# Water Resources Center
# Annual Technical Report
# FY 2004

## Introduction

The Rhode Island Water Resources Center is undergoing a period of positive change. New internal and external committees are being formed which will serve to enhance both the mission of the Center as well as the quality of research. The Center has had improvements in infrastructure and is beginning to enhance communications through an active website and a future newsletter. In addition to providing information to our congressional delegation the research projects that were funded addressed important State water resources issues including; the impacts of development around streams and rivers on the erosion of bridge supports, alternative, environmentally safe methods of de-icing planes and an innovative treatment of once-through fishery waters for reuse.

## Research Program

The Rhode Island Water Resources Center supported three research proposals for funding; Scour Potential for Rhode Island Bridges, URI Water Reserve Project and Mitigating Runoff Contamination Due to Deicing and Antiicing Operation at TF Green Airport.

The first project involves a study to determine the impacts of development on bridge scour. In Rhode Island, as well as in other areas, rapid development is occurring along streams and rivers. This development tends to increase the magnitude and intensity of stream flows. A model needs to be developed to allow the bridge designer to be able to predict the hydraulic impacts of development and design bridge supports to accomodate them.

The second project is an investigation of potential treatment processes to recycle water used in breeding freshwater fishes. This water is high in BOD, solids and ammonia. Several treatment processes were evaluated and the University of Rhode Island is in the process of implementing them.

The final project is a study, with recommendations, on various alternative method for treating ice buildup on planes. The results of this study will not only benefit Rhode Island but they can be applied to other airports.

# Stream Stability and Scour Potential for Rhode Island Bridges

## Basic Information

| | |
|---|---|
| **Title:** | Stream Stability and Scour Potential for Rhode Island Bridges |
| **Project Number:** | 2004RI23B |
| **Start Date:** | 3/1/2004 |
| **End Date:** | 2/28/2005 |
| **Funding Source:** | 104B |
| **Congressional District:** | 2 |
| **Research Category:** | Not Applicable |
| **Focus Category:** | Water Use, Sediments, Management and Planning |
| **Descriptors:** | |
| **Principal Investigators:** | George Tsiatas |

## Publication

**Note: This is a draft.**

## 1. Scour Models

In this section two scour models that will be used in the study are described. These include the widely used in the United States HEC model and an alternative recent Chinese model. It is noted that the HEC model uses one equation to predict scour whereas the Chinese model utilizes two equations depending on the flow conditions. In subsequent sections these two models will be compared based on a reliability analysis using existing scour data in order to determine the best model to be used in evaluating effects of changing land use.

### 1.1 HEC Equation

The approach which is used most often in the USA is the "HEC-Equation". The name is originated in the fact that the procedure is outlined in the Hydraulic Engineering Circular #18. It has been developed at the Colorado State University which is the reason why sometimes it is also called "Colorado-Equation". According to the HEC model the expected scour depth can be calculated as the following:

$$y_s = 2 * (K_1 * K_2 * K_3 * K_4) * (\frac{b}{y_1})^{0.65} * Fr^{0.43} \tag{1}$$

In this Equation the following definitions are used:

- $y_s$ = predicted scour depth
- $K_1, K_2, K_3, K_4$ = correction factors due to the appearance of several pier shapes, flow attack angles, bed conditions and armouring of the bed material; see below for details
- $b$ = pier width
- $y_1$ = flow depth measured directly upstream of the site
- $Fr$ = Froude number, [William Froude, Englishman, 1810-1879]; see below for details

The *Froude number* is of great importance in various areas of hydrodynamic science. It is a dimensionless quantity defined as the ratio of inertial force and the gravitational force in a specific hydrodynamic system. The Froude number is expressed as:

$$Fr = \frac{v}{\sqrt{g * h}} = \frac{v}{c} \qquad (2)$$

where:

- $v$ = stream velocity
- $g$ = acceleration of gravity
- $h = y_1$ (flow depth measured directly upstream of the site)
- $c$ = wave velocity

Based on the value of the Froude number a flow can be categorized into one of three cases:

1. $Fr < 1 \rightarrow$ drifty flow
2. $Fr = 1 \rightarrow$ critical flow
3. $Fr > 1 \rightarrow$ supercritical flow

The following picture visualizes the meaning of the different areas of the Froude number. It shows a river right after a stone is thrown into it:

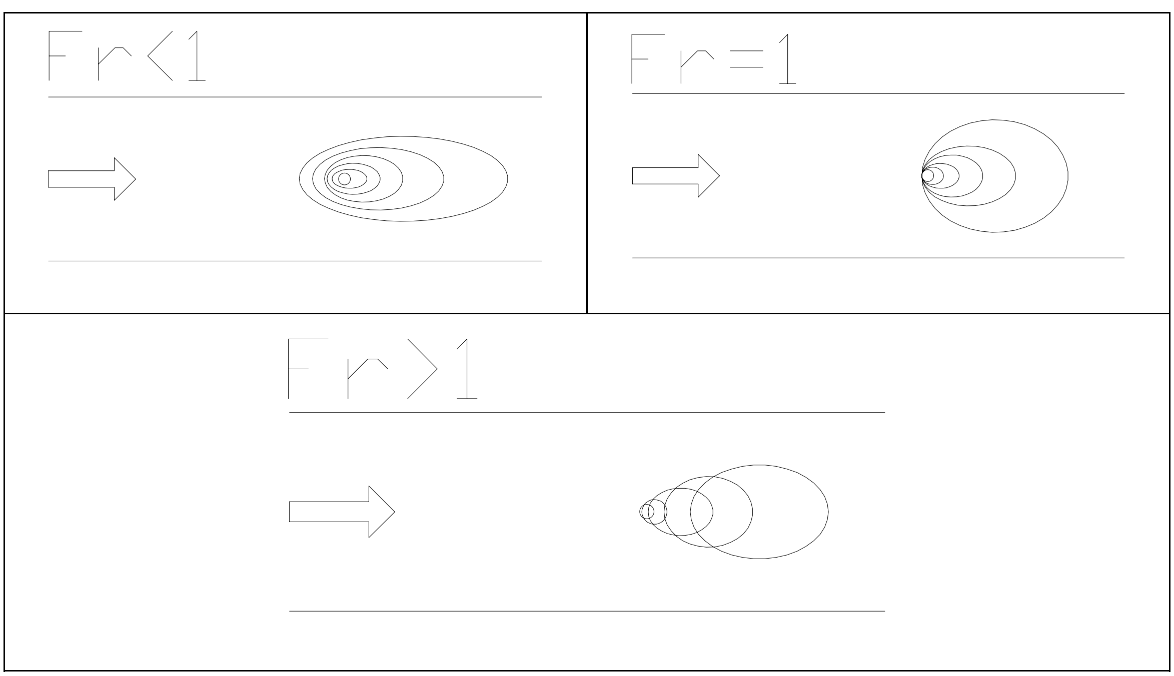


Fig. 1 Illustration of Froude number areas

Note the analogy which exists between the Froude number and the Mach number [Ernst Mach, Czech, 1838-1916] which is used in aviation.

$$Ma = \frac{v}{c_s} \quad (3)$$

Where:

- $v$ = velocity of the specific compound
- $c_s$ = sonic speed

In the HEC equation (Eq. 1), four correction factors appear. The first, $K_1$ accounts for the different pier shapes which are used most often for bridge piers. The following table illustrates those:

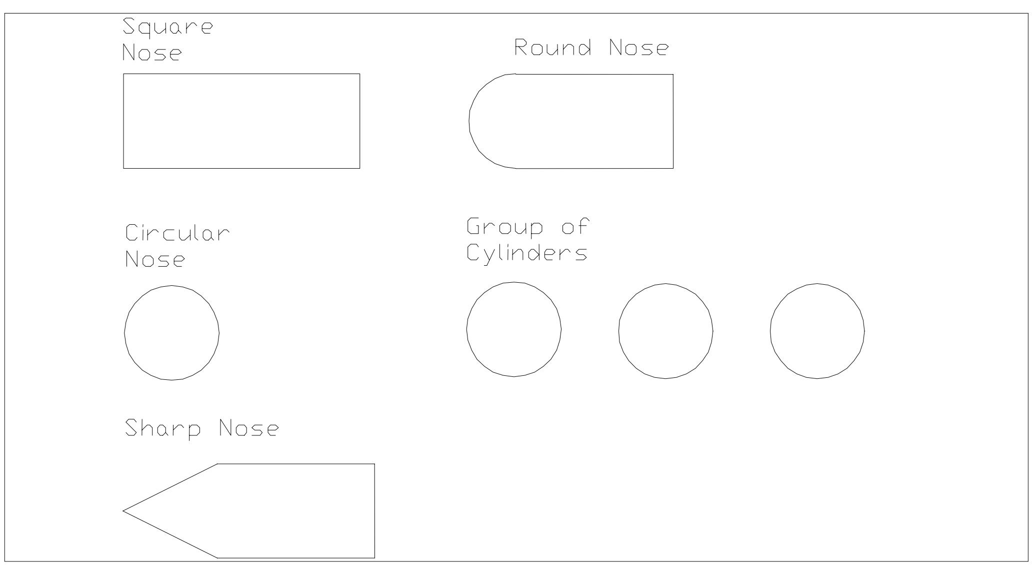



Fig. 2 Typical pier shapes

Values for $K_1$ :

| | |
|---|---|
| square nose | 1.1 |
| round nose | 1.0 |
| circular nose | 1.0 |
| group of cylinders | 1.0 |
| sharp nose | 0.9 |

Note: $K_1$=1.0 if the angle of flow attack exceeds 5°.

$K_2$ is a function of the angle of flow attack θ and the ratio of the pier length to the pier width $\frac{L}{b}$. It can be determined by:

$$K_2 = (\cos\theta + \frac{L}{b}\sin\theta)^{0.65} \quad (4)$$

Typical values for $K_2$ are as follows:

| θ, [°] | L/b=4 | L/b=8 | L/b=12 |
|---|---|---|---|
| 0 | 1.0 | 1.0 | 1.0 |
| 15 | 1.5 | 2.0 | 2.5 |
| 30 | 2.0 | 2.8 | 3.5 |
| 45 | 2.3 | 3.3 | 4.3 |
| 90 | 2.5 | 3.9 | 5.0 |

Depending on the size of the underwater dunes and on the sediment transport conditions, $K_3$ can be found as:

| Bed Conditions | Dune Height, [m] | K3 |
|---|---|---|
| clear-water | N/A | 1.1 |
| plane bed and anti-dune flow | N/A | 1.1 |
| small dunes | 0.6 to 3 | 1.1 |
| medium dunes | 3 to 9 | 1.1 to 1.2 |
| large dunes | ≥9 | 1.3 |

For the definition of the last correction factor, $K_4$, the soil particle size D is needed. The size of the medium-sized soil particle is called $D_m$ and has length units. Another name is $D_{50}$ where the "50" is the percentage of soil particles which have already passed a grid once this size is met. Grading curves show the distribution of sizes and give information about the soil. Other characteristic particle sizes are $D_{16}, D_{84}$ and $D_{95}$.

The last correction factor, $K_4$, is a dimensionless factor that can be determined by:

$$K_4 = \sqrt{1 - 0.89 * (1 - V_R)^2} \tag{5}$$

Where $V_R$ is a dimensionless velocity ratio: $V_R = (\frac{V_0 - V_i}{V_{c(D90)} - V_i})$ (6)

$V_i$ is the incipient motion velocity meaning that at this velocity the average-sized soil particle starts floating:

$$V_i = 0.645 * (\frac{D_{50}}{b})^{0.053} * V_{c(D50)} \tag{7}$$

Generally speaking, the incipient flow velocity can be determined for a soil particle of size $D_n$, where n again is the mass-percentage of soil which has already passed the grid. The velocity can be calculated as:

$$V_{c(Dn)} = 6.19 * y_0^{\frac{1}{6}} * D_n^{\frac{1}{3}} \tag{8}$$

The pier width *b* is being measured as shown in the following sketch irrespective to the number of pier columns:

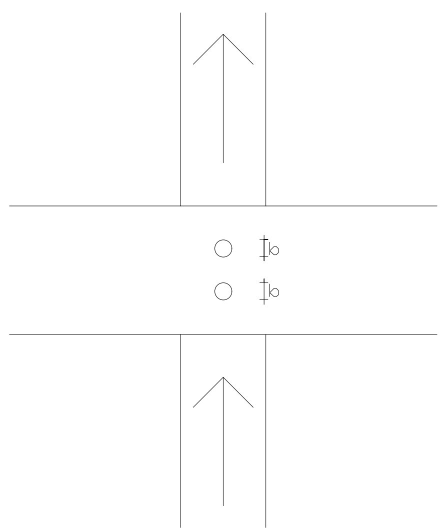



Fig. 3 Definition of pier width, *b*

## 1.2 Chinese Scour Model

As a result of laboratory tests as well as field data, several scour equations were investigated in China. Gao et al. [1992] finally developed a simplified pier-shape coefficient and came up with two equations, one for clear-water conditions and another for live-bed conditions:

For clear-water conditions the Chinese model is**:**

$$y_{sp} = 0.78 * K_s * b^{0.6} * y_0^{\ 0.15} * D_m^{\ -0.07} * (\frac{V_0 - V_c'}{V_c - V_c'}) \tag{9}$$

In this equation the following parameters are used:

- $K_s$ = factor related to pier shape. It takes values of 1.0 for cylinders, 0.8 for round nosed piers and 0.66 for sharp nosed piers.
- $b$ = pier width
- $y_0$ = water depth at the pier
- $D_m$ = diameter of the average sized soil particle
- $V_0$ = flow velocity
- $V_c$ = critical flow velocity; see below for details
- $V_c'$ = approach velocity in the constricted reach; see below for details

To visualize the meaning of the critical velocity, $V_c$, one can consider that whether the soil particles are in motion (live-bed) or not (clear-water) depends on the ratio of actual flow velocity to critical velocity. If this ratio is greater than one, live-bed conditions are present whereas clear-water conditions can be expected if the ratio is less than one. The actual value for $V_c$ has units of velocity and is given by:

$$V_c = (\frac{y_0}{D_m})^{0.14} * (17.6 * (\frac{\rho_s - \rho}{\rho}) * D_m + 6.05E(-7) * (\frac{10 + y_0}{D_m^{\ 0.72}}))^{0.5} \tag{10}$$

- $\rho_s$ = density of the sediment particles of the soil
- $\rho$ = density of water

Once the critical velocity is known, the incipient approach velocity can be calculated by:

$$V_c' = 0.645 * (\frac{D_m}{b})^{0.053} * V_c \tag{11}$$

The term $(\frac{V_0 - V_c'}{V_c - V_c'})$, inherent in both the clear-water and live-bed equations, is a dimensionless parameter characterizing the flow intensity.

For live-bed conditions, the Chinese model becomes:

$$y_{sp} = 0.65 * K_s * b^{0.6} * y_0^{0.15} * D_m^{-0.07} * (\frac{V_0 - V_c'}{V_c - V_c'})^c \tag{12}$$

Looking at both equations (Eqs. 9 and 10) the only differences between live-bed and clear-water is the factor 0.65 which was 0.78 for clear-water and the power of c for live-bed conditions which is defined as:

$$c = (\frac{V_c}{V_0})^{9.35+2.23*\log(D_m)} \tag{13}$$

The parameter c will always be less than one, making sure that the estimated scour depth for clear-water conditions will never be less than the one for live-bed conditions.

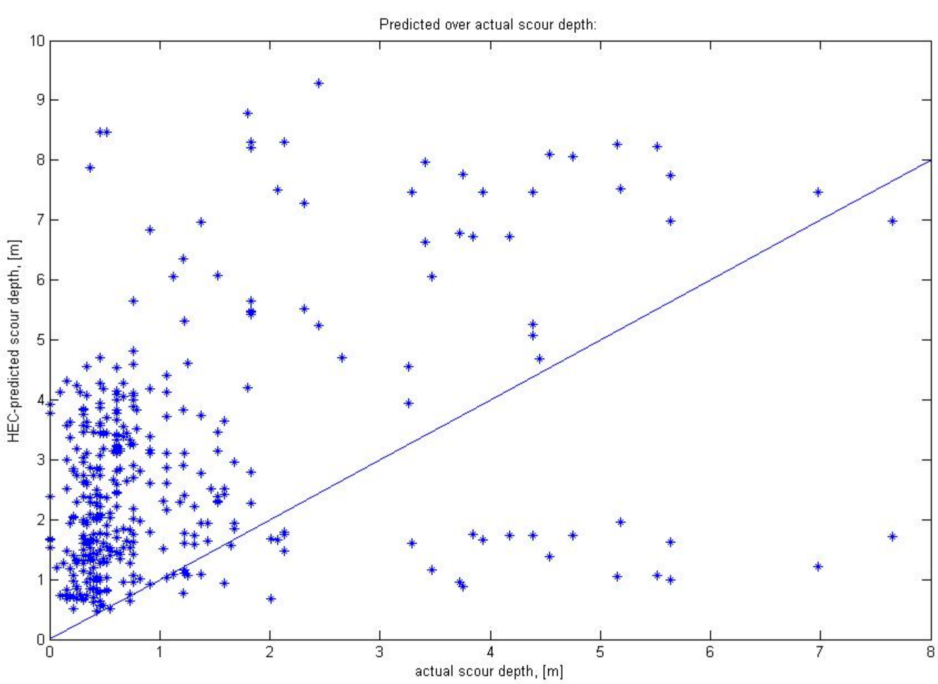
An important note is the fact that all the above equations used for the Simplified Chinese approach are dimensional and have to be used with SI-units. Therefore, lengths have to be inputted in [m] and velocities in [m/sec]. Theoretically, the densities have to be also used with SI-units [kg/m³] but in this case it does not matter since when looking at the whole term that includes the densities it is found that it is dimensionless.

## 2. Reliability Analysis of the HEC Equation

The ultimate test of any prediction model is how reliably does it predict the behaviour it is trying to model. In the present section a summary of the reliability procedures used to critically compare the two scour models (HEC Model and Simplified Chinese Equation Model) is provided. The first procedure is based on the use of a reliability index, β, whereas the second approach is based on regression analysis. The data used for the reliability studies are based on the report "Channel Scour at Bridges in the United States" (FHWA-RD-95-184) by Landers and Mueller.

*Reliability estimates using "lamda" values*

As mentioned before the scour predicting equation which is used most frequently in the area of the USA is the HEC-18-equation. Taking the measurements from the Landers data as an input for this equation, assuming that the correction factor $K_3$ = 1.15 for all live-bed conditions (medium height dunes) enables to compare the HEC results to the actual measured scour depths:

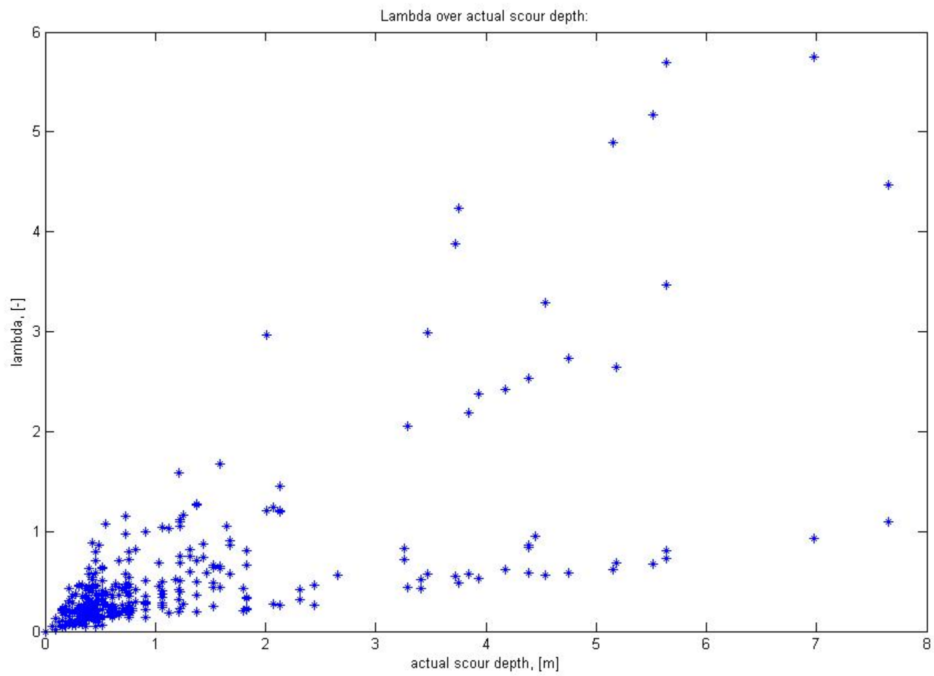


The data points are sorted by increasing actual scour depth and the continuous even symbolizes the optimal prediction where actual scour depth = predicted scour depth. The vast majority (88.6%) of actual scour depths are below 2.5 meters (8.2ft) and for this range there are hardly underestimations. Unfortunately this does not necessarily mean that the approach is quite close to the actual scour depth. As it can be seen in the picture above, overestimations are quite enormous and up to 9 times the actual scour depth. An advantage of the HEC-equation is that statistically speaking there are not many bridge sites where scour depths deeper than 2.5 meters can be expected and therefore it should be a conservative approach for the majority of sites.

But does the hope just to overestimate satisfy completely?

As per definition $\lambda = \frac{actual}{predicted}$ scour depth, it can be said that as the scour depth increases, the variation of the HEC equation increases as well. At the point of maximum actual scour depth in the Landers data the underestimation is up to 500% and at another point of about the same actual scour depth the prediction meets the actual scour depth quite close as $\lambda \approx 1.0$.

When comparing the numbers of points which are under- and overestimated it comes out that 89.9% of all HEC-predictions provide overestimations, i.e. $\lambda < 0$.



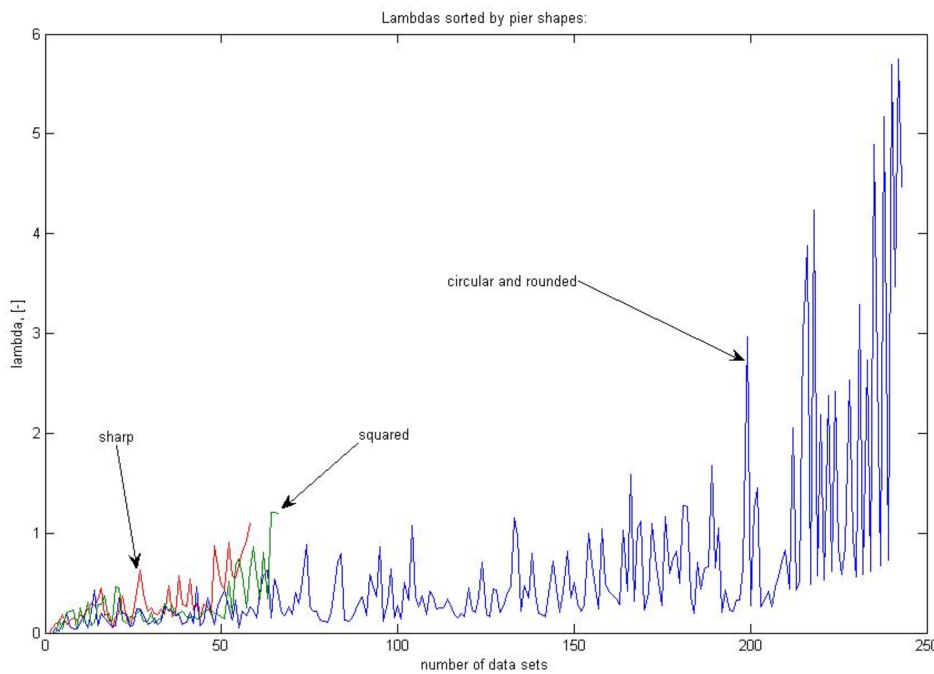

When determining the reliability index $\beta$, its quality essentially depends on the performance of the lambda table. In the case of bridge scour there are many parameters which are used and for this reason there are many options to sort the data sets.

Examples are

- pier-shape,
- conditions (live-bed or clear-water),
- cohesive or non-cohesive bed material,
- bed material size,

- Froude number,
- Reynolds number,
- etc.

As the pier shape is a factor which is used by most of the existing scour equations, the following picture illustrates the relation of the lambda values for data sets with the same pier shapes:



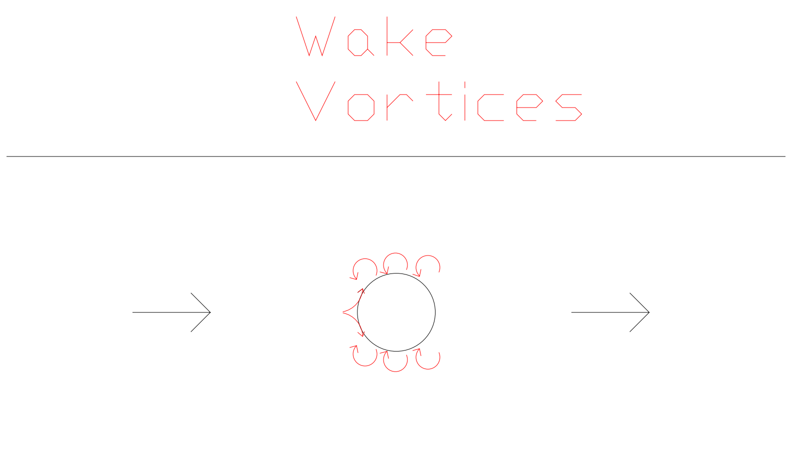

The lambda values for sharp nosed (58 data sets) and for squared (66 data sets) piers are quite similar respectively. The latter have an COV of 7.6%, the sharp nosed sets of 6.1%. When looking at the 243 data sets for circular and rounded piers it comes out that there is a huge variation ranging from lambda values of 0.02 to 5.75 and a COV of 87.3% indicating that a sorting only by pier-shapes is not sufficient yet. Especially taking one group for all the circular and rounded piers and therefore getting a lot of data sets (243) is not pertinent.

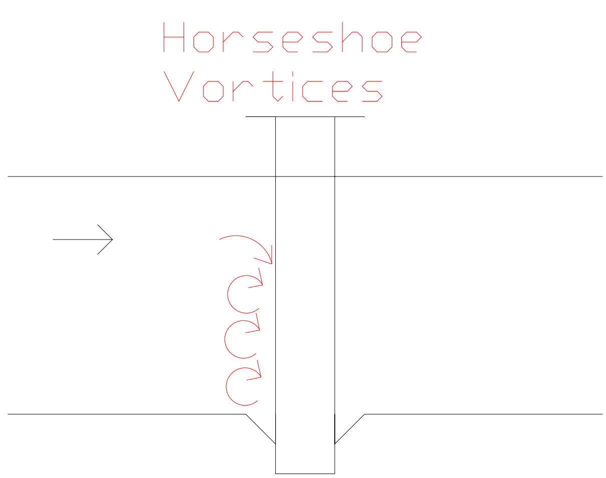
To approve one will have to sort by another characteristic parameter additionally.

Shen et al. [1969] found the so called *Reynolds number* [Osborne Reynolds, Irishman, 1842-1912] to be important:

“Since the horseshoe vortex system is the system of local scour and the strength of the horseshoe vortex system is a function of the pier Reynolds number, the equilibrium depth of scour should be functionally related to the pier Reynolds number”

Horseshoe vortices are produced by the flow which streams against a barrier, i.e. a bridge pier. They are normal to the water surface while the so called wake vortices are those existing parallel to the water surface.



