RATE-CONTROL QUOTIENT OF MINERAL DISSOLUTION FROM WASTE ROCK DUMPS

Zhong-Sheng (Simon) Liu[A]; Cheng Huang[A]; Liang Ma[A]; Eben Dy[A]; Zhong Xie[A]; Kidus Tufa[A]; Elizabeth Fisher[A]; James Zhou[A]; Kevin Morin[B]; Mike Aziz[C]; Cody Meints[C]; Mike O'Kane[D]; Lindsay Tallon[D]

[A]Energy, Mining and Environment
National Research Council Canada, 4250 Wesbrook Mall,
Vancouver, BC, V6T1W5, Canada
[B]Minesite Drainage Assessment Group
Surrey, BC, Canada
[C]Equity Silver Mine, Reclamation Operations, Goldcorp Inc.
PO Box 1450, Houston BC, V0J 1Z0, Canada
[D]O'Kane Consultants Inc, 200 – 1121 Centre Str., NW, Calgary, AB, T2E7K6, Canada

ABSTRACT

Rain-water and/or snow-melt water infiltrate into or through waste rock dumps at mine sites and dissolve minerals (salts) from rock surfaces. Collecting and treating the drainage is required to meet mine-water-discharge regulations. Generally speaking, less solute loadings in the collected drainage would mean lower cost (e.g., less lime consumption). Thus it is important to identify the rate-control mechanisms of mineral dissolution under different storage configurations of waste rock dumps. In this paper, the authors present an analysis of rate-control mechanisms. The main point is *the rate of water-infiltration* Q *relative to the rate of solute production* $(k\beta\lambda)$, i.e., $(k\beta\lambda)/Q$. Here k represents the effective kinetic constant of a mineral species' dissolution from a rock surface, β represents rock dump depth, and λ represents the sum of rock surface areas that are flushed by infiltrated water within a unit volume of rocks. One significance of the quotient $(k\beta\lambda)/Q$ is its quantitative indication of the rate-control mechanisms. When $(k\beta\lambda)/Q$ becomes smaller, say $(k\beta\lambda)/Q < 0.5$, the rate of solute production becomes in control because the solute loading is nearly independent of water-infiltration rate Q; when $(k\beta\lambda)/Q$ becomes larger, say $(k\beta\lambda)/Q > 2.5$, infiltration rate Q is in control, that is, the solute concentration would become close to the saturation concentration of the mineral species and the solute loading would become proportional to infiltration rate Q; when $0.5 < (k\beta\lambda)/Q < 2.5$, both water-infiltration rate Q and the rate of solute production $(k\beta\lambda)$ are in control, a mixed control mechanism.

INTRODUCTION

Many waste rock dumps at mine sites contain minerals that could be leached out by rain-water or snow-melt water. The leached minerals elements/compounds could contain chemical elements such as arsenic, selenium, lead, zinc, iron and copper etc. As a result, the drainage from waste rock dumps can be toxic, corrosive or radioactive, or a combination of these, posing hazards to the environment and humans. Contemporary mining operations are associated with higher volumes of wastes than previously produced because of the depletion of high-grade ores. Overtime, large amounts of waste rocks have accumulated. As a consequence, the cost for collecting and treating the drainage has been increasing. It is not uncommon that it costs $2-$3 million annually to collect and treat mine drainage from a waste rock dump of 80 millions of tons of waste rocks, a typical size at open-pit mine sites. Therefore, a question arises: how to configure a waste rock dump so that the cost for treating the drainage could be significantly

reduced? This question is mainly about how to reduce the solute loadings in the drainage. To address the question, one needs to identify the rate-control mechanisms of mineral dissolution from waste rock dumps.

In this paper, a non-dimensional quantity is proposed for quantitatively indicating rate-control mechanisms of mineral dissolution from waste rock dumps. The non-dimensional quantity α is a ratio of the rate of solute production ($k\beta\lambda$) to water-infiltration rate Q,

$$\alpha = \frac{K\beta\lambda}{Q}$$

The definition of the quantities in the above expression is given in Table 1 below.

