Hydrometric Monitoring and Effluent Discharge Mixing in Challenging Natural Conditions

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Abstract

River systems prone to backwatering present difficult conditions for collecting reliable hydrometric monitoring data. Furthermore, passive discharge of treated effluent in low-velocity receiving environments may not achieve full mixing without additional measures to promote dilution. Knight Piésold Ltd (KP) designed a hydrometric monitoring network and a treated effluent discharge system for the Rainy River Mine (RRM) in Northwestern Ontario that had both these conditions.

The Pinewood River provides a challenging environment for hydrometric monitoring due to backwatering effects from downstream obstructions, which precluded developing stable stage-discharge relationships to facilitate continuous discharge measurements. Consequently, an alternative to the traditional flow-measurement approach was required. To overcome the difficulties associated with stage-discharge relationships, an acoustic Doppler-type instrument was selected that measures the velocity profile and the water depth continuously. These data are used in combination with a user-specified cross-section to record continuous real-time discharge data.

The treated effluent to be discharged into the local receiving environment must meet strict mixing and water quality standards, as dictated by RRM's Environmental Compliance Approval (ECA). The permitted conditions include constraints on the ratio of instream flow to effluent discharge, in addition to achieving full transverse mixing within a short distance from the discharge point. An analytical mixing model was developed to evaluate the performance of various diffuser options under a wide range of effluent and ambient discharge condition. This data was then used to guide the final diffuser selection and design. The selected design includes a diffuser system with two planar jets using duckbill-type neoprene rubber check valves. This design also provides back-flow and fish-entrance prevention, as the rubber check valves close when the outflow is discontinued. To prevent channel erosion from the discharge jets and prevent utilization

by fish for habitat in the vicinity of the diffusers, grouted gabion boxes, grouted riprap, and interlocked concrete blocks were used to create a protected and stable cross-section.

Introduction

RRM is a gold and silver mine owned by New Gold Inc. that started operations in September of 2017. It is located in the Township of Chapple, approximately 65 kilometers (km) northwest of Fort Frances, Ontario. The mine received Permits to Take Water (PTW) from and discharge treated effluent water to the Pinewood River, both of which are conditional on the actual flows in the river at the time of withdrawal or discharge. To regulate this process, high quality real-time discharge measurements in the Pinewood River are necessary and are required by the mine's ECA and PTW that were issued by the Ministry of the Environment, Conservation and Parks (MECP).

RRM has collected hydrometric data in the Pinewood River since 2015 using a bubbler system and a pressure transducer backup system, both of which rely on an established stage-discharge relationship, or rating curve, to calculate the discharge. There have been ongoing issues with the collection of reliable discharge data along the Pinewood River. During the first few years of operation, the hydraulic control section was impacted several times. This is primarily due to the very low gradient of 0.07% of the Pinewood River, which results in backwatering effects propagating for long distances upstream of obstructions. Ongoing beaver and land use activities, as well as potential ice jams and log jams downstream of the hydrometric monitoring station, have caused backwatering effects that impacted the stage-discharge relationship. To avoid the reliance on stage-discharge relationships for discharge measurements, the hydrometric monitoring network was upgraded to utilize real-time discharge measurements using acoustic Doppler-type instruments, and also expanded to include several monitoring locations. The selected SonTek-IQs are not impacted by backwatering conditions and provide better quality and more reliable discharge data for the mine.

An effluent discharge system consisting of two effluent mixing structures (EMS1 and EMS2) at two different locations was designed and constructed to discharge treated surplus water from the mine to the Pinewood River. Real-time data from the hydrometric monitoring network is used to inform the effluent discharge strategy on a daily basis. The design of EMS1 and EMS2 was informed by the results from an analytical effluent mixing model. After commissioning of the systems, a field-based mixing study was completed to confirm the mixing performance of the systems.

