the technique, that is, less than 0.1 mg/L. Third, Fig. 8 reveals that the injection of PAM did not cause flocculation in water taken at Bridge #2. Flocculation could reduce the available nutrient concentration for fauna/flora living in the watercourse. Fourth, Fig. 9 compares the appearance of water samples taken at the injection point, at Bridges #3, #5, and #8, and plain water from the canal with a controlled added concentration of 20 ppm of PAM. This comparison seems to indicate that the sample taken at the injection point contained more than 20 ppm of PAM (higher compaction, maybe due to a nonperfect injection process), while samples taken at the bridges further downstream contained less than 20 ppm (lower compaction, maybe due to some deposition on the bed).

In an initial aim to estimate the deposits of PAM on the bed of the canal, sediment samples were collected just after the trial. Nevertheless, although there are a number of published methods for identifying PAM in soils, many methods suffer from technical challenges when measuring low concentrations (Kang et al. 2014). Consequently, estimates of the adsorption of anionic polymers by the sediments of the watercourse cannot be provided. However, the canal was emptied at the end of October 2019, and no visual evidence of PAM deposits could be observed either at the injection point or further downstream.

The midterm fate of injected compounds in water was examined by Guezennec et al. (2015) in a dedicated review paper. The authors stated that the amount of acrylamide in the water should not increase over time, because generation of AMD through PAM degradation is not expected, as previously studied by Soponkanaporn and Gehr (1989). The review indicated that PAM should be adsorbed rapidly by bed sediments and detailed the different mechanisms (mechanical, chemical, bacterial, enzymatic) for its degradation. The review also indicated that AMD is hardly adsorbed by beds and should remain within the water column, where its degradation can take several days. The rate and possibility of degradation appears to be dependent on conditions such as soil nature and content, pH, temperature, and so forth. The main finding was the lack of pertinent and detailed data about the behavior, fate, and impact of PAM-based flocculants in the environment. More recent reviews have addressed the same topics with about the same conclusions (Joshi and Abed 2017; Xiong et al. 2018), adding more recent specific studies on biodegradation of PAM and AMD. Wennberg et al. (2017) added that biodegradation of PAM decreases with its molecular weight, affecting the possibility of its biodegradability in seawater.

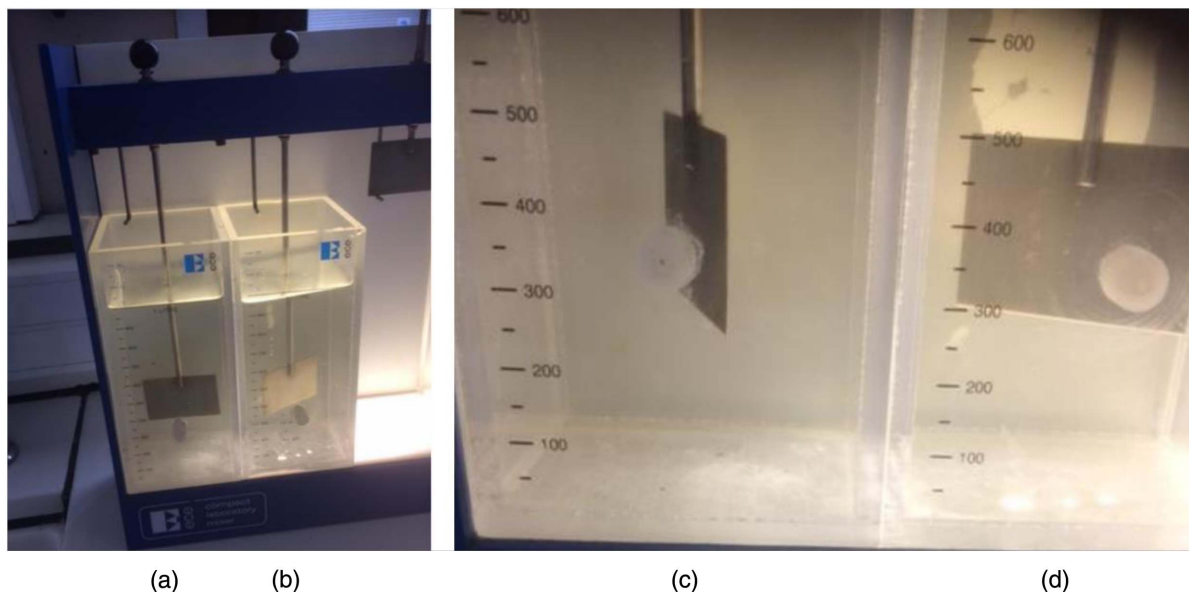


Fig. 8. Flocculation test results with water taken below Bridge #2 (a and c) the day before the polymer injection; and (b and d) at 8:00 p.m. during the experiment.