Table 1   List of Quantities

Quantity Name	Symbol	Dimension
Solute concentration	C	ML^{-3} (Mass/Volume)
Water infiltration rate	Q	LT^{-1} (Length/Time)
Sum of rock surface areas in a water-flow channel divided by the volume of the channel	λ	L^{-1} (1/Length)
Effective kinetic constant, k, of a mineral dissolution $$\frac{dM}{dt} = -Ak(C - C_e)$$ where A is the surface area and M is the mass of the solute leached out, t is time.	k	LT^{-1} (Length/Time)
The depth of a waste rock dump	β	L (length)
Saturation concentration of a solute in water	C_e	ML^{-3} (Mass/Volume)

MINERAL DISSOLUTION

Consider a waste rock dump. When rain falls or snow melts, water wets the entire top layer of the waste rock dump first. When the top layer is not able to hold the excess water, the excess water would start to infiltrate into the waste rock dump and eventually infiltrates through it. According to experimental observations, water tends to flow through waste rock dumps via many separate flow-channels, called fingered-flow, channeled-flow or preferential flow. Let us pick up a single flow-channel and figure out how the solute concentration at the bottom of the flow-channel is dependent upon k, β, λ and Q. Here β is the depth of the flow-channel, λ is the sum of rock surfaces within the flow-channel divided by the volume of the channel, and k is the effective kinetic constant of a mineral dissolution from a rock surface defined by $dM/dt = Ak(C_e - C)$, here A is the rock surface area, and C and C_e are respectively the solute concentration on the rock surface and its saturation concentration, and dM/dt is the mass of leached out solute in a unit surface area. Here we assume that a fixed volume of pore space within the flow-channel is

continuously flushed with water and that water is well mixed so that the concentration of a dissolved species within the flow channel is horizontally uniform, but the concentration of dissolved species increases as water flows downward in the vertical axis. Therefore, the concentration C of the solute species is a function of vertical location x, expressed as C(x), which increases with x. At x=0, C(0)=0, meaning fresh water enters into the top layer position; when water travels downward more mineral species would be added into the water making the solute concentration C(x) go up; at x=β, the bottom position of the waste rock dump, the concentration C(β) achieves its largest value. The mineral species are added to the pore water by dissolution of a sparingly soluble salt so that over short time scales the pore water volume does not increase. For simplification, here we assume a steady state (i.e. assume that concentration C(x) does not change with time, but change with x only when Q, k, β and λ are specified).

The expression for the conservation of mass and boundary condition (Liu et al, 2017) is:

$$Q \frac{dc(x)}{dx} = \lambda k [C_e - C(x)]$$
$$C(x) = 0 \text{ at } x=0$$
$$C(\beta) = ? \text{ at } x=\beta$$

Solving this differential equation gives,

$$C(\beta) = C_e(1 - e^{-\alpha})$$

where

$$\alpha = \frac{k\beta\lambda}{Q}$$

THE RATE-CONTROL MECHANISMS: THE QUOTIENT α

We name α as rate-control quotient, a non-dimensional quantity, a pure number without any unit attached. It is a ratio of solute production rate (kβλ) to flushing rate Q, $\alpha = (k\beta\lambda)/Q$. It quantitatively indicates the rate-control mechanisms, as shown in Figure 1.

(1) When $0 < \alpha < 0.5$, solute production rate (kβλ) is in control.

When $0 < \alpha < 0.5$, $-e^{-\alpha}$ can be approximated as $e^{-\alpha} \approx 1 - \alpha$, so expression $C(\beta) = C_e(1 - e^{-\alpha})$ can be re-written as:

$$C(\beta) \approx \alpha C_e \text{ or } C(\beta) \approx \frac{k\beta\lambda}{Q} C_e$$

Then the loading of the solute species T from the flow-channel can be expressed as:

$$T = SQC(\beta)$$
$$= (k\beta\lambda)C_e$$

where S is the cross-sectional area of the flow-channel.