Hydrometric monitoring network

Original hydrometric monitoring network

RRM is committed to collecting continuous hydrometric data in the Pinewood River, and as part of that program, the first hydrometric monitoring station, H1, was commissioned on October 9, 2015. This station is located approximately 800 meters (m) downstream of one of the two effluent mixing structures (EMS1). In addition, Water Survey Canada (WSC) operates their own hydrometric station (05PC023), located approximately 3.8 km downstream of H1. The discharge recorded at this station and at H1 is similar, as there are no tributaries between the two stations. The Pinewood River at this location has a mean annual discharge of approximately 1.6 cubic meters per second (m^3/s), which translates to a relatively low average annual runoff depth of approximately 231 millimeters (mm), based on data from station 05PC023 for the period of record from 2008 to 2015. The mean annual precipitation in this area is 710 mm.

The bubbler and the pressure transducer instruments installed at H1 rely on a rating curve to calculate the discharge, which is subject to changes due to obstructions and resulting backwatering effects in the river. A rating curve is developed by relating the discharge measurements (Q) to water levels or stage (H), where both are measured manually for various flow conditions. Stage-discharge relationships are usually subject to minor fluctuations and typically show some scatter, some of which may be due to the inherent limitations of the measuring equipment and measuring methods. The rating curve for a hydrometric station may change over time if the hydraulic control or the channel characteristics change. Any larger deviations or shifts from the rating curve may indicate a change in the stage-discharge relationship, which could occur due to several reasons, including a change in the cross-section at the onset of overbank flow, channel erosion, sediment deposition or bed shifting, and backwatering due to beaver activity or ice/log jam formation downstream. A change in the rating curve relationship that persists for an extended period indicates that a new rating curve should be developed.

Hydrometric monitoring network upgrade and expansion

In order to improve the ability to discharge the effluent to the Pinewood River within the permitted requirements, three additional hydrometric monitoring stations were established. The monitoring network consists of one station upstream (H2) and one station downstream (H1) of the RRM on the Pinewood River, and two stations in a diversion channel (H3 and H4) within the mine site. All four stations use the same monitoring setup to avoid the challenges experienced at H1, and as such this paper primarily focuses on the H1 discharge monitoring station.

The upgrade of the H1 monitoring station and expansion of the hydrometric monitoring network required several factors to be considered, as discussed below.

Design criteria

The Pinewood River is subject to a wide range of flows, from near zero during the winter and dry summer periods to well over 20 m^3/s during the spring freshet periods and during convective storms in the summer and early fall. The Pinewood River flow data were used in combination with the applicable permit criteria as the basis for establishing the design criteria for the hydrometric network:

- Establish several stations on the Pinewood River and on the mine site to assist with effluent discharge and water-taking operations.
- Provide accurate measurement of flows over the range for which effluent discharge may occur (i.e., 0.1 to 0.6 m^3/s, with maximum measurements up to 2 m^3/s), as specified by permitting requirements. However, it was also desired for the hydrometric stations to provide reasonably accurate measurement for a full range of river flows.
- Designs to limit backwatering and upstream flooding and to be able to withstand high flows without damage.
- Maintain habitat connectivity for species that are resident in or use the Pinewood River for one or more of their life stages (e.g., running, spawning, rearing).

Monitoring network upgrade alternatives

Several alternative discharge collection techniques were reviewed for upgrading the RRM hydrometric network, including using rated discharge structures that provide a hydraulic control, or using continuous discharge data collection instruments. The evaluated alternatives included a natural channel with a rating curve (i.e., the original method that was already in use), rated discharge structures (e.g., flumes or weirs), as well as different acoustic Doppler flow measuring devices. Each alternative was assessed using the design criteria for flow range, fish passage potential, flooding potential, and backwatering susceptibility.

Based on the alternatives review, the options that prevent fish passage, those that increase the risk of upstream flooding, and those that can be impacted by downstream backwatering were considered inappropriate for further consideration. It was concluded that acoustic Doppler instruments, specifically SonTek-IQs (SonTek, 2015a), would constitute the most effective and reliable option for continuous collection of high-quality discharge data.

Selected design and installation

The primary advantage of SonTek-IQ instruments is that they continuously measure the velocity profile and the water depth, which is then used in combination with a user-supplied cross-section data to record continuous discharge in real-time. The discharge measurements are not affected by backwatering conditions (SonTek, 2015b) that may occur due to downstream obstructions in the river. Some of the other advantages of these instruments include the following:

- Accurately measure the flow range of 0.1 m^3/s to 2.0 m^3/s that is required for mine effluent discharge monitoring, but can also measure much higher flows of up to 50 m^3/s.
- Provide continuous discharge record without the need for a rating curve.