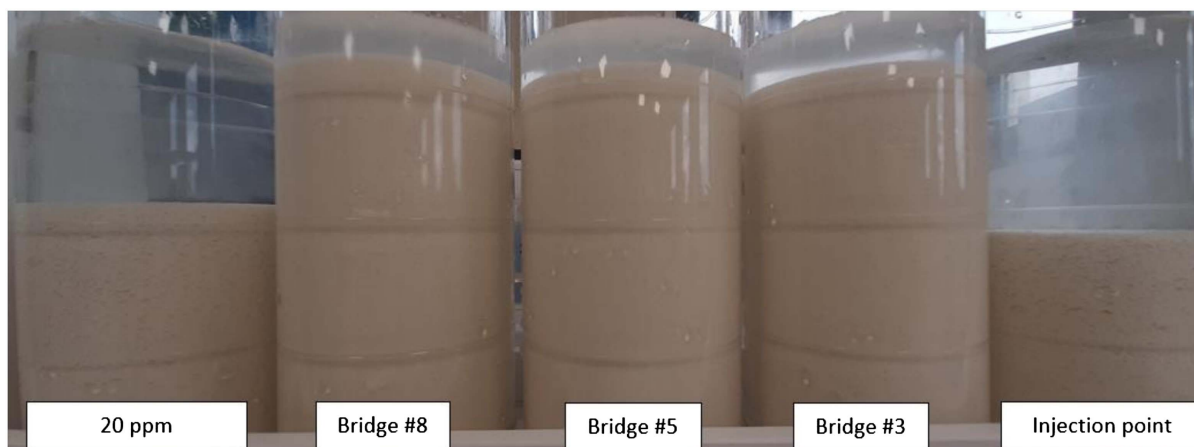


Fig. 9. PAM analysis by flocculation method for samples taken at 8:00 p.m. during the trial.

However, none of the published works on the toxicity and lethality in hydrosystems of residual monomer (AMD) involved the injection of high volumes of PAM (even at low concentration) as was the case in the present work, in which about 10.5 t were delivered on the same day (at a 20 mg/L concentration) at a given location of a watercourse. Although no evidence of accumulation on the bed or of fish and invertebrate lethality was observed, more work should be undertaken on the environmental consequences of very high PAM volume released in geophysical open channels (even at relatively low concentrations) possibly leading to local polymer accumulation in the bed before the procedure proposed herein is further considered for application in the field.

Conclusion

The present paper aimed at assessing the possible drag reduction by injection of a polymer in a large-scale open-channel watercourse and at measuring the water depth decrease and gain in discharge

capacity. A quantity of 10.5 t of polymer was continuously injected in an irrigation canal under steady inflow discharge over 15 h, and the water elevation along the centerline of the canal was recorded at 10 sections downstream over a 26-km-long reach. Most measurement sections exhibited a reduction in water depth, with the most efficient reduction being obtained at the upstream-most section but with a decreasing drag reduction efficiency downstream. However, the downstream-most measurement section exhibited a slight water depth increase. An estimate of the Manning friction coefficient during the release confirmed a maximum reduction in friction coefficient near the injection point. Finally, as expected, analyses of water and soil samples indicated that the concentration of the residual monomer (acrylamide) was very low in the water and the soil.

Drag reduction appears to be effective in large scale and high Reynolds number configurations. However, the selected canal was particularly adapted to drag reduction, given the limited number of emerging obstacles (such as emerging vegetation), its quite prismatic shape, which limited the number of geometrical singularities

(enlargements, dead zones, dikes, etc.), and the relatively smooth nature of the bed. The present work was performed in a man-made channel, and the transfer of the technique to a more natural watercourse should be performed with care.

The experiment presented here was a proof-of-concept of drag reduction by polymer injection at large scale. From a technical perspective, more experiments are required to assess the robustness of the method and to enable the prediction of water depth reduction as a function of time, distance from injection, flow discharge, polymer discharge, sediment load, and so forth. For potential flood control applications, the optimal timing of polymer injection needs to be further studied in order to mitigate any detrimental effects in downstream sections of a watercourse. Before considering application of this technique in the field, thorough impact assessments are required to account for the particular vulnerability of the ecosystems in a considered watercourse and its floodplains and downstream areas, notably in terms of risk for water use for agriculture and drinking water and for fauna and flora in the river and the bed. Any field application would need to be implemented in agreement with authorities and under the condition that risks and benefits have been carefully balanced and that wide societal acceptance has been gained.

Data Availability Statement

All data that support the findings of this study are available from the corresponding author upon request.

