

**User Manual**  
**Standalone Decision Support Tool for Risk-**  
**based Watershed Health Management and**  
**TMDL Assessment.**

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## Abstract

In the United States, several federal and state agencies are involved in collecting water quality data from stream networks and performing different analyses. However, as the available water quality (WQ) data are usually sparse in time, it is often necessary to reconstruct the WQ time series using surrogate variables such as streamflow before they can be used in other analyses. In collaboration with U.S.EPA NRMRL, a web-based tool has been developed to allow users to reconstruct WQ time series for any constituent (e.g. sediments, nitrogen, phosphorus, etc.) using user inputs in the form of formatted continuous streamflow and WQ data files. The tool uses LOADEST equations in conjunction with relevance vector machine to provide estimates of model error associated with each reconstructed point. The tool enables users to view and download plots and text files of reconstructed water quality loads and other statistical measures. The reconstructed water quality time series and the associated error information can then be used in several applications. The tool shows two such applications: (i) risk-based watershed health assessment and (ii) risk-based TMDL assessment. In the case of watershed health assessment, reconstructed data are compared to established standards to determine if violations have occurred. The frequency and severity of water quality violations are then used to compute risk measures such as reliability, resilience, vulnerability (R-R-V), and watershed health. The associated uncertainty in the risk measures can be viewed in the form of plots and tables. For TMDL assessment, the reconstructed series are compared with target TMDL concentrations and number of permissible violations (e.g. 10% violations, 3 in 100 violations etc., usually set by EPA and other state agencies), and then plots of probability of non-compliance for different levels of load reduction (or increase) and permitted violations are shown. It is expected that this web-based tool will serve as a first stop for the scientific community, regulators, and decision makers for evaluating ecologic and hydrologic risk, and implementing better management practices.

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# Standalone Decision Support Tool

## Introduction:

The standalone decision support tool (DST) can be accessed by users through a *web browser*. The tool allows users to reconstruct water quality (WQ) time series for any constituent (e.g. sediments, nitrogen, phosphorus, etc.) using formatted (comma separated values or CSV and tab-delimited) input files of continuous streamflow and observed WQ data (usually sparse) from any sampling location around the world. The tool uses LOADEST equations in conjunction with relevance vector machine to provide estimates of model error associated with each reconstructed point (Hoque et al., 2012). The tool also enables users to view and download plots and text files of reconstructed water quality loads and other statistical measures. This output can then be used in any application.

The tool shows examples of two applications. The first application involves risk-based watershed health assessment where measures of reliability, resilience, vulnerability (R-R-V; Hoque et al., 2012) and watershed health are computed for user defined numerical target (or standard) of the water quality constituent being analyzed. The results can be viewed on the web browser in form of tabular summaries, and the uncertainty in the estimates of these risk measures can be viewed using histograms. For mathematical details we refer the reader to Hoque et al. (2012), however we present a brief description:

Suppose,  $X_t$  is the daily reconstructed time series of a water quality parameter with standard numerical target  $X^*$ , then using the definitions of risk measures given by Hashimoto et al. (1982) and Hoque et al. (2012), reliability ( $\rho$ ) is defined as the probability of the system to be in compliant state.

$$\rho = 1 - P\{X_t \in F\} = 1 - \frac{1}{n} \sum_{t=1}^n z_t \quad (1)$$

where  $z_t = 1$  when  $X_t \in F$  and 0 when  $X_t \in S$ , and  $n$  is the total number of data points. Also,  $S: \{X_t \leq X^*\}$  is safe/compliant state and  $F: \{X_t > X^*\}$  is failed/noncompliant state.

Resilience ( $r$ ) is defined as the probability of the system to recover from a non-compliant state.

$$r = P\{X_{t+1} \in S | X_t \in F\} = \frac{P\{X_{t+1} \in S \cap X_t \in F\}}{P\{X_t \in F\}} = \frac{\sum_{t=1}^n y_t}{\sum_{t=1}^n z_t} = \frac{l}{m}$$

$$r = 1 \text{ when } X_t \in S \text{ for all } t \quad (2)$$

where  $y_t = 1$  when  $X_{t+1} \in S$  and  $X_t \in F$  and 0 otherwise, and  $m$  is number of times where  $X_t > X^*$  or  $m = \sum_{t=1}^n z_t$ , and  $l = \sum_{t=1}^n y_t$ .

Vulnerability is defined as the magnitude of damage during a noncompliant event. For water quality violations in stream networks there is no objective way in which magnitude of damage can

be quantified. Hoque et al. (2012) have computed vulnerability by quantifying magnitude of violations with respect to a chosen standard. These resulting vulnerability measures did not scale from 0 to 1. Therefore, in this study we have proposed a new metric – opposite of vulnerability – that scales between 0 and 1, and can be mathematically defined as the exponent of the negative of the sample mean of log normalized ratio of  $X_t$  to the standard value as follows

$$v = \exp \left\{ -\frac{1}{m} \sum_{t=1}^n \ln \left[ \frac{Q_t X_t \Delta t}{Q_t X^* \Delta t} \right] H[X_t - X^*] \right\} \quad (3)$$

where  $m$  is number of times where  $X_t > X^*$ ,  $Q_t X_t \Delta t$  is the water quality load at time  $t$ ,  $Q_t X^* \Delta t$  is the standard water quality load at time  $t$  and  $H[.]$  is the Heaviside function that accounts only for the noncompliant events. When the deviations of  $X_t$  from  $X^*$  are large  $v \rightarrow 0$ ; when deviations are small  $v \rightarrow 1$ , which is consistent with definitions for reliability ( $\rho$ ) and resilience ( $r$ ). Vulnerability can now be quantified as:

$$V = 1 - v \quad (4)$$

We now define a conservative composite measure of watershed health ( $h$ ) as:

$$h = (\rho r v)^{\frac{1}{3}} \quad (5)$$

If  $\rho = r = v = 1$ ,  $h = 1$ , if either one is 0,  $h = 0$ , i.e. the drainage area is healthy when all risk measures are high, otherwise it is not.