Here it shows that when α is small, solute production rate (kβλ) is in control: the total loading is proportional to (kβλ), independent of flushing rate Q, and solute concentration C(β) is proportional to (kβλ), inversely proportional to flushing rate Q.

(2) When $\alpha > 2.5$, flushing rate Q is in control

When $\alpha > 2.5$, $(1 - e^{-\alpha})$ becomes less sensitive with respect to α, that is, $C(\beta) = C_e(1 - e^{-\alpha})$ can be re-written as

$$C(\beta) \approx C_e$$

Then the loading of solute species T from the flow-channel can be expressed as:

$$T = SQC(\beta)$$
$$\approx SQC_e$$

Here it shows that when $\alpha > 2.5$, flushing rate is in control: the total loading is proportional to flushing rate Q, independent of solute production rate $(k\beta\lambda)$, and the concentration $C(\beta)$ becomes almost constant being close to saturation concentration C_e.

(3) When $0.5 < \alpha < 2.5$, both flushing rate Q and solute production rate $(k\beta\lambda)$ are in control, a mixed control mechanism.

When $0.5 < \alpha < 2.5$, both Q and $(k\beta\lambda)$ contribute to α and none of them can be neglected without affecting $C(\beta)$ significantly. As a result, expression $C(\beta) = C_e(1 - e^{-\alpha})$ cannot be simplified in the above manner. It means both flushing rate Q and solute production rate are in control, a mixed control mechanism.

IS THE EXPRESSION $C(\beta) = C_e(1 - e^{-\alpha})$ IN AGREEMENT WITH THE FIELD DATA?

The expression $C(\beta) = C_e(1 - e^{-\alpha})$ shows the dependence of solute concentration $C(\beta)$ upon $(k\beta\lambda)$ and Q. When we assume that $(k\beta\lambda)$ is unchanged and Q varies alone, the expression shows the dependence of $C(\beta)$ upon Q alone. For the purpose of comparison, let us perform a coordinate transformation from C-Q to y-x: $y = \ln[1 - C(\beta)/C_e]$, and $x = 1/Q$. Under the y-x coordinate, the expression $C(\beta) = C_e(1 - e^{-\alpha})$ becomes $y = -(k\beta\lambda)x$. The y-x relation is a straight line with its slope as $-(k\beta\lambda)$. Is full-scale field data in agreement with this straight line?

To test the straight-line relationship, here we use the full-scale field monitoring data from the waste rock dump at Equity Silver mine, Houston, BC, Canada, which is shown in Figure 2. The waste rock dump sits at the lower part of Figure 2. The drainage from the waste rock dump flows into the ARD ditch which is shown by the blue line in Figure 3. Near the end of the ARD ditch marked by C7, the solute species concentrations and drainage-flow rates were available over the past 20 years (1998-2017) at the time interval of two weeks. All the Zn concentration readings and the associated flow-rates at C7 location were grouped according to their months, and to each month we plot those C-Q data points on the y-x coordinates, and perform a linear regression as shown in Figures 4-11. The winter months (i.e. November, December, January and February) have very low flow rates, so we only consider the other 8 months here.

The overall trend of the data points in Figures 4-11 seems supportive of the equation given above on the dependence of solute concentration C on flushing rate Q in that their overall trend is in agreement with straight lines $y = -(k\beta\lambda)x$. Ongoing follow-up work is to carry out column-leach testing under controlled conditions for testing the equation, and will report the results later.