- Allow discharge measurements to be collected to an accuracy of ±5 – 10%.
- Cause little environmental disturbance due to their small size with no incremental upstream flooding.
- Allow for uninterrupted fish passage, sediment passage, and the passage of floating debris.
- Have the potential for remote monitoring and can be tied to the existing data logger that has cellular telemetry allowing flow data to be accessed real-time.
- Can operate within a temperature range of –5 to 60°C.
- Have a fixed factory calibration and do not require periodic recalibration.

SonTek instruments have been used and tested by Water Survey of Canada, United States Bureau of Reclamation (USBR, 2016), and the United States Geological Survey (USGS, 2007; USGS, 2015), and have been found to be effective in river conditions similar to the Pinewood River (SonTek, 2012). These systems have also been tested in cold weather conditions in Colorado (USGS, 2007), comparable to those found in Northwestern Ontario, and they were found to perform well.

To increase the measurement accuracy and reduce the requirement for cross-section surveys following larger flow events that may cause changes to channel geometry, a decision was made to install the SonTek-IQ instrument at station H1 in a concrete-lined channel. This would create a stable river cross-section that promotes good flow and velocity profiles across the channel, facilitates discharge measurement accuracy, and provides a stable foundation for the instrument to remain firmly anchored in the channel.

The proposed channel design utilized a concrete canvas, a material comprising a proprietary fiber reinforced concrete mix placed between two membranes that hardens once hydrated (Concrete Canvas, 2018). Prior to the canvas installation, the riverbanks were shaped to a slope of no greater than 1.5H:1V. The SonTek-IQ was mounted on a levelled concrete block embedded in the channel bottom at the centre of the concrete section.

The installation for the other hydrometric stations differed from H1 in that the SonTek-IQs were anchored to the bases of existing culverts on flat concrete platforms. The cross-sections of the culverts were surveyed for input into the internal instrument programming.

Effluent discharge system

KP designed an effluent discharge system consisting of two mixing structures (EMS1 and EMS2) to effectively discharge treated surplus water from the mine to the Pinewood River. Requirements for the design included compliance with the ECA, as follows:

- No discharge is allowed during the winter months from December 1 of each year to the start of the spring melt of the following year, i.e., discharge is allowed only during ice-free periods.

- A minimum Pinewood River flow of 10,000 m^3/day must be sustained in any given day during the permitted release period for effluent discharge to be allowed.
- The effluent discharge to the environment must be submerged and must not exceed a 1:1 ratio with Pinewood River flows.
- Pinewood River water downstream of the effluent discharge locations must meet water quality benchmarks at the surface water sampling locations.
- Effective and rapid mixing of the effluent within the receiving environment must be facilitated, if necessary, by installing effluent mixing structures to improve the overall mixing efficiency.

In addition to the ECA conditions, the discharge effluent is required to mix rapidly with the receiving environment in a manner that does not pose a barrier or physical threat to fish. The effluent mixing structure should minimize formation of visual or auditory barriers that result in a behavioural response in fish that could potentially impede migration or movement patterns.

Design options

Based on the environmental constraints described above, KP completed a preliminary feasibility assessment of effluent mixing options, which is summarized below:

- Natural mixing, where the natural river currents in the Pinewood River disperse the mine effluent.
- Construction of alternating rockfill groyne structures that extend from the opposing river banks partway across the channel and enhance cross-currents and turbulence.
- Aeration with injection of air bubbles along the channel bed that rise to the water surface and generate cross-currents that enhance mixing.
- Installation of a diffuser system on the outlet of the discharge pipe resulting in high velocities and effective dispersion and mixing through entrainment of ambient water.