The dimensionless Reynolds number $\mathrm{Re}$ is defined as:

$$\mathrm{Re} = \frac{\rho * \upsilon * L}{\eta} = \frac{\upsilon * L}{\nu} \tag{1}$$

Where:

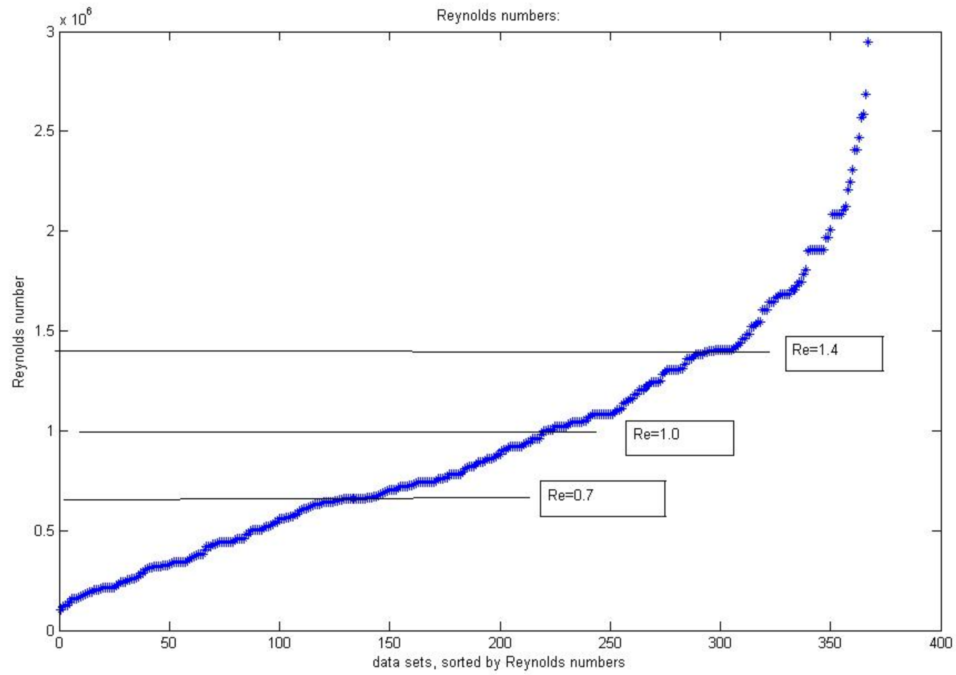
- $\rho$ = characteristic density of the medium, [kg/m³)
- □ = absolute value of the characteristic velocity, [m/s]
- L = characteristic length, in our case: pier width, [m]
- $\eta$ = characteristic dynamic viscosity, [kg/(m*s)]
- $\nu$ = characteristic kinematical viscosity, [m²/s]

Once the Reynolds number exceeds a specific critical value the flow turns from a laminar to a tumultuous or also known as turbulent behaviour. Generally speaking the Reynolds number can be applied for any media like fluids and gas. It is widely used in the fluid mechanics. Commonly applied for pipes it is obvious that for a river usually we will have laminar flow but still the Reynolds number has an important meaning. Assuming that we have a constant kinematical viscosity at an average water temperature the Reynolds number is somewhat related to the discharge rate Q. As $Q = V * A = V * b * y_0$, the Reynolds number can be found as:

$$\mathrm{Re} = \frac{Q}{\nu * b} \tag{2}$$

Neglecting the fact that $\nu$ is a function of the water temperature, the Reynolds number is the discharge rate per unit pier width.

For water at a temperature of 5°C (41°F) the kinematical viscosity $\nu$ can be found to be $1.52004 * 10^{-6}$ [m²/s].

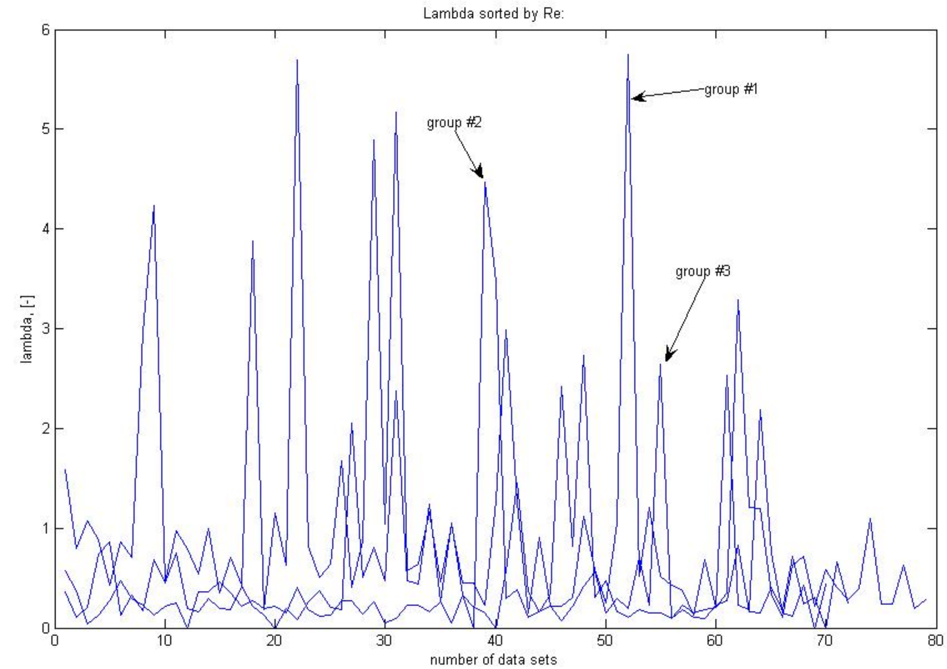


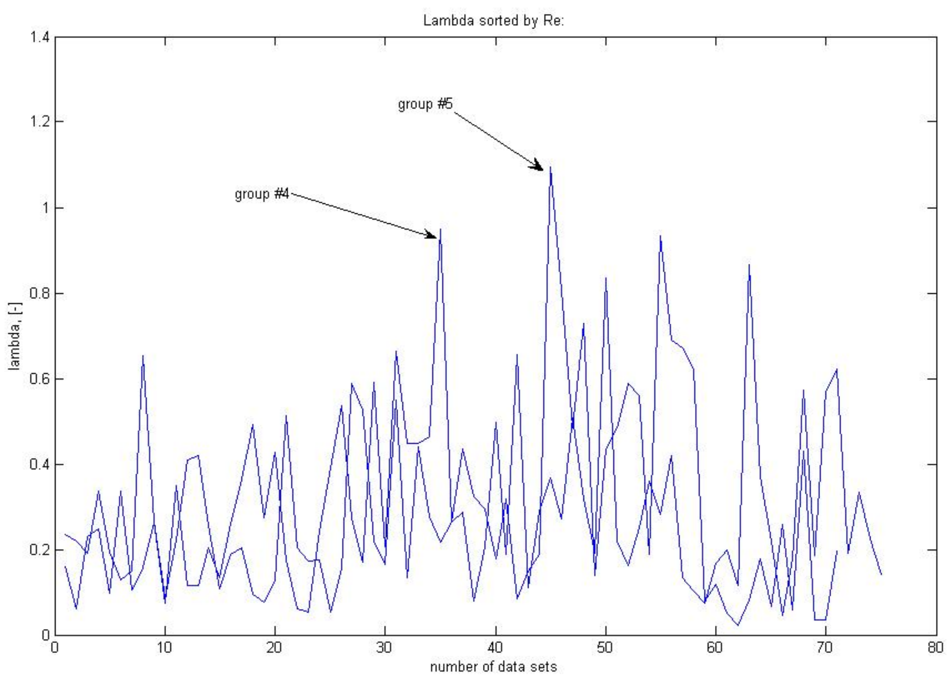

The Reynolds numbers for the whole Landers data ranges from approximately 100,000 to 3,000,000.

I will introduce five groups:

1. $0 < \mathrm{Re} \leq 450{,}000$
2. $450{,}000 < \mathrm{Re} \leq 700{,}000$
3. $700{,}000 < \mathrm{Re} \leq 1{,}000{,}000$
4. $1{,}000{,}000 < \mathrm{Re} \leq 1{,}400{,}000$
5. $1{,}400{,}000 < \mathrm{Re} \leq 3{,}000{,}000$

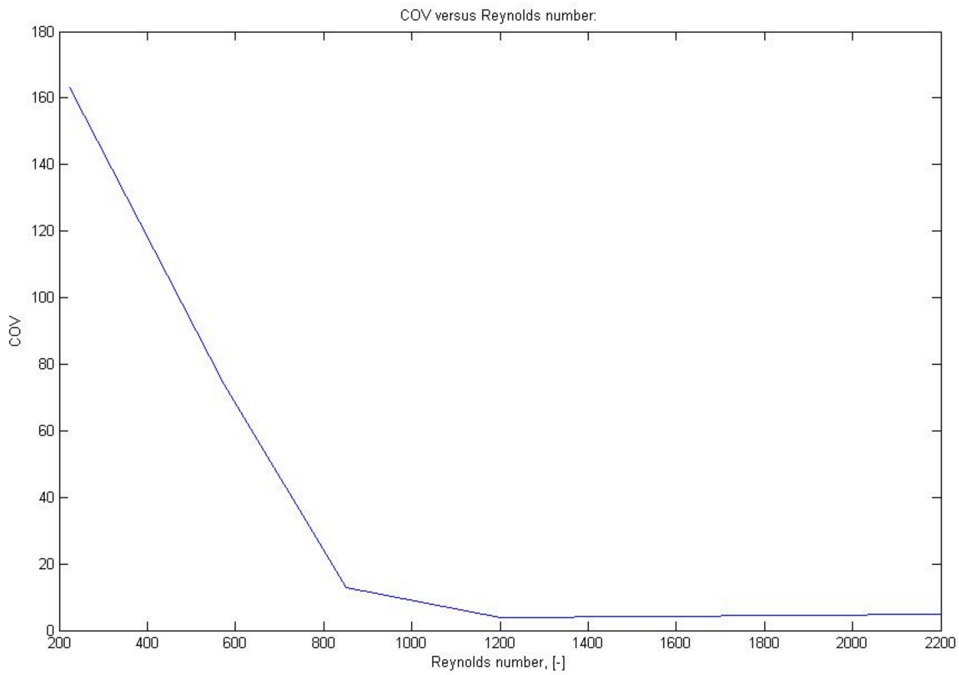
The lambda values for each of the four groups are plotted below:




The coefficients of variation of group 1 to group 5 are 163.2%, 74.4%, 12.7%, 3.9% and 5.3% respectively. The numbers of data sets for each group are 79, 70, 72, 75 and 71.

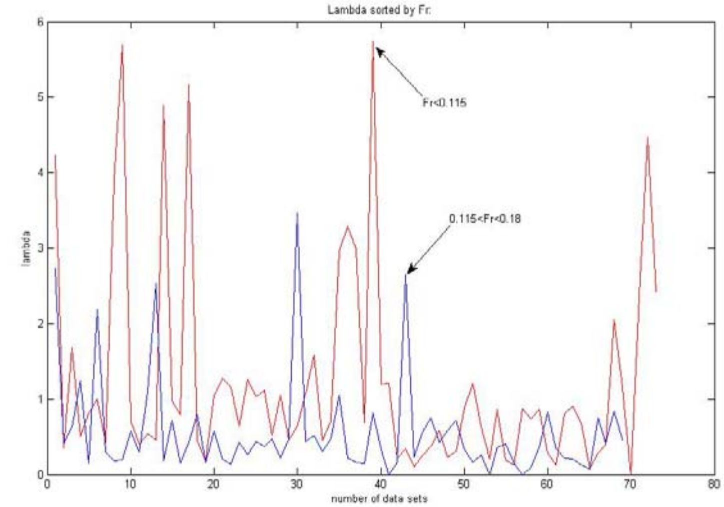
The COVs of group one and two are pretty high but indicate another interesting relation when plotting COV over average Reynolds numbers of each group:

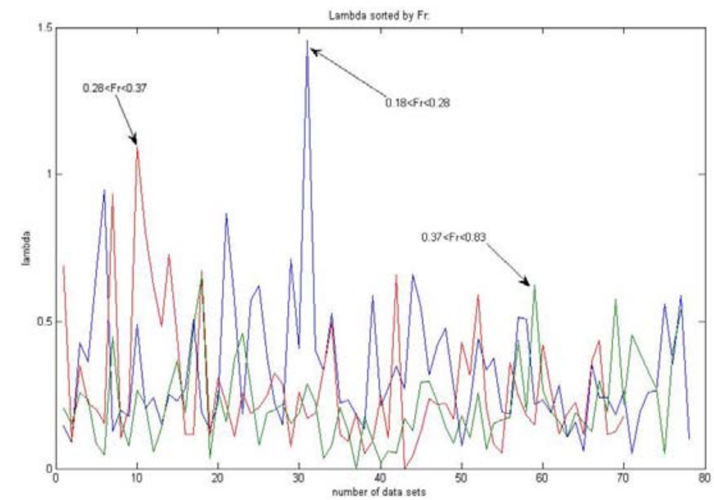



In words: The more water volume per time runs against the bridge pier, the less the variation of the lambda values produced by the HEC equation. Starting at approximately Re=1200, the COV is acceptable.

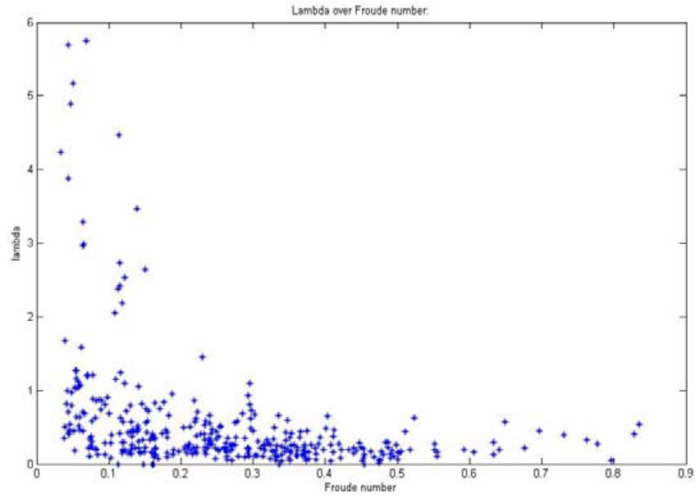
Using the Froude number introduces another important hydraulic parameter as a value to sort by. The smallest Froude number is 0.033 and the biggest was 0.835 if applied to the Landers database. Again I used five approximately equally sized groups:

1. $0 \le Fr < 0.115$
2. $0.115 \le Fr < 0.180$
3. $0.180 \le Fr < 0.280$
4. $0.280 \le Fr < 0.370$
5. $0.370 \le Fr < \infty$

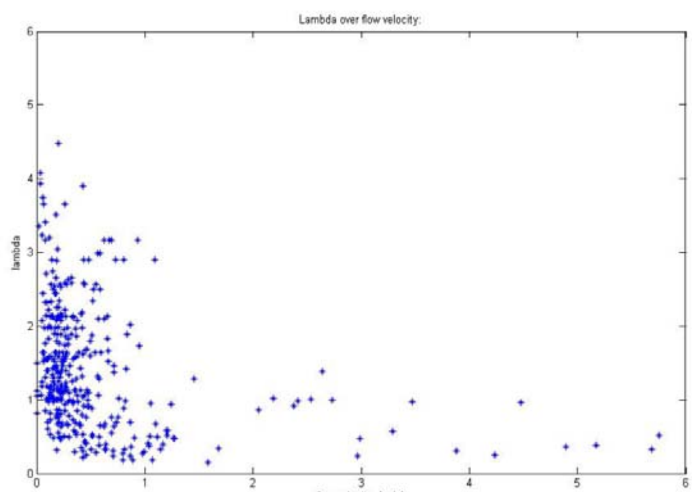


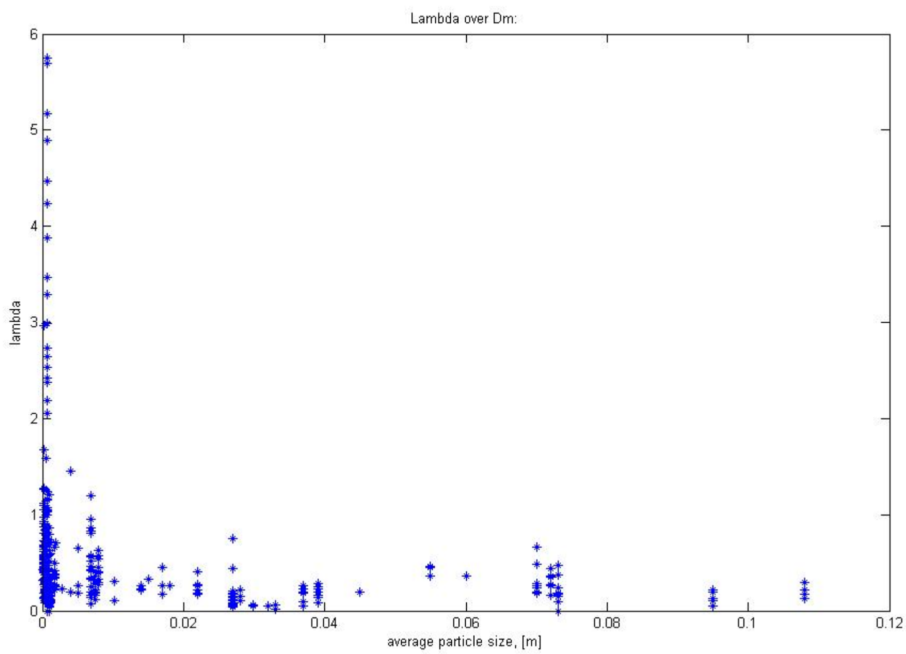

The coefficients of variation are 191.5%, 44.8%, 5.2%, 4.9% and 2.1% for groups one to five respectively. As per definition $Fr = \frac{V_0}{\sqrt{g * y_0}}$, the bigger the flow velocity and the shallower the stream, the smaller the variation of the ratio $\frac{actual}{HEC - predicted}$ scour depth:




As the flow velocity is located in the enumerator in both parameters, the Reynolds and the Froude number, it is very likely that the faster the stream goes the less variation the HEC results have. Even when using all the Landers data sets and plotting lambda over flow velocity a similarity to the plots of lambda over Froude number and accordingly Reynolds number can not be denied:




To have an improved accuracy of the predictions and a fewer COV for each group I will use two parameters in a row for the lambda table. As the flow velocity influences both, Re and Fr, I will use only one of those: The Froude number. Consequently the other parameter to take into consideration for the lambda table should not be related to the flow velocity. As mentioned above a sorting by the pier-shape is not very useful. Instead using a parameter which is not related to the flow velocity either can be achieved with the average particle size $D_m$.




As the picture above illustrates, the HEC results seem to become less varying as the average sized soil particle becomes bigger.

Using pier shape and the size of the average soil particle the following table of the left side was produced. For each result with a COV of the included lambdas of more or equal to 10% I subdivided those results depending on its Froude number. The results can be seen on the right side:

| pier shape | median lambda, [-] | COV, [%] | | Fr limits | median lambda, [-] | COV, [%] |
|---|---|---|---|---|---|---|
| squared | 0.2902 | 7.58 | | 0 to 0.12 | 1.4862 | 228.01 |
| rounded, circular | 0.6337 | 87.27 | ---> | 0.12 to 0.21 | 0.5327 | 35.81 |
| sharp | 0.3279 | 6.09 | | 0.21 to 0.32 | 0.3541 | 5.27 |
| | | | | 0.32 to unlim | 0.2266 | 2.31 |

| Dm limits | median lambda, [-] | COV, [%] | | Fr limits | median lambda, [-] | COV, [%] |
|---|---|---|---|---|---|---|
| 0 to 0.005 | 0.69906 | 92.73 | ---> | 0 to 0.08 | 1.3705 | 227.54 |
| 0.005 to 0.02 | 0.3817 | 5.53 | | 0.08 to 0.15 | 0.8023 | 83.15 |
| 0.02 to 0.035 | 0.1559 | 1.92 | | 0.15 to 0.25 | 0.3983 | 15.08 |
| 0.035 to unlim | 0.2255 | 1.7 | | 0.25 to unlim | 0.302 | 5.51 |

As the pretty high COVs for low Froude numbers less or equal 0.15 indicates, there is still a high level of modelling uncertainties even if a two-step-division as obtained above is used. To continue a further subdivision one would need more data. This is because the smallest group used above already contains approximately only 60 data sets. For example: Rounded, circular piers <u>and</u> $0 \le Fr < 0.12$ includes 57 measurements.

The lambda table shown above is only one of the possible ways to sort the database. Other criteria could be chosen which again would provide different lambda tables.

*Reliability estimates using regression analysis*

To perform a reliability analysis several parameters have to be known and a way in finding them has to be chosen previously. The reliability index β can be calculated as the following:

$$\beta = \Phi^{-1} * P_f \tag{1}$$

$$\beta = \frac{\mu_R - \mu_Q}{\sqrt{\sigma_R^{\ 2} + \sigma_Q^{\ 2}}} \tag{2}$$

In eq. (1) $P_f$ is the Probability of Failure and $\Phi$ is the function of the cumulative normal distribution. To interpret β for practical use the following table can be used which shows the values for β as a function of the Probability of Failure:

| Pf | β |
|---:|---:|
| 0.1 | 1.28 |
| 0.01 | 2.33 |
| 0.001 | 3.09 |
| 0.0001 | 3.71 |
| 0.00001 | 4.26 |
| 0.000001 | 4.75 |
| 0.0000001 | 5.19 |
| 0.00000001 | 5.62 |
| 0.000000001 | 5.99 |

In most practical situations the use of equation (2) will take place as the exact determination of $P_f$ is linked with several difficulties and uncertainties.

Basically the idea behind is to take the input data a designer would use with the HEC-equation. Subsequently this result is being compared with the actual scour depth and its variations. Theoretically when calculating reliability indices both standard deviations have to be considered: The one from the resistance and the one from the load. In our case where the resistance is being symbolized by the designer's result using the HEC-equation, we only have one value and for this reason the standard deviation for the resistance equals zero.

Basically there are two ways to determine the mean and standard deviation of the load Q: Using a regression analysis or using a lambda table.

The way to perform a regression analysis is to put in several parameters which are considered to influence the scour depth significantly and also to put in the measured actual scour depth. Therefore to come up with a regression analysis it is necessarily to have lots of data from existing sites and accurate measurements. After that a computer can calculate an equation which approximately fits the measured scour depths. The difference between actual scour depth and the depth provided by the regression equation is quite important, of course, and its minimization is most important. The researcher has to find parameters and its pertinent limits for which the included data sets have approximately the same dependencies of input parameters and scour depth.

If the use of Lambda Tables is the way to go one takes a scour prediction equation, for example the HEC equation, the SCE or others and applies it to existing data where also the actual scour depth has to be known. After calculating the prediction results those have to be compared to the actual scour depth as ratio actual divided by predicted scour depth. As already mentioned, this ratio is known as *bias* or l. The most challenging part with the use of lambda tables is to find parameters which are not kept under consideration by the used scour equation. In other words when sorting the lambda table by parameters which are already used for the scour equation the table should provide a limited range of lambda values respectively.

Of course the above said is only true if the equation used to predict the scour depth accounts for the parameter correctly. As some parameters can be used directly (e.g. pier width) but others are hard to put into numbers (e.g. pier shape). Empirically chosen numbers may vary from site to site, soil to soil, country to country, etc.

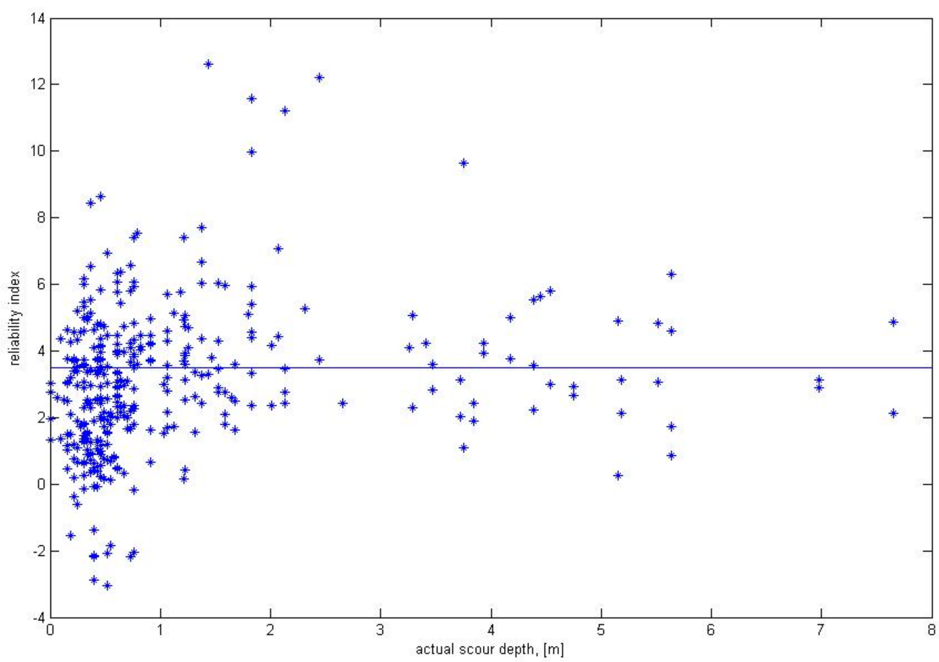
$\mu_Q$ is the prediction obtained by the Regression analysis or by the use of Lambda tables. I will use the result of a regression analysis as I expect more accurate results this way. When using one value for each parameter using the HEC-equation we get one prediction depth which automatically equals $\mu_R$. I will produce random variables for each parameter needed as input for the regression equation. Each will be produced following its pertinent random distribution. For this reason we will have several predictions from the regression analysis to compare it with the HEC-prediction and subsequently we will have $\sigma_Q \neq 0$. The number of random variables produced for each data set of the Landers database can be chosen. I will start with 10 cycles and in the beginning I will just use one regression analysis for all Landers data. When using the pier width b, the flow velocity $V_0$, the flow depth $y_0$, the average particle size $D_m$, the Froude number Fr and the actual scour depth $y_s$ as an input it turns out that the result provided by a multiple regression analysis is:

$$y_s = (-0.1155) + 0.2668 * b - 0.8078 * V_0 + 0.2452 * y_0 - 9.0795 * D_m + 3.9384 * Fr \qquad (3)$$

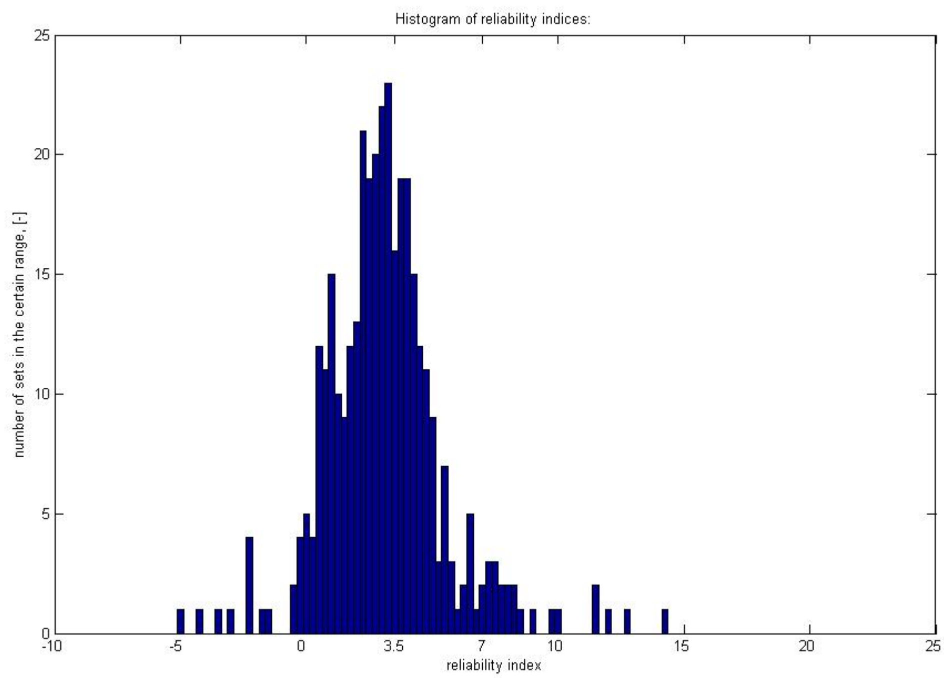
After having deleted the parameters with unknown values there were 358 data sets left to be used with the HEC-equation. As described before, the parameters used in eq.(3) are each following either normal or lognormal distributions. The following table summarizes the random distribution and the standard deviation for the several parameters respectively:

| parameter name | meaning | random distribution | standard deviation |
|---|---|---|---|
| y0 | flow depth | lognormal | 10%*mean |
| b | pier width | deterministic | |
| V0 | flow velocity | lognormal | 25%*mean |
| Dm | average particle size | lognormal | given in database |
| Fr | Froude number | lognormal | 16%*mean |
| e | residual error | normal | 0.41 |

The calculated reliability indices are plotted over the actual scour depth where the straight even symbolizes a reliability index of 3.5 which usually is the target value:




Apparently the scattering is quite huge and when looking at the whole set of reliability indices, the obtained coefficient of variation equals 5.18. When running the procedure 10 times the average percentage of data sets which actually provide a reliability index greater than 3.5 is 37.6%. The scattering becomes less once a certain actual scour depth is exceeded. The histogram reveals that although the average of 3.01 is quite close to the desired 3.5, the majority (62%) of sets provides a beta value of less than 3.5. Approximately one third (37.15%) of sets have a beta value less than 2.33 which represents a probability of failure of only 1:100 and for 5.4% the reliability index becomes even negative.