CONCLUDING REMARKS

This paper proposes to use a quotient α, $\alpha = (k\beta\lambda)/Q$, to quantitatively indicate rate-control mechanisms of mineral dissolution from waste rock dumps. The quotient α is a non-dimensional quantity, and is the ratio of solute production rate $(k\beta\lambda)$ to flushing rate Q. The quotient α is from the expression $C(\beta) = C_e(1 - e^{-\alpha})$ where $\alpha = (k\beta\lambda)/Q$. The expression has a few assumptions: that first-order leaching kinetics holds, that the water-flow rate along a flow-channel is in a steady state, that solute concentrations increase downward and are uniformly distributed horizontally, and that solute concentrations at any vertical location do not change with time. The testing of the expression $C(\beta) = C_e(1 - e^{-\alpha})$ against the monitoring data from Equity Silver mine at Houston BC Canada seems to show that the expression holds. We are testing the expression using our lab test data which have better controlled conditions, and will report the results later.

The quotient α can quantitatively indicate rate-control mechanisms. When α is small, say $\alpha < 0.5$, solute production rate $(k\beta\lambda)$ is in control; when α is large, say $\alpha > 2.5$, flushing rate Q is in control. When $0.5<\alpha<2.5$, both $(k\beta\lambda)$ and Q are in control, a mixed control mechanisms. The rate-control mechanisms are needed for figuring out how to place waste rock dumps for reduced solute loadings. The authors have not seen any explicit use of the rate-control mechanisms for the design of waste rock dumps, but believe that the concept here would be effective and quantitative for understanding how minerals are leached out from waste rock dumps.

REFERENCE

Z-S Liu, C. Huang, L. Ma, E. Dy, Z. Xie, M. O'Kane and S. Pearce, 2017, Experimental Models of Metal Leaching for Scaling-Up to the Field, The 9-th Australian Workshop on Acid and Metalliferous Drainage, P.44