The use of rockfill groynes as a means of enhancing mixing was rejected as it was determined that these structures could cause backwatering and increase the potential for upstream overbank flooding. Aerator devices would enable substantial mixing of the effluent without causing backwatering effects, but would require ongoing power and maintenance work, with the additional disadvantage that they may have to be removed during winter months, or might pose visual barriers to fish. Natural mixing would be the least intrusive and cost-effective option, but might not achieve adequate mixing under all flow conditions before reaching the compliance points. It was determined that using a diffuser system would result in the highest likelihood of achieving full mixing of the RRM effluent and Pinewood River flows, while meeting all aquatic life water quality criteria and having minimal operational requirements.

Design criteria

Effluent discharge volume and timing requirements from the ECA, in combination with Pinewood River flow data, fish habitat requirements, structure constructability and operational requirements, as well as mixing efficiency, were used as the design basis for assessing the suitability of the various mixing/diffuser options considered in this study. A summary of the design criteria is provided below:

- ***Full transverse mixing*** – governed by the ECA requirement of achieving full transverse mixing by the time the effluent reaches the compliance point approximately 100 m downstream of the discharge point. Full transverse mixing is considered achieved once the concentration everywhere across the channel cross-section is within 5% of its mean concentration (Fischer et al., 1979).
- ***Effluent discharge rate*** – the minimum and maximum effluent discharge rates vary between 5,000 m^3/day and 20,000 m^3/day. A minimum of 1:1 ambient-to-effluent discharge ratio must be achieved. Scenarios investigating mixing of effluent discharges at higher ambient flows in the Pinewood River (e.g., during freshet or large storm events), were also assessed to ensure full transverse mixing is achieved within the required distance.
- ***Effluent water quality*** – the discharged effluent consists of surplus water collected around the mine site that is treated to meet the end-of-pipe water quality criteria set under the ECA.
- ***Effluent temperatures and densities*** – the collected surplus water around the mine site has a similar temperature to the water in the Pinewood River due to having the same atmospheric conditions. The concentration of constituents is sufficiently low (end-of-pipe water quality requirement) and the density of the effluent is equal to the ambient water density. Consequently, buoyancy forces due to small temperature or density differences between the effluent and the receiving environment are negligible considering the large initial momentum forces of the discharged effluent jets.
- ***Effluent pressure*** – hydraulic losses through the effluent delivery pipeline and diffuser system are modelled using the Darcy-Weisbach equation. Modelling results are used to confirm sufficient pressure head conditions at the diffuser inlet to ensure adequate functioning of the system based on ambient water levels and flow characteristics for a range of operating conditions.
- ***Erosion control*** – to prevent erosion along the channel bed and banks due to jet impacts, a combination of grouted gabion boxes, grouted riprap, and interlocked concrete Armortec open cell blocks (Contech, 2020) is used to create a protected cross-section with adequate transition back to the natural riverbed.

Diffuser types

The diffuser design was an iterative process that considered both single and multi-port diffuser systems, with a combination of either round jets or planar jets, where planar jets are typically discharged through a rubber check valve, or a so-called duckbill diffuser. The diffuser design was undertaken in combination with effluent mixing modelling to confirm that the proposed diffuser system would achieve the effluent mixing conditions required by the time the downstream compliance point is reached.

Based on the geometry of the receiving environment, it was determined that duckbill check valves would provide better mixing performance, with the additional advantage of providing backflow and fish-entrance prevention, as the rubber check valves close when outflow is discontinued. In addition, the variable orifice size optimizes jet velocity, improving the mixing process during start-up and shut-down periods, or at lower discharge rates.

Combinations of single or double-port diffuser systems with different types of check valves were analyzed in this study. It was determined through two-dimensional hydrodynamic modelling (HEC-RAS 2D) of the receiving environment that a single-port diffuser system would not remain fully submerged under low-flow conditions due to the larger check valve size requirement, thus not satisfying the design requirement for submerged discharge. This prompted the use of a double-port diffuser system using two 8-inch nominal diameter sleeve-type check valves, which would remain submerged under all effluent discharge conditions, as shown in Figure 1.