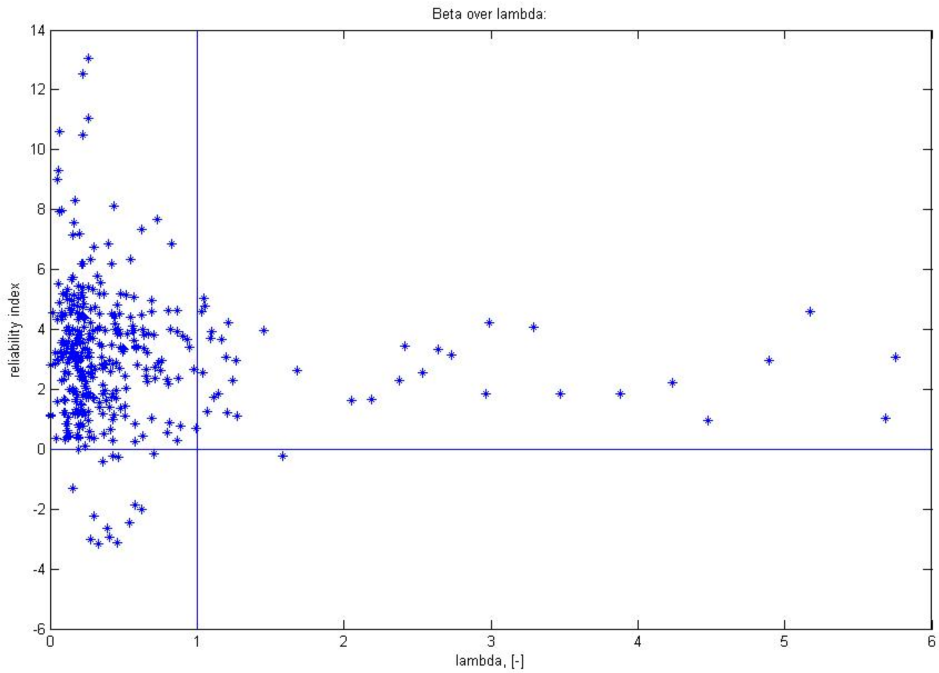

To answer the question in which cases a greater reliability index can be expected it is quite obvious to look at the equation for beta first. The enumerator includes the designer's prediction result using the HEC equation minus the average result of the regression equation:

$$\mu_R - \mu_Q$$

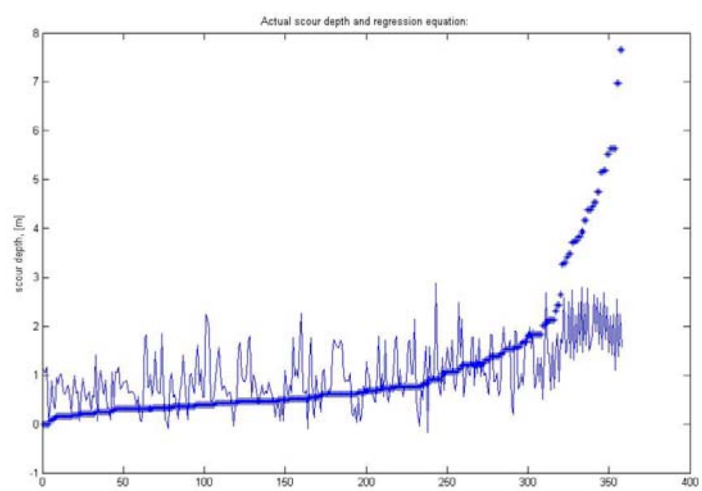
Therefore the bigger the designer's result and the smaller the regression result, the bigger the reliability gets in the end. When comparing the lambda values with the reliability indices and looking at those sets where $\lambda > 1$, one could expect beta values with negative algebraic signs as consequently $\mu_Q > \mu_R$ and as the denominator equals

$$\sqrt{\sigma_R{}^2 + \sigma_Q{}^2}$$

it can not take any negative values.




As can be seen above, for l >1 nearly all beta values are >0. One explanation could be the lack in accuracy originated in the fact that the scour depths calculated by using the regression equation do not exactly match the actual scour depths. As a result I will perform another regression analysis using subdivided parts of the database later on to reduce the differences between actual scour depths and those



determined with the regression equation which at this point are still quite big.

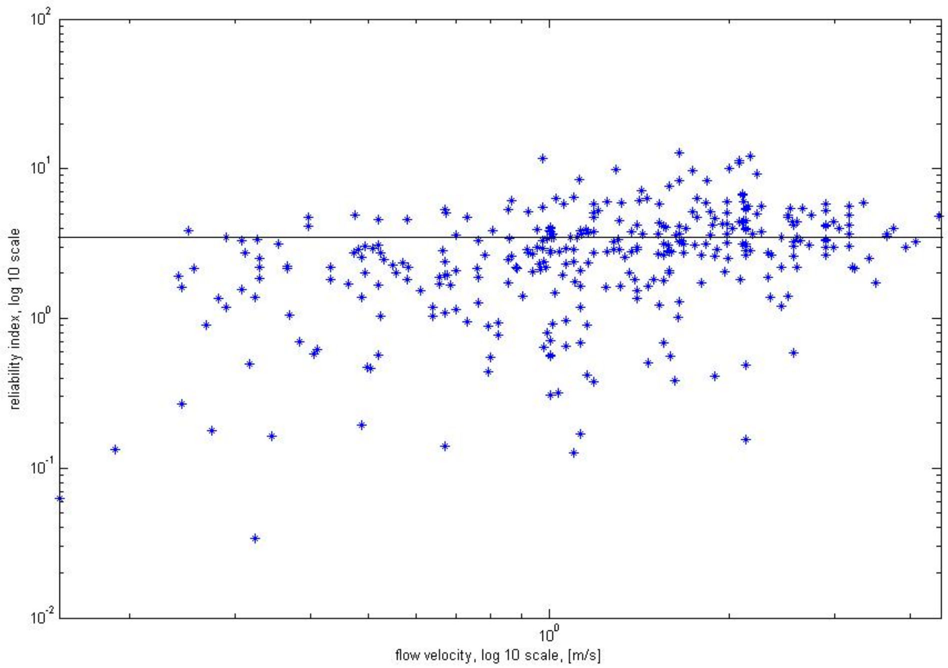
Another way to find explanations for the variety of reliability indices is to look at it as a function of other hydraulic or hydrodynamic parameters such as the flow velocity, discharge rate per flow width, discharge rate per pier, the Froude number or the flow intensity. The discharge rate per flow width can be determined as:

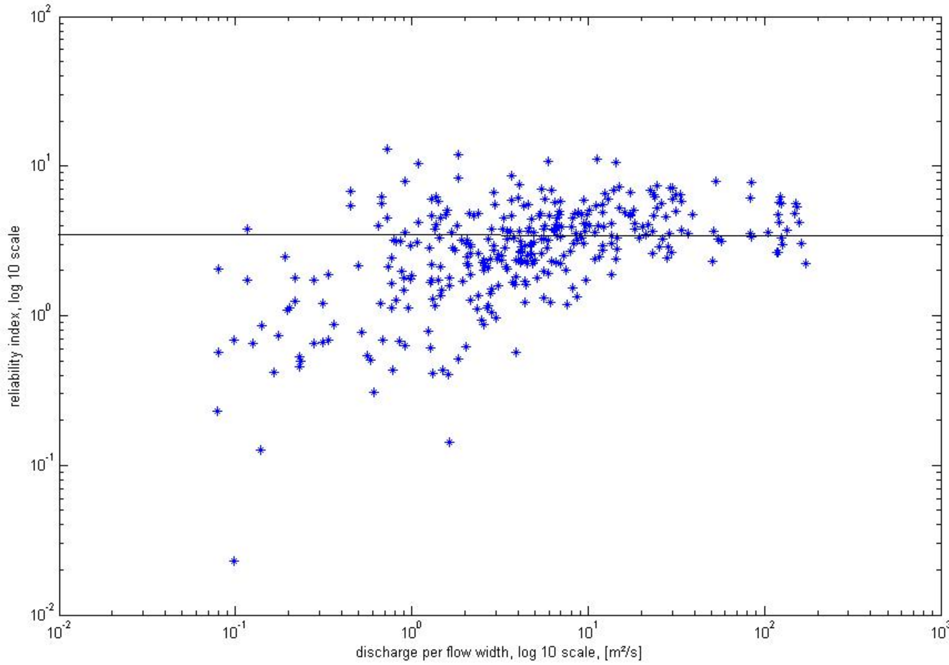
$$Q = V_0 * y_0 = [\frac{m^2}{\sec}]$$

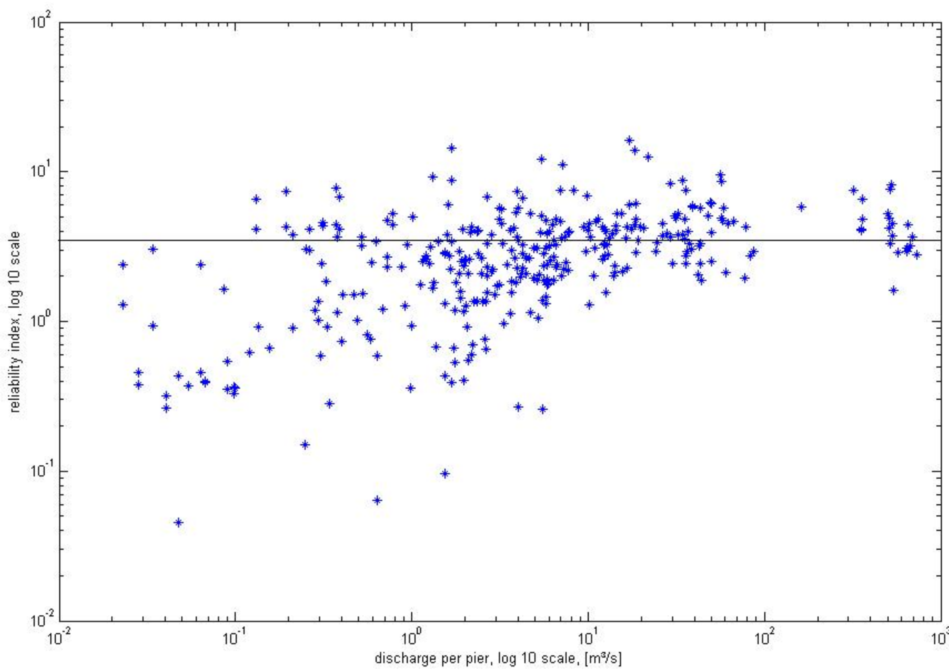
If additionally multiplied by the pier width one gets the discharge rate per pier:

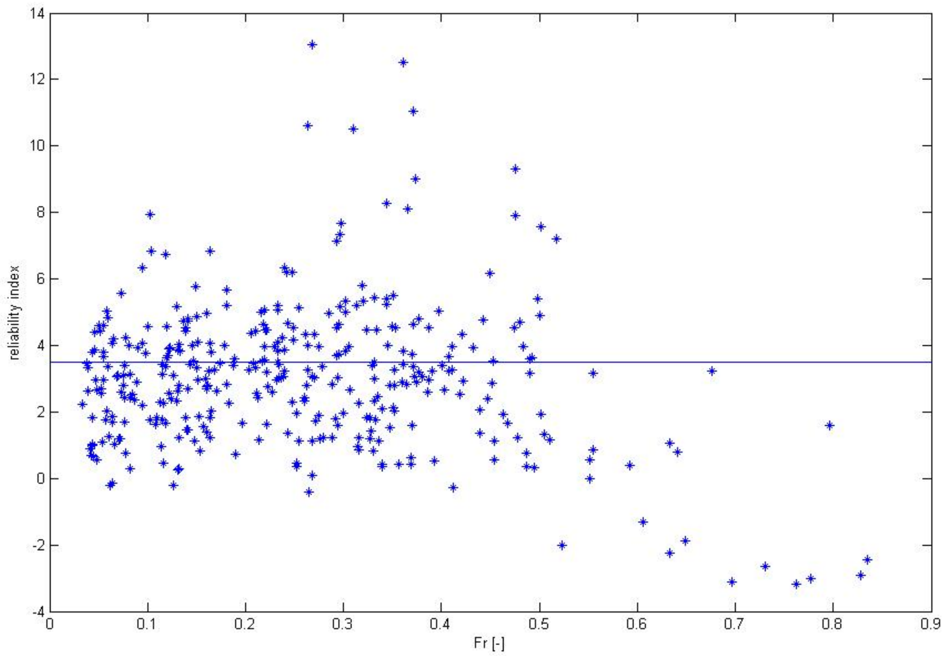
$$Q = V_0 * y_0 * b = [\frac{m^3}{\sec}]$$

The following plots can be used to interpret the reliability indices β as a function of the several parameters. Again the straight even symbolizes a desired β of 3.5.

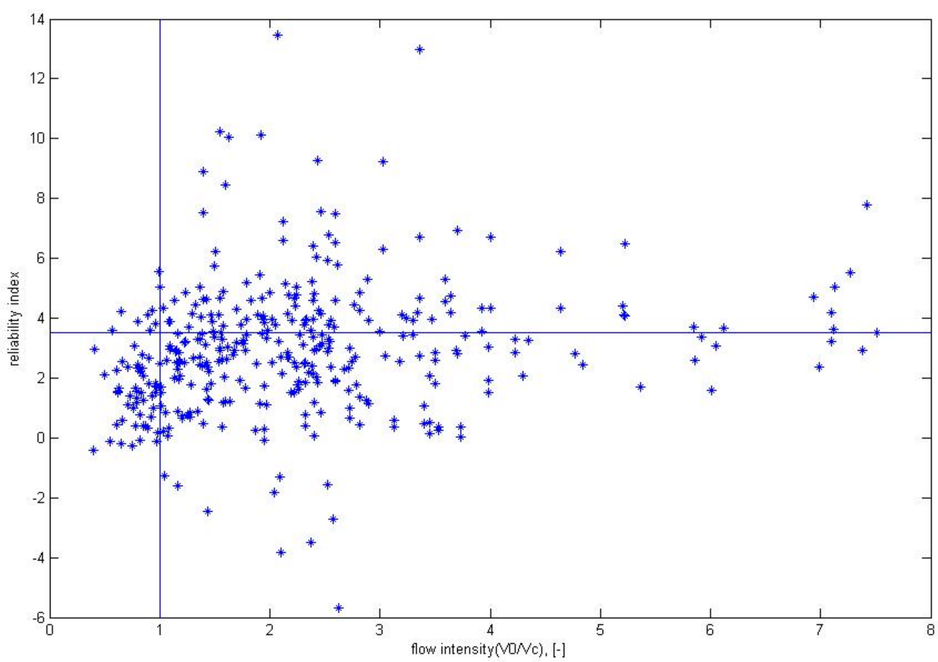



reliability index, log 10 scale
discharge per flow width, log 10 scale, [m²/s]


reliability index, log 10 scale
discharge per pier, log 10 scale, [m³/s]



14
12
10
8
6
4
2
0
-2
-4
reliability index
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
Fr [-]

14
12
10
8
6
4
2
0
-2
-4
-6
reliability index
0
1
2
3
4
5
6
7
8
flow intensity(V0/Vc), [-]

When using a basis-10-logarithmic scale for the reliability index over the **flow velocity** respectively, it reveals that the scattering increases while the flow velocity is increasing, too. After sorting the beta values by increasing flow velocity and dividing into three approximately equally spaced groups of 119 (120), the following means can be determined: 2.49, 2,75, 4.12. The coefficients of variation take the following values: 3.51, 4.58, 9.19. Concluding with increasing flow velocity both, the reliability and the variation of the beta values increase. For faster streams the HEC-equation obtains conservative results. Still, the percentage of reliabilities less than 3.5 are 72.5%, 66.7% and 41.5% sorted by increasing flow velocity.

Usually the **discharge rate** is determined as water volume per time and bridge pier. When calculating it following the first equation above as discharge per meter flow width the observed dependencies clear out more accurate. This can be found when sorting the determined reliability indices by the discharge rate not using the pier width b and another time sorting by the discharge rate per pier which does include the pier width b. I divided each time into three groups which are approximately equally spaced with 120 (118) data sets.

| **Discharge per Flow Width:** | | |
|---|---|---|
| small discharge | mean | 1.64 |
| | COV | 5.88 |
| | sets >3.5 | 14.20% |
| | sets <3.5 | 85.80% |
| medium discharge | mean | 3.15 |
| | COV | 2.49 |
| | sets >3.5 | 36.7 |
| | sets <3.5 | 63.3 |
| large discharge | mean | 4.02 |
| | COV | 3.67 |
| | sets >3.5 | 55.9 |
| | sets <3.5 | 44.1 |

| **Discharge per Pier:** | | |
|---|---|---|
| small discharge | mean | 1.81 |
| | COV | 6.85 |
| | sets >3.5 | 18.30% |
| | sets <3.5 | 81.70% |
| medium discharge | mean | 2.93 |
| | COV | 2.34 |
| | sets >3.5 | 28.3 |
| | sets <3.5 | 71.7 |
| large discharge | mean | 4.08 |
| | COV | 3.17 |
| | sets >3.5 | 60.2 |
| | sets <3.5 | 39.8 |

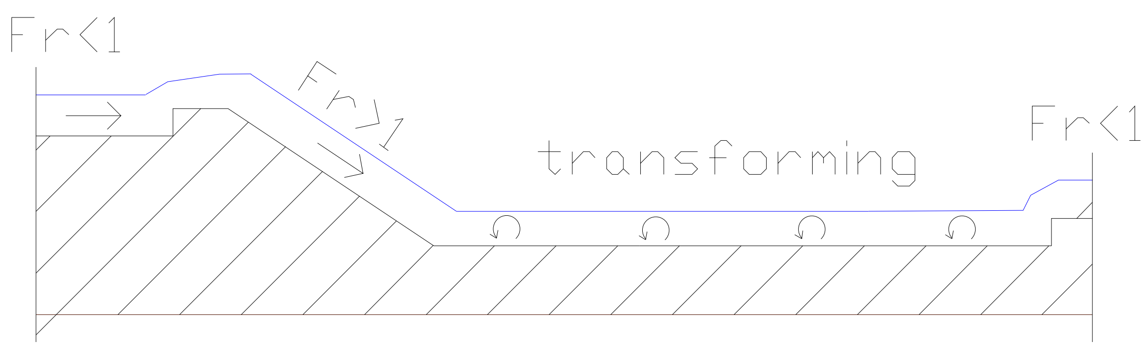
The change in average reliability is more significant for the discharge per flow width. For the COV no certain rule can be observed. Looking at the percentage of sets in each group which exceed a reliability index of 3.5 it can be found that the difference between group one and two (small and medium discharge) is bigger for a discharge per flow width while for the difference between group two and three (medium and large discharge) the opposite can be found. Looking at both plots the behaviour of the general reliability as a function of the discharge rate can be found to be quite similar. With an increasing discharge rate the reliability seems to get close to the desired value of 3.5 than it is for a small discharge rate. This counts no matter in which way the discharge rate is been calculated and no matter whether the pier width is included or not.

Quite an interesting notice can be taken when comparing reliability plotted over the flow velocity and a second time reliability over the **Froude number**. Although the flow velocity can be found in the enumerator of the latter, the behaviour of β with increasing Froude number is actually different to the one from β wich increasing flow velocity.
I divided the data sets into three parts:

1. $0 \le Fr < 0.25$
2. $0.25 \le Fr < 0.5$
3. $0.5 \le Fr < 1.0$

Due to this ranges the observation numbers are not equally spaced but consist 187, 148 and 23 data sets. While in the beginning the reliability indices get bigger with increasing Froude numbers when getting closer to the critical Froude number of 1.0 β starts decreasing extremely. The mean values of β are 2.89, 3.47 and -0.18 for groups 1 to 3 respectively. Unlike this the variation is increasing continuously with COVs of 2.77, 5.57 and 7.84. As one could expect the percentages of data sets which have a reliability index greater than 3.5 behaves analogically to the mean β. Speaking in numbers a percentage of 32.6%, 43.2% and 8.7% can be observed. The significant difference between flow velocity and Froude number and especially its origin is of outstanding interest.

Trying to explain on possible reason I will give some more information on the Froude number:
When looking at a dam Fr would usually be subcritical before and after the dam but supercritical when accelerating while falling down the dam.




Exceeding the critical Froude number Fr=1 is quite uninterrupted but once the flow has a negative acceleration and the Froude number falls below the critical value intense vortices occur which again cause a lot of erosion. For this reason designer set huge rocks or concrete blocks right underneath the dam to make sure the transformation happens where they want it to prevent scour of the stream bed. Additionally some people use concrete for the whole basin next to the dam as it will sustain the erosion.
Knowing this one has to consider an extreme flood event. The discharge will not be constant any more but increase. Also the flow velocity and the depth will increase. But as the flow

depth is in the denominator to the 0.5th power and also the flow velocity will raise more intense the Froude number is going to transform to the supercritical area at one point. After a certain period of time this process will go back analogically to the procedure described for the dam and therefore will cause intense erosion.

The measurements of flow velocity and depth given in the Landers database are collected while no flood event was present. As some data sets are already pretty close to the critical Froude number under normal conditions they tend to get to a supercritical level more likely than those which have lower Froude numbers under normal conditions. Again this could cause a lower reliability index.

The above said proofs the necessity to account for the subcritical or supercritical flow behaviour of a river and does not support the opinion of some authors who claim the Froude number to be of identical explanatory power as the flow velocity. Both are important hydrodynamic parameters and have to be kept under consideration.

The **flow intensity** is an important parameter and equals the ratio of flow velocity to critical flow velocity. The latter is the velocity at which an incipient motion of the average sized soil particle can be observed. Several equations have been developed to determine the critical velocity. I am going to use the one used in the Simplified Chinese Equation:

$$V_c = (\frac{y_0}{D_m})^{0.14} * (17.6 * (\frac{\rho_s - \rho}{\rho}) * D_m + 6.05E(-7) * (\frac{10 + y_0}{D_m{}^{0.72}}))^{0.5}$$

Where:

- $y_0$ = flow depth,

- $D_m$ = average particle size,
- $\rho$ = density of water,
- $\rho_s$ = density of soil,

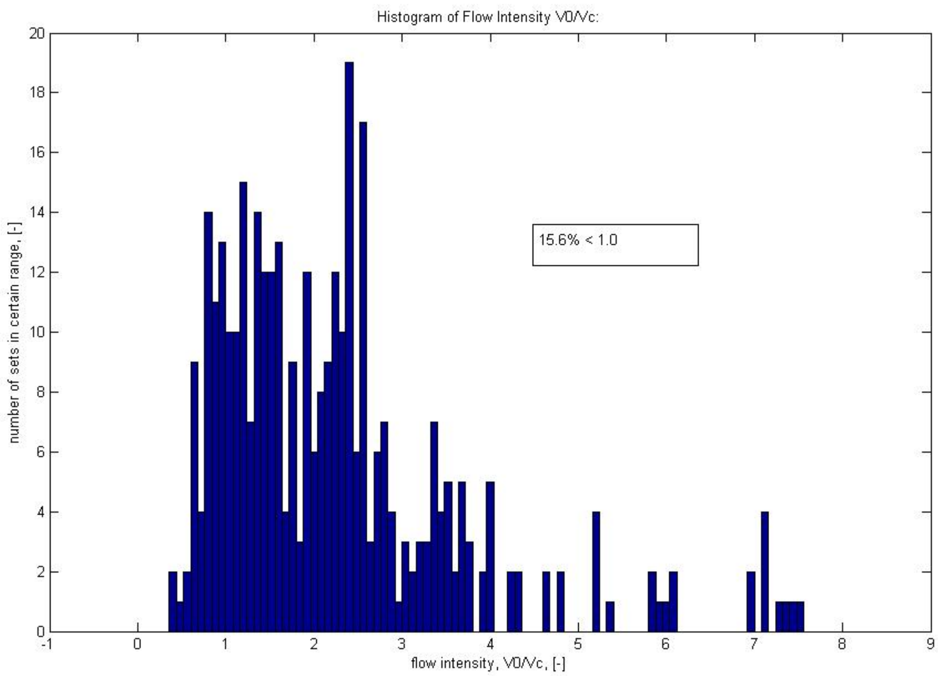
Knowing the flow velocity at which the average sized soil particle starts floating one can calculate the flow intensity defined as the actual flow velocity over the critical flow velocity.

$$Int = \frac{V_0}{V_c}$$

In order to calculate the flow intensity several approaches have been provided especially to account for the difference between $V_c$ in the open river compared to the corresponding $V_c$ in the constricted reach of the pier site. The Simplified Chinese Equation uses another definition to account for the flow intensity which includes the "…approach velocity corresponding to the critical velocity and incipient scour in the accelerated flow region at the pier" $V_c'$. I am going to use the $V_c$ for the open river conditions to find out about general relations and dependencies.

A general subdivision has to be taken to consider whether clear-water or live-bed conditions are present. The necessity for this subdivision is due to the fact that for clear-water conditions, there is no soil particle "input" into the scour hole. In other words the soil volume taken out of the scour hole equals the volume of the future hole. It is not being filled up afterwards either. Whereas for live-bed conditions soil is being transported out of the scour hole and into the scour hole at the same time. Therefore the volume of the future scour hole equals the volume of soil taken out minus the volume of soil put in the hole. Also, once the flood event is over the hole will be filled up to a certain level. The limit between clear-water and live-bed conditions is symbolized by the vertical straight even in the plot below whereas the horizontal even equals a desired reliability index of 3.5.

The following plot illustrates the distribution of the entirety of calculated flow intensities. Note that a flow intensity equal to 1.0 is the limit state between clear-water and live-bed conditions.




As for most of the sites live-bed conditions were found to be present the explanatory power of the 56 data sets which represent only 15.6% of the whole database is questionable.

Despite this I want to mention the differences in the averages of reliability indices which equals 3.15 for live-bed conditions but only 1.76 for clear-water conditions. This indicates that the HEC Equation is predestined to be used with live-bed conditions although it tries to account for channel bed conditions by the different values of factor $K_3$.

I break down those β values for live-bed conditions one more time.