The second application of reconstructed WQ time series is for risk-based TMDL analysis. Here, the reconstructed WQ series are compared with user-specified target TMDL concentration to compute the probability of complying with this target concentration for different levels of load reduction (or increase) and for a given limit of permissible violations (e.g. 10% violations, 3 in 100 violations etc., usually set by EPA and other state agencies). These results are then shown in the form of tables and plots.

Let  $C^*$  be the user defined numerical target (in mg/l or ug/l) for TMDL. We then define the probability of compliance ( $K$ ) to permissible violations ( $p$ ) as:

$$K = P[c_p < C^*] \quad (6)$$

where  $c_p = F^{-1}[1 - p]$ , is the inverse CDF of reconstructed WQ concentration time series evaluated at  $1 - p$ , and  $p$  is the permissible violations in percentile (5%, 10%, 15%, 20% etc.) or frequency (3 in 30, etc.). The probability of non-compliance ( $\beta$ ) is therefore defined as:

$$\beta = 1 - K \quad (7)$$

The graphical representation of risk-based TMDL analysis is shown in Figure 1.

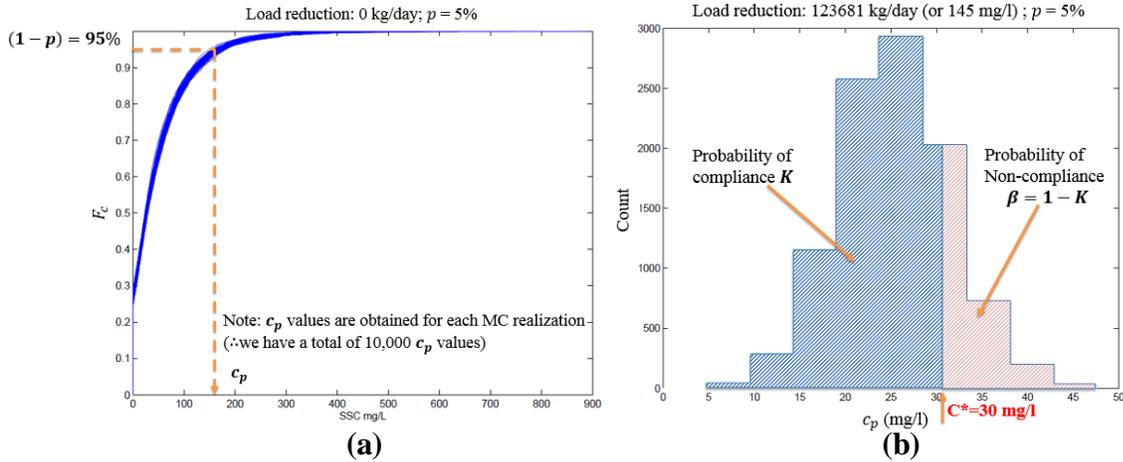


Figure 1: Graphical representation of risk based TMDL analysis for suspended sediment concentration (SSC) with a user defined target TMDL concentration ( $C^*$ ) of 30 mg/l. (a) calculating  $c_p = F^{-1}[1 - p]$  for the original reconstructed series (i.e. no load or concentration reduction) when  $p = 5\%$ , and (b) calculating probability of compliance ( $K$ ) from  $c_p$  values that were obtained after a constant concentration reduction of 145 mg/l from the original reconstructed WQ time series.

### System Requirements

- An active internet connection is required for using the standalone tool.
- A web browser (e.g. Chrome, Firefox, Internet Explorer) to access the standalone tool [website](https://engineering.purdue.edu/WaterDST/StandAloneTool/).

### Accessing the Standalone DST

Users can access the tool from the URL

(<https://engineering.purdue.edu/WaterDST/StandAloneTool/>) as shown in Figure 2.

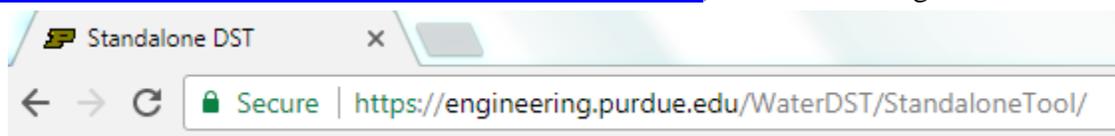


Figure 2: Entering the URL in the web browser.

### Standalone tool User Interface

This will load the standalone tool user interface (see Figure 3). The interface consists of a header section that contains the page title along with four navigation buttons that redirect the user to other relevant webpages. The main layout of the standalone tool consists of a form that allows the user to upload pre-formatted streamflow and water quality data files, and specify other necessary inputs such as units of measurement, watershed area ratio, choice of LOADEST regression equation (Runkel et. al., 2004), numerical target for risk-based watershed health assessment, and target concentration for risk-based TMDL analysis. When the user clicks on the *Submit* button provided

at the end of the form, MATLAB computations are carried out on the server. Once the results are available, they are displayed on the web browser in the form of tables and plots.

Standalone DST

Secure | <https://engineering.purdue.edu/WaterDST/Stan>

## Water quality reconstruction, IMDL, and R.R.V. computations using your own data

[Refresh page](#) [User Manual](#) [Try our web-based DST](#) [Bibliography](#)

This web interface allows the user to use pre-formatted inputs of streamflow and water quality measurements to reconstruct WQ loads and other relevant risk measures.

### User Inputs

Provide streamflow and water quality measurements as separate CSV files.

Streamflow data (Sample streamflow file)  
Browse...

Units of measurement for streamflow  
1) cfs (cubic feet)

Watershed area ratio  
1

Water quality data (Sample water quality file)  
Browse...

Water quality input or standard units  
1) mg/L (millig)

LOADEST regression equation number  
1)  $a_0 + a_1 \ln Q$

Water quality standard  
(in units selected above)  
1

Target concentration for TMDL  
(in units selected above)  
1

Submit

Copyright © 2017, Purdue University, all rights reserved. The U.S. Environmental Protection Agency through its Office of Research and Development funded the research (Contract Number: EP-C-15-010). This support is acknowledged. Any opinions, findings, and conclusions or recommendations expressed by this tool are those of the authors and do not necessarily reflect the views of the U.S. Environmental Protection Agency.

Figure 3: Loading page for the standalone decision support tool.