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References

- Amos, C. L., J. Grant, G. R. Daborn, and K. Black. 1992. "Sea carousel—A benthic annular flume." *Estuarine Coastal Shelf Sci.* 34 (6): 557–577. [https://doi.org/10.1016/S0272-7714\(05\)80062-9](https://doi.org/10.1016/S0272-7714(05)80062-9).
- Bechert, D. W., M. Bruse, W. Hage, J. G. T. V. der Hoeven, and G. Hoppe. 1997. "Experiments on drag-reducing surfaces and their optimization with adjustable geometry." *J. Fluid Mech.* 338: 59–87. <https://doi.org/10.1017/S0022112096004673>.
- Best, J. L., and M. R. Leeder. 1993. "Drag reduction in turbulent muddy seawater flows and some sedimentary consequences." *Sedimentology* 40 (6): 1129–1137. <https://doi.org/10.1111/j.1365-3091.1993.tb01383.x>.
- Brostow, W. 2008. "Drag reduction in flow: Review of applications, mechanism and prediction." *J. Ind. Eng. Chem.* 14 (4): 409–416. <https://doi.org/10.1016/j.jiec.2008.07.001>.
- Caulfield, M. J., G. G. Qiao, and D. H. Solomon. 2002. "Some aspects of the properties and degradation of polyacrylamides." *Chem. Rev.* 102 (9): 3067–3084. <https://doi.org/10.1021/cr010439p>.
- Chanson, H. 1994. "Drag reduction in open channel flow by aeration and suspended load." *J. Hydraul. Res.* 32 (1): 87–101. <https://doi.org/10.1080/00221689409498791>.
- De Rosemond, S. J. C., and K. Liber. 2004. "Wastewater treatment polymers identified as the toxic component of a diamond mine effluent." *Environ. Toxicol. Chem.* 23 (9): 2234–2242. <https://doi.org/10.1897/03-609>.
- Dey, S., and A. Papanicolaou. 2008. "Sediment threshold under stream flow: A state-of-the-art review." *KSCE J. Civ. Eng.* 12 (1): 45–60. <https://doi.org/10.1007/s12205-008-8045-3>.
- El Kadi Abderrezzak, K., R. Ata, and F. Zaoui. 2015. "One-dimensional numerical modelling of solute transport in streams: The role of longitudinal dispersion coefficient." *J. Hydraul.* 527 (Aug): 978–989. <https://doi.org/10.1016/j.jhydrol.2015.05.061>.
- European Commission. 2002. *European union risk assessment report: Acrylamide*. CAS:79-06-1, EC: 201-173-7. Luxembourg: Office for Official Publication of the European Communities.
- Garcia-Mayoral, R., and J. Jimenez. 2011. "Hydrodynamic stability and breakdown of the viscous regime over riblets." *J. Fluid Mech.* 678 (1): 317.
- Graham, M. D. 2004. "Drag reduction in turbulent flow of polymer solutions." *Rheol. Rev.* 2 (2): 143–170.
- Guezennec, A. G., C. Michel, K. Bru, S. Touzé, N. Desroche, I. Mnif, and M. Motelica-Heino. 2015. "Transfer and degradation of polyacrylamide-based flocculants in hydrosystems: A review." *Environ. Sci. Pollut. Res.* 22 (9): 6390–6406. <https://doi.org/10.1007/s11356-014-3556-6>.
- Harford, A. J., A. C. Hogan, D. R. Jones, and R. A. van Dam. 2011. "Ecotoxicological assessment of a polyelectrolyte flocculant." *Water Res.* 45 (19): 6393–6402. <https://doi.org/10.1016/j.watres.2011.09.032>.
- Hart, J., L. Cotter, and V. Jason. 2011. "Polymer addition to increase trunk sewer flow capacity at the resort municipality of whistler during the 2010 winter Olympic games." In *Proc., Water Environment Federation 2011*, 5763–5774. Alexandria, VA: Water Environment Federation. <https://doi.org/10.2175/193864711802766344>.
- HES SNF (Health and Environmental Safety). 2017. *FLOPAM AN900 range of products*. Andrezieux, France: HES SNF.
- Janosi, I. M., D. Jan, K. G. Szabo, and T. Tel. 2004. "Turbulent drag reduction in dam-break flows." *Exp. Fluids* 37 (2): 219–229.
- Joshi, S. J., and R. M. Abed. 2017. "Biodegradation of polyacrylamide and its derivatives." *Environ. Processes* 4 (2): 463–476. <https://doi.org/10.1007/s40710-017-0224-0>.
- Kang, J., T. Sowers, O. Duckworth, A. Amoozegar, J. L. Heitman, and R. A. McLaughlin. 2014. "Turbidimetric determination of anionic polyacrylamide in low carbon soil extracts." *J. Environ. Qual.* 42 (6): 1902–1907. <https://doi.org/10.2134/jeq2013.07.0279>.
- Li, M. Z., and G. Gust. 2000. "Boundary layer dynamics and drag reduction in flows of high cohesive sediment suspensions." *Sedimentology* 47 (1): 71–86. <https://doi.org/10.1046/j.1365-3091.2000.00277.x>.
- Mignot, E., N. Riviere, A. Lefevre, and B. Quillien. 2019. "Smoother than smooth: Increasing the flow conveyance of an open-channel flow by using drag reduction methods." *J. Hydraul. Eng.* 145 (4): 04019011. [https://doi.org/10.1061/\(ASCE\)HY.1943-7900.0001583](https://doi.org/10.1061/(ASCE)HY.1943-7900.0001583).
- Pang, M. J., J. J. Wei, and B. Yu. 2014. "Numerical study on modulation of microbubbles on turbulence frictional drag in a horizontal channel." *Ocean Eng.* 81: 58–68. <https://doi.org/10.1016/j.oceaneng.2014.02.012>.
- Petersen, D. W., K. M. Kleinow, R. C. Kraska, and J. J. Lech. 1985. "Uptake, disposition and elimination of acrylamide in rainbow trout." *Toxicol. Appl. Pharmacol.* 80: 58–65. [https://doi.org/10.1016/0041-008X\(85\)90101-2](https://doi.org/10.1016/0041-008X(85)90101-2).
- Rutherford, J. C. 1994. *River mixing*. New York: Wiley.
- SNF-Group. 2016. "Water height reduction timelapse." Accessed March 1, 2020. <https://vimeo.com/382568921>.
- Soponkanaporn, T., and R. Gehr. 1989. "The degradation of polyelectrolytes in the environment: Insights provided by size exclusion chromatography measurements." *Water Sci. Technol.* 21 (8–9): 857–868. <https://doi.org/10.2166/wst.1989.0288>.
- Toms, B. A. 1949. "Some observation on the flow of linear polymer solutions through straight tubes at large Reynolds number." In *Vol. 2 of Proc., 1st Int. Congress of Rheology*, 135–141. Netherlands, Amsterdam: North Holland, Amsterdam.
- USEPA. 2007. *Toxicological review of acrylamide*. EPA/635/R-07/009A. Washington, DC: USEPA.
- Virk, P. S. 1971. "Drag reduction in rough pipes." *J. Fluid Mech.* 45 (2): 225–246. <https://doi.org/10.1017/S0022112071000028>.
- Virk, P. S. 1975. "Drag reduction fundamentals." *AICHE J.* 21 (4): 625–656. <https://doi.org/10.1002/aic.690210402>.
- Wang, Z., P. Larsen, F. Nestmann, and A. Dittrich. 1998. "Resistance and drag reduction of flows of clay suspensions." *J. Hydraul. Eng.* 124 (1): 41–49. [https://doi.org/10.1061/\(ASCE\)0733-9429\(1998\)124:1\(41\)](https://doi.org/10.1061/(ASCE)0733-9429(1998)124:1(41)).