- $1 \leq Int < 3.5$

- $3.5 \leq Int$

The average reliability increases while the variation decreases. The averages and COVs are respectively:

Averages:

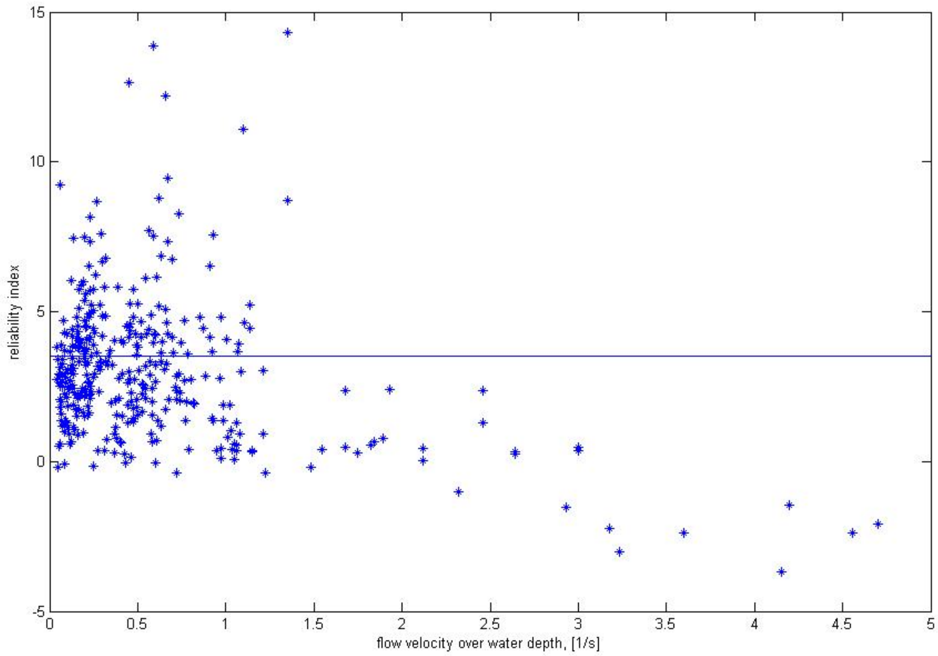
- 3.08
- 3.49

Coefficients of variation:

- 5.71
- 2.89

The result which one can interpret due to these observations is that for a ratio of $\frac{V_0}{V_c}$ >3.5 the average reliability is pretty close to the desired 3.5 and although the COV is still quite high, it is way less the one for lower values of the flow intensity. Still, one has to keep in mind that for the observed 50 sets where the flow intensity exceeded 3.5 still 20% of sets had an reliability index $\beta$less than 2.0 which meaning is a probability of failure of approximately 1:80.

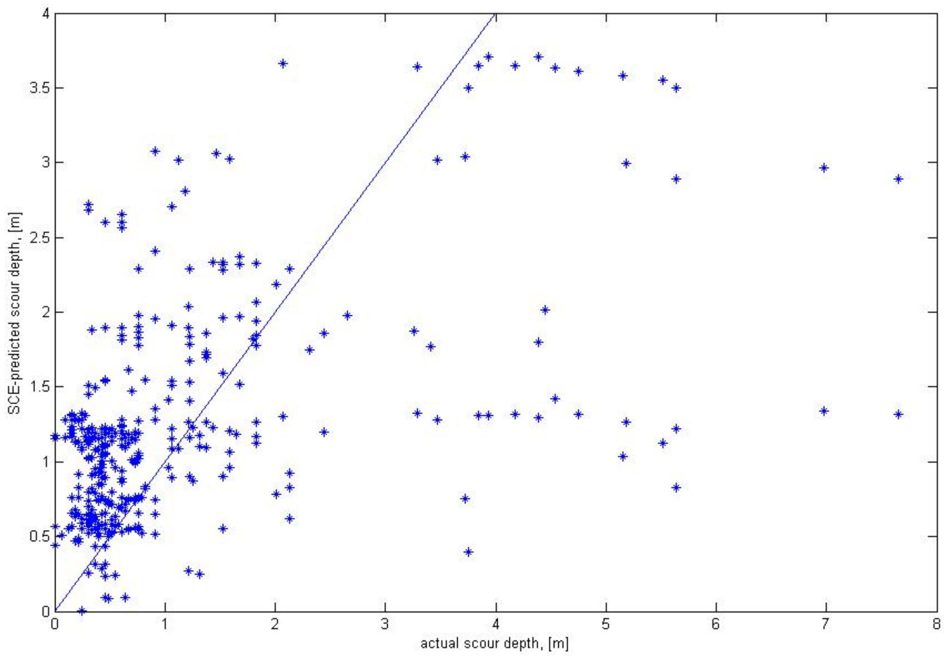
As the flow depth inherent in the Froude number's denominator has the power of 0.5, its weight in the resulting value is reduced. When taking the ratio of **flow velocity over water depth**, this reduction is taken away and the trend is more obvious as can be seen in the plot below. Although the vast majority of measurements provide a ratio of less or equal 1.0, a trend can be found: As the above mentioned ratio increases, the average reliability index decreases.  Although only 26 sets which represent 7% of the whole database have a $\frac{V_0}{y_0}$ ratio greater 1.5 one can observe the reliability indices to decrease abruptly for this range. For a ratio less than 1.5 the average $\beta$ equals 3.2 with a COV of 4.05 whereas for those sets with a ratio greater than 1.5 the average β beta is even negative and equals -0.51 with a COV of 3.81.




**Simplified Chinese Equation Analysis**

When attempting to interpret the scour depths predicted by the Simplified Chinese Equation one has to know that the purpose of this equation is not to be used directly as a design equation but to predict the expected scour depth pretty accurate. In other words the result obtained by the SC-Equation is not supposed to be conservative.

Plotting the SCE-predicted scour depth over the actual measured scour depth delivers some facts of interest. Note that the straight even represents an optimal prediction where predicted scour depth equals measured scour depth.




Like the HEC-equation, the uncertainties increase for an actual scour depth greater than 3.5m (11.5ft). Unlike the HEC-equation underestimations can already be observed for actual scour depth less than 3.5m, too. As already mentioned this is due to the fact that the Simplified Chinese Equation lacks of a safety factor as the HEC-equation has. The SCE tends to overestimates though.

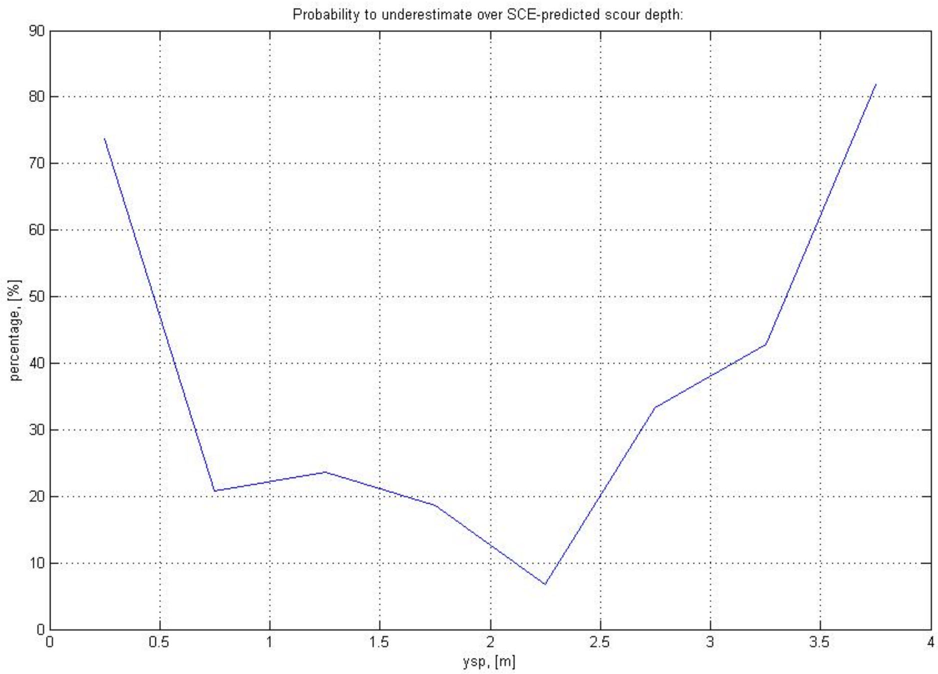
Two ranges of predicted scour depth can be found for which the SCE varies quite a lot compared to the actual scour depth:

$$\approx 1.3m$$

$$\approx 3.6m$$

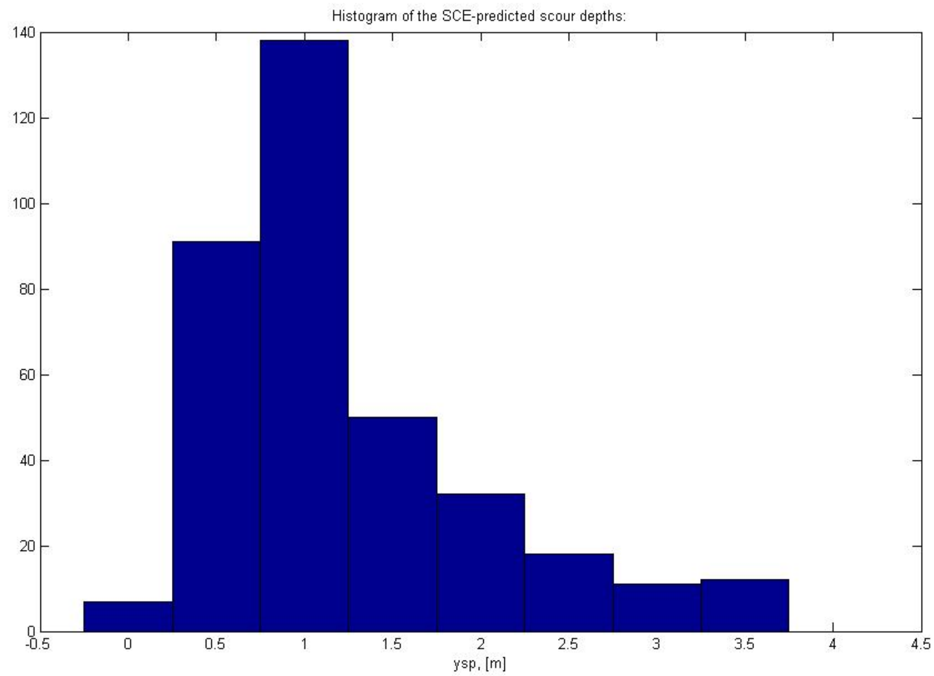
When comparing the SCE results to the measured scour depth one finds underestimations of 10 to 15 times which is quite enormous.

These similarities with the results of the regression analysis are quite interesting as one could presume those to be of the same origin. I will focus on that later on and try to find reasonable explanations. Assuming that the used database it statistically significant one can approach a prediction to find out about the probability of underestimation.



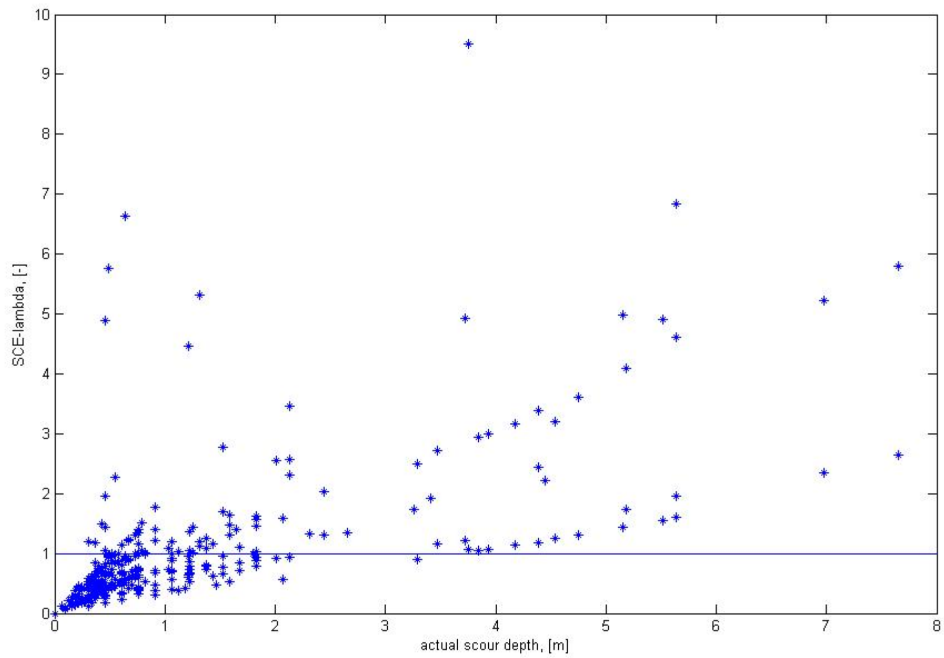

As can be seen with increasing predicted scour depth the probability to underestimate first increases until $y_{sp}$ equals approximately 2.25m (7.4ft) after which it goes up again. The minimum probability is 6.7% while the greatest slightly exceeds 80%.

To find out how useful this plot actually is one needs to know about the distribution of the SCE-predicted depths. I will plot the histogram in steps of 0.5m.




For predictions less 0.5m (1.64ft) and greater than 2m (6.5ft) the number of sets in this range falls below 20 thus the statistically significance can be questioned out of those limits. Within these limits the found percentages might be a rough support to interpret the predicted scour depths and its accuracy.

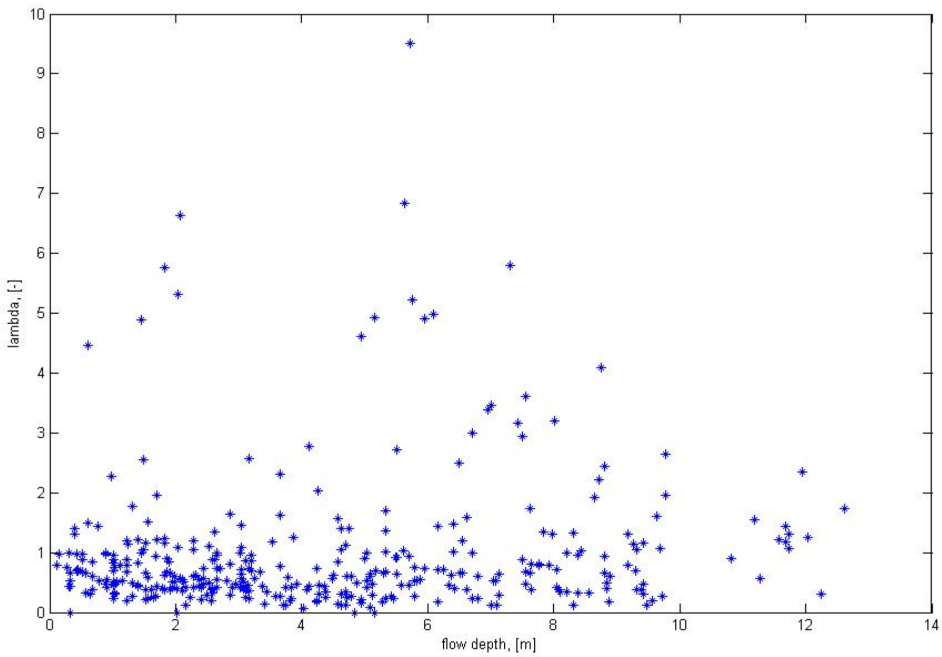
Another way to judge the over- and underestimation is to plot lambda over the measured scour depths. Remember that $\lambda = \frac{s}{y_{sp}}$ where s equals the actual scour depth and $y_{sp}$ is the SCE-predicted depth. The even shows the location of the optimal prediction meaning that the predicted scour depth equals the actual scour depth.



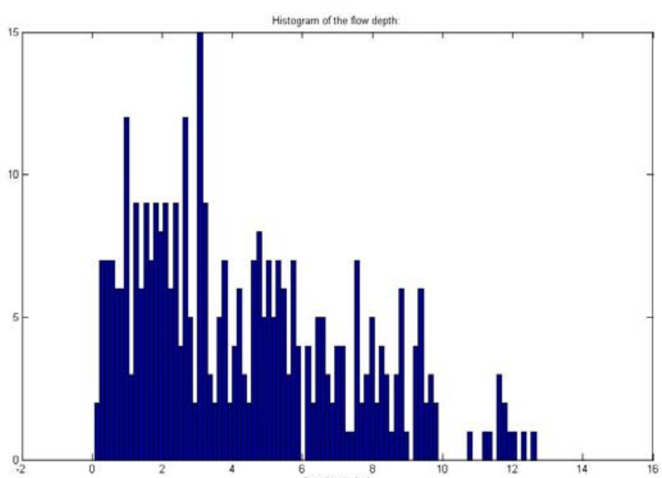

The scattering appears somewhat similar to a shaft of light starting in the axes' origin. In other words with increasing actual scour depth both the mean lambda as well as the COV of the lambdas increase. This could be expected as the actual scour depth s happens to be in the enumerator of l and for this reason an increasing s causes an increasing l, too. The accession in scattering can be explained due to the fact that with an increasing s a deflection of a certain amount between s and the SCE-predicted scour depth $y_{sp}$ causes a larger difference for the l-value.

For actual scour depths less than 1m the mean l equals 0.76 with a coefficient of variation of 593%. Ranging from 1m to 3m of measured scour depth the mean increases to 1.19 varying by a COV of only 70%. The average lambda for all sets with an actual scour depth exceeding 3m equals 2.85, the COV goes up to a value of 360%.

Although some dependencies can be found the **flow depth** directly upstream of the bridge pier seems to have a rather small influence on l. While the average lambdas take values between 0 and 1.5 an increasing ratio of actual over predicted scour depth can be obtained for flow depths between the limits of approximately 4m (13.1ft) and 10m (32.8ft).

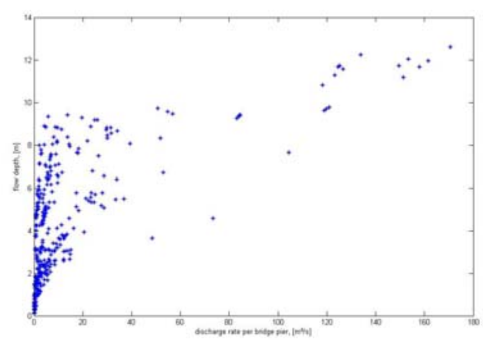


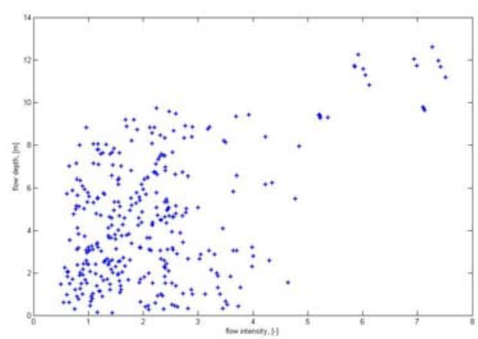

The majority of data sets happen to show a flow depth between 0m and 4m but there are still quite a few sets with $y_0$ increasing 4m. See the histogram of the flow depth on the right side.



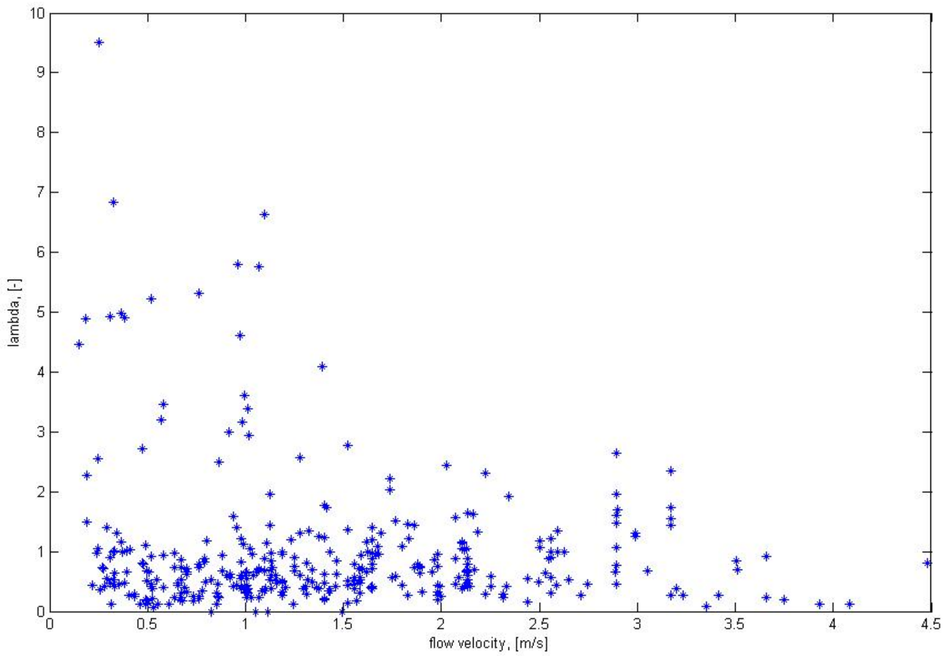
The reason for the increase of lambda values for a range of flow depth of 4m to 10m could be that starting in this range both, the discharge rate per bridge pier as well as the flow intensity start to increase. The SCE seems to be more accurate once the incipient increase of flow intensity is completed.

The plots below show the flow depth over the discharge rate per bridge pier (left) and the flow intensity (right) respectively.





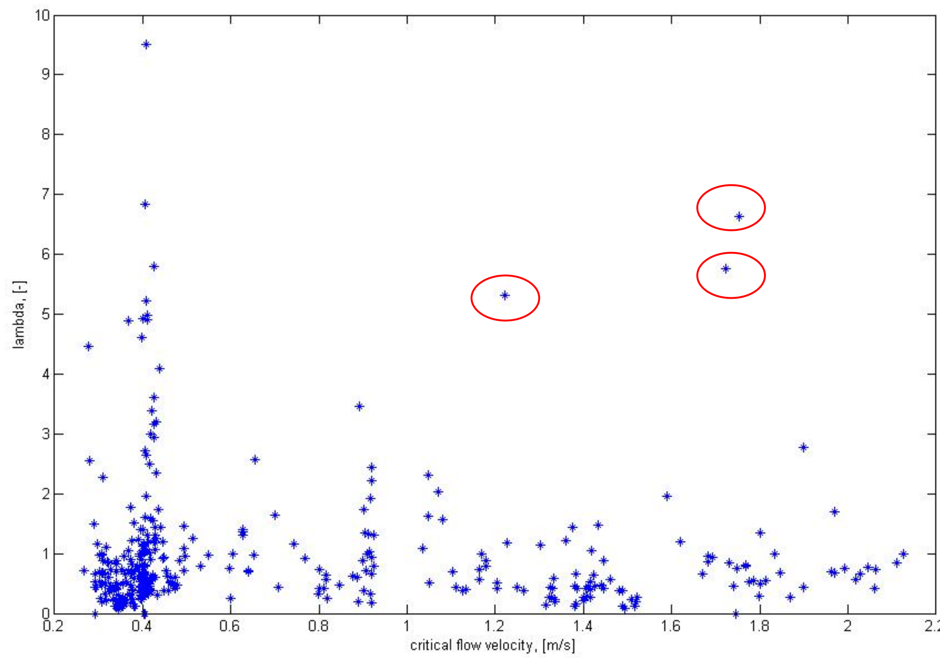
Unlike the flow depth the lambda values occur to be much more linked to the **flow velocity** $V_0$. For $V_0 < 1.5\frac{m}{s}$ the mean lambda equals 1.24 with a huge COV of 815%. Those represent about 60% of all data sets. The lambdas for flow velocities that exceed $1.5\frac{m}{s}$ the average lambda equals 0.84 while the COV cuts down to 30%.



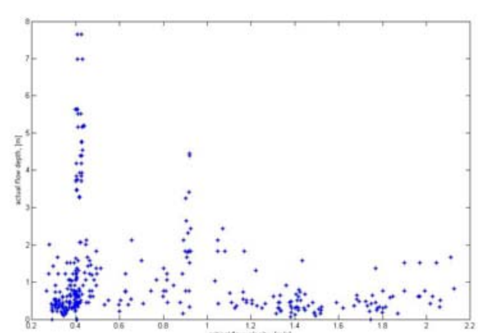

The plot above illustrates that the scour causing potential of slow flow velocities is being underestimated. A conclusion related to that is that apparently the SCE assumes a distinct dependency between scour depth and flow velocity which does not exist to that extent. Although the flow velocity influences the predicted scour depth in different ways in the HEC and SCE equation the same underestimation can be found using the HEC equation. For the HEC equation the flow velocity appears in the enumerator of the Froude number which itself is taken to the 0.43th power. Looking at the SCE-equation the flow velocity is inherent in the flow intensity term:

$$\frac{V_0 - V_c'}{V_c - V_c'}$$

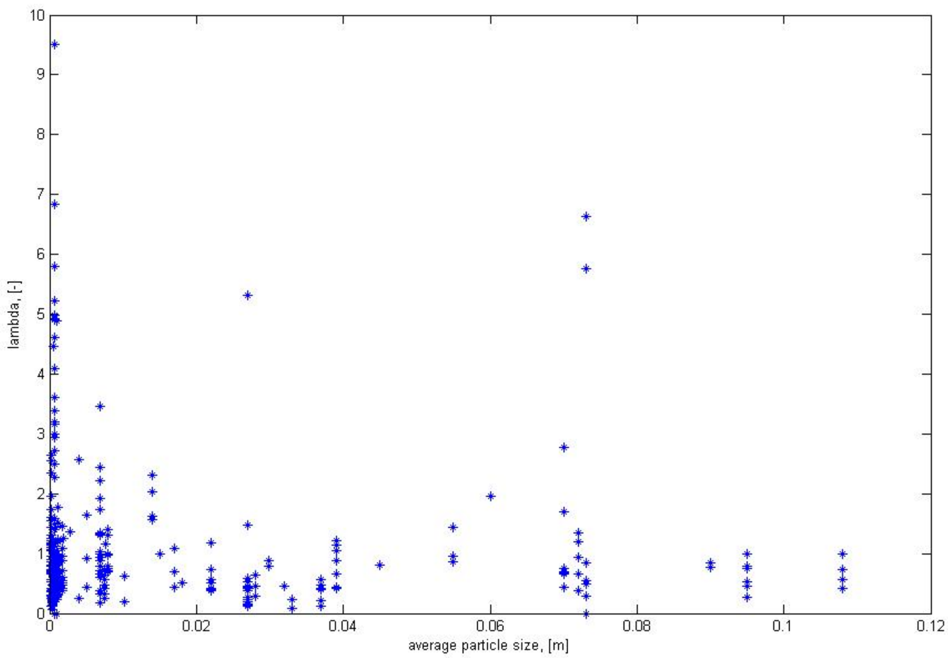
Neglecting the three marked outliers with increasing **critical flow velocity** $V_c$ lambda decreases continuously.

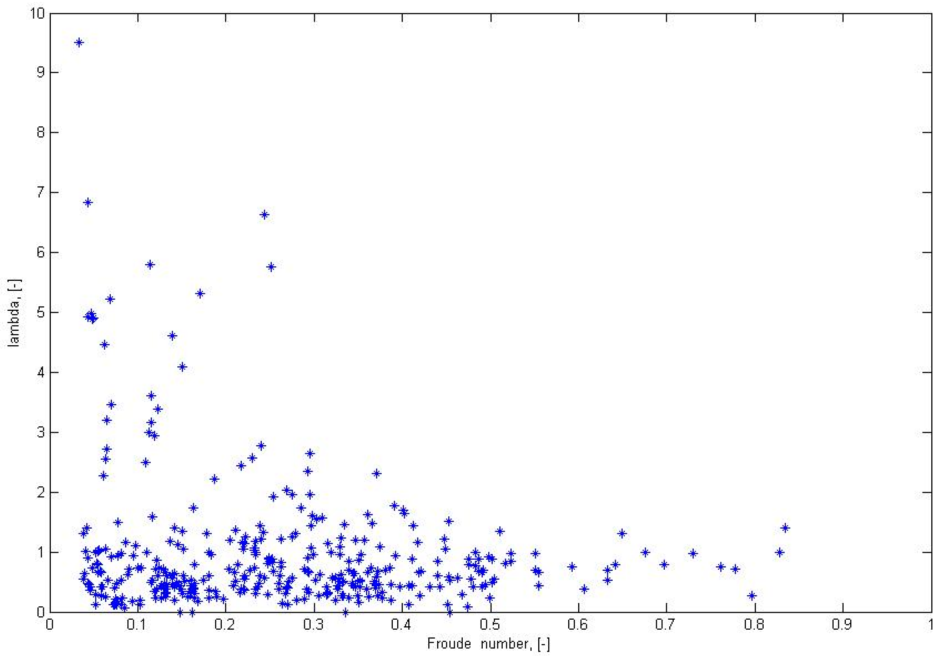



Comparing the plot above to the one on the right which shows actual scour depth over critical flow velocity reveals that there is a pronounced dependency between critical flow velocity and scour depth which the SCE does not account for to a pertinent extent yet.