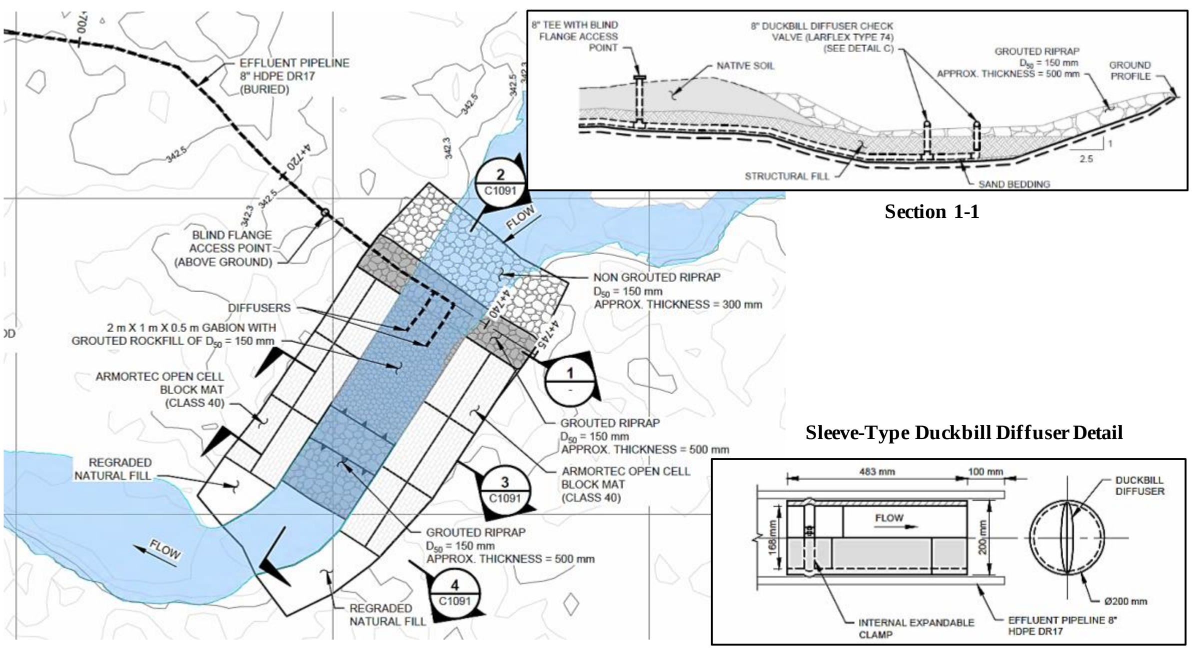

Figure 1: Effluent discharge system design with a double-port sleeve-type duckbill diffuser

Analytical mixing model results

The diffuser design was undertaken in combination with mixing modelling analysis to confirm that full transverse mixing of the discharged effluent is achieved within 100 m from the point of discharge.

Considering that the effluent discharge would be driven by the initial momentum of the fluid exiting the diffuser, the discharge can be characterized as a turbulent jet. As such, the mixing modelling procedure followed the turbulent jet calculations outlined in Fischer et al. (1979).

Analytical mixing modelling results are presented in Figure 2 in terms of effluent concentrations and velocities along the cross-section of the channel at various distances along the point of discharge for the maximum (20,000 m^3/day) effluent discharge rate scenario. Mixing modelling results indicate that the double-port diffuser design system will achieve fully mixed conditions by the time it reaches the compliance point located at 100 m downstream from the point of discharge. In addition, effluent velocities at the jet's centreline dissipate quite rapidly at short distances downstream from the point of discharge.

Effluent concentrations are presented in a non-dimensional form, calculated as a ratio of the predicted effluent concentration (C) at any point to the initial or maximum effluent concentration (C_0), thus representing percentage effluent mixing results in terms of C/C_0. The results shown in Figure 2a indicate that effluent concentrations in the horizontal plane and along each jet's centreline dissipate quite rapidly at short distances downstream from the points of discharge.