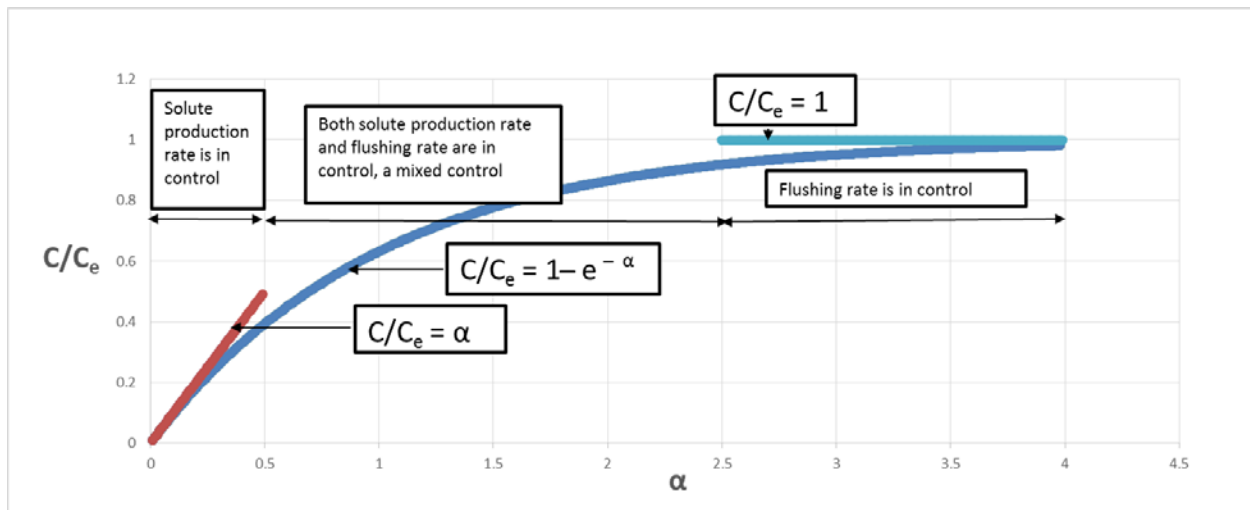Figure 1: Rate-Control Mechanisms

Figure 2. The Waste Rock Dumps of the Equity Silver Mine at Houston, BC, Canada

Figure 3. Simplified Layout of the Waste Rock Dumps at Equity Silver Mine
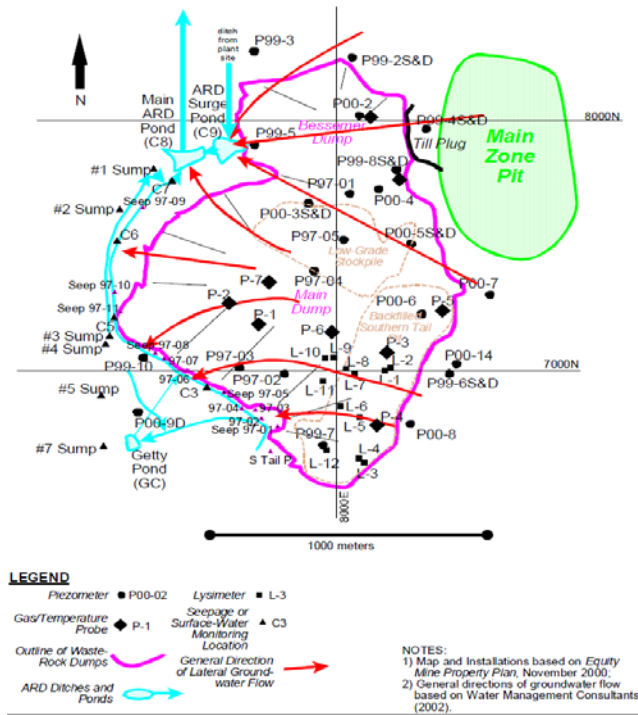
Simplified Layout of the Equity Waste-Rock Dumps

LEGEND

Piezometer	● P00-02	Lysimeter	■ L-3
Gas/Temperature Probe	◆ P-1	Seepage or Surface-Water Monitoring Location	▲ C3
Outline of Waste-Rock Dumps		General Direction of Lateral Ground-water Flow	➡
ARD Ditches and Ponds			

NOTES:
1) Map and Installations based on *Equity Mine Property Plan*, November 2000;
2) General directions of groundwater flow based on Water Management Consultants (2002).

Figure 4. Flow Rate Q vs. Zn Concentration C at Location C7 March from 1998-2017

$y = -0.2103x - 0.18$
$R^2 = 0.0979$

Y-axis: Ln(1-C/Ce) Ce = Saturation Concentration

X-axis: 1/Q
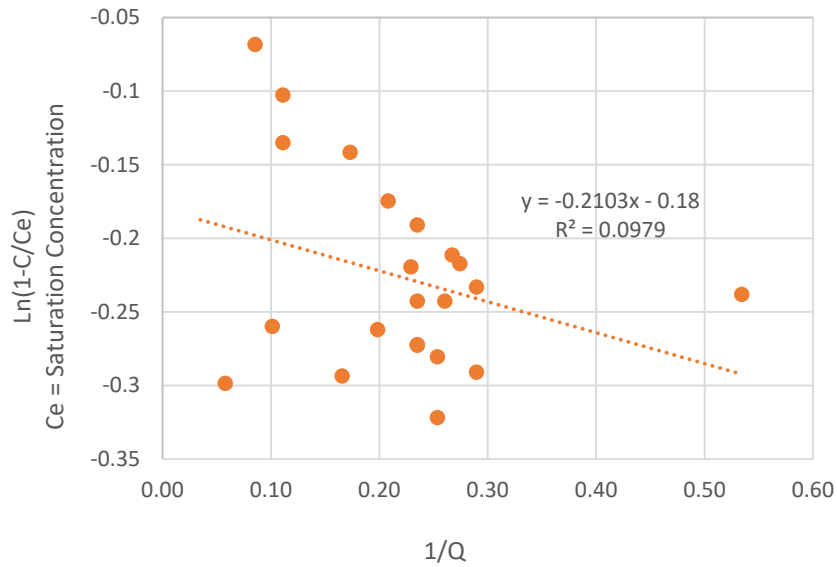
Figure 5. Flow Rate Q vs. Zn Concentration C at Location C7 April from 1998-2017