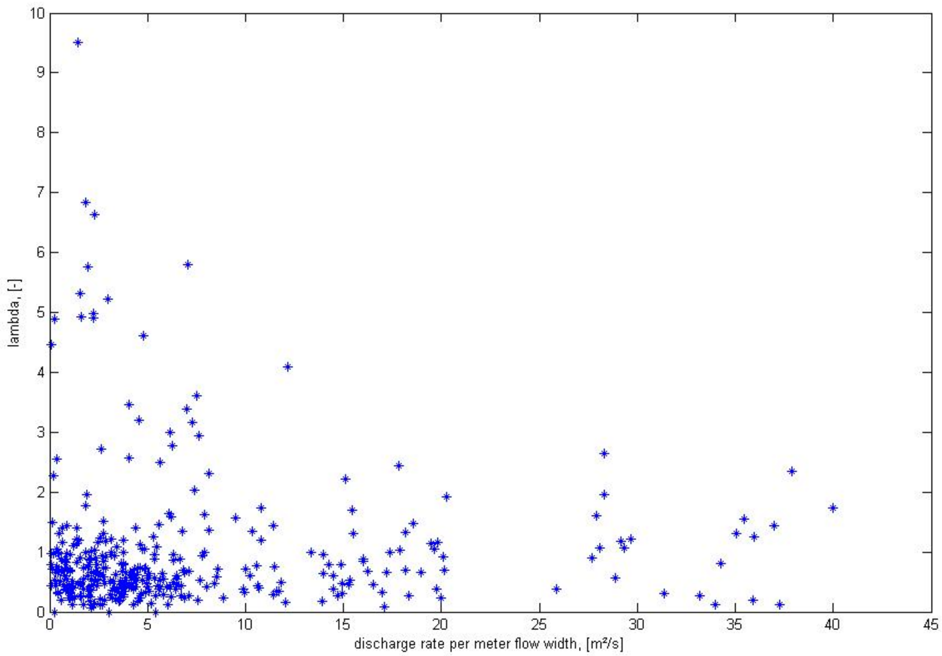
The vast majority (75%) of average particle sizes happens to be smaller than 0.02m (0.8inch) which leads to a limited statistical significance of the remaining data sets. Lambdas seem to take greater values for small $D_m$ and for those around 0.075m (3inches). As mentioned before the explanatory power of this observation is questionable.





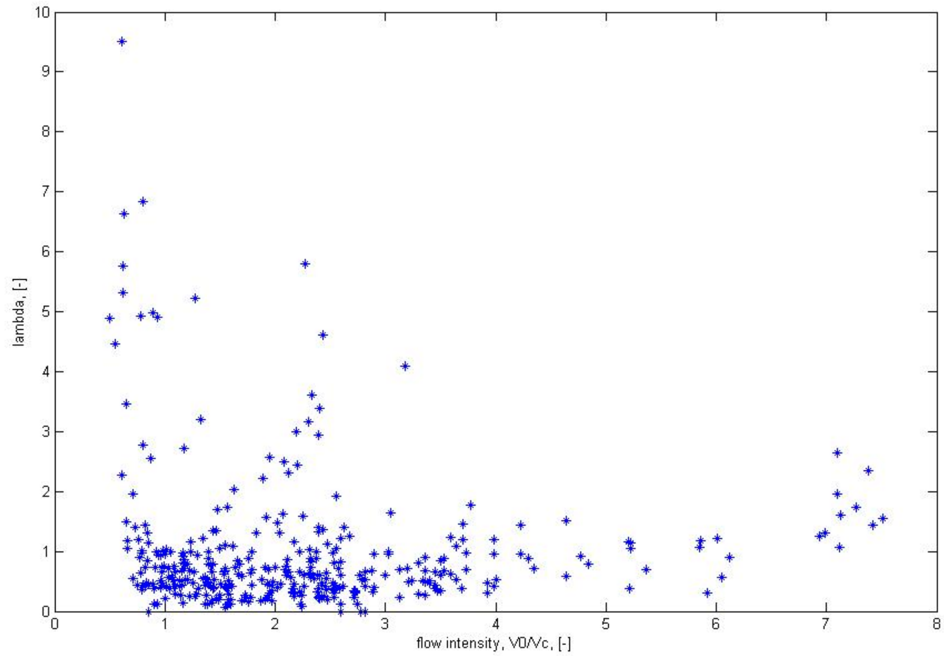

The plot above shows l over the **Froude number** Fr. As could be expected the plot appears somewhat similar to l over $V_0$ as the latter happens to be in the enumerator of the Froude number. Unlike the plot showing the flow velocity on the abscissa, the graphic including the Froude number shows lambda values close to 1.0 for Fr>0.5. Note that for fast flow velocities l appears somewhat asymptotically to 0.

Besides this difference it can be found that for increasing flow velocities as well as for increasing Froude numbers the lambda values decrease and generally speaking the SCE results become more conservative.




To find out about the links between lambda and the **discharge rate** Q I will use the discharge rate per meter flow width. It equals flow velocity times flow depth. The flow depth does have a less distinct influence on l thus the plot shown above is quite similar to lambda over flow velocity. The maximum scour occurs when the discharge is maximal while this happens during flood events. Assuming that the measurements on which the data is based were taken under ordinary conditions the calculated Q would not be the discharge rates which caused the measured scour depths. Again for live-bed scour this assumes that the scour hole is not filled up again yet.

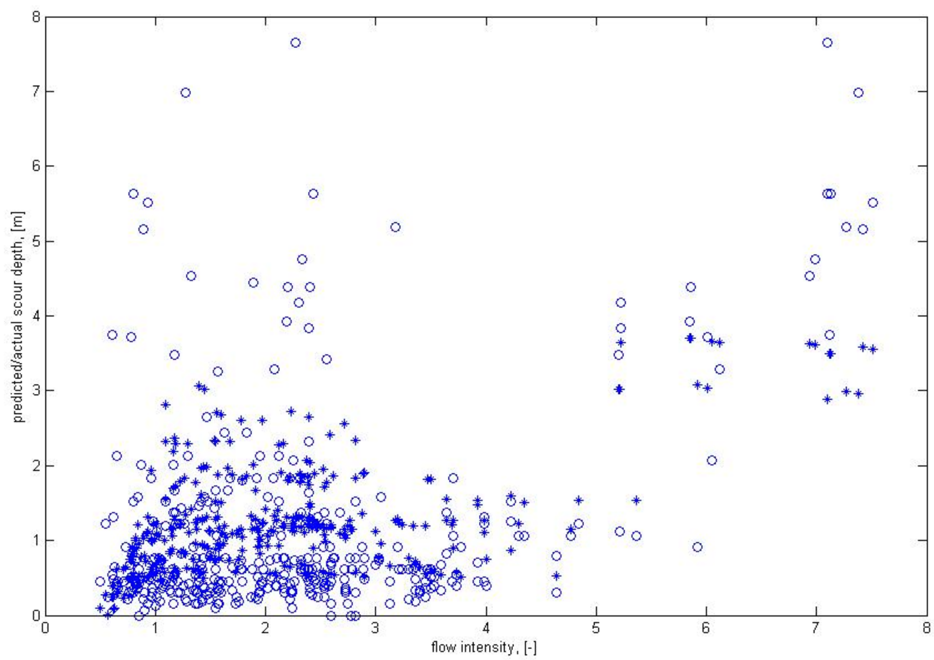
Knowing that the **flow intensity** equals $\frac{V_0}{V_c}$ the plot below can be interpreted. It is quite similar to both plots: l over $V_0$ and l over $V_c$. This indicates that the influence of $V_0$ is more intense than the one from $V_c$.




For a ratio of $V_0$ to $V_c$ greater than 3.5 the lambda values level off where nearly all values are less than 2.0. Dividing the plot above into three ranges delivers a trend regarding to average values and coefficients of variation:

- Int<2.0: mean: 1.24
  COV: 913%
- 2.0≤Int<4.0 mean: 0.85
  COV: 77%
- 4.0≤Int mean: 1.14
  COV: 30%

To figure out whether the flow intensity is being accounted for in a pertinent way one shall look at the plot below which shows predicted (*) and actual (o) scour depth over flow intensity.

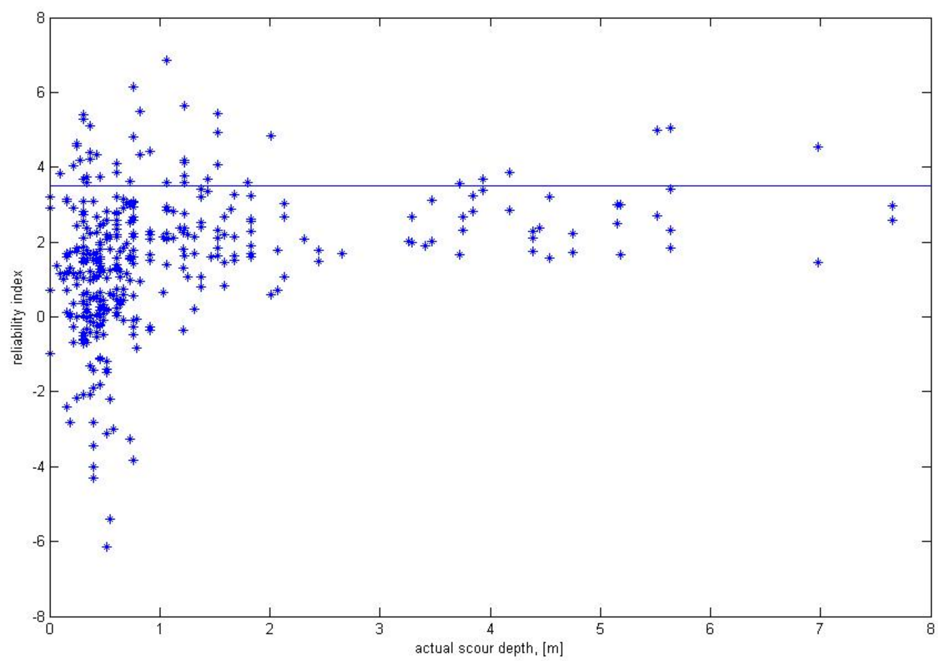



The trend appears to be quite similar: Most of the values are in a flow intensity range less than 3.5 (86%) and a scour depth less than 2.5m (92% of $y_{sp}$, 89% of s). For flow intensities greater than 5 the scour depth increases for both, the predicted as well as the actual scour depth.

Although the mentioned similarities can be observed there are still recognizable differences. 32 values (representing 9% of the whole database) of the actual scour depth with a flow intensity less than 3.5 have greater actual scour depth than the maximal predicted scour depth. The latter equals 3.71m while the maximal actual scour depth equals 7.65m. The same trend can be observed for flow intensities $\geq$ 3.5.

Besides these huge differences which can be found, for a small range of 3.5<Int<5 the predicted and actual scour depths do not vary that much. Looking at the predicted (actual) scour depth a mean of 0.97 (0.81) with a COV of 15% (18%) can be observed. Those values represent 8.1% of the whole amount of available data sets.

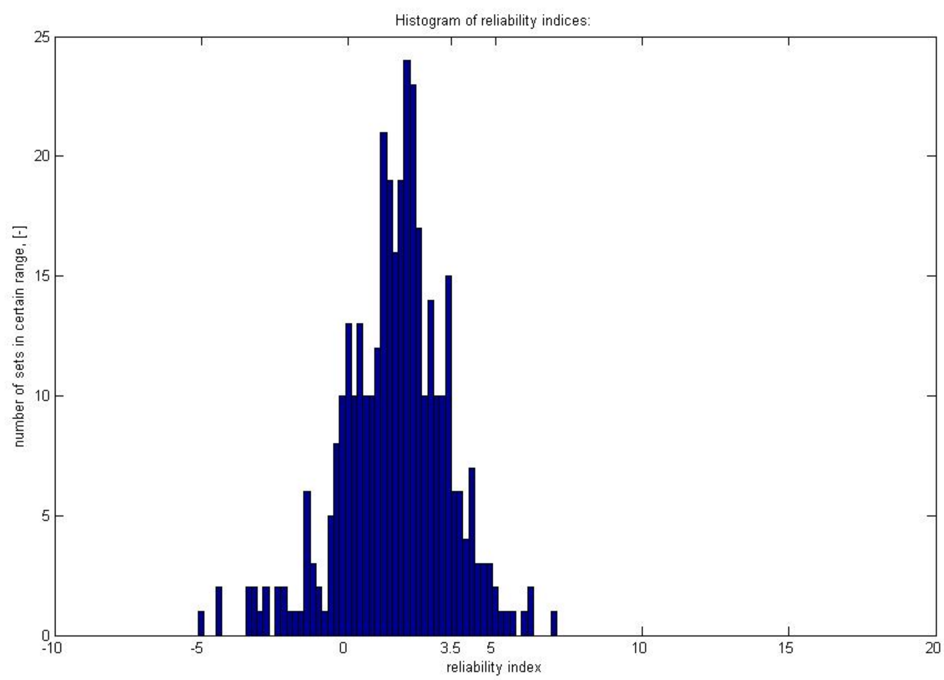
The reliability index is plotted over the actual scour depth while the straight even illustrates the location of the desired reliability index of 3.5.



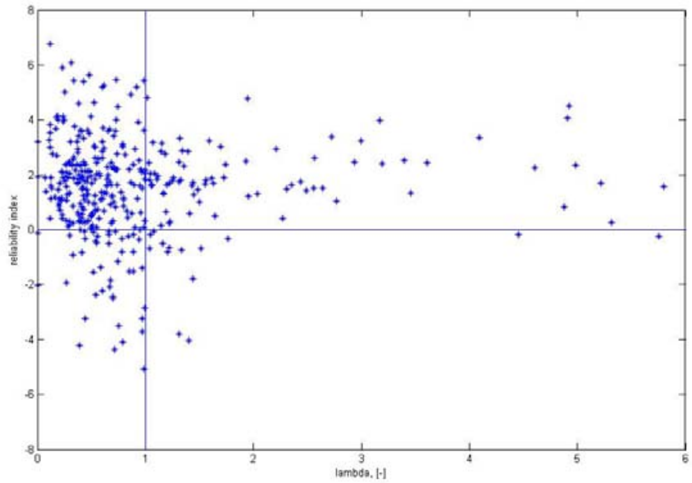

Running the reliability analysis 1,000 times the mean reliability index β equals 1.53 and produces a coefficient of variation of 337%. Taking a look at the target reliability index of 3.5 an average of 37.9 data sets (10.6%) have a β actually greater than that. In other words 10.6% of the SCE-predicted scour depths satisfy the claim to have a probability of failure less than ≈1:1,050.

The shown plot itself looks similar to the graphic which shows β over actual scour depth for the HEC-equation.

The distribution of reliability indices can be visualized with the help of the plot below.

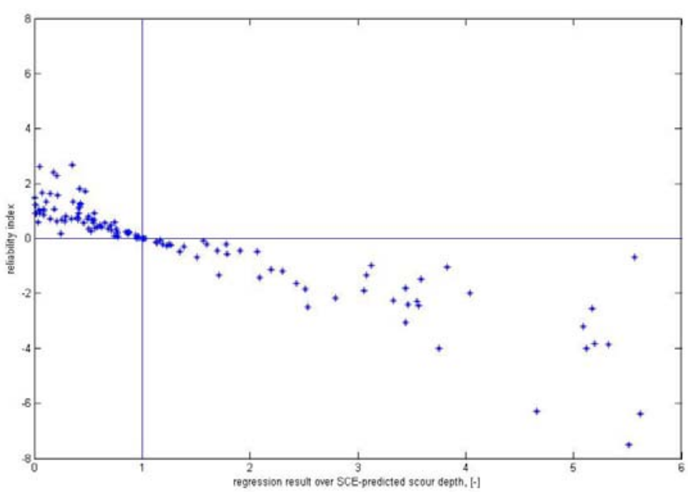



One simple way to check the results is two plot β over **lambda** which reveals the same deficiencies as could be found analyzing the HEC-equation. The regression equation seems to include some uncertainties.



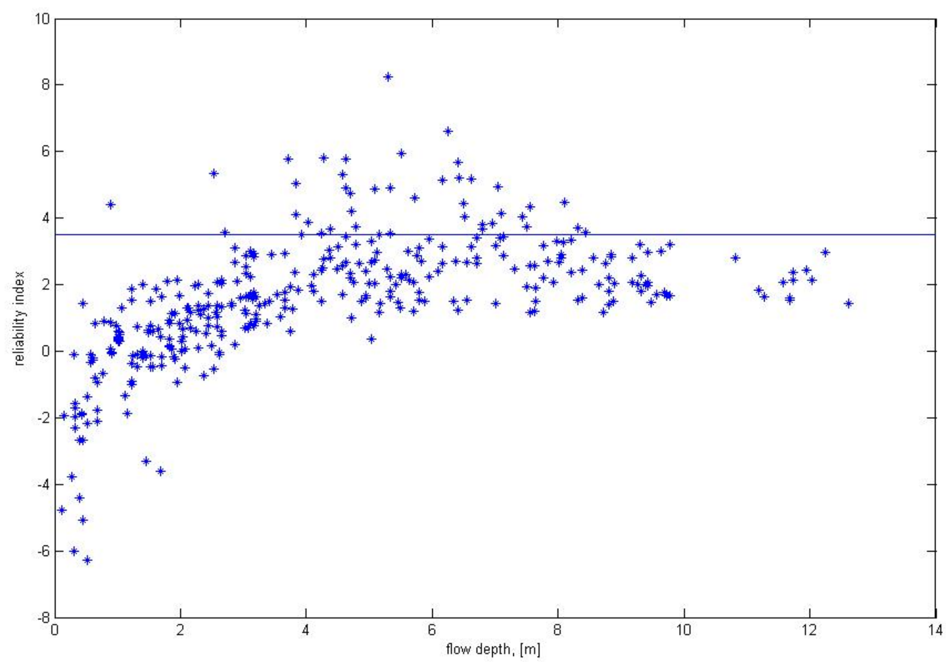

For l>1.0 the reliability indices should be all in the negative range which most of them are not.

Again replacing lambda by the quotient of regression result over SCE-predicted scour depth obtains a plot that appears more logically.



Although this new plot appears somehow theoretically correct it proofs that the regression results and the actual scour depths still have discrepancies. If they would be identical the plots of beta over lambda and beta over the quotient of regression result and SCE-prediction should be the same. To find a regression equation which fits accurately is hard and I will focus on that later on. Theoretically the other way to get rid of the uncertainties described above would be to use the actual measured scour depth for the determination of the expected scour depth $\mu_Q$ as well instead of using a regression equation. The reason why this is not recommendable at all is because one should treat $\mu_Q$ as a random variable to account for its nature as a random distributed variable. Therefore if one does not want to accept an uncertainty in the result the only way is to find another improved regression equation. Nevertheless I will use this one first regression equation for all of the data sets for the further calculations and come up with an improvement equation later on. Note that one will have to accept a certain amount of inaccuracy inherent in the regression equation no matter which one is used. The less these uncertainties are the better the results will be and the more realistic the calculated reliabilities are.

For shallow rivers a limited reliability can be found. With very small $\beta$ values going down to -6 the SCE-results become more reliable with increasing **river depth** where the increase of beta is somewhat linear until a flow depth of approximately 4.0m (13.1ft) is reached. From that point on the reliability indices level off but still quite a huge variation can be found for $4.0m \leq y_0 \leq 8m$.



Dividing the flow depth in three ranges the following data can be found:

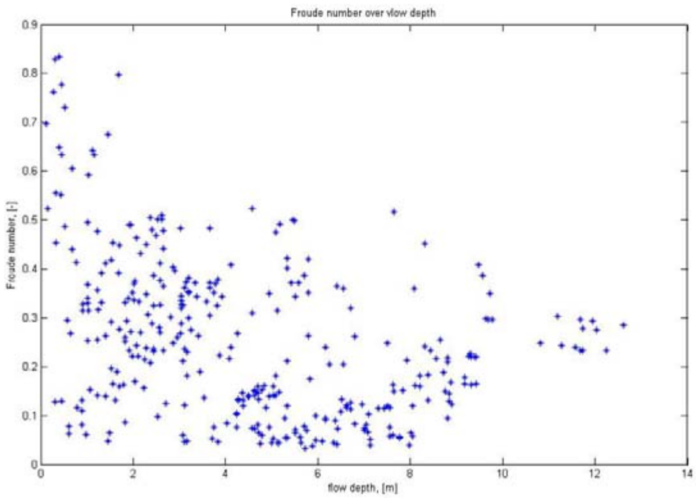
- $y_0 < 4.0m$: mean β 0.54
  COV of β 316%

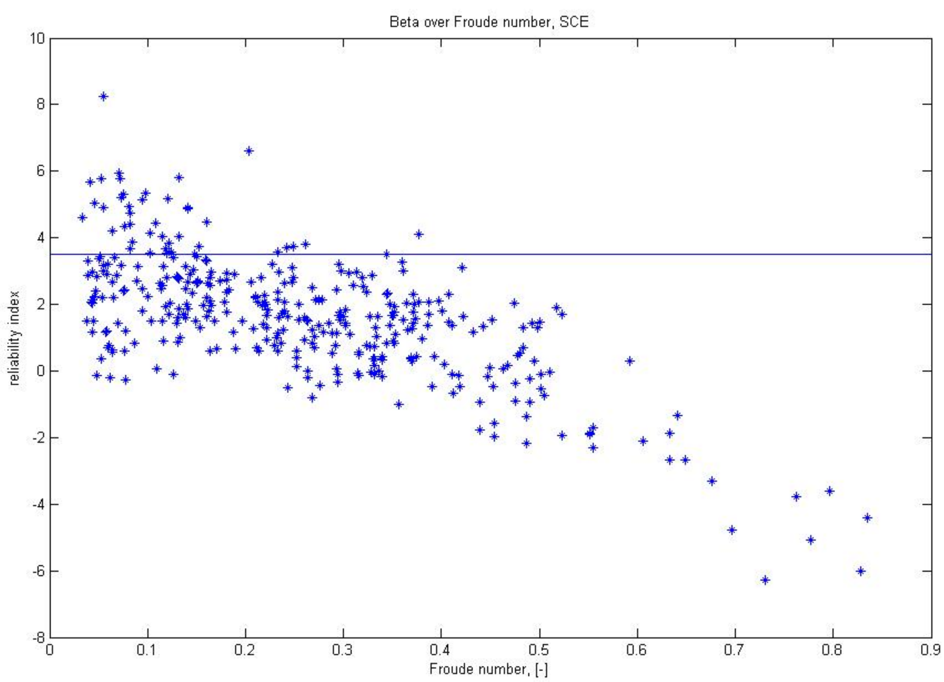
- $4.0m \le y_0 < 8.0m$: mean β 2.94
  COV of β 177%

- $y_0 \ge 8.0m$: mean β 2.32
  COV of β 50%

As the flow depth is part of the Froude number looking at the plot above which reveals a distinct dependency between the reliability index β and the flow depth $y_0$ one expects a relation between the Froude number and the reliability against failure due to scour as well.

The following plot shows the **Froude number** over the river depth to proof and illustrate the relation between Fr and $y_0$ while the plot below that shows β over Fr. As usual the even symbolizes the location of a desired β=3.5.

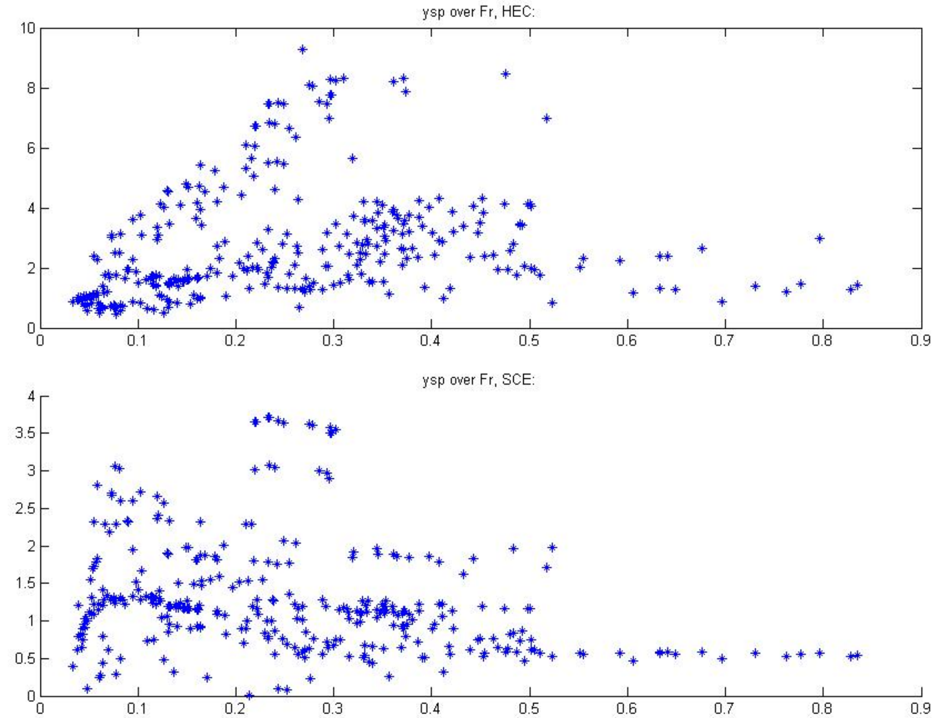


Looking at the lower plot shown above one can find an important difference between the results obtained by the HEC equation and those from the SCE equation. While one could find rather less clear dependencies for the HEC results the ones that can be find at this point are more helpful. While for small Froude numbers the variation of reliability indices still is quite huge the COV becomes less with increasing Froude number. As can be seen the average $\beta$ clearly decreases once the Froude number gets closer to 1.0. Although less obvious the latter trend could also be found for the HEC equation and the explanation given at the comments in the HEC chapter of this thesis are very likely to be the reason for the decrease found in the plot above, too: For a river with Fr close to a critical value of 1.0 it is more likely to exceed it when a flood event occurs. Once the flood is gone and the Froude number drops below 1.0, the occurring scour is immense. For further details look at the chapter about the HEC equation and its comments on that topic.