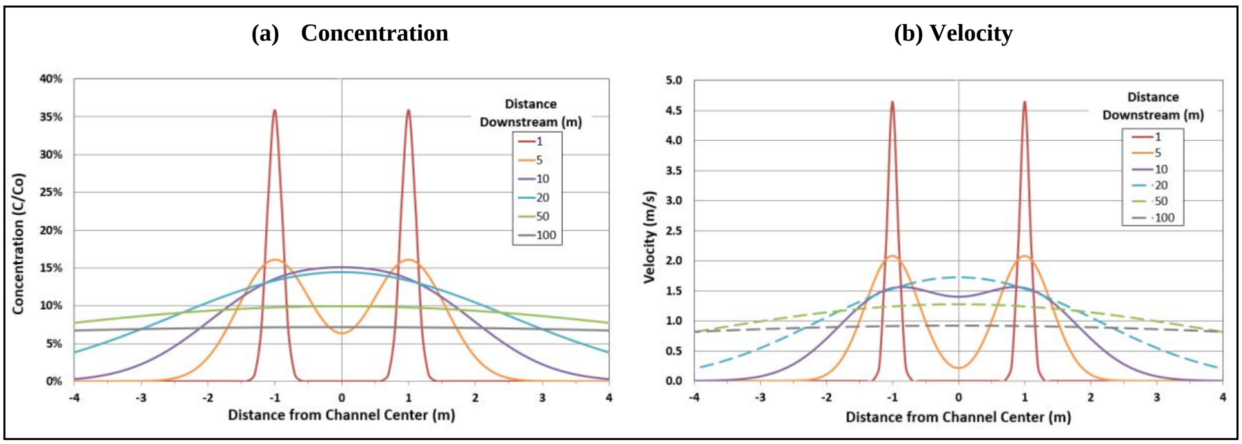

Figure 2: Predicted effluent profile across the double-port jet at various distances from the origin for 20,000 m³/day discharge rate: (a) Concentration, and (b) Velocity

A different way to visualize the mixing is illustrated in Figure 3, which shows the predicted effluent concentration cloud in plan view. It is predicted that the jets will initially reach the channel banks approximately 15 m downstream from the point of discharge, while the lengths required to achieve full transverse mixing are expected to range from 20 m to 40 m for the required range of discharge rate scenarios.

Effluent velocities were calculated for a number of points across the river at various locations downstream from the point of discharge. Analytical jet equations do not consider physical boundaries in the receiving environment (i.e., channel bed, channel banks, and air-water surface boundaries), resulting in higher modelled jet velocities compared to reality. For this reason, the velocity profiles presented for distances greater than 20 m downstream from the point of discharge are expected to be overestimated and are shown with dashed lines. The analytically modelled effluent jet velocities provide a conservative upper bound that was used in the design of the effluent mixing structure and the associated erosion control measures. The maximum effluent jet velocities at the nozzle exit were predicted to be over 6 m/s, rapidly decreasing to 2 m/s approximately 5 m downstream from the point of discharge (Figure 2b). Velocities were also found to drop rapidly in the horizontal plane laterally from the jet centreline.