$y = -0.5078x - 0.1066$
$R^2 = 0.2551$
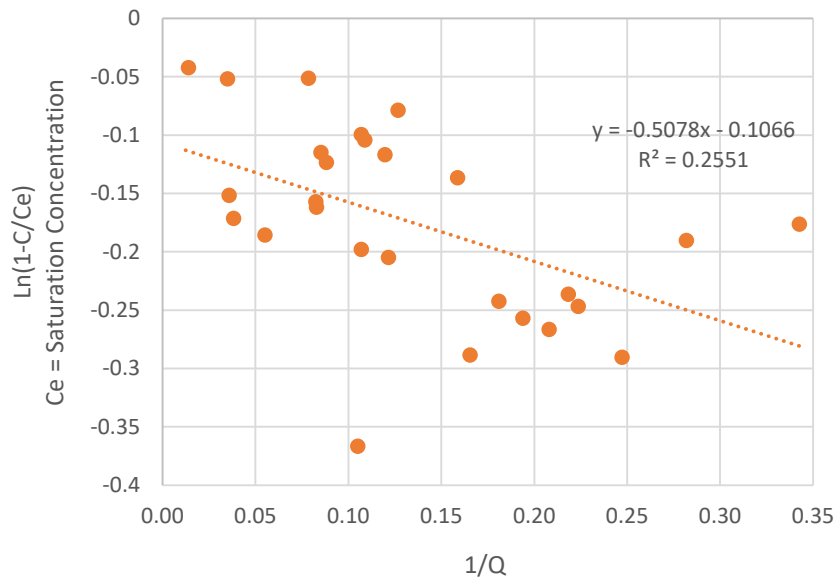
Figure 6. Flow Rate Q vs. Zn Concentration C at Location C7, May from 1998-2017

$y = -0.5169x - 0.1442$
$R^2 = 0.0286$
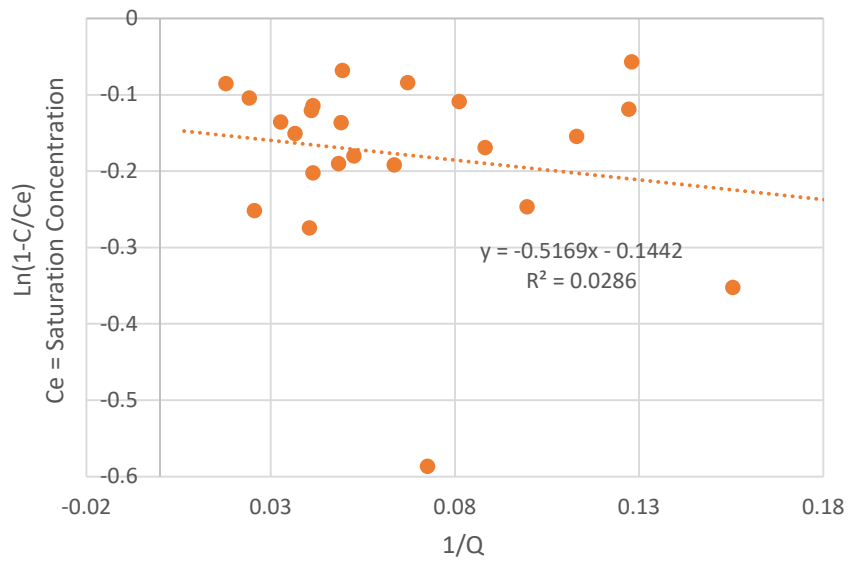
Figure 7. Flow Rate Q vs. Zn Concentration C at Location C7 June from 1998-2017