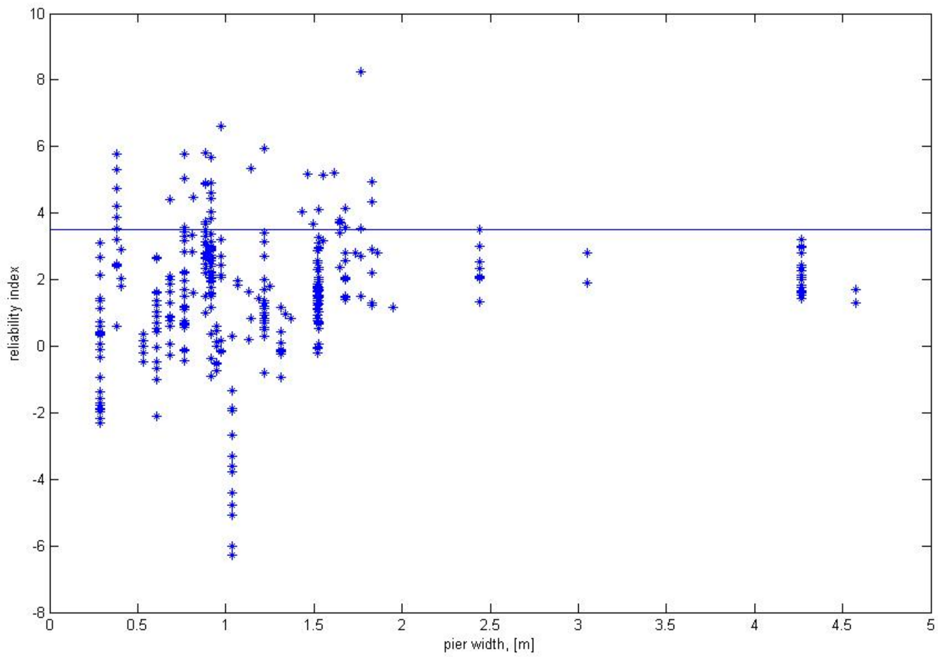
The difference in dependency between reliability indices and Froude numbers when comparing HEC and SCE predictions is due to the fact that the Froude number is already used to predict scour depth in the HEC but not in the SCE equation. Therefore it is quite useful to improve the SCE predictions using Fr while the help it provides for the HEC results is not that reasonable. The Froude number has already been used for the HEC equation and for this reason its predictions do not depend on Fr anymore.

The following plots illustrate the above said. Those show predicted scour depth over Froude number for the HEC (upper plot) and the SCE (lower plot) equation. Although linear dependencies can only be found in certain ranges of Froude numbers it is quite obvious that the HEC predictions depend more on the Froude number than those provided by the SCE equation.

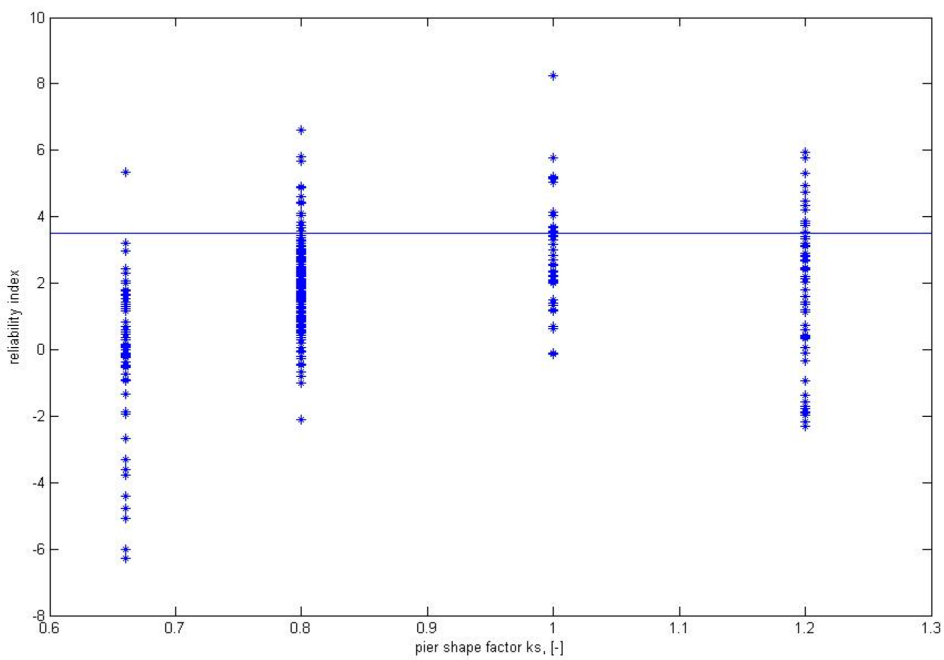



Generally speaking parameters that are already inherent in the SC-equation have a less distinct dependency on the reliability indices β than those which has not been accounted for yet. This statement assumes a pertinent input of the certain parameter in the prediction equation. The above said is true not matter which scour depth prediction equation is used, the equation out of the Hydraulic Engineering Circular or the Simplified Chinese Equation.

Looking at the relations between beta and the **pier width** b shows that for small pier widths the variation of the produced reliability indices is huge while it becomes smaller with increasing b. Note that for a b equal to 1.04m (3.4ft) β drops down to values less reliable than -6. To find out a reason for that I will take wave lengths, wave periods, orbital velocities of the water particle, etc. into consideration later on.



Close to the pier width b is the **correction factor** $k_s$ which accounts for the pier shape. Although it would be inaccurate to get safety factors out of the plot of reliability index over $k_s$ a trend can be found. For small values equal to 0.66 (sharp nosed piers) of the pier shape factor an average β of -0.1 can be found. For $k_s$=0.8 (round nosed piers) the mean beta equals 1.9, for $k_s$=1.0 it is 2.8 and for $k_s$=1.2 the average beta equals 1.7. Therefore one can find the general rule that the greater $k_s$ is, the greater the average reliability index will be. The observations regarding to this safety factor have to be taken carefully though as the values it takes are man-made and not measurements.



The flow intensity can be determined as the flow velocity over the critical velocity:

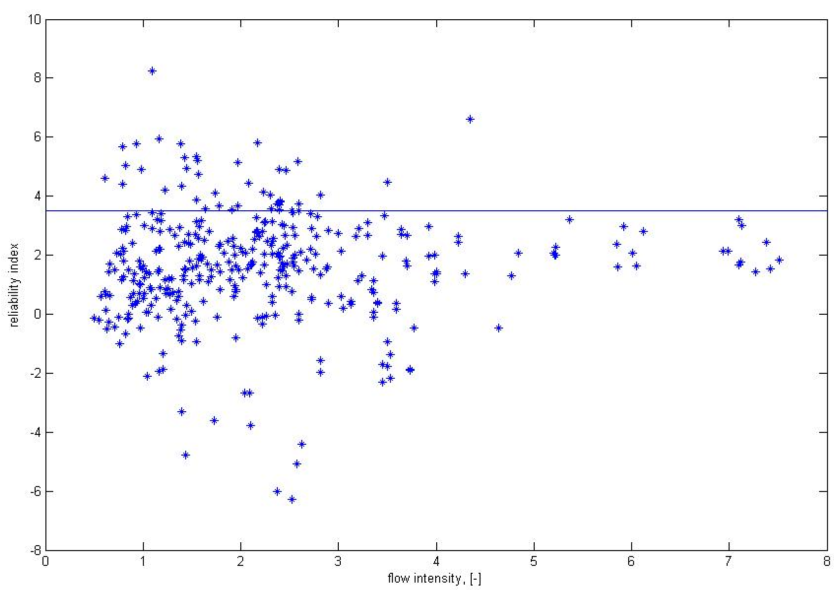
$$Int = \frac{V_0}{V_c}$$

For usual values of Int the reliability indices scatter a lot whereas for greater values of Int the variation is quite small. Unfortunately the number of sets in this range is quite small, too, thus the statistical significance is questionable.

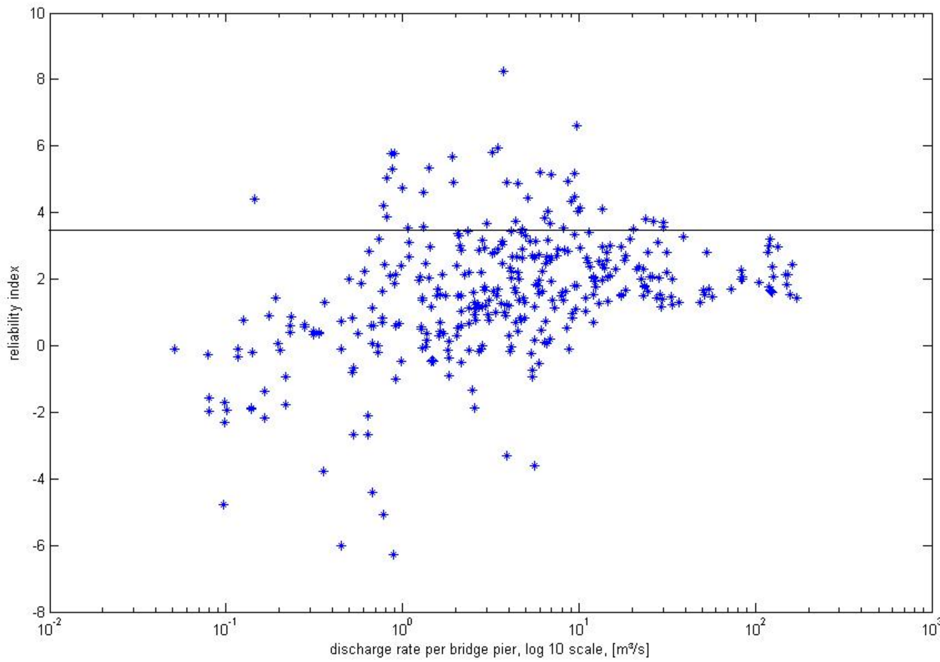
When subdividing the database into two parts the mean betas and pertinent COVs are respectively:

- $Int < 4.0$ mean β = 1.55
  COV = 374%
- $4.0 \le Int$ mean β = 2.08
  COV = 142%

Note that the first range represents 91.4% of all sets while the second one represents only 8.6%.



Most of the **discharge rates per bridge pier** that could be found take values less or equal to 30[m³/s] (1,060 ft³/s). Plotting the abscissa in a logarithmic scale to the basis 10 while keeping the ordinate in linear scale points out that all the negative reliability indices occur for a discharge rate Q less than 10 m³/s. For greater Q the noted $\beta$ start levelling off while still having quite a huge variation. The data sets which actually exceed a reliability of 3.5 are located in the medium range of flow intensities in a range between approximately 0.6 m³/s to about 30 m³/s.




**Comparison of the two scour prediction models and analysis of the effect of changing land use**

This work is in progress.

# URI Water Reserve Project

## Basic Information

| | |
|---|---|
| **Title:** | URI Water Reserve Project |
| **Project Number:** | 2004RI25B |
| **Start Date:** | 3/1/2004 |
| **End Date:** | 2/28/2006 |
| **Funding Source:** | 104B |
| **Congressional District:** | 2 |
| **Research Category:** | Not Applicable |
| **Focus Category:** | Water Use, Conservation, Treatment |
| **Descriptors:** | |
| **Principal Investigators:** | Vincent celmer Rose |

## Publication

The purpose of the study was to develop and implement a system for partial or complete recycle of the 100,000 gallons of water that is used daily at the URI Aquaculture Facility at East Farm in a once through process.

One graduate student was hired to research solutions to treating and reusing the water and to develop a plan.  A literature search has been conducted, along with visits to the URI Aquaculture Facility. Based on this information a preliminary treatment process was developed.  A biological treatment process, developed and manufactured by Bioprocess Technologies LLD in Portsmouth, RI was identified as a  potential system for treating the effluent to better prepare it for recycle . A high BOD, high solids generator, using this process in Massachusetts, was visited to better understand the process.

Since the University was in the process of hiring an outside energy consulting firm to handle their energy and water conservation projects, it was suggested that the project be delayed until a firm had been selected. That selection process now has been completed and a firm will be hired starting July 1st.

# Mitigating Runoff Contamination Due to DeIcing and Anti-Icing Operations at T.F.Green Airport

## Basic Information

| | |
|---|---|
| **Title:** | Mitigating Runoff Contamination Due to DeIcing and Anti-Icing Operations at T.F.Green Airport |
| **Project Number:** | 2004RI26B |
| **Start Date:** | 3/1/2004 |
| **End Date:** | 2/28/2006 |
| **Funding Source:** | 104B |
| **Congressional District:** | 2 |
| **Research Category:** | Water Quality |
| **Focus Category:** | Management and Planning, Waste Water, None |
| **Descriptors:** | |
| **Principal Investigators:** | Christopher Dickerson Hunter |

## Publication

# Mitigating Anti-icing and Deicing effects at TF Green

## Chapter 1. Introduction

The deicing and anti-icing of aircraft and airfield surfaces is required by the Federal Aviation Administration (FAA) to ensure the safety of passengers; however, when performed without discharge controls in place, airport deicing operations can result in environmental impacts. In addition to potential aquatic life and human health impacts from the toxicity of deicing and anti-icing chemicals, the biodegradation of propylene or ethylene glycol (i.e., the base chemical of deicing fluid) in surface waters (i.e., lakes, rivers) can greatly impact water quality, including significant reduction in dissolved oxygen (DO) levels. Reduced DO levels can ultimately lead to fish kills.

Deicing involves the removal of frost, snow, or ice from aircraft surfaces or from paved areas including runways, taxiways, and gate areas. Anti-icing refers to the prevention of the accumulation of frost, snow, or ice on these same surfaces. Deicing and anti-icing operations can be performed by using mechanical means (e.g., brooms, brushes, plows) and through the application of chemical agents. Typically, airlines and fixed-base operators (i.e., contract service providers) are responsible for aircraft deicing/anti-icing operations, while airports are responsible for the deicing/anti-icing of airfield pavement. Although compliance with environmental regulations and requirements associated with deicing/anti-icing operations may be shared between the airlines/fixed-base operators and the airports (e.g., airport authority) as co-permittees, the airport is ultimately responsible for the management of the wastewater that is generated. This responsibility is typically outlined in the airport's discharge permit.

In Rhode Island, T.F. Green is the primary of six state airports supervised by the Rhode Island Airport Corporation (RIAC). Mitigating the impact of deicing and anti-icing fluids from T.F. Green is of significant importance. According to EPA, on average, 70%

of applied deicing and anti-icing fluids is retrieved. Though T.F Green does a good job in their retrieval of these fluids, they have realized the need to increase the efficiency of their collection.

This research project is intended to propose or provide a solution or solutions to RIAC for TF Green Airport by investigating and analyzing different treatments, processes, and collection techniques to provide a better environmental mitigation process. The solutions process will be conducted within the boundaries of the following 3 objectives:

- To identify alternatives to glycol-based deicing/anti-icing fluids and determine the possibilities for deployment for T.F. Green
- To review procedures or methods of waste water collection from deicing operations to identify the best way to minimize deicing product from contaminating ground water.
- To provide a recommendation for possible alternatives, and procedures to improve T.F. Green's mitigation process for better removal of deicing fluids.

**Achieving Objectives**

The discussions that follow will outline procedures and actions that will be taken to achieve the aforementioned objectives.

Before discussing these procedures it is necessary to point out that the "success" of any process or solution is not only defined by how well it works, but to an equal extent on cost.

1. To identify alternatives to glycol based deicing fluids it will be necessary to interact with manufacturers of these fluids to find out what other deicing fluid technologies are available on the market. An internet and literature search would also be used in conjunction with corporate interaction.

b. In order to justify claims made by different manufactures, airports using these technologies will be contacted to determine the success of the technology employed at their facilities.

2 Different methods of wastewater collections from deicing operations are discussed in the EPA report entitled: *Airport Deicing Operations.* The methods will be reviewed and compared with information obtained from airports operating in similar climatic regions and having similar enplanements.

b. Manufacturers will also be contacted to determine any improved methods or processes available.

3. The recommendation of alternatives will be determined from results from steps 1 and 2 and how well these solutions balance efficiency and cost.

## Chapter 2. Pollution Prevention

To date, there are four basic approaches to pollution prevention for aircraft deicing/anti-icing operations: (1) elimination of glycol-based fluids through the development of an environmentally benign alternative fluid; (2) minimization of the volume of fluid applied to aircraft through the development of better fluids, improved application methods, and innovative aircraft deicing technologies; (3) development of collection and disposal strategies that prevent the release of ADF-contaminated wastewater to the environment; and (4) development of glycol recycling methods. Approaches to pollution prevention for airfield pavement deicing/anti-icing operations include: (1) adoption of alternative pavement deicing/anti-icing chemicals that are less harmful to the environment; (2) reduction or elimination of pavement deicing/anti-icing chemicals through the implementation of alternative deicing/anti-icing technologies; and (3) minimization of the amount of agents applied through the use of good maintenance practices, preventive anti-icing techniques, and runway condition monitoring systems. Although each approach is discussed separately, combinations of pollution prevention practices are typically used at U.S.airports. The pollution prevention practices selected by an airport or airline for use at a particular airport often depend on a variety of airport-specific factors, including climate; total amount of chemical deicing and anti-icing agents applied; number of airlines; aircraft fleet mix; number of aircraft operations; costs; presence of existing infrastructure; availability of land; and impact on aircraft departures. Some of the pollution prevention practices discussed in this section may not be practical or economically feasible for all U.S. airports.

## 2.1 Alternative Aircraft Deicing/Anti-Icing Agents

One plausible solution to the environmental problems associated with glycol-based ADFs is their replacement with more environmentally benign products. Despite considerable interest in developing substitute ADFs, little progress has been made. Most of the current research is thought to be in a preliminary stage and it will likely be some time before a suitable replacement is found. Substitute products need to be biodegradable and less toxic than current products, but must also contain compounds that are non-corrosive to aircraft parts. To be economically viable, substitute chemicals must be inexpensive and at least as effective in maintaining air safety as the glycol-based fluids they replace. The National Aeronautics and Space Administration's Ames Laboratory in California is attempting to develop effective, non-glycol-based aircraft deicing and anti-icing agents (1). The current status of the project is unknown, but the research is believed to be progressing slowly. The U.S. Air Force has also expressed interest in finding an environmentally benign substitute for glycol-based ADFs (2). The Air Force Office of Scientific Research is currently funding a number of research projects designed to discover a nontoxic, biodegradable ADF. Many of these projects focus on discovering how naturally occurring antifreeze molecules inhibit ice crystal growth. For example, Professor John Duman at the University of Notre Dame is exploring the structure of antifreeze molecules found in overwintering larvae of the beetle *Dendroides canadensis* to determine how these molecules inhibit ice crystal growth. A similar project directed by Professor Chi-Hing Cheng-DeVries of the University of Illinois is investigating antifreeze molecules found in polar fish. The goal of these projects is to synthesize a naturally occurring compound that can be formulated into an effective, nontoxic, anti-icing agent.

## 2.2 Aircraft Deicing Fluid Minimization Methods

Since it is unlikely that any new products will be available in the near future, the U.S. Air Force and some domestic carriers have been investigating ways to reduce the volume of ADF used, without compromising safety. The ADF minimization methods described in this section enable pollution to be reduced through source reduction.

### 2.2.1 Type IV Anti-icing Fluids

Aircraft anti-icing fluids are designed to adhere to aircraft surfaces and prevent ice and snow build-up for set periods of time, known as holdover times. Currently, two types of aircraft anti-icing fluids are used in the United States, Type II and Type IV fluids. Although Type I fluids can provide limited anti-icing protection, they are primarily used for deicing aircraft, are generally applied in much larger volumes, and typically provide less than 15 minutes holdover time. Type II and Type IV fluids are similar to Type I fluids, but contain thickening agents, usually polymers, that provide improved anti-icing properties. The viscosity of anti-icer fluids decreases with wind shear, which enables the fluids to be shed from aircraft surfaces during takeoff. Type IV fluids represent the most recent advances in aircraft anti-icing agents and provide longer holdover times than Type II fluids. Although holdover times vary with weather conditions, the typical holdover time for a Type II fluid is approximately 45 minutes in a light snow. Type IV fluids, however, may provide protection for as long as 70 minutes under the same weather conditions (3). Due to their improved anti-icing capabilities, Type IV fluids have been credited with reducing the amount of deicing fluid used by eliminating repeated deicing and anti-icing of aircraft prior to takeoff (4). Most of the larger U.S. carriers now use Type IV fluids exclusively for anti-icing.

One potential disadvantage of using Type IV fluids is the possibility for increased airfield contamination. Because Type IV fluids adhere to aircraft surfaces, greater use of Type IV fluids may increase the volume of fluid deposited on runways and adjacent grassy areas. Since runways rarely have contaminated storm water collection systems, anti-icing fluids shed from aircraft during takeoff enter the environment and may contaminate soils, groundwater, and nearby streams. Although some components of anti-icing fluids, such as glycols, are easily degraded by microorganisms present in soils, other components, such as tolyltriazoles, are believed to persist in the environment

### 2.2.2 Preventive Anti-icing

Preventive anti-icing is the application of glycol-based anti-icing fluid prior to the start of icing conditions or a storm event to limit ice and snow build-up and facilitate its removal. The principal advantage of this method is an overall reduction in the volume of glycol-based fluids applied to aircraft. Anti-icing fluids are applied in much smaller volumes than their deicing Type I counterparts. A Boeing 727, for example, can be anti-iced using approximately 35 gallons of fluid, whereas deicing requires at least 150 gallons of Type I fluid and may be as much as 2,000 gallons during a severe storm event. To be effective as preventative, anti-icing fluids must be applied to aircraft prior to the advent of icing conditions or a storm event. The U.S. Air Force has also experimented with preventive anti-icing techniques and has concluded they can be effective in reducing the volume of fluid applied to aircraft, provided operations personnel carefully coordinate their activities with local weather reports (2). The U.S. Air Force has not implemented widespread use of preventive anti-icing practices due to concerns that anti-icing fluids may degrade aircraft parts, particularly those made from composite materials, when the fluids are left on for extended periods (5).

One drawback to preventive anti-icing is the problem of obtaining accurate weather forecasts containing enough information for operations personnel to make informed decisions. Inaccurate forecasts may result in unnecessary anti-icing. Operations personnel typically rely on local weather stations to provide accurate and timely weather forecasts; however, several U.S. airlines have established meteorological groups, which provide weather forecasts for major destinations. The National Center for Atmospheric Research in Boulder, Colorado, has developed a new weather forecasting system specifically designed for use at airports that provides snowfall forecasts thirty minutes in advance of precipitation. The system is known as Weather Support to Deicing Decision Making (WSDDM) and its development was funded by the Federal Aviation Administration (FAA) (6). Forecasts are based on information collected from surface weather stations, snow-weighing gauges, and Doppler radars located at or near the airport. The information is processed by computers and displayed graphically on video monitors at the airport. During the 1997-1998 winter season, the system was tested by Delta and U.S. Airways at La Guardia airport in New York and by United and American at O'Hare airport in Chicago. In July 1998, the WSDDM system became available commercially from ARINC, a company specializing in aviation communication and air traffic management systems. The system costs approximately $100,000 to install. It is currently in operation at La Guardia airport, where it is used by Delta for managing aircraft deicing/anti-icing and by the New York Port Authority for managing airfield snow removal.

Airlines hope this system will provide sufficient storm warning information to perform preventive anti-icing of aircraft prior to the arrival of a storm, enabling airlines to continue to operate safely with less deicing fluid. Anti-icing fluids are sometimes applied to aircraft to provide overnight protection from frost and storm events. This practice is purported to greatly reduce the volume of Type I fluid needed to remove ice and snow from aircraft surfaces the following morning. For example, a fixed-base operator at one airport reported applying Type IV fluid for overnight protection to one of two aircraft parked side by side. A major snow storm occurred during the night and both aircraft were deiced the next morning using Type I fluid. The aircraft treated with Type IV fluid required 860 gallons of Type I fluid to deice, while the untreated aircraft required 1,820 gallons. Several airlines, however, have expressed concern that anti-icing fluids may dry out and damage aircraft if left on for extended periods. Several U.S. airlines (United, Delta, American, and Midwest Express) have experimented with anti-icing aircraft immediately after landing . The intent is to prevent ice and snow build-up while the aircraft is at the gate, and consequently reduce the amount of deicing and anti-icing required before departure. For aircraft with short turn-around times, the protection afforded by preventive anti-icing may even eliminate the need for further deicing prior to departure. Study results indicate this practice saves time and reduces the amount of Type I fluid used during a storm event.

### 2.2.3 Forced-Air Aircraft Deicing Systems

Forced-air aircraft deicing systems have been available for many years, but have not seen widespread application in the United States primarily due to their high cost over conventional deicing systems. The first systems used a high-pressure air jet to blast ice and snow from aircraft surfaces, which has proven to be very effective for removing dry, powdery snow from cold, dry aircraft surfaces. All Nippon Airways, for example, has used forced-air systems for over 20 years to remove overnight accumulations of snow at several northern airports in Japan and believe it removes dry snow faster than using deicing fluids. All Nippon Airways personnel can reportedly remove 5 cm of snow from a passenger jet in about 15 minutes using a forced-air deicing system.

In the past, U.S. carriers were less enthusiastic about forced-air systems because they were not very effective for removing ice and wet snow; conditions that are typical for most U.S. airports. In recent years, however, the development of new hybrid systems, which combine forced-air with fine sprays of heated Type I fluids, have rekindled interest in this technology.

In the early 1990s, FMC Corporation (formerly Aviation Environmental Compliance Inc.) developed a forced-air aircraft deicing system designed to remove snow and ice from aircraft surfaces using a high-pressure air stream combined with a fine spray of glycol-based aircraft deicing fluid. The system is known as the AirFirst Deicing System™ and can be used in an air-only mode for removing light snow and ice. The system consists of a self-contained, truck mounted unit fitted with a turbine engine and a dual source nozzle. The dual source nozzle allows deicing fluid to be added to the air stream to help remove ice and protect against freezing precipitation.

Today, forced-air aircraft deicing systems are also manufactured by Premier, Global, and Vestergaard and are similar to the FMC AirFirst Deicing System™. The Premier system, known as the Hybrid Deicing System™ (HDS), was developed in collaboration with Allied Signal and consists of a centrifugal compressor, an ADF storage tank with heater, a high pressure fluid pump, and a coaxial nozzle. The coaxial nozzle is designed to emit a high-velocity stream of heated ADF surrounded by a high-velocity air jet. The compressed air exits the nozzle at approximately 750 miles per hour. ADF can be applied at either 9 gpm (7,500 psi) or 20 gpm (3,300 psi), depending on the weather conditions. The unit can also be operated in an air-only mode for removing dry snow. HDS units are currently used by Delta Airlines at General Mitchell International Airport in Milwaukee, Wisconsin, and by the U.S. Navy at the Brunswick Naval Air Station in Maine. For the 1998-1999 deicing season, Delta estimates the HDS unit enabled the airline to reduce the volume of ADF used in Milwaukee by about 85%.

The Vestergaard system is mounted on Vestergaard’s Elephant Gamma Deicer truck and uses forced air combined with an ADF spray to deice aircraft. The unit supplies forced air at a pressure of 56 psi and can be operated with or without ADF injection. The first Vestergaard forced-air system was purchased by All Nippon Airways last year and is currently used at the Nagano Airport in Japan to remove snow from aircraft parked at the airport overnight. The Global system, known as AirPlus™, is a self-contained unit weighing approximately 85 pounds that consists of a compressor and two articulated nozzles (one for ADF and the other for forced air). Unlike the other forced-air systems where the compressor is mounted on the truck, the compressor on the Global system is mounted under the operator's seat in the enclosed cab attached to the articulated boom. AirPlus™ can be operated in four different modes: (1) forced air only; (2) forced air with ADF injection; (3) ADF and forced air (supplied by separate nozzles); and (4) ADF only. The forced air exits the forced air nozzle at 725 miles per hour (about 1,350 cfm) with a pressure of 11 psi. ADF can be injected into the air stream at approximately 10 gallons per minute. The second nozzle can provide either heated Type I fluid at 60 gallons per minute or Type IV fluid at 20 gallons per minute. The cargo carrier, Emery Worldwide, tested the unit at Dayton International Airport in Ohio during the 1998-1999 deicing season. For the 1999-2000 deicing season, five AirPlus™ systems will be used by American Airlines at Chicago O'Hare International Airport and two will be used by Skyway Airlines (a division of Midwest Express) at General Mitchell International Airport in Milwaukee. According to Global representatives, the AirPlus™ system can reduce the volume of ADF used by an airline by at least 30 percent.