- Warholic, M. D., H. Massah, and T. J. Hanratty. 1999. "Influence of drag-reducing polymers on turbulence: Effects of Reynolds number, concentration and mixing." *Exp. Fluids* 27 (5): 461–472. <https://doi.org/10.1007/s003480050371>.
- Wennberg, A. C., K. Petersen, and M. Grung. 2017. *Biodegradation of selected offshore chemicals*. Rep. No. M-911/2017. Trondheim, Norway: Norwegian Environment Agency.
- White, C. M., and M. G. Mungal. 2008. "Mechanics and prediction of turbulent drag reduction with polymer additives." *Annu. Rev. Fluid Mech.* 40: 235–256. <https://doi.org/10.1146/annurev.fluid.40.111406.102156>.
- Xi, L. 2019. "Turbulent drag reduction by polymer additives: Fundamentals and recent advances." *Phys. Fluids* 31 (12): 121302.
- Xiong, B., R. D. Loss, D. Shields, T. Pawlik, R. Hochreiter, A. L. Zydney, and M. Kumar. 2018. "Polyacrylamide degradation and its implications in environmental systems." *NPJ Clean Water* 1 (1): 1–9.
- Yen, B. C. 1992. "Dimensionally homogeneous Manning's formula." *J. Hydraul. Eng.* 118 (9): 1326–1332. [https://doi.org/10.1061/\(ASCE\)0733-9429\(1992\)118:9\(1326\)](https://doi.org/10.1061/(ASCE)0733-9429(1992)118:9(1326)).
- Zanke, U. C. E. 1977. *Neuer Ansatz zur Berechnung des Transportbeginns von Sedimenten unter Stromungseinfluss*. Hannover, Germany: Mitt. DesFranzius-Institut, Technical Univ. Hannover.