$y = -0.5306x - 0.1029$
$R^2 = 0.3594$
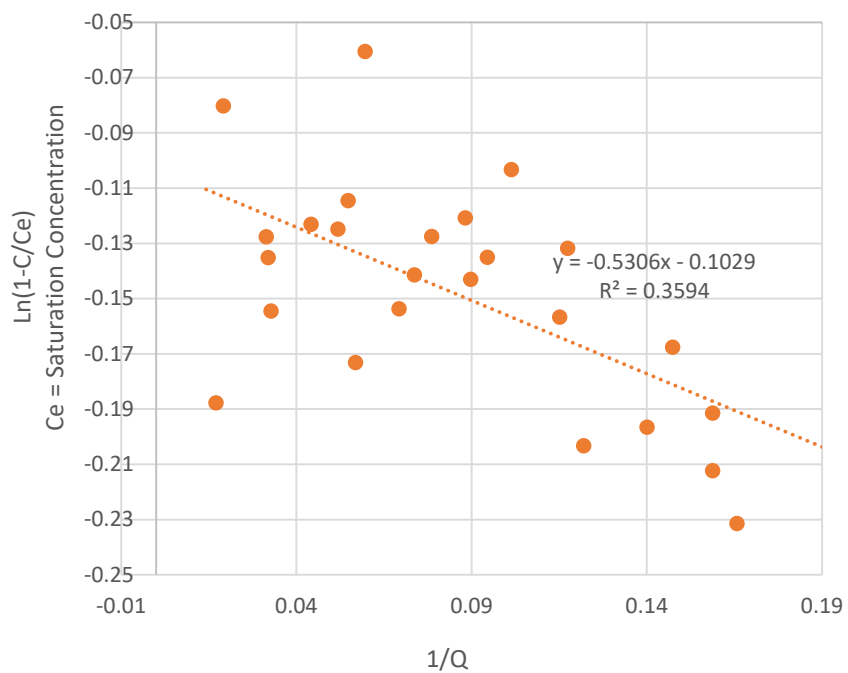
Figure 8. Flow Rate Q vs. Zn Concentration C at Location C7 July from 1998-2017

$y = -0.6829x - 0.0927$
$R^2 = 0.5287$
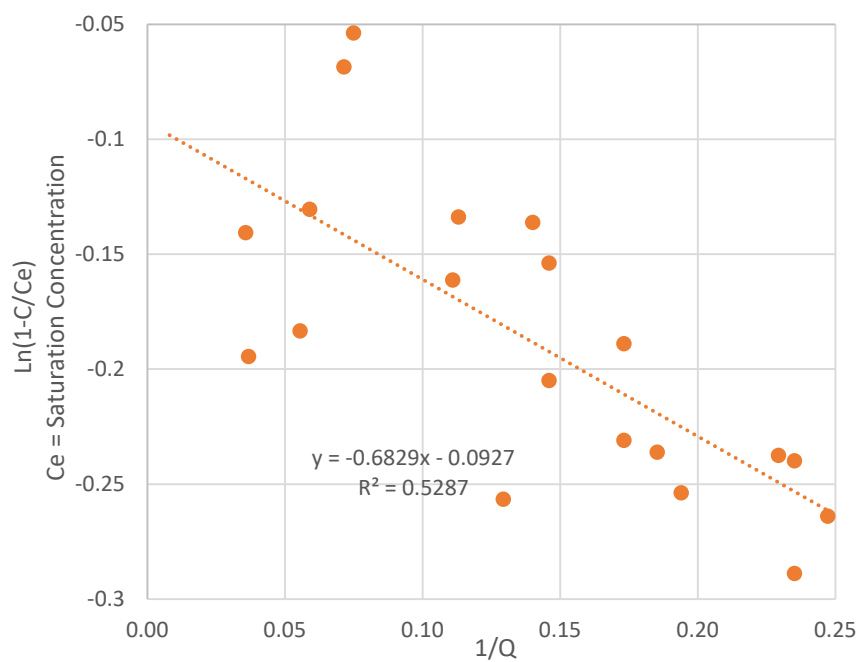
Figure 9. Flow Rate Q vs. Zn Concentration C at Location C7
August from 1998-2017