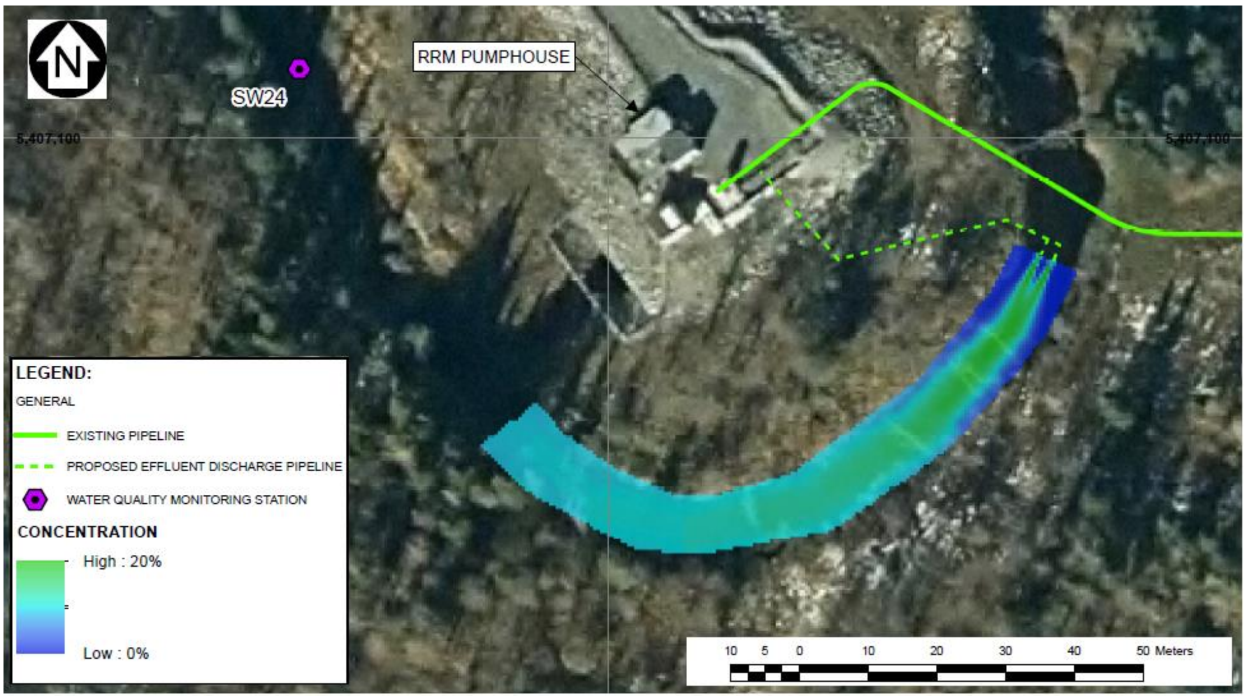

Figure 3: Effluent concentration for the double-port diffuser system at 20,000 m³/day

Effluent mixing evaluation

A mixing study was conducted after commissioning the effluent diffuser system to confirm that there is adequate effluent mixing with the receiving environment by the time the downstream compliance points are reached. The effluent discharge and the discharge in the Pinewood River were both at 10,000 m^3/day at the time the study was conducted. Rhodamine dye was injected into the effluent discharge pipeline at a constant rate. Monitoring of the rhodamine concentrations was conducted at various transects downstream from the discharge location using YSI 600 OMS sondes until it was determined that a steady-state condition in the river had been established and maintained for at least 15 minutes.

The YSI sondes were calibrated to background conditions and were set up to record measurements every two seconds. The YSI sondes were then placed across the river at transects downstream of the effluent discharge system, with one YSI sonde placed at the channel centre, and one placed at each bank within the active flow area, for a total of three YSI sondes per transect. A total of four transects located at 10 m, 20 m, 25 m, and 58 m downstream from the discharge points were assessed, two transects monitored at a time. Transect A (10 m) was the closest to the diffuser, transects C (20 m) and B (25 m) were just upstream and just downstream of a river bend, and transect D (58 m) was located at the water quality sampling dock.

The results are presented using box and whisker plots, with the median represented using a line within the box, and the first and third quartiles of the data set represented by the lower and upper bound of each box, respectively. The size and symmetry of the boxes can provide insights into the typical values, the amount of spread, the symmetry of the dataset, with the “whiskers” and outlier points representing extreme values. The percent differences of each YSI sonde reading from the mean transect concentration over the steady state period, as well as the ±5% envelope indicative of complete transverse mixing, as defined by Fischer et al. (1979), are summarized on the box plot shown in Figure 4a for Transects A and B, and in Figure 4b for Transects C and D (reminding that Transect C is upstream of Transect B).