The forced-air systems cost approximately $250,000. FMC and Global also market retrofit kits for use on existing deicing trucks that cost between $80,000 and $100,000. To date, only a limited number of hybrid forced-air deicing systems have been purchased by U.S. carriers (e.g., Delta, United, American, Northwest, Emery Worldwide, Skyway, and Federal Express). Airlines have been cautious about investing in this new technology for a variety of reasons, the most important being concern the high-velocity air jet will damage aircraft surfaces.

When a forced-air system is used to remove ice, airlines are concerned that ice chunks blasted from aircraft surfaces at high velocity will injure ramp personnel or damage aircraft. Many airlines are also worried the forced-air systems will be more expensive to maintain and less reliable than traditional deicer trucks. Some airlines believe that widespread use of forced-air systems will result in higher purchase prices for ADF due to reduced demand. Despite these problems, forced air deicing systems offer several benefits to the airline industry, including reductions in the volume of fluid purchased, less frequent refilling of deicer trucks, and reduced costs for wastewater disposal.

The principle environmental benefit of the hybrid forced-air deicing systems is their ability to minimize the volume of fluid required to deice aircraft; however, glycol-based anti-icing fluids may still need to be applied in certain weather conditions. While conventional deicing with large volumes of hot Type I fluids provide temporary anti-icing protection by heating the aircraft surface, forced-air deicing systems provide little anti-icing protection. Consequently, the time between completion of deicing and application of anti-icing fluids may be less than with conventional deicer trucks.

The U.S. Air Force has also experimented with forced-air deicing and has developed a system that uses forced hot air to remove snow and ice from aircraft surfaces. The forced hot air is supplied by MA1A compressors, which have been fitted to existing deicer trucks. The forced hot air system does not eliminate glycol-based ADFs, which are typically applied to aircraft after treatment with forced hot air. Nevertheless, it greatly reduces the volume of fluid required to effectively deice aircraft. The forced hot air system is currently in use at several northern Air Force bases.

### 2.2.4 Computer-Controlled Fixed-Gantry Aircraft Deicing Systems

An alternative approach to aircraft deicing are the fixed-gantry systems, which are self-contained “car wash style” aircraft deicing systems. Fixed-gantry systems have been installed at only a few airports worldwide, and, although purported to deice aircraft quickly and efficiently, they have failed to receive widespread approval from the industry. EPA knows of no U.S. airports at which fixed-gantry systems are in use today.

In the typical fixed-gantry system, aircraft taxi onto the gantry pad and nozzles mounted on the gantry frame spray the aircraft with hot deicing fluid. The nozzles are controlled by computers that are programmed to deliver the appropriate amount of fluid uniformly over the entire aircraft for a variety of aircraft types and sizes. The deicing process takes approximately 8 to 12 minutes. Runoff is collected either in gutters or trench drains and pumped to storage tanks for treatment, recycling, or disposal. Gantry systems are typically located on taxiways near the end of the principal departure runway, reducing the time between aircraft deicing and take-off.

Deicing Systems AB (DSAB), based in Kiruna, Sweden, is a leading manufacturer of fixed-gantry deicing systems. DSAB installed its gantry system at the Munich Airport in Germany in 1992 at a cost of approximately $5 million. The system consists of a computercontrolled, movable steel frame fitted with nozzles. The frame passes over the parked aircraft while the computer controls the operation of the nozzles, starting and stopping the flow from each nozzle as appropriate, depending of the type of aircraft. The speed of the gantry can be adjusted to suit prevailing weather conditions. The gantry is 70 meters wide and 21 meters high and can deice aircraft ranging in size from the Fokker 100 to the Boeing 747-400. The Munich system also includes a collection system for spent aircraft deicing fluid. The collected runoff is sent to an on-site glycol recycling facility also operated by DSAB. In addition to Munich, DSAB has installed its gantry system at the Kallax Airport in Lulea, Sweden and the Standford Field Airport in Louisville, Kentucky. United Parcel Service (UPS) purchased the DSAB gantry for its hub operations at Stanford Field Airport in 1988 at a cost of approximately $6 million. The system purchased by UPS was designed to deice Boeing 727s, Boeing 757s and McDonnell Douglas DC-8s.

An alternative gantry system, called the Whisper Wash™, has been developed by Catalyst and Chemical Service, Inc. The Whisper Wash™ is a portable deicing system that uses both deicing fluid and high-pressure hot air to deice/anti-ice aircraft. The system consists of adjustable, cantilevered arms mounted on two modified flat-bed trailers. To accommodate different types of aircraft, the height of the arms is adjusted using hydraulic jacks. Each arm supports two sets of nozzles; one set delivers high-pressure hot air while the other delivers low pressure deicing fluid. The nozzles used to deliver the deicing fluid are specially designed low shear nozzles, which can be used to apply Type IV fluids as well as Type I fluids. The Whisper Wash™ system can also be operated in an air-only mode to remove light snow. According to the manufacturers, Whisper Wash™ can reduce ADF usage by up to 70% and can deice an aircraft in less time than is required for convention deicing using deicing trucks.

Two versions of the system are currently available: a large system capable of handling wide-bodied aircraft and a small system capable of deicing general aviation aircraft and commercial narrow-bodied aircraft. The system costs $1.2 million, with annual maintenance and labor costs of approximately $209,000. The manufacturer also offers an optional ADF-containment system consisting of a perforated pipe installed around the perimeter of the deicing area, which drain to sumps. Currently, no commercial application of the Whisper Wash™ system is known.

Proponents of the computer-controlled gantry systems assert that these systems:

(1) quickly and efficiently deice aircraft using the minimum volume of aircraft deicing fluid, (2) can be operated by personnel with minimum training and experience, and (3) can collect as much as 80% of the deicing fluid sprayed. Despite these purported advantages, fixed-gantry systems are not popular with airlines or airport authorities. Airports are reluctant to invest in fixed-gantry systems because they require a relatively large capital investment and require considerable space that cannot be converted to other uses during good weather conditions. Airlines dislike fixed gantries because they can cause bottlenecks and delay aircraft departure. Some users argue that gantry systems actually apply more deicing fluid than necessary because they deice aircraft indiscriminately, including areas that may not require deicing. In addition, gantry systems cannot deice engine inlets, the undercarriage, or the underside of aircraft wings, making it necessary for airlines to perform additional deicing using traditional deicer trucks.

According to recent reports, dissatisfaction with the performance of their fixed-gantry systems prompted UPS and some European airports to dismantle them.

### 3.2.5 Infrared Aircraft Deicing Technology

In recent years, a new method of aircraft deicing has been developed that relies on infrared radiation. The leading manufacturers of infrared-based aircraft deicing systems are Radiant Energy Corporation (formerly Process Technologies, Inc.) and Infra-Red Technologies, Inc. Radiant Energy markets a fixed-hangar deicing system known as InfraTek™, while Infra- Red Technologies markets a mobile system known as Ice Cat™. Both systems have the potential to greatly reduce the amount of glycol-based fluids used for aircraft deicing. Neither system is widely used by airlines or airports, although the InfraTek™ system is currently in commercial use at three U.S. airports. A third system, under development by Sun Lase Inc., is designed to use computer-controlled infrared lasers to deice aircraft. Each system is described in detail below.

### *2.2.5.1 InfraTek™*

InfraTek™ was developed under a Cooperative Research and Development Agreement between Radiant Energy and the FAA. Under the agreement, Radiant Energy developed the system and FAA provided expertise, advice, and test aircraft. A prototype was tested at Rochester International Airport in February 1996. Tests conducted by the FAA in March 1996 demonstrated that the InfraTek™ system could deice a Boeing 727 in six minutes, the approximate time required to deice an aircraft using conventional fluids. Additional testing conducted by the FAA and Radiant Energy showed that the infrared radiation did not damage aircraft components. The FAA measured aircraft surface temperatures during deicing and found that they never exceeded 94 F. Based on these results, the FAA approved deicing/antiicing procedures that use the InfraTek™ system for commercial aircraft in 1997.

The InfraTek™ system consists of an open-ended, hangar-type structure with infrared generators suspended from the ceiling. The infrared generators, called Energy Processing Units (EPUs), are fueled by natural gas. The infrared wavelengths are targeted to heat ice and snow, while minimizing the heating of aircraft components. The energy and wavelength generated by the EPUs can be adjusted to suit aircraft type. The system, operated similarly to a car wash, is controlled by computer and is designed to be operated by one person. Prior to deicing, the hangar floor is heated for 30 minutes to facilitate the melting of ice from aircraft landing gear and the underparts of the wings and fuselage. Once the floor is heated, the system is ready to receive aircraft. Aircraft taxi or are towed into the open-ended hangar immediately before takeoff. Typically, a six-minute cycle is used, which includes two minutes at full EPU power followed by four minutes at half power. The cycle time can be shortened for aircraft covered with a light frost.

Although the system can deice aircraft, it cannot provide anti-icing protection. When the ambient temperature is below freezing, precipitation can rapidly freeze on aircraft surfaces after it leaves the InfraTek™ hangar. Consequently, anti-icing fluid is applied to the aircraft when necessary to protect the aircraft during taxiing and takeoff. In addition, a small volume of deicing fluid may be required to deice areas of the aircraft not reached by the infrared radiation, including the flap tracks and elevators. While the InfraTek™ system does not completely eliminate glycol-based fluids, it greatly reduces the volume required. Radiant Energy estimates that the system reduces the volume of glycol-based deicing fluids applied to aircraft by approximately 90%. InfraTek™ is reportedly less effective with snow (as compared to ice), where the crystal structure of the flakes is thought to diffuse and reflect the infrared radiation rather than absorbing it. Radiant Energy is, therefore, considering adding blowers to remove loose snow from aircraft surfaces and improve efficiency. The first commercial InfraTek™ system was installed at Buffalo-Niagara International Airport in March 1997 and is used for deicing general aviation and commuter aircraft. The hangar installed at Buffalo is 42 feet high, 111 feet wide, and 126 feet long and is capable of deicing aircraft as large as the ATR 72. In bad weather, it can deice four or five aircraft per hour (20). Customers are charged a fixed fee based on the size of their aircraft (i.e., wing span and fuselage length), as opposed to conventional deicing using Type I fluids, where charges are based on the volume of fluid applied. Customers prefer the fixed-fee payment structure because it enables them to budget for winter operations more accurately. Due to the success of the InfraTek™ system, Buffalo-Niagara International Airport is considering installing a larger system capable of handling commercial jets and cargo aircraft. Radiant Energy installed its second commercial InfraTek™ system at the

Oneida County Airport in Rhinelander, Wisconsin in February 1998. This system is similar in size to the one installed at Buffalo-Niagara International Airport, but is slightly taller, allowing British Aerospace 146 commuter aircraft to be deiced (21). A third InfraTek™ system has been installed at Newark International Airport by Continental Airlines for use during the 1999-2000 winter. This system is capable of deicing narrow-bodied commercial aircraft as large as the Boeing 737, and will be used primarily by Continental Airlines, although general aviation and other commercial airlines have also expressed interest.

In addition to reducing fluid use, deicing using the InfraTek™ system reportedly costs less than traditional deicing with deicing agents. InfraTek™ reportedly deices a Boeing 727for under $350, compared with the cost of approximately $5,000 for deicing the same aircraft with glycol-based fluids. Radiant Energy markets several different hangar sizes for the InfraTek™ system. The smallest system is designed to handle small general aviation and corporate aircraft, while the largest system is designed to handle large passenger jets and cargo aircraft. The largest system currently available is 95 feet high, 275 feet wide, and 320 feet long, which can accommodate aircraft as large as the Boeing 747 (19). The capital cost of the InfraTek™ system depends on the size of the hangar and ranges from $1 million to $4 million.

The principle disadvantages of the InfraTek™ system are its physical size and aircraft processing capacity. Land-locked airports located in urban areas may have difficulty finding sites for the InfraTek™ system, particularly since the selected site must both comply with FAA regulations and be convenient for aircraft taxiing to active runways. Airlines worry that the system’s limited processing capacity will cause bottlenecks, resulting in unnecessary delays.

While airport-wide implementation of the InfraTek™ system may be impractical at large airportswith heavy traffic volumes, implementation may be practical at smaller airports that do not have congestion problems or by some tenants at larger airports (e.g., commuter airlines, general aviation). Airlines are also concerned about the potential for melted precipitation to refreeze in aerodynamically quiet areas, possibly resulting in the wing flaps and elevators malfunctioning. Although Radiant Energy reports that it has not seen any evidence that refreezing occurs in these areas, the company plans to undertake a test program with APS Aviation, Inc. to study the issue.

#### *2.2.5.2 Ice Cat*™

The Ice Cat™ system is a mobile, truck-mounted system that uses infrared radiation to remove frost, ice, and snow from aircraft surfaces. Infrared radiation is provided by an array of flameless infrared emitters (i.e., catalytic heaters) fueled by natural gas, propane, or butane. The infrared emitters are mounted on an articulated boom fitted to a specially designed truck. The boom lifts and positions the infrared emitters approximately 2 to 5 feet above the aircraft surface. Each unit is computer controlled. Depending on the size of the aircraft, one or two Ice Cat™ trucks may be used to deice an aircraft. According to the manufacturer, the deicing process requires approximately 6 to 10 minutes to complete, during which infrared radiation melts ice and snow accumulated on the aircraft and raises the temperature of the aircraft skin. By raising the temperature of the aircraft skin, Ice Cat™ temporarily prevents residual surface water and/or precipitation from freezing on aircraft surfaces. Sensors mounted on the boom monitor the surface temperature of the aircraft to ensure it never exceeds 140 F.

Infra-Red Technologies sponsored a demonstration of the Ice Cat™ in November 1997 at Kansas City International Airport where it was used to deice a Beechcraft Queen Air. Further tests were conducted in March 1998 at Kansas City where Ice Cat™ was used to deice a Boeing 727 and at the Pittsburgh National Guard Base where it was used to deice a military KC-135 supertanker. Ice Cat™ has also been tested by Transport Canada using an Air Canada Boeing 737 and Fokker F-428 (23). Infra-Red Technologies has continued to improve Ice Cat™ and recently added a spray system designed to apply a light coating of Type IV (anti-icing) fluid.

Ice Cat™ is reportedly a cost-effective alternative to deicing with traditional glycol-based aircraft deicing agents. According to the manufacturer, Ice-Cat™ can deice a Boeing 737 for as little as $5 (23). The cost of the system is unknown, but is believed to be comparable to that of traditional deicer trucks.

Despite its purported advantages, no commercial application of the Ice Cat™ system is currently known. Although Ice-Cat™ is equipped with temperature sensors, many U.S. airlines are worried that it may damage aircraft by overheating the aircraft's skin. In addition, the large size of the infrared panels may make Ice-Cat™ difficult to maneuver in the confined space of the gate area. Airlines are concerned about the potential for collisions between Ice-Cat™ and parked aircraft.

#### *2.2.5.3 Sun Lase Inc.*

Sun Lase Inc. is currently developing an infrared laser-based system designed to quickly and efficiently deice aircraft. The system will use a high-power, infrared (i.e., 10-micron wavelength) laser beam to melt ice on aircraft surfaces. The laser beam will be generated by CO2 lasers and directed at the aircraft surface using mirrors. The mirrors will be controlled by computer, allowing the laser beam to be moved across the aircraft in a predetermined manner. The computer will control the laser alignment and simultaneously monitor the thermal temperature of the aircraft skin. The laser beam will cover a surface area of approximately 1 square meter and deliver an intensity of 2.5 Watts/cm. For safety, the laser beam will be 2 combined with red light to enable operators to observe the position of the beam. The lasers can be mounted on a truck or on telescopic poles. The system is designed to be operated by one person. Sun Lase has applied for a U.S. patent and is currently constructing a prototype

**2.2.6 Hot Water Aircraft Deicing**

The FAA permits aircraft to be deiced using hot water followed by the application of an anti-icing fluid when ambient air temperatures are above 27 F (3). None of the major U.S. airlines currently use this method because they believe it would compromise the safety of passengers and ground operations staff. Airlines are concerned about flash freezing and the potential to build up thick layers of ice both on the aircraft and on the pavement. The water may also enter and freeze on flap tracks, elevators, and other aircraft parts, potentially affecting aircraft handling and performance. Water freezing in hoses, nozzles, and tanks when deicer trucks are not in use is also a concern.

**3.2.7 Varying Glycol Content to Ambient Air Temperature**

Although Type I fluid can be purchased in a pre-diluted ready-to-use form, many airlines and fixed-base operators prefer to purchase their Type I fluid in concentrated form (approximately 90% glycol) and dilute to a glycol concentration appropriate to the local weather conditions (13, 25). Some airlines mix Type I fluids specific to each deicing event based on prevailing weather conditions, thereby minimizing the amount of deicing fluid sprayed. For example, Delta Airlines uses a “Local Area Expert,” a person well trained in deicing operations, to determine the glycol concentration appropriate for the prevailing temperature. This practice enables Delta to use Type I fluids containing as little as 30% glycol, rather than the typical 50/50 glycol and water mixture, when weather conditions are mild. A similar practice is used at Denver International Airport where the airport’s FBO supplies airlines with Type I fluids containing glycol concentrations that are appropriate for the ambient air temperature. The FBO purchases Type I fluid in a concentrated form, stores it in 20,000-gallon storage tanks at the airport's glycol recycling facility, and mixes it with water in a 10,000-gallon tank equipped with a mixer. The concentrated fluid and water are metered into the mixing tank in the appropriate proportions and a built-in densitometer is used to verify the glycol concentration. Due to storage problems and concerns about human error, some airlines prefer to mix Type I fluids to meet historical temperature minimums. Northwest Airlines, for example, analyzes historical temperature data for a given airport and selects a glycol content to match the lowest temperature the airport is likely to experience. This practice may result in fewer mistakes and is particularly suited to some smaller airports that lack storage for preparing multiple-strength solutions.

Where possible, the U.S. Air Force also adjusts the glycol concentration of its aircraft deicing fluids based on ambient air temperatures. At some bases, the Air Force uses deicer trucks with two-chamber tanks: one for concentrated aircraft deicing fluid and the other for heated water. The flow rate from each tank can be adjusted to alter the glycol concentration of the fluid as it is applied to aircraft. One disadvantage of the two-chamber deicer trucks is that the water may freeze when the trucks are not in use. This problem caused personnel at some northern bases to remove the baffles and create a single tank in which the deicing fluid can be mixed to meet prevailing or anticipated weather conditions prior to application.

### 3.2.8 Enclosed-Basket Deicing Trucks

Airlines typically use open-basket configurations, called "cherry pickers," to apply ADF. The open baskets provide little protection for personnel, who are frequently sprayed by aircraft deicing and anti-icing fluids. An enclosed-basket design is now available that improves operator working conditions (2). By enabling operators to get closer to the aircraft, the enclosed basket reportedly reduces over-spray and helps to minimize the volume of fluid used to deice aircraft. As a result, some airlines have reported 30% reductions in aircraft deicing fluid usage. As a result of these benefits, many U.S. airlines now employ a fleet of enclosed-basket deicing trucks at their hubs and larger stations.

Several companies manufacture the enclosed-basket deicing trucks, including Simon Aviation Ground Equipment, Elberta Industries, Premeir, and FMC.

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### 2.2.9 Mechanical Methods

The volume of ADF applied to aircraft can be minimized by mechanically deicing the aircraft prior to chemical deicing. The U.S. Air Force, for example, uses brooms, squeegees, and ropes to remove ice and snow from aircraft surfaces (26, 27). These methods are more effective at removing snow rather than ice. When performed incorrectly, they can damage aircraft antennas and sensors. Mechanical methods are generally only practical for smaller aircraft; for large aircraft, they can be prohibitively time-consuming and labor intensive. Despite these drawbacks, Northwest Airlines uses brooms fitted with long handles to remove snow from large passenger aircraft. This method is used only in the early mornings, when it is least disruptive to Northwest's departure schedule.

### 2.2.10 Aircraft Deicing Using Solar Radiation

At several U.S. Air Force bases, aircraft parked on ramps are oriented to maximize the melting of accumulated snow and ice by sunlight. This method reduces the volume of aircraft deicing fluid used during the winter season, but is practical only for general aviation and certain military flights that can be delayed without negative economic or operational impacts.

### 2.2.11 Hangar Storage

Many general aviation aircraft and some commuter and military aircraft are stored in hangars overnight and during storm events, eliminating the need for aircraft deicing. In addition, heated aircraft hangars are sometimes used to deice aircraft. In either case, anti-icing may be necessary in certain weather conditions to prevent ice and snow from accumulating on aircraft surfaces during taxiing and takeoff. After leaving the hangar, aircraft are anti-iced by spraying with a small volume of glycol-based anti-icing fluid (typically 2 gallons for very small aircraft). Because of the small volumes applied, the volume of ADF-contaminated wastewater generated is much less than would have been generated had aircraft been stored outdoors. The Tri-State Airport in Huntington, West Virginia, for example, estimates that their 84-foot-by-120- foot heated aircraft hangar saved approximately 1,500 gallons of Type I fluid last year and estimates that a new 70-foot-by-100-foot heated hangar will save an additional 1,000 gallons of Type I fluid during the 1999-2000 deicing season. Tri-State Airport handles approximately 46,000 operations each year of which approximately 70% are conducted by general aviation aircraft that are easily stored in aircraft hangars.

### 2.2.12 Aircraft Covers

Where hangar space is not available, aircraft covers or blankets are sometimes used as an alternative method to minimize frost, ice, and snow accumulation on aircraft surfaces . Aircraft covers are typically used for small general aviation aircraft to protect the wings, tail, and engine inlets. There are currently two types of covers available: solid and mesh covers. Solid covers are made from nylon or canvas and should not be used in strong winds. In cold weather, they tend to become hard and freeze to the wings, making them difficult to remove. Mesh covers are made from a very fine mesh fabric and are designed for use in windy conditions. They are easier to remove in cold weather but provide less protection, tending to leave residual ice on wing surfaces. Northwest Airlines experimented with aircraft covers for large passenger aircraft, but was dissatisfied with their performance. Northwest found them to be relatively easy to install, but difficult and time-consuming to remove as they become hard and inflexible when cold. In some instances, condensation trapped between the wing and the cover froze, binding the cover tightly to the wing surface. In addition, covers that came in contact with the pavement picked up grit, which damaged aircraft surfaces as the covers were pulled into place. Based on this experience and the high cost of the covers (approximately $10,000), Northwest concluded that aircraft covers are impractical for use on large passenger aircraft.

**2.2.13 Thermal Blankets for MD-80s and DC-9s**

The MD-80 and DC-9 aircraft are particularly prone to icing. Fuel stored in tanks located below the aircraft's wings becomes super-cooled during flight. Ice forms on wing surfaces as the aircraft descends and lands, and may form on days when the ambient air temperature is well above freezing. This ice is removed prior to takeoff by applying a small volume of ADF, typically 25 to 50 gallons, in a process known as “clear ice” deicing. Although the volume of fluid used is small, “clear ice” deicing is regularly performed on these aircraft throughout the winter months. Consequently, many airlines operating large fleets of MD-80s and DC-9s are attempting to eliminate the need for “clear ice” deicing by retrofitting these aircraft with specially designed thermal blankets. The blankets are bonded to the wing surface and consist of nickel-plated carbon fibers sandwiched between fiberglass layers.

The blankets are manufactured by Allied-Signal Aerospace and cost approximately $35,000 (2). The airlines are pleased with the overall performance of the blankets and believe they significantly reduce the volume of aircraft deicing fluid used for “clear ice” deicing of MD-80s and DC-9s.

### 2.2.14 Ice-Detection Systems

Pilots and aircraft deicing crews often have difficulty detecting ice on aircraft wings, particularly at night when visibility is poor. Consequently, aircraft are deiced whenever ice is suspected to be present. This conservative approach is appropriate from a safety standpoint, but may lead to unnecessary application of ADFs. One solution is the use of ice-detection systems. Although some ice-detection systems are known to have difficulty detecting ice on painted surfaces and composite materials, most systems improve safety while increasing the efficiency of aircraft deicing/anti-icing operations. There are currently two types of ice-detection systems available: a remote system and a wing-mounted system. SPAR Aerospace markets a remote detection system developed by Cox and Company. The system is known as the Contamination Detection System™ (CSD-1) and uses an infrared camera to detect ice and evaluate the integrity of anti-icing fluids on aircraft surfaces. The camera can be used at distances of 58 feet from the aircraft. The CSD-1 is reported to be capable of detecting clear ice films as thin as 0.01 inches and can detect ice crystals forming in Type IV fluids.

The system costs approximately $60,000. Allied-Signal Aerospace has developed a wing-mounted system known as the Clean Wing Detection System™. This system uses sensors mounted in the upper surface of the wing to detect surface contamination. The sensors can identify the type of contamination (e.g., frost, ice, snow, and deicing/anti-icing fluid) and measure its thickness. The system is also designed to measure the performance of anti-icing fluids and can determine when additional deicing/anti-icing is warranted. The cost of this system depends on the number of sensors installed and ranges from $50,000 for four sensors to $75,000 for eight sensors.

BF Goodrich, a leading manufacturer of in-flight ice detectors, markets a remote detection system, called the IceHawk™ Wide Area Ice Detector, which uses an infrared light beam to detect ice, snow, and frost on aircraft surfaces. The IceHawk™ is designed to detect frozen contamination up to 60 feet from the aircraft and has been approved by the FAA to replace the tactile inspection. The system works by scanning the aircraft surface with a polarized infrared beam. The system analyzes the polarization of the reflected signal and generates an image on a color, LCD monitor. Infrared signals reflected from surfaces contaminated with ice, frost or snow are unpolarized. These areas are displayed on the monitor in red. The system can detect ice covered by deicing and anti-icing fluids and can be used in any lighting or weather conditions without recalibration. The units are portable and may be either handheld or mounted on deicer trucks and are currently being used by Delta Airlines, Federal Express, and the U.S. Air Force. BF Goodrich is also developing an onboard version of the IceHawk™ in which the sensor is installed above a passenger window in the fuselage at a position behind the wing. The company has tested a prototype of the new system on an FAA Boeing 727 last winter and plans to conduct additional testing during the 1999-2000 winter.

### 2.2.15 Airport Traffic Flow Strategies and Departure Slot Allocation Systems

More effective airport management plans and better communication during storm events can help avoid unnecessary repeated application of ADF, particularly at the busier and more congested airports. The FAA recommends that airport management collaborate with the airlines, FBOs, air traffic control, and other interested parties to develop communication procedures and traffic flow strategies for winter operations. Winter traffic flow strategies can identify the shortest taxiing routes and minimize holdover times for deiced aircraft, thereby reducing or eliminating the need for repeated deicing/anti-icing and reducing the amount of fluid used for secondary deicing.

Some airports have instituted a departure slot allocation system to reduce delays caused by runway congestion and enable aircraft to depart immediately after being deiced. Using this system, air traffic control estimates the number of departures possible based on the particular weather conditions and assigns departure times (slots) to aircraft before they are deiced. Since the number of departures is normally reduced during snow and ice conditions, the available departure slots are usually allocated to airlines based on their percentage of the total flights scheduled that day. For example, on a typical day, the schedule may have 200 flights, with 70% of the departures by airline A, 25% by airline B, and 5% by airline C. If the departure rate is reduced to 20 aircraft every hour due to bad weather, then air traffic control will assign 70% of available departure slots (14 slots) to airline A, 25% (5 slots) to airline B, and 5% (1 slot) to airline C. This practice is particularly beneficial at large, congested airports where it enables airline operations personnel to coordinate the deicing of an aircraft with its allocated takeoff time.

One problem encountered by airports using the slot allocation system is the difficulty of enforcing compliance. While most airlines voluntarily comply with the slot allocation system, aircraft from some airlines start taxiing even though they have not been allocated a departure slot. For the slot allocation system to work effectively, air traffic control must police the system by denying errant aircraft takeoff clearance. Several airlines cancel inbound flights prior to or during severe weather conditions. This traffic flow strategy reduces the volume of fluid used by reducing the number of aircraft requiring deicing. For example, at General Mitchell International Airport in Milwaukee, Wisconsin, some airlines cancel flights and transport passengers by bus to nearby Chicago O’Hare International Airport.