### Navigation Menu

Navigation buttons are located in the header section of the web page. The *User Manual* button allows the user to download a PDF version of the user manual. The *Try our web-based DST* button redirects to the DST with Google maps interface that allows users to reconstruct water quality data for constituents monitored at USGS Water Quality stations and USGS National Water Quality Assessment (NAWQA) Program stations and perform risk-based watershed health assessment. The *Bibliography* button opens a new web page containing the relevant citations used in developing the standalone tool.

## User Inputs to the standalone tool

The user-inputs required by the tool are listed in Table 1.

Table 1: List of inputs required by the tool with their format

| Input                         | Format           |
|-------------------------------|------------------|
| Streamflow data               | CSV or Text file |
| Units of streamflow data      | -                |
| Watershed area ratio          | Numeric          |
| Water-quality data            | CSV or Text file |
| Units of streamflow data      | -                |
| LOADEST equation              | -                |
| Water-quality standard        | Numeric          |
| Target concentration for TMDL | Numeric          |

The file containing the streamflow data has to be browsed in the local directories of the user's system. Click on the *Browse* button provided under *Streamflow data* menu (Figure 4).

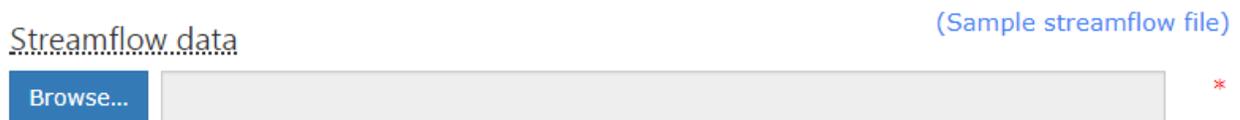


Figure 4: Streamflow data menu allows users to upload pre-formatted streamflow data file.

Upon clicking the *Browse* button, a file navigation window is shown (Figure 5a). Browse through the local directories and select the file (\*.csv, \*.txt or \*.dat) file that contains pre-formatted streamflow data. Figure 5b shows one such pre-formatted (csv) streamflow data file. The first column represents the year of streamflow measurement in YYYY format, second column represents the month in MM format, third column represents the day of measurement in DD format, followed by the numeric value of streamflow recorded for that day. The sample input file shown in Figure 5b can be downloaded by clicking on *Sample streamflow file* link.

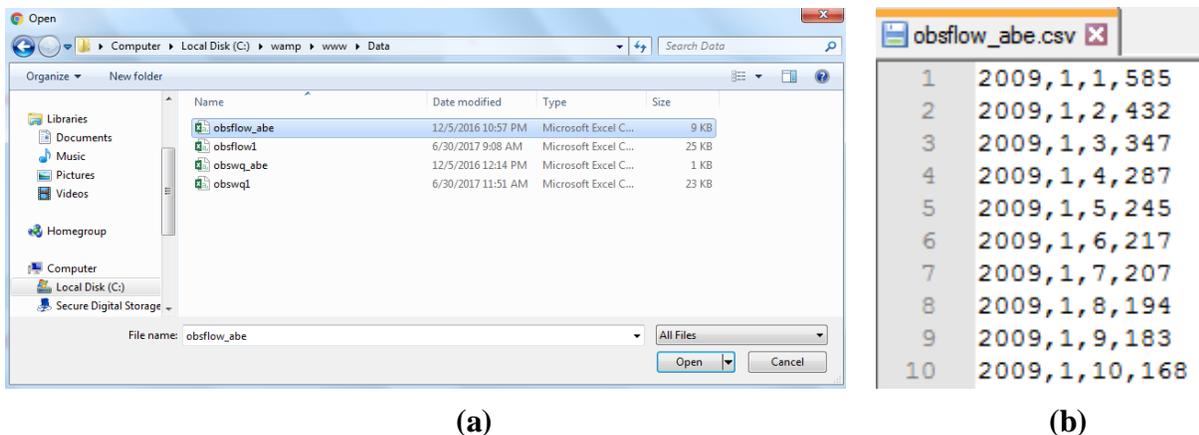


Figure 5: (a) File navigation window. (b) pre-formatted streamflow data file.

The next menu is *Units of measurement for streamflow* (Figure 6). Using the dropdown the user can specify the units of streamflow measurement for the data (data in the fourth column) uploaded in the previous step. Two units of measurement are available through the dropdown: 1) *cubic feet per second (cfs)* and 2) *cubic meters per second (cms)*.

### Units of measurement for streamflow

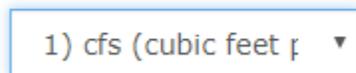


Figure 6: Dropdown for selecting *units of measurement for streamflow*.

*Watershed area ratio* menu allows users to enter a numeric value that represents the conversion factor for streamflow (numeric value > 0.01). This is useful when the water quality sampling station is not co-located with the streamflow gauge. Therefore, the flow at the ungauged sampling site can be calculated [according to](#):

$$Q_u = \left( \frac{A_u}{A_g} \right)^b Q_g$$

where  $Q_u$  is the flow at the ungauged water quality sampling site that is of interest,  $A_u$  is the drainage area to the ungauged sampling site,  $Q_g$  is the known streamflow at the streamflow gauge (data for this gauge is uploaded using the *Streamflow data* menu),  $A_g$  is the drainage area for the streamflow gauge, and  $b$  is the exponent that varies with region, but can be assumed to be equal to one when unknown. The *Watershed area ratio* menu expects users to input the conversion factor  $\left( \frac{A_u}{A_g} \right)^b$  for obtaining streamflow at the ungauged sampling site. When streamflow measurements are available at the water quality sampling site, this conversion factor will be equal to one. When the sampling site is located upstream of a streamflow gauge, the conversion factor will be less than

one. Similarly, when the sampling site is located downstream of a streamflow gauge, the conversion factor will be greater than one.

**Watershed area ratio**

\*

Figure 7: Watershed area ratio.

The user then clicks on the *Browse* button under *Water quality data* menu (Figure 8a), and selects a pre-formatted water quality input data file using the file navigation window (Figure 8b). This file may be a comma-separated value file (\*.csv) or a tab-delimited file (\*.dat or \*.txt). The first three column comprises of year (YYYY), month (MM), and day (DD) of water quality measurement. The fourth column (see Figure 8c) represents the magnitude of water quality measurement (floating point value). The water quality observations available in this file are usually not continuous in time, however their dates should coincide with the streamflow observation records (see Figure 5). The sample input file shown in Figure 8b can be downloaded by clicking on *Sample water quality file* link.

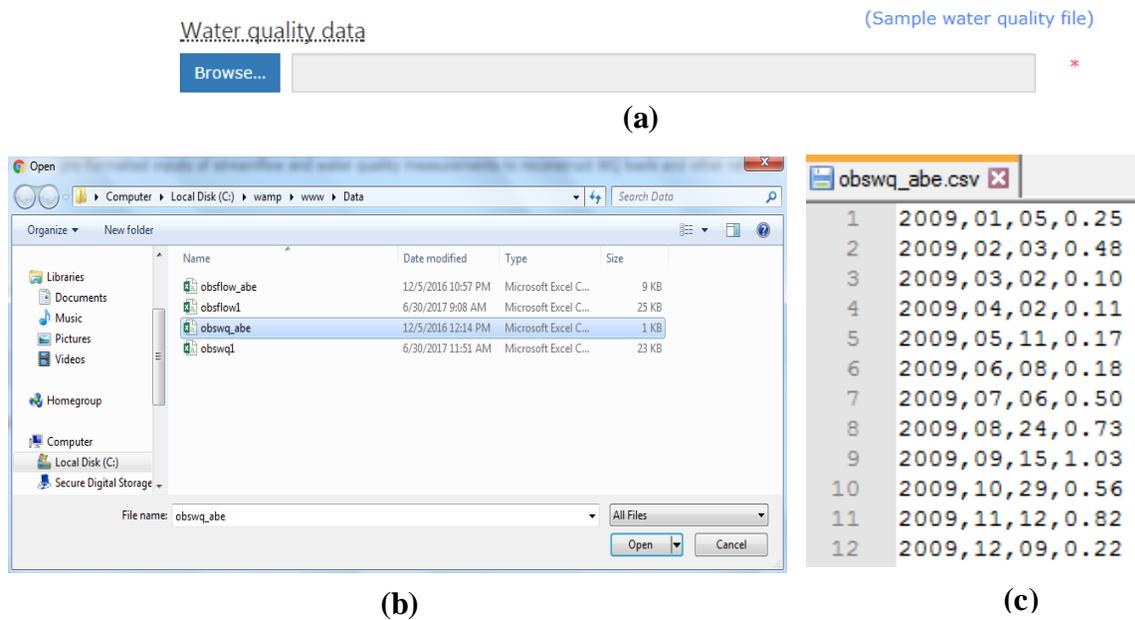


Figure 8: (a) Water quality data menu, (b) File navigation window, (c) pre-formatted water quality data file.

Once the water quality data file has been selected, the user has to specify the units for the WQ measurements available in the file. To do so, use the dropdown menu (Figure 9) under *Water quality input or standard units*. Two choices are available: 1) *milligram per liter (mg/l)* and 2)

*microgram per liter (ug/l)*. The units chosen here also apply for user inputs provided under *Water quality standard* and *Target concentration for TMDL* menus (Figure 11).

### Water quality input or standard units



Figure 9: Menu to specify the units for Water quality input, Water quality standard, and Target concentration for TMDL.

The user then selects the *LOADEST regression equation number* using the dropdown menu (Figure 10) that consists of nine regression equations used for water quality reconstruction (Runkel et al., 2004; Hoque et al. 2012).

### LOADEST regression equation number



Figure 10: Menu for selecting LOADEST regression equation.

The user then specifies two numeric inputs – *Water quality standard* to be used in risk-based watershed health assessment (Figure 11a), and *Target concentration for TMDL* used in risk-based TMDL analysis (Figure 11b). The units for both these inputs are same as those specified for water quality data input file (see Figure 9).

### Water quality standard

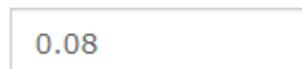
(in units selected above)



(a)

### Target concentration for TMDL

(in units selected above)



(b)

Figure 11: Input fields for (a) *Water quality standard* and (b) *Target concentration for TMDL*

This completes the data entry. The user then clicks the *Submit* button, following which MATLAB computations are carried out on the server. A notification window is displayed to the user that shows the current status of MATLAB computation (Figure 12). When the MATLAB computations are complete, the notification window closes and the results are displayed in the web browser in form of tables and plots (discussed in the next section). This notification window also contains a

button that allows users to *Cancel Matlab Computation*. When the users click this button, the MATLAB computations are aborted on the server, and as a consequence no results are available for display in the browser. If there are errors in user-provided inputs or files, appropriate error messages are displayed in the browser. The user can then resolve the errors based on the messages displayed and re-*Submit* the form.

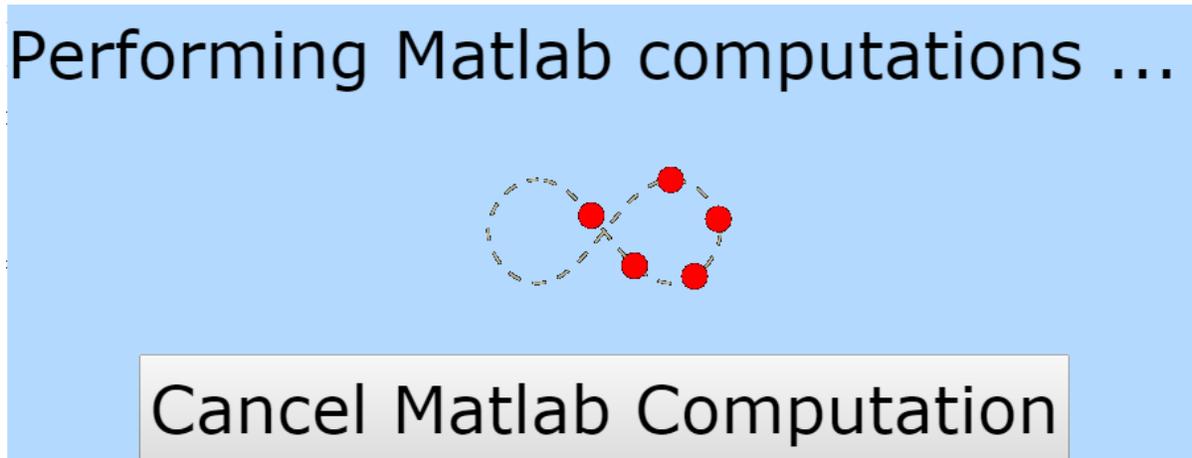


Figure 12: Notification window upon clicking *Submit* button.

### Visualize Results in the DST

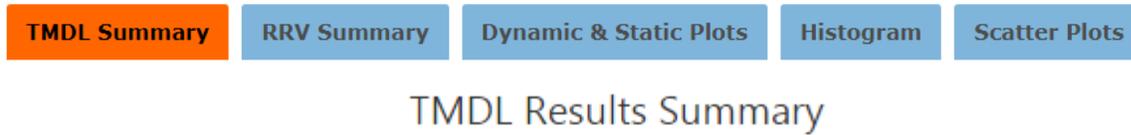
Once MATLAB computations are complete the message box (Figure 12) closes automatically, and the results are now available in the web browser for visualization. A list of outputs along with their brief description has been provided in Table 2. Upon scrolling down the web page, five tabs named as *TMDL Summary*, *Results Summary*, *Dynamic & Static plots*, *Histogram*, and *Scatter Plots* are visible to the user. The current active tab has an orange background color, while the dormant tabs have a blue background (see Figure 17). The user can switch between tabs by clicking on them.

Table 2: A list of outputs and their brief description

| Output                 | Format      | Brief description   |
|------------------------|-------------|---|
| TMDL summary           | Table       | Estimated load, TMDL and average load reduction to meet the TMDL criterion are recorded                               |
|                        | Table       | List of percentage compliance with different values of permissible violations and load and concentration reduction    |
|                        | Two figures | Probability of non-compliance against load and concentration reduction for different values of permissible violations |
| RRV summary            | Table       | Mean and standard-deviation of R-R-V and watershed health metrics   |
|                        | Table       | Goodness of fit for all nine LOADEST equations  |
| Dynamic & Static plots | Two plots   | Reconstructed WQ time-series with uncertainty band and user-input streamflow and WQ data                              |
| Histogram              | Plots       | Histograms of R-R-V and watershed health metric   |
| Scatter plots          | Plots       | Observed vs. mean-predicted WQ data for all nine LOADEST equations  |

### TMDL Summary

The *TMDL Summary* tab (Figure 13) displays the average daily (kg/day) and average annual (kg/year) values of (i) estimated WQ load, (ii) TMDL based on user specified target concentration, and (iii) average load reduction required to meet TMDL.



| Statistic                           | Average daily value (kg/day) | Average annual value (kg/year) |
|-------------------------------------|------------------------------|--------------------------------|
| Estimated Load                      | 156.2                        | 56997.7                        |
| TMDL                                | 94.2                         | 34382.6                        |
| Average Load reduction to meet TMDL | 62.0                         | 22615.0                        |

Figure 13: *TMDL Summary* tab. Tab with orange background is active while the tabs with blue background are dormant.

Below the *TMDL results summary* table, *TMDL compliance summaries* for *constant load reduction case* are provided (Figure 14). The first column of this table lists possible magnitudes of constant load reduction over time. It is assumed that this load reduction is achieved only through concentration reduction, while the flow remains unchanged. The remaining columns in the table represents the percentage compliance ( $K$ ) of reconstructed WQ load series with respect to user defined *target TMDL concentration* (Figure 11b), for different levels of violations permitted ( $p$ ) by regulatory agencies (e.g. state environmental agencies such as IDEM or federal agencies such as EPA).

TMDL Compliance Summaries  
CASE - constant load reduction

| Load Reduction (kg/day) | K (when p = 5%) | K (when p = 10%) | K (when p = 15%) | K (when p = 20%) |
|-------------------------|-----------------|------------------|------------------|------------------|
| 120.0                   | 0.00%           | 0.00%            | 0.00%            | 0.00%            |
| 126.3                   | 0.00%           | 0.00%            | 0.00%            | 0.00%            |
| 132.6                   | 0.00%           | 0.00%            | 0.00%            | 0.00%            |
| 138.9                   | 0.00%           | 0.00%            | 0.00%            | 0.59%            |
| 145.3                   | 0.00%           | 0.00%            | 0.00%            | 17.27%           |
| 151.6                   | 0.00%           | 0.00%            | 0.36%            | 73.98%           |
| 157.9                   | 0.00%           | 0.00%            | 12.59%           | 98.91%           |
| 164.2                   | 0.00%           | 0.05%            | 62.98%           | 100.00%          |
| 170.5                   | 0.00%           | 1.93%            | 96.33%           | 100.00%          |
| 176.8                   | 0.00%           | 24.52%           | 99.93%           | 100.00%          |
| 183.2                   | 0.00%           | 74.11%           | 100.00%          | 100.00%          |
| 189.5                   | 0.16%           | 97.47%           | 100.00%          | 100.00%          |
| 195.8                   | 3.99%           | 99.96%           | 100.00%          | 100.00%          |
| 202.1                   | 26.50%          | 100.00%          | 100.00%          | 100.00%          |
| 208.4                   | 68.59%          | 100.00%          | 100.00%          | 100.00%          |
| 214.7                   | 93.39%          | 100.00%          | 100.00%          | 100.00%          |
| 221.1                   | 99.43%          | 100.00%          | 100.00%          | 100.00%          |
| 227.4                   | 99.97%          | 100.00%          | 100.00%          | 100.00%          |
| 233.7                   | 100.00%         | 100.00%          | 100.00%          | 100.00%          |
| 240.0                   | 100.00%         | 100.00%          | 100.00%          | 100.00%          |

Figure 14: For user-defined target TMDL concentration and a threshold of acceptable violations ( $p = 5\%$  or  $10\%$  or  $15\%$  or  $20\%$ ), TMDL compliance ( $K$ ) summaries are computed at different levels of constant load reductions.

The tool also shows tabular results of *TMDL compliance (K)* for *constant concentration reduction case* (Figure 15). Here we assume that reconstructed WQ concentration series are reduced by a constant magnitude (see first column in Figure 15). The columns describing percentage compliance ( $K$ ) are interpreted in the same manner as described before.

TMDL Compliance Summaries  
CASE - constant concentration reduction

| Concentration Reduction | K (when p = 5%) | K (when p = 10%) | K (when p = 15%) | K (when p = 20%) |
|-------------------------|-----------------|------------------|------------------|------------------|
| 0.40                    | 0.00%           | 0.00%            | 0.00%            | 0.00%            |
| 0.45                    | 0.00%           | 0.00%            | 0.00%            | 0.15%            |
| 0.51                    | 0.00%           | 0.00%            | 0.00%            | 22.20%           |
| 0.56                    | 0.00%           | 0.00%            | 0.06%            | 91.34%           |
| 0.62                    | 0.00%           | 0.00%            | 7.53%            | 99.99%           |
| 0.67                    | 0.00%           | 0.00%            | 63.80%           | 100.00%          |
| 0.73                    | 0.00%           | 0.13%            | 98.23%           | 100.00%          |
| 0.78                    | 0.00%           | 5.56%            | 99.99%           | 100.00%          |
| 0.84                    | 0.00%           | 42.06%           | 100.00%          | 100.00%          |
| 0.89                    | 0.00%           | 87.84%           | 100.00%          | 100.00%          |
| 0.95                    | 0.03%           | 99.26%           | 100.00%          | 100.00%          |
| 1.00                    | 0.52%           | 100.00%          | 100.00%          | 100.00%          |
| 1.06                    | 6.31%           | 100.00%          | 100.00%          | 100.00%          |
| 1.11                    | 29.06%          | 100.00%          | 100.00%          | 100.00%          |
| 1.17                    | 64.77%          | 100.00%          | 100.00%          | 100.00%          |
| 1.22                    | 90.00%          | 100.00%          | 100.00%          | 100.00%          |
| 1.28                    | 98.41%          | 100.00%          | 100.00%          | 100.00%          |
| 1.33                    | 99.84%          | 100.00%          | 100.00%          | 100.00%          |
| 1.39                    | 99.99%          | 100.00%          | 100.00%          | 100.00%          |
| 1.44                    | 100.00%         | 100.00%          | 100.00%          | 100.00%          |

Figure 15: TMDL compliance ( $K$ ) summaries with respect to user defined target TMDL concentration, for different levels of constant concentration reductions and for four thresholds (5%, 10%, 15%, and 20 %) of acceptable violations.

Following the tabular results, plots of *probability of non-compliance* ( $\beta = 1 - K$ ) of user defined target TMDL concentration versus constant load reductions, for four thresholds (5%, 10%, 15%, and 20 %) of acceptable violations are shown. Similar plots for constant concentration reduction case are also available when the user clicks on the arrows shown on right (or left) hand side of the plot.

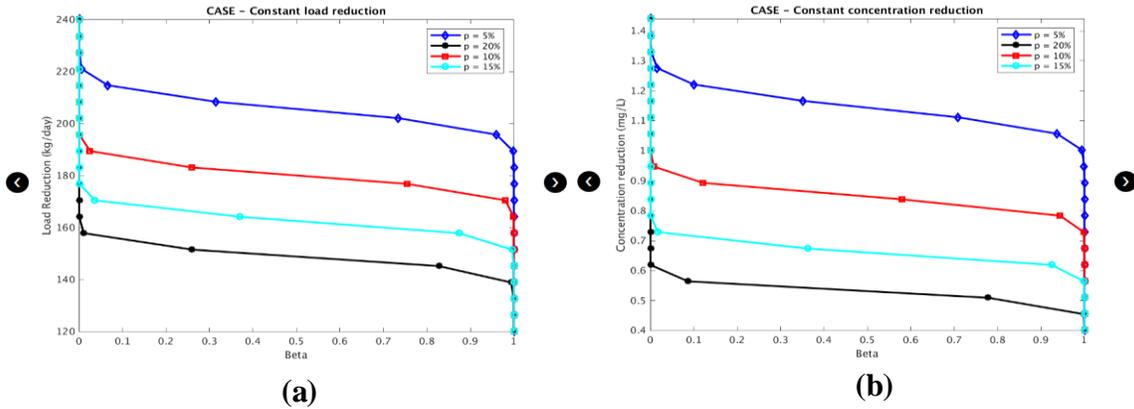


Figure 16: Probability of non-compliance ( $\beta$ ) of user defined target TMDL concentration versus (a) constant load reductions, and (b) constant concentration reductions from reconstructed WQ time series for four thresholds ( $p = 5\%$ ,  $10\%$ ,  $15\%$ , and  $20\%$ ) of acceptable violations

### Results Summary

The *Results Summary* tab (Figure 17) displays the mean and standard deviation of the R-R-V and watershed health measures in a tabular format. A table showing the goodness of fit metrics, adjusted  $R^2$  and Nash-Sutcliffe coefficient, for all regression models are also shown.

## RRV Summary

| Statistic      | Reliability | Resilience | Vulnerability | Watershed Health |
|----------------|-------------|------------|---------------|------------------|
| Mean           | 0.18        | 0.11       | 0.75          | 0.17             |
| Std. Deviation | 0.01        | 0.01       | 0.01          | 0.01             |

Goodness of fit metric for all models

| Goodness of Fit Measure | Model |
|-------------------------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
|                         | - 1   | - 2   | - 3   | - 4   | - 5   | - 6   | - 7   | - 8   | - 9   |
| Adjusted R2             | 0.16  | 0.21  | 0.09  | 0.53  | 0.14  | 0.52  | 0.62  | 0.60  | 0.55  |
| Nash-Sutcliffe          | 0.22  | 0.33  | 0.22  | 0.63  | 0.33  | 0.65  | 0.73  | 0.74  | 0.74  |

Figure 17: *Results Summary* tab contains mean and standard deviation of risk measures used in watershed health assessment. The goodness of fit measures for nine LOADEST models are also shown.

### *Dynamic and Static Plots*

The user can then select the *Dynamic & Static Plots* tab to visualize a dynamic chart (Figure 18a) showing the time-series of water quality standard load and reconstructed water quality load as line plots. The water quality observations (converted from concentration to load) are shown as markers. The green shaded region around the reconstructed load series denotes the uncertainty associated with each reconstructed point.

The user can zoom in to any section of the plot by simultaneously clicking the left mouse button, dragging the pointer across the area of interest (in the chart) and releasing the mouse button. At any time, the user can double click the left mouse button to return to full chart view. The dynamic chart provides a legend box in the upper right hand corner with current values of the variables plotted, as the cursor hovers across the chart.

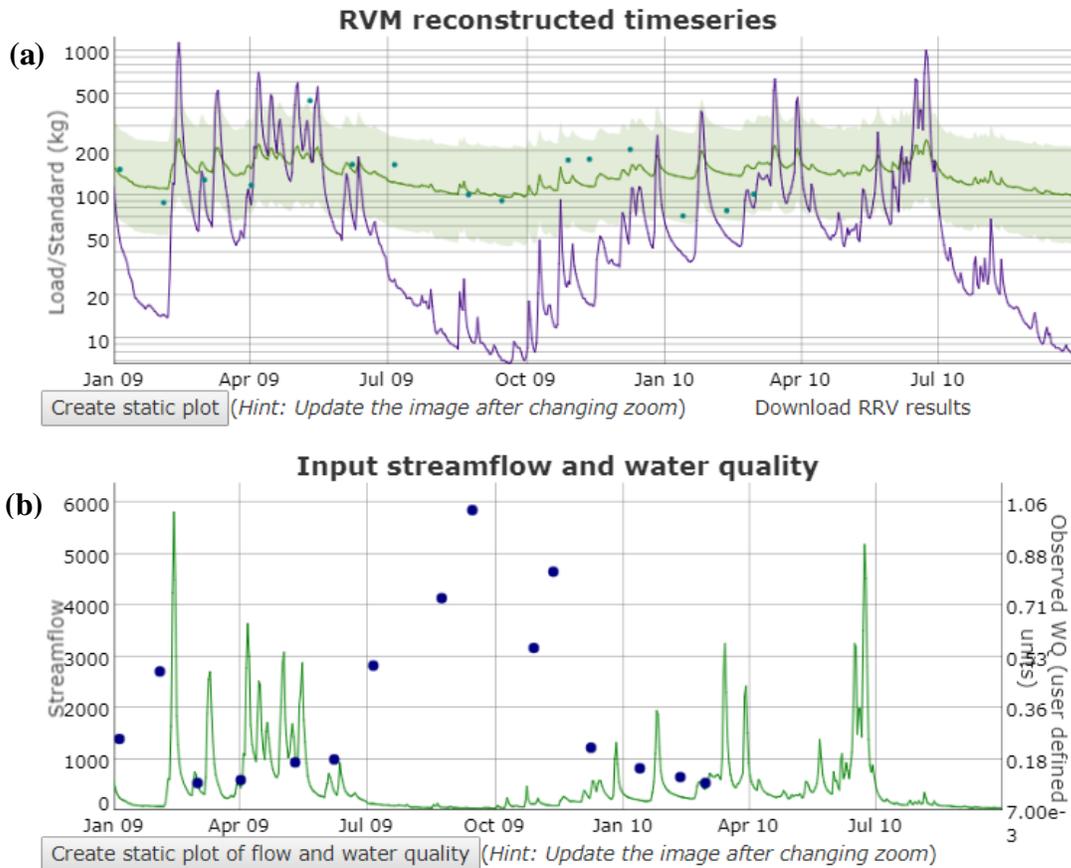


Figure 18: Dynamic time-series plot of (a) the standard load and reconstructed WQ load at the sampling station, and (b) watershed area adjusted streamflow and observed water quality concentration at the sampling station. A link to download the RRV results and buttons to generate static plots are also shown.

Upon clicking the *Create static plot* or *Create static plot of flow and water quality* button, static images (which can be saved by the user by right clicking the mouse button and selecting *Save image as* option) of the current dynamic plot extents are created in the bottom panel. The legend is shown below the x-axis when static plots are generated. By clicking the *Download RRV results* link, the user can download a text file containing the results (Figure 19). The text file contains the summary of R-R-V results along with reconstructed water quality load series.

A dynamic time series chart (Figure 18b) for streamflow and observed water quality concentration data at the sampling station are also shown.

```

RRV Calculation Summary
*****

Approximate code execution time (seconds) : 5.849531
WQ Standard defined by the user : 0.08 mg/L
Regression equation number : 1
Date range : 2009-1-1 to 2010-9-30

Reliability    Resilience    Vulnerability    Watershed Health
0.18    0.11    0.75    0.17

Date    Load(kg)    Load Variance(kg^2)    WQStandard(kg)    Observations(kg)
2009/01/01    161.03    7330.17    114.55    NaN
2009/01/02    152.42    6314.81    84.59    NaN
2009/01/03    146.48    5713.97    67.95    NaN
2009/01/04    141.53    5268.62    56.20    NaN
2009/01/05    137.52    4943.73    47.97    149.92
2009/01/06    134.53    4719.87    42.49    NaN
2009/01/07    133.38    4638.32    40.53    NaN
2009/01/08    131.82    4530.92    37.99    NaN
2009/01/09    130.44    4438.73    35.83    NaN
2009/01/10    128.43    4310.95    32.90    NaN
2009/01/11    125.04    4109.80    28.39    NaN
2009/01/12    123.60    4029.17    26.63    NaN
2009/01/13    122.25    3956.51    25.06    NaN
2009/01/14    118.74    3779.75    21.34    NaN

```

Figure 19: R-R-V results output to a text file

### Histograms of Monte-Carlo Simulations

The *Histogram* tab allows the user to visualize the plots from the Monte-Carlo simulations for different R-R-V measures (Figure 20). The variables can be chosen using the drop-down menu provided below the histogram plot.

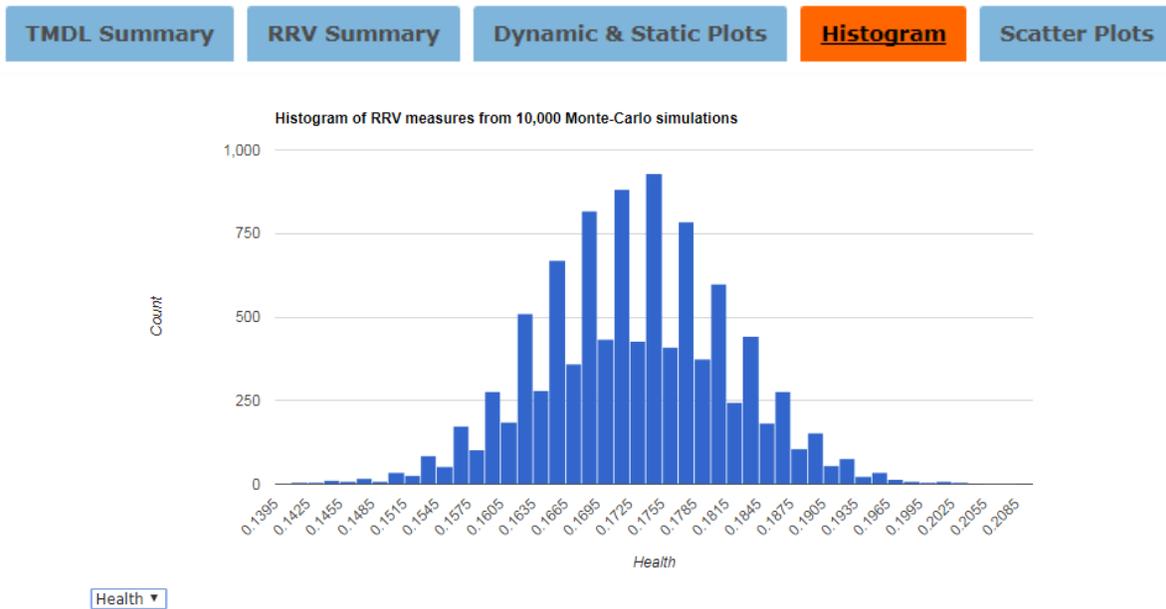


Figure 20: Histogram plot of Monte-Carlo simulations for R-R-V measures. The drop-down menu allows the user to switch between variables.

### Scatter Plots of Observed WQ v/s Model Predicted WQ

The *Scatter Plots* tab enables the user to visualize the fit between the output of any regression model and the observed values for the water quality parameter. The plot (see Figure 21) displays the best fit line and its equation, along with the  $R^2$  value. A drop-down menu below the plot allows the user to switch between different regression models.

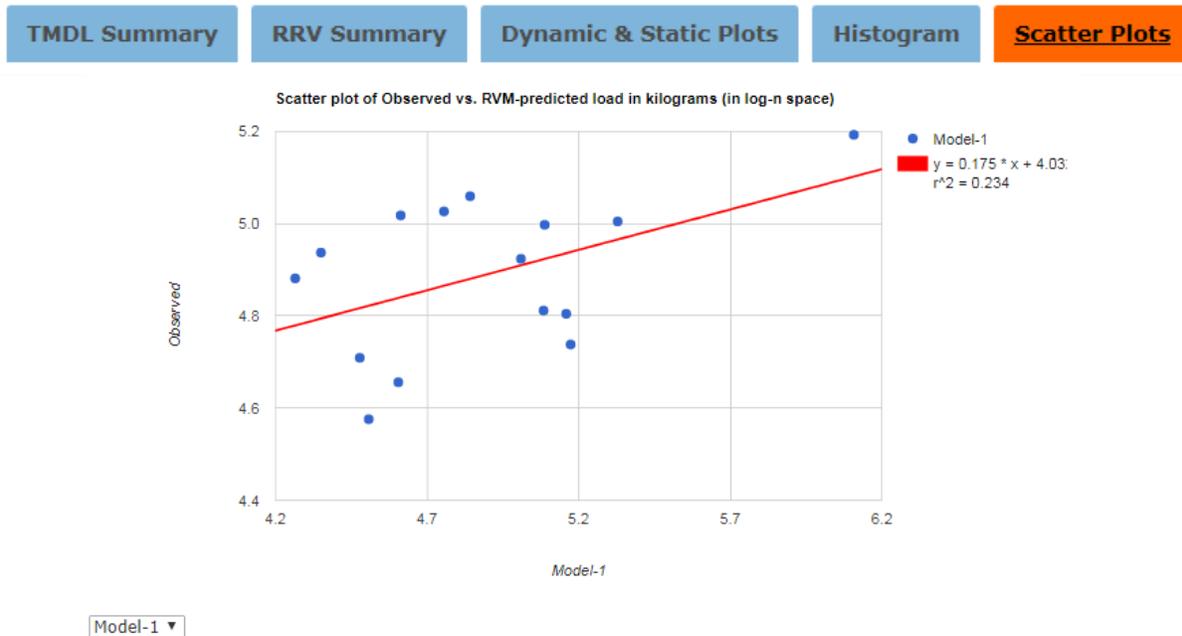


Figure 21: Scatter plot between the output of regression model and the water quality observations. Drop-down menu below the plot allows the use to switch between different models.

## References

- Hashimoto, Tsuyoshi, Jerry R. Stedinger, and Daniel P. Loucks. 1982. "Reliability, Resiliency, and Vulnerability Criteria for Water Resource System Performance Evaluation." *Water Resources Research* 18 (1): 14–20. doi:10.1029/WR018i001p00014.
- Hoque, Yamen M., Shivam Tripathi, Mohamed M. Hantush, and Rao S. Govindaraju. 2012. "Watershed Reliability, Resilience and Vulnerability Analysis under Uncertainty Using Water Quality Data." *Journal of Environmental Management* 109 (0): 101–12. doi:10.1016/j.jenvman.2012.05.010.
- Runkel, Robert L, Charles Gene Crawford, and Timothy A Cohn. 2004. *Load Estimator (LOADEST): A FORTRAN Program for Estimating Constituent Loads in Streams and Rivers*. US Department of the Interior, US Geological Survey.
- US EPA. 2009. "National Recommended Water Quality Criteria." <http://water.epa.gov/scitech/swguidance/standards/criteria/current/index.cfm>.

———. 2015. “Quality Criteria for Water 1986 [The Gold Book] | US EPA.” Accessed June 16. <http://yosemite.epa.gov/water/owrccatalog.nsf/9da204a4b4406ef885256ae0007a79c7/1888fcb7d1b9dc285256b0600724b5f!OpenDocument>.

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