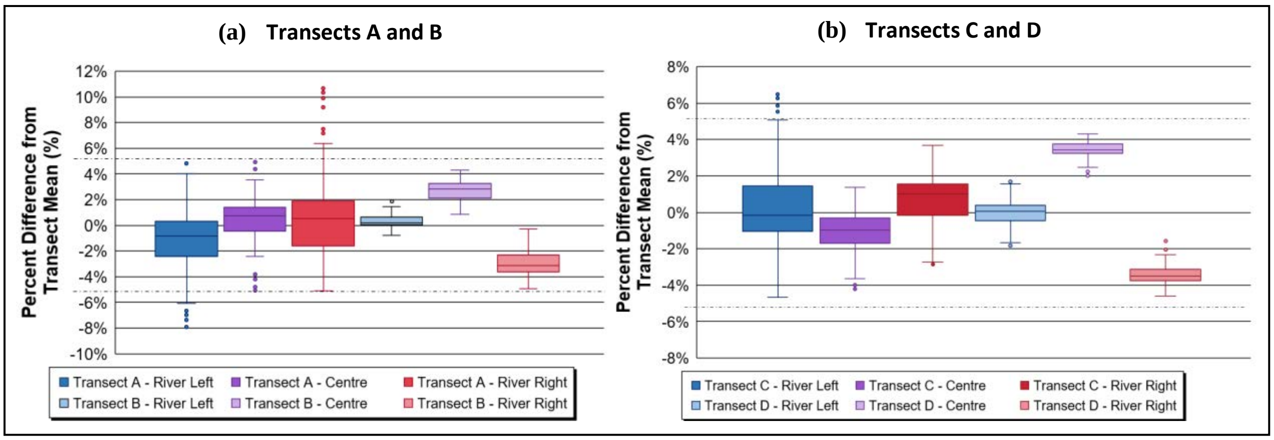

Figure 4: Percent difference from transect mean concentrations at four transects downstream from the point of discharge

The box plots provide a visual representation of the degree of variability, and thus the degree of mixing, within the channel. These results show that the variability in the concentrations across the channel transects decreases progressively from Transects A and C to a low degree of variability by the time the flow reaches Transects B and D. By the time the effluent reaches Transect B located 25 m downstream from the point of discharge, the variability is notably reduced, and all points fall within the 5% envelope, indicating fully mixed conditions. Thus, the results from the field study confirm that the performance of the designed system meets the ECA requirements for adequate effluent mixing.

Conclusions

Hydrometric monitoring has been in place at the H1 hydrometric monitoring station at the Rainy River Mine since 2015. The stage-discharge relationship at this site was frequently affected by backwatering from downstream obstructions and beaver activity, which resulted in periods of poor quality discharge data. The hydrometric monitoring network was upgraded and expanded to help improve the quality of the hydrometric data collection required for effluent discharge from the mine. This was primarily achieved by using SonTek-IQ acoustic Doppler flow measuring devices that measure the discharge in real time without relying on traditional stage-discharge relationships.

An effluent discharge system was designed and constructed to discharge treated surplus water from the mine to the Pinewood River. The design utilized the results from an analytical mixing model, and a double-port duckbill rubber valve diffuser was selected to satisfy the mixing requirements. After commissioning the effluent mixing system, a mixing study was completed to confirm the performance. The mixing study results indicate complete transverse mixing as close as 25 m from the discharge point, suggesting comparable or slightly better mixing results than predicted using analytical methods that estimated a mixing length of about 30 m at the tested low flow rate of 10,000 m^3/day. The differences may be due to better mixing conditions in the field compared to the simplifications and conservative assumptions made in the analytical assessment. This was supported by field observations, which indicated strong mixing conditions close to the duckbill diffusers.

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References

Concrete Canvas. 2018. *Concrete Canvas: Concrete Impregnated Fabric*. Brochure. United Kingdom.

Contech Engineered Solutions (Contech). 2020. Armortec Hard Armor Solutions. USA.

Fischer, H.B., E.J. List, R.C.Y. Koh, J. Imberger and N.A. Brooks. 1979. Mixing in inland and coastal waters. New York: Academic Press, Inc., a division of Harcourt Brace & Company.

SonTek. 2012. *SonTek-IQ Shallow Flow Meter Revolutionizes Flow Measurement in the Australian Bush*. Brochure. Xylem, Inc., USA

SonTek. 2015a. *SonTek-IQ Series: Standard, Plus and Pipe. Brochure*. Xylem, Inc., USA

SonTek. 2015b. *Acoustic Doppler Velocity Meter Site Requirements*. Xylem, Inc., USA.

U.S. Geological Survey (USGS). 2007. *Evaluation of the Acoustic Doppler Velocity Meter for Computation of Discharge Records at Three Sites in Colorado, 2004–2005*. Virginia, USA.

U.S. Geological Survey (USGS). 2015. *Hydraulic Laboratory Testing of SonTek-IQ Plus.* USGS Open-File Report 2015–1139.

U.S. Department of the Interior, Bureau of Reclamation (USBR). 2016. *Field Evaluation of Low Cost Ultrasonic Flow Meter*. Report ST-2016-8632-1, p.15.