**2.2.16 Personnel Training and Experience**

An important factor affecting the efficiency of aircraft deicing/anti-icing operations is the training and experience of personnel involved in aircraft deicing/anti-icing. Most airlines and FBOs do not have employees dedicated to aircraft deicing/anti-icing and use ground operations personnel (e.g., baggage handlers, mechanics) or hire temporary staff. Due to low pay and poor working conditions, employee turnover is typically high. Consequently, a large portion of aircraft deicing/anti-icing staff, particularly at larger airports, is newly hired and trained each year. Due to inexperience and concerns about the consequences of inadequate deicing/anti-icing, new hires often spray more fluid than necessary. While the eight hours of FAA-mandated training received by new hires ensures the safe operation of aircraft, several years of experience may be necessary for an employee to become efficient at aircraft deicing/anti-icing. Well-trained and experienced deicing/anti-icing personnel improve the efficiency of aircraft deicing/anti-icing operations and minimize the volume of fluid used, while ensuring passenger safety.

The training and experience of airport personnel may also affect the efficiency of aircraft deicing/anti-icing operations. Airport personnel are typically responsible for clearing taxiways, gate areas, ramps, aprons, and deicing pads. When these areas are not adequately cleared, snow and ice accumulate on the undercarriage and the underside of aircraft during taxing and must be removed prior to takeoff. As a result, poor winter maintenance of airfields tends to increase the volume of aircraft deicing fluids applied by making it necessary to perform secondary aircraft deicing at departure runways.

**2.2.17 Other ADF Minimization Practices**

Additional sources of ADF discharges to the environment include spills from overfilling deicer truck tanks and leaks from worn or defective fittings on deicer trucks and other application equipment. These sources of ADF can be greatly reduced by equipping deicer trucks with dripless fittings and automatic filling shutoff valves. At Albany International Airport, all deicer trucks are required to be fitted with sight gauges and automatic filling shutoff valves that prevent tanks from being filled above 80% of their capacity. The cost of retrofitting existing deicer trucks was approximately $250 per truck.

Unnecessary releases of ADF to the environment can also be reduced by locating ADF storage tanks within the boundaries of the designated aircraft deicing/anti-icing collection and containment areas. At Denver International Airport, for example, deicer trucks are refilled from ADF storage tanks located on the aircraft deicing/anti-icing pads. Since the deicer trucks do not leave the containment area, any spills or leaks from defective fittings or overfilled tanks are collected along with the other ADF-contaminated storm water.

### 2.2.18 Glycol Minimization Methods Currently Under Development

Foster-Miller, Inc. is developing a surface treatment or coating that would provide anti-icing protection by preventing ice and snow from adhering to aircraft surfaces. Theoretically, this technology combined with the forced-air deicing system previously discussed  could greatly reduce the need for glycol-based ADFs by enabling snow and ice to be easily blown from aircraft surfaces. Foster-Miller is currently evaluating possible aircraft surface coatings.

Professor Victor Petrenko of Dartmouth's Thayer School of Engineering is developing an alternative deicing technique that uses electricity to loosen ice from aircraft surfaces. The electricity disrupts the orientation of surface water molecules, breaking bonds between the ice crystals and the metal substrate. Similar to the surface coatings discussed above, this method would rely on forced-air to blow snow and ice from aircraft surfaces. To date, the method has only been demonstrated in the laboratory using steel and other solid materials. Additional research will be necessary to determine whether the electrical current used to loosen the ice will interfere with sophisticated aircraft navigational equipment and electrical systems.

Polaris Thermal Energy Systems, Inc., in association with Transport Canada and Continental Airlines, is investigating the possibility of introducing heated fuel in wing fuel tanks to prevent frost, ice, and snow from forming on wing surfaces when the aircraft is on the ground. Polaris believes this method will be especially advantageous for MD-80s and DC-9s, where fuel stored under the wings tends to become super-cooled during flight, causing clear ice to form on the surface of the wings after the aircraft has landed. In preliminary tests conducted by Polaris and Transport Canada, the method has proven effective in minimizing the volume of deicing fluids required. One test, conducted by Polaris in March 1997, demonstrated that the method could, under certain weather conditions, eliminate the use of conventional glycol-based deicing fluids. The test was conducted at Cleveland's Hopkins International Airport using an MD-80 owned by Continental Airlines. The aircraft arrived at the airport at 1:08 a.m. with approximately 8,000 pounds of super-cooled fuel stored in its tanks. Polaris introduced 1,000 pounds of heated fuel (heated to approximately 85 F) into the aircraft's fuel tanks at 2 a.m. Polaris monitored the wing temperature using infrared photography and found the surface temperature rapidly increased by 10 F. Additional heated fuel was added at 2:20 a.m. and 3:00 a.m., raising the average wing surface temperature to 79 F. Although the ambient temperature was about 18 F and a light to heavy snow fell during the early morning hours, the aircraft did not need deicing with conventional fluids prior to its scheduled 7:40 a.m. departure. Polaris estimates the cost of heating the fuel was approximately $40. While this method may reduce discharges of ADF to U.S. surface waters by reducing the overall volume of ADF applied to aircraft, it may result in additional cross-media impacts (e.g., increased air emissions). Table 3.1 shows a summary of the fluid minimization methods that were discussed.

Table 3.1 Fluid Minimization Methods.

| Method | Advantages | Disadvantages | Airport | Airline |
|---|---|---|---|---|
| Type IV Anti-Icing Fluids | ▪ Longer Hold over time (70mins)<br>▪ Reduce the usage of D.I fluids<br>▪ Used by most US carriers | ▪ Possibility of increased airfield contamination | | |
| Preventive Anti-icing | ▪ Reduction in glycol based fluids applied to aircraft.<br>▪ Reduce deicing time | ▪ May degrade aircraft parts when left on for extended periods. | | |
| Hybrid De-Icing Systems | ▪ Reduce volume of ADF by 85% | ▪ High velocity may injure ramp personnel or damage aircraft parts | ▪ General Mitchell<br>▪ Brunswick Naval Air Station | ▪ Delta<br>▪ U.S. Navy |
| Computer Controlled Gantry Systems | | ▪ No widespread approval from industry<br>▪ Require relatively large capital investment and space | ▪ Munich, Germany<br>▪ Lulea, Sweden | |
| Infrared De-Icing Technology | ▪ Reduce Fluids by 90%<br>▪ Suitable for small to medium facilities not having significant congestion | ▪ Needs Space<br>▪ Concerns about processing capacity | ▪ Buffalo-Niagara<br>▪ Oneida County, WI<br>▪ Newark Intl. | |
| Aircraft Covers | ▪ Easy to Install | ▪ Not suitable for large passenger craft | | |
| Ice Detection | | | | US Air force<br>FedEx<br>Delta |
| | | | | |

## Chapter 3. Aircraft Deicer/Anti-icer Collection and Containment Methods

In response to EPA's 1990 storm water program and state and local requirements, many U.S. airports are collecting wastewater from aircraft deicing/anti-icing operations to prevent or minimize discharges at storm water outfalls. Airports use a variety of collection methods, including gate and ramp area drainage collection systems, storm sewer plugs, designated aircraft deicing pads, temporary aircraft deicing pads, storm drain valves, and specially designed glycol vacuum vehicles. Individual airports often rely on a combination of these collection strategies, varying the collection method to suit tenant requirements, utilize existing infrastructure, or adapt to site-specific constraints. Collected wastewater may then be processed to recycle/recover glycol, treated on site, discharged to a publicly owned treatment works (POTW), or a combination of these methods. The following subsections describe in detail the various wastewater collection methods used by the industry. Federal aid from the FAA-administered Airport Improvement Program may be used to finance construction of wastewater collection systems and storage facilities.

### 3.1 Aircraft Deicing Facilities

As airport authorities began to grapple with the problems of collecting wastewater from aircraft deicing operations and meeting NPDES permit limits, they soon realized that wastewater could be collected more efficiently by confining aircraft deicing operations to small, designated areas where provisions for containment and collection could be installed. As a result, several U.S. airports constructed specially designed aircraft deicing facilities called aircraft deicing pads. Denver International Airport, Salt Lake City International Airport, Pittsburgh International Airport, Baltimore Washington International Airport, Dayton International Airport, Minneapolis-St. Paul International Airport, and Detroit Metropolitan Wayne County Airport are currently using deicing pads.

In Canada, Toronto's L.B. Pearson International Airport and Montreal's Dorval International Airport have constructed large deicing facilities consisting of multiple deicing pads.

In general, aircraft deicing pads consist of a concrete or asphalt platform, a drainage collection system, and a wastewater storage facility. The platform is graded and sometimes grooved to channel wastewater to the drainage collection system. The collection system typically consists of trench or square drains connected to underground storm water pipes, which are usually fitted with diversion boxes to allow ADF-contaminated wastewater to be diverted to a wastewater storage facility during the deicing season. The wastewater is stored in detention ponds, tanks, or underground concrete basins. The pads are typically designed to accommodate more than one aircraft at a time and are usually divided into individual aircraft deicing bays. Some pads also include snow melters for disposal of ADF-contaminated snow collected on and around the deicing pad. The resultant wastewater is collected by the pad's drainage collection system and diverted to the wastewater storage facility.

Aircraft are deiced on the pads using conventional deicer trucks or fixed-boom applicators. To avoid collisions, deicer trucks are parked in designated areas when aircraft are entering or exiting the pad. Fixed-boom applicators are less popular with airlines and are known to be installed at only three aircraft deicing pads in the U.S. (one pad at Denver International Airport and two pads at Pittsburgh International Airport. When not being used for deicing, the pads often serve as aircraft parking aprons or holding pads.

Since most commercial aircraft are able to taxi prior to deicing and can be deiced with their engines running, aircraft deicing pads may, upon approval by FAA, be located on taxiways, on cargo or general aviation ramps, near departure runways, or adjacent to passenger terminals. The FAA recommends that pads should be constructed to accommodate the largest aircraft the airport serves (i.e., widest wingspan and longest fuselage) and should have sufficient capacity to handle peak periods of aircraft departures without causing departure delays.

Deicing pads may also require additional personnel for monitoring aircraft movements on the pad and managing wastewater collection. The number, location, and size of aircraft deicing pads required for a particular airport depends on the number of operations, the types of aircraft using the airport, the meteorological conditions typically experienced, the availability of land, and the physical layout of the airport. For some airports, deicing pads may be unnecessary due to efficient ADF-collection systems installed at the passenger terminals and cargo ramps.

The largest and most technologically advanced aircraft deicing pads are located in Canada at Montreal's Dorval International Airport and Toronto's L.B. Pearson International Airport. These airports have constructed centralized aircraft deicing facilities that include storage tanks and filling stations for aircraft deicing/anti-icing agents and control towers for monitoring deicing operations and controlling traffic flow. The Montreal pad accommodates up to seven aircraft at a time and has a laser guidance system to assist pilots in maneuvering and parking aircraft on the deicing pad (36).

The Toronto pad consists of four deicing bays, but is currently being expanded to

six bays. Once the expansion is completed, the deicing facility will be able to accommodate up to six Boeing 747s and will cover an area of 65 acres. Each deicing bay is approximately 328 feet wide and 780 feet long. A high-density polyethylene liner, installed underneath the deicing bays, collects any fluid that seeps through the concrete pad. Inset lighting assists pilots in positioning aircraft on the pad, while surveillance cameras are used to record activities on the pad. An electronic sign board system provides pilots with deicing operational information, minimizing verbal communication requirements. Wastewater from aircraft deicing/anti-icing operations is collected in 14 diversion vaults, which are equipped with automated diversion valves. A pump located in the bottom of each diversion vault pumps samples of the wastewater to a small, on-site laboratory, where the glycol concentration is measured. If the glycol concentration is less than the Canadian voluntary guideline of 100 mg/L, the wastewater is discharged through the storm water drainage system. If the glycol concentration is greater than 100 mg/L, the operator diverts the wastewater to one of three underground storage tanks. The storage tanks have a combined capacity of approximately 3.5 million gallons. The stored wastewater is either trucked to a glycol recycling plant or discharged to a local POTW.

Although the principal environmental advantage of deicing pads is their ability to collect a high percentage of the aircraft deicing fluid sprayed, the wastewater they collect has a high glycol content, an important advantage for airports considering glycol recovery/recycling. For example, at Denver International Airport, aircraft deicing pads collect wastewater with glycol concentrations of approximately 20 percent (20). By collecting wastewater with high glycol concentrations, Denver's aircraft deicing pads make its on-site glycol recycling economically viable. Aside from their environmental benefits, deicing pads provide several operational and safety advantages. First, they allow aircraft to move away from the gate area so that arriving flights have access to gates. Second, they allow for much more efficient spraying of aircraft, especially for aircraft with wide wing spans, such as the new Boeing 777. Third, they ease ramp and gate area vehicle congestion. Fourth, they improve safety and working conditions for baggage handlers, maintenance engineers, and other airline personnel working in the gate area. Finally, they improve passenger safety by enabling aircraft to be deiced closer to the departure runway, decreasing the time between deicing and takeoff and reducing the potential for an aircraft to exceed its holdover time. Despite these advantages, some airlines have been reluctant to use aircraft deicing pads. Airlines are primarily concerned that aircraft deicing pads may create a bottleneck, resulting in departure delays. To prevent unnecessary delays, the FAA recommends deicing pads be constructed with bypass taxiways that allow aircraft not requiring deicing to proceed without hindrance to active runways. Airports serving a wide range of aircraft types can often reduce congestion by constructing separate aircraft deicing pads for general aviation, cargo, commuter aircraft, and large passenger jets. For example, Pittsburgh International Airport has constructed five aircraft deicing pads: two for large passenger jets, one for cargo carriers, and two smaller pads for commuter aircraft.

Airlines also complain of congestion on aircraft deicing pads caused by the presence of deicer trucks from several different airlines. Currently, most passenger airlines deice their aircraft using their own deicer equipment. The presence of multiple deicer trucks increases the potential for collisions with aircraft or other airport vehicles. This problem can be solved by air carriers allowing their aircraft to be deiced by a single carrier or a fixed-based operator. At Dorval International Airport in Montreal, for example, aircraft deicing/anti-icing is performed exclusively by the airport's FBO, Aeromag 2000. Similarly, aircraft deicing/anti-icing at the L.B. Pearson International Airport's new central deicing facility is conducted by Hudson General Aviation Services, Inc. However, due to liability issues and concerns over equitable access to deicing pads, airlines often have difficulty agreeing on who should provide aircraft deicing services at deicing pads and which fluid formulations should be used. These issues are particularly difficult to resolve at airports that have no dominant carrier and a large number of competing airlines.

Although not limited to aircraft deicing pads, one environmental problem encountered by airports is the tracking of aircraft deicing and anti-icing fluids from the pad onto nearby taxiways and runways. This problem is caused primarily by fluids dripping from aircraft after they have left the deicing pad, but may also be caused by jet blast, drippage from aircraft undercarriages, and the wheels of airport vehicles carrying fluid across the pad's threshold.

For some airports, deicing pads may be impractical due to their physical size and capital and operational costs. The construction costs for aircraft deicing pads vary with the size and complexity of the system. For example, Denver International Airport constructed three deicing pads with drainage collection systems for approximately $2 million per pad. Dorval International Airport's pad, complete with storage facilities, new deicer equipment, laser guidance system and control tower, cost approximately $22 million.

**3.2 ADF Collection Systems for Ramps and Passenger Terminal Gate Areas**

At most airports, aircraft deicing operations are performed on aircraft parking ramps or at the passenger terminal gates. To collect wastewater generated at these locations, some airports have installed new collection systems or modified existing storm water drainage systems. The typical collection system consists of graded concrete pavement with trench or square drains connected to a wastewater storage facility via a diversion box. The storage facility may consist of detention ponds (covered or uncovered), tanks, or underground concrete basins. The diversion box allows uncontaminated storm water to be diverted to storm water outfalls.

The construction or modification of drainage collection systems with their associated underground piping, diversion boxes, and storage facilities can be extremely expensive, especially for larger airports that have several passenger terminals and a large number of gates. In addition to the expense, these projects are often disruptive to airline operations. Many U.S. airports already experience delays due to congestion, and temporary gate closures would exacerbate the situation. Similar to deicing pads, ADF may be tracked outside the containment area onto nearby runways and taxiways.

Because of the large drainage area typical of passenger terminals and aircraft parking ramps, large volumes of very dilute wastewater are collected. Airports located in urban areas may not have sufficient land available to construct storage facilities large enough to accommodate the volume of wastewater generated. The relatively low glycol concentrations typical of wastewater collected by these systems make glycol recycling/recovery difficult and expensive; however, low glycol concentrations can be an advantage to airports that discharge their wastewater to a POTW.

The principal advantage of installing ADF collection systems at aircraft parking ramps and passenger terminals is that they enable airports to collect wastewater from aircraft deicing and anti-icing without requiring airlines to alter their winter operating practices. Many airlines believe that deicing and anti-icing aircraft at these locations is an unavoidable part of winter operations, because aircraft can be damaged by taxiing prior to being deiced. For example, aircraft engines may be damaged by ingesting ice shed from aircraft surfaces during taxiing. Aircraft with engines mounted on the rear fuselage, such as the MD-80, are particularly at risk.

Consequently, most airports with deicing pads allow airlines to conduct some limited gate and ramp deicing. Several U.S. airports, such as Kansas City International, Greater Rockford, Bradley International, Minneapolis-St. Paul International, and Albany International, have installed new collection systems or modified existing storm water drainage systems to enable them to collect ADF-contaminated storm water from these areas.

Several example systems are described below. Additional information about ADF collection systems, including the systems used at Dallas-Ft. Worth International and Albany International

### 3.2.1 Temporary Aircraft Deicing Pads

Temporary aircraft deicing pads are specially designed platforms used to collect contaminated wastewater generated during aircraft deicing and anti-icing operations. They are constructed from reinforced rubber or polypropylene mats and sometimes use inflatable air or foam berms to contain contaminated wastewater. The temporary pads cost less than permanent structures, are portable, and can be assembled on taxiways close to departure runways. EPA does not know of any U.S. airports using this collection method.

### 3.2.2 Storm Drain Inserts

Storm drain inserts or plugs are used by some airports to close storm drains and prevent glycol-contaminated wastewater from entering storm water drainage systems. Some airports, such as Minneapolis-St. Paul International Airport, have designed their own inserts, while other airports use manufactured inserts. One company that manufactures storm drain inserts is AR Plus. This company

manufactures inserts that consist of a steel plate with a gate valve, a mounting bracket with sealing mastic, and a detachable valve driver. The inserts are mounted directly beneath the storm drain grate with the steel plate bolted to the mounting bracket. During periods of aircraft deicing/anti-icing, the valves are closed manually using the detachable valve driver, thereby preventing ADF-contaminated storm water from entering the storm water drainage system. The valves can be opened when deicing/anti-icing activities cease, allowing uncontaminated storm water to pass through the drain. The steel plate containing the valve is removed for maintenance by removing the bolts that attach the plate to the mounting bracket. AR Plus manufactures the inserts in standard valve diameters of 6, 8, and 10 inches. The 6-inch valve is the most commonly used. The inserts cost between $1,200 and $1,800 and have a life expectancy of approximately 7 years. AR Plus also manufacture custommade inserts for drains of unusual shape or size or to meet individual customer specifications.

Drain inserts are often used in conjunction with glycol vacuum vehicles to collect contaminated storm water. To enable the vacuum trucks to efficiently collect fluid retained above the insert, the drain inserts are typically mounted approximately 2 inches below the storm drain grate. Although the inserts may be mounted lower to allow the storm drains to be used as sumps, AR Plus does not recommend this practice because the valves are more difficult to inspect and maintain. In addition, residual ADF retained in the drain after evacuation may be washed into the storm water drainage system when the valve is opened. The inserts may also be used in an emergency to prevent fuel and other spills from entering storm water drainage systems. The sealant used in the inserts was specially selected for its chemical resistance to both glycol and aviation fuel.

In response to customer comments, AR Plus is currently developing a new system that will automate the valves so that an operator could close or open several valves by pushing a single button.

### 3.2.3 Glycol Vacuum Vehicles

Specially designed vacuum vehicles provide an alternative approach to the collection of wastewater generated by aircraft deicing/anti-icing operations. Vacuum vehicles offer a number of advantages over traditional collection systems: they are versatile, enabling wastewater to be collected at gate areas, ramps, aircraft parking aprons, taxiways, and aircraft holding pads; they are cost-effective, enabling airports to avoid the high capital costs of installing traditional drainage collection systems or deicing pads; and they can collect spent aircraft deicing fluid in high concentrations, making glycol recovery/recycling economically feasible. Critics of vacuum vehicles state that they are slow moving, have insufficient collection capacity, require regular maintenance by trained personnel, and cause ramp and gate area congestion. Some airports also believe that the airport-wide use of vacuum vehicles is impractical and prohibitively expensive for airports with high traffic volumes because a large number of units would be necessary to efficiently collect the wastewater generated.

Vacuum vehicles are typically used in conjunction with storm drain inserts or valves that prevent ADF-contaminated storm water from entering storm water drainage collection systems. The contaminated storm water ponds around the closed drain grates or surface depressions and vacuum vehicles collect the ponded fluid. Aircraft parking ramps and gate areas must be cleared of snow prior to vacuum vehicle use, since collecting large quantities of clean snow along with contaminated storm water significantly lowers the efficiency of vacuum vehicles.

Several U.S. airports currently use vacuum vehicles, including Minneapolis-St. Paul International Airport, Baltimore Washington International Airport, Indianapolis International Airport, Bradley International Airport, Portland International Airport, Washington Dulles International Airport, Ronald Reagan Washington National Airport, and General Mitchell International Airport. The U.S. Air Force has also experimented with glycol vacuum vehicles and currently uses them at several bases. During deicing operations most military aircraft must be deiced prior to starting their engines; therefore, military aircraft are typically deiced where they are parked. For the military, glycol vacuum vehicles represent a low-cost collection alternative to the installation of expensive underground drainage collection systems for large aircraft parking ramps. Suppliers of specialized glycol vacuum vehicles for the collection of aircraft deicing fluids include Vactor Manufacturing, Tennant, Tymco, and VQuip/AR Plus.

## Chapter 4. Airport Correspondence

In order to receive practical information about the efficiency and feasibility of the fluid minimization and containment methods previously discussed, it was necessary to communicate with different airports. The following airports were contacted.

- Washington Reagan
- Washington Dulles
- JFK
- Newark International (EWR)

A reply was received only from the Washington Airports.

Efforts were also made to contact official at the Rhode Island Airport Corporation. This was necessary to receive information about current fluid mitigation practices at TF Green. In order to further analyze or recommend mitigation methods that were researched it was important to know what methods were being practiced at TF Green. An official from RIAC replied and requested answers to specific questions she had about the project. These questions were addresses after which no further contact was received.

Attached below is a copy of the e-mail that was received from our efforts to contact the airports and RIAC:

**Washington, D. C. Dulles:** ***Inquiry Regarding Deicing Chemicals and Recovery Practices Used at Ronald Reagan Washington National Airport***

*Thank you for your inquiry regarding usage of deicing chemicals at Ronald Reagan Washington National Airport (DCA). You need to be aware that the FAA strictly controls the types of deicer fluids and their application for both aircraft and for control of snow and ice on runways and taxiways. Only deicing chemicals or techniques approved by the FAA can be used.*

*The Airport has been using potassium acetate as a liquid runway deicer for over a decade. DCA was among the first commercial airports in the U S to cease using ethylene glycol as a liquid runway deicer. While liquid potassium acetate is the primary chemical used for runway deicing, weather conditions occur where the use of a solid deicer is necessary. The Airport uses primarily sodium acetate for this purpose, although urea is used as an alternative. Reliance on urea has diminished in recent years due to its less desirable environmental impacts and its poor storage characteristics. Only urea and sodium acetate are approved by the FAA as solid forms of runway deicer. DCA owns and uses state-of-the-art, computer controlled chemical application equipment to minimize the potential for over application of all runway deicer products, both for environmental and cost control.*

*The airlines operating flights into and out of DCA provide deicing for the aircraft. All airlines at DCA use only propylene glycol for aircraft deicing. The airlines use both Type I and Type IV fluid at DCA. The Type I fluid is typically mixed with water at a ratio of 50-50, where the Type IV is used full strength. The greatest volume of deicing fluid used is the Type I propylene glycol. The majority of the airline deicing application vehicles use state-of–the–art fluid application equipment to minimize over application.*

*DCA operates under an EPA storm water permit for discharge of storm water containing deicing fluids. Under the conditions of the permit, DCA must provide best management practices (BMPs) for control and recovery of the deicing fluid. DCA uses a combination of glycol recovery vehicles which vacuum up the spent fluid, deicing pads with drainage collection and drain blockers to control the discharge of fluid into the storm drains. The recovered fluid is then processed, concentrated and sold as recycled antifreeze. We have found these management practices to be effective in reducing the environmental impact of the deicing fluids to the environment.*

# Information Transfer Program

# Student Support

| Student Support | | | | | |
|---|---|---|---|---|---|
| **Category** | **Section 104 Base Grant** | **Section 104 RCGP Award** | **NIWR-USGS Internship** | **Supplemental Awards** | **Total** |
| **Undergraduate** | 2 | 0 | 0 | 0 | 2 |
| **Masters** | 3 | 0 | 0 | 0 | 3 |
| **Ph.D.** | 0 | 0 | 0 | 0 | 0 |
| **Post-Doc.** | 0 | 0 | 0 | 0 | 0 |
| **Total** | 5 | 0 | 0 | 0 | 5 |

# Notable Awards and Achievements

The Director of the RI Water Resources Center was able to use the resources of the Center to help prepare a proposal submitted to the the Department of the Interior for the creation of a laboratory that could be used for teaching and training in the area of drinking water treatment. This grant was awarded and $132,000 was made available. The resources of the Center are being used to select the equipment. This laboratory will allow the Center to conduct outreach by allowing hands on experience in the operation of water treatment processes.

The RIWRC was active in supplying technical information to Senator Chaffee's staff on the importance of the RIWRC to Rhode Island. Based upon this input, Senator Chaffee became the lead sponsor of the reauthorization of the bill establishing the water resource centers.

# Publications from Prior Projects


1. 2003RI15B ("A Preliminary Web Portal for RI Water Resources ") - Conference Proceedings - Boving, T., DelSesto, D., Fastovsky, D., 2004: A Preliminary Web Portal for RI Water Resources. Poster presentation at the Annual meeting of the Geological Society of America, Denver, November 11, 2004. Session 243 Hydrogeology, Abstract pg. 562.
2. 2002RI1B ("Hydrologic Relational Database for Rhode Island") - Articles in Refereed Scientific Journals - Veeger, A.I., Murray, D.P., Hermes, O.D., Boothroyd, J.B., Hamidzada, N., 2004, Harnessing the power of relational databases for managing subsurface geotechnical and geologic data: Environmental and Engineering Geoscience, vol. 10, no. 4, pp 339-346.
3. 2002RI1B ("Hydrologic Relational Database for Rhode Island") - Articles in Refereed Scientific Journals - Veeger, A.I., Murray, D.P., Hermes, O.D., Boothroyd, J.B., Hamidzada, N., 2003, Geographic information system-based digital catalog for managing subsurface geotechnical and geologic data: Transportation Research Record, no. 1821, pp. 90-96.
4. 1999RI02 ("Isotope Hydrology Investigation of the Pawcatuck Watershed") - Conference Proceedings - Meritt, D.L., and Veeger, A.I., 2002, Anthropogenic influence on the water chemistry of the Upper Wood River Basin, Rhode Island, USA, [abstr.] in Abstracts with programs, 37th

Annual Meeting Northeastern Section Geological Society of America, vol. 34, no. 1, p. A-64.

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