$y = -0.3844x - 0.1504$
$R^2 = 0.2229$
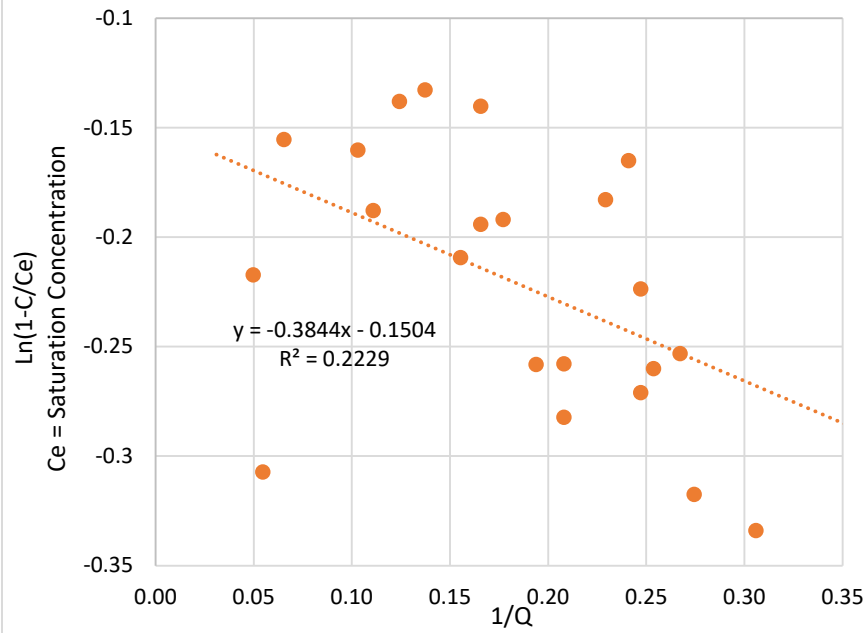
Figure 10. Flow Rate Q vs. Zn Concentration C at Location C7
September from 1998-2017
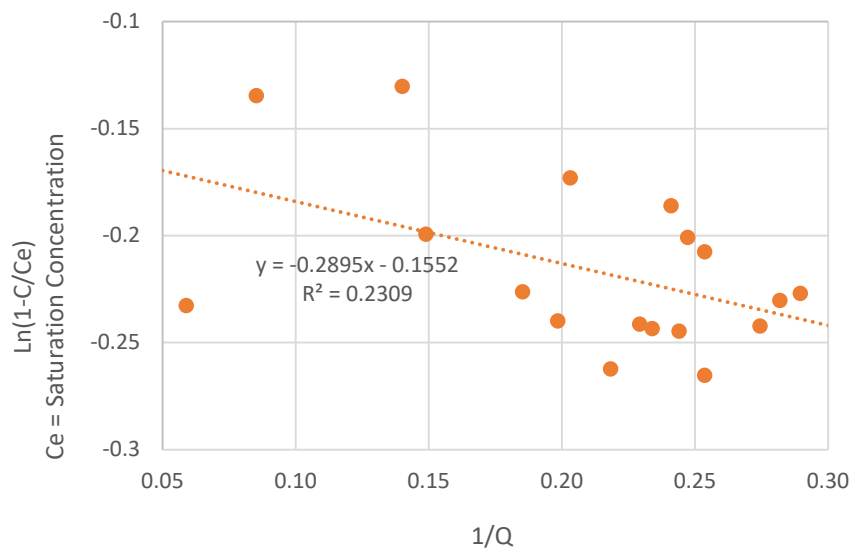
$y = -0.2895x - 0.1552$
$R^2 = 0.2309$

Figure 11. Flow Rate Q vs. Zn Concentration C at Location C7 October from 1998-2017

$y = -0.2838x - 0.119$
$R^2 = 0.1777$

Ln(1-C/Ce)
Ce = Saturation Concentration

1/Q