# Standard Procedure for Rapid Direct Seepage Testing of Animal Waste Storage Ponds

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# Table of Contents

# 1. Introduction

This procedure implements the methods of Ham and Baum (2009) and Ham (2002) to determine the seepage rate through the liner of an animal waste storage pond. It employs more recent, improved measurement technologies that enhance the utility of these methods in livestock operations. Improvements include higher sensor accuracy for faster testing, practical direct measurement of evaporation to compliment estimated evaporation, and real-time computation of seepage rates and accuracies. Diligent application of this procedure will provide for safe and efficient seepage testing with results that are useful for evaluation of the pond liner.

## Background

Ham and Baum (2009) identify the need for and teach a test method to evaluate the bulk hydraulic performance of the liner of an animal waste storage pond for compliance with regulatory standards. The method is based on research and testing at over 150 ponds in Kansas.

The test method determines the seepage rate, or specific discharge rate, through the pond liner using the **water balance equation**. Inputs to the equation are the measured water level displacement in the pond, and the estimated evaporation from the pond, during a definite test period under controlled conditions. Evaporation is estimated using integration of the **bulk transfer equation** of Ham (1999) with inputs from measurements of pond surface temperature, relative humidity, wind speed, and air temperature.

The pond is hydraulically isolated for the test by stopping all known inflows and outflows, and testing when precipitation is expected to be negligible. Other important controls include testing during conditions of low evaporation and wind speed.

Regulatory standards typically specify a design seepage rate limit 1 x $10^{-6}$ cm/sec. To visualize, this equates to only 0.864 mm/day. The evaporation rate varies with weather conditions but is typically much greater and tends to mask detection of seepage. These factors highlight the importance of measurement precision and accuracy, and controlling for evaporation during testing.

Indeed, Ham and Baum (2009) call out the need for higher measurement accuracy for faster testing. This is often necessary to achieve useful results within a window of suitable controlled conditions that are limited in duration by livestock operations and weather.

It is important to know the accuracy, or error band, of the computed seepage rate if it is to be used in evaluation of the pond liner for compliance. Ham (2002) describes a method to determine the accuracy at 95% confidence interval. The method uses the **root sum square equation**, with inputs from the accuracy of each input variable times the partial differential of the bulk transfer equation with respect to each variable.

## 2. Facility Characterization

Advance facility characterization is necessary for a successful test. A comprehensive nutrient management plan (CNMP) Overview, Farm Headquarters Map, and previous evaluations will provide some of the required information. Other sources are the CNMP provider, facility operator, as-built drawings, online maps, and facility inspection. Information shall be re-reviewed on the test date and revised as necessary to reflect actual conditions for use in the report. The following information, as available, will provide for effective planning, test control, and reporting.

- Logistical information including facility name and street address, CNMP provider name and contact info, facility operator name and contact info, and facility access and safety requirements.
- Scale drawing of plan view of pond and surrounding area showing prevailing wind direction; structures and other obstructions to wind flow across pond; previous soil borings; embankments, side slopes and vegetation; shoreline at design capacity and during testing; waste inflow and outflow locations; and test location including shore station and embankment station.
- Scale drawing of cross section of pond showing embankments and vegetation; pond surface at design capacity and during test; liner construction including embankments, floor, sump, and soil type and hydraulic conductivity; and host geology and water table.
- Use of pond including seasonal cycle of waste inflows, outflows, and pond depth; daily cycle of inflows and outflows; provisions to halt inflows and outflows; provisions to aerate or circulate the waste; and pond depth during testing.
- Pond surface including character and distribution of matter that may affect evaporation or operation of water level sensors including algae, duckweed, other vegetation, larvae and insects, film, scum, crust, and debris.
- Waste character as may affect operation of the water level sensors including qualitative description of viscosity (water, thin slurry, thick slurry, sludge).

## 3. Planning

### 3.1. Personnel and Training

Testing shall be done under the direction of an engineer that is familiar with animal waste storage ponds, this procedure and appendix, and references herein. The engineer shall have credentials and title as necessary for certification of the pond liner in accordance with the applicable regulatory program.

Testing shall be done by a field technician that is trained in this procedure and appendix, safety requirements, and manufacturer recommendations for operation of the seepage meter system components.

### 3.2. Coordination and Scheduling

Review this procedure with the facility operator and CNMP provider. Review and complete the facility characterization. Review specific safety and bio-security requirements and facility preparations for test control. Determine a proposed test date and schedule with all involved parties.

### 3.3. Safety and Bio-Security

Testing shall be done under a separate job-specific health and safety plan in accordance with applicable regulations. The plan shall review potential hazards of depleted atmospheres, water hazards, and other potential hazards; and shall specify precautions to mitigate these hazards.

Personnel shall not enter into the waste. Plan ahead to reduce exposure of personnel and equipment to the waste to the maximum extent practical. See Section 4.5 for cleaning and decontamination procedures.

## 4. Test Control

Test control is directed mainly at hydraulically isolating the pond and controlling for wind and evaporation, to detect and measure seepage amidst the overall hydrologic regime. Also important are cleaning and decontamination procedures for bio-security.

Following are ideal conditions for testing. Practically speaking it is unlikely they can all be met simultaneously at a given facility. Also, there are likely to be conflicts. The engineer shall balance all considerations and make the final determination of suitable conditions for testing at a given facility.

### 4.1. Facility Preparation

The pond shall be as full as possible, preferably to within about 3 m of the top of the embankment. This is an important assumption for the wind speed input to the bulk transfer equation for estimation of evaporation. It also provides for testing near the design pond depth and full hydraulic head on the liner. Note that the projected seepage rate $S_P$ is equal to the determined seepage rate $S_D$ times the design pond depth divided by the actual pond depth during testing (See Section 6.3).

The vegetation on the embankments shall be mowed to provide access to the test. They shall also be mowed in the area around the shoreline to mitigate evapotranspiration from the saturated zone of the liner soil during testing. Aeration or recirculation of the waste if possible prior to testing should be considered to improve pond surface characteristics for testing.

All aeration, recirculation, and known inflows and outflows shall be stopped prior to and during testing. Allow as much time as possible for the pond to equilibrate prior to testing.

### 4.2. Location of Shore Station and Embankment Station

Measurement sensors are deployed at a shore station at waters edge, and at an embankment station on top of the embankment adjacent to the shore station. See Sections 5.3 and 5.4 for sensor requirements. Locate the shore station and embankment station in accordance with the following considerations.

- The stations shall be located for safe and practical access of personnel to the test.
- The stations shall be located at the downwind side of the pond.
- The stations shall be located "in the clear", as far away as possible from unusual obstructions that may interfere with the sensors, to ensure representative measurements.
- The shore station shall be located at the approximate center of the longitudinal extent of to pond to mitigate tidal effects.
- The embankment station shall be located at the top of the embankment as close as possible to the shore station.

### 4.3. Weather Conditions

Keep current with the local weather forecast and plan for testing accordingly.

- Dry conditions during the entire test period are necessary for useful results. While trace rain less than about 0.1 mm may be tolerable, more significant rain will complicate results with runoff from the embankments into the pond.
- Measurements of initial and final water level displacements in the pond, as used in computation of seepage rates, shall be taken when the wind speed $W_{SE} \leq 4$ m/s to avoid the effects of wind push and ensure representative measurement.

### 4.4. Deployment Period, Test Period, and Test Duration

The deployment period refers to the entire period of time that the seepage meter system is deployed and operating (measuring, computing, and recording) and encompasses one or more test periods. The test period refers to the period of time that is selected for analysis and determination of the seepage rate. The test period shall be within a window of suitable controlled conditions as described above.

A nighttime test period is preferred, when weather conditions are generally more stable with lower wind speed, temperatures, and evaporation. A daytime test period may be acceptable so long as it produces results of suitable accuracy and validity as demonstrated with the methods of Section 6.

The minimum test duration is the minimum duration of time that produces suitable accuracy for evaluation of the liner. Equations A6.1 and A6.2 of the appendix show that accuracy increases with test duration. For best results the test duration should be as long as possible within the window of suitable controlled conditions.

For example, the following table shows test durations and absolute accuracies, at 95% confidence interval, of the computed seepage rate with measured evaporation using water level sensors with an accuracy of ±0.035 mm.

| Test Duration, $\Delta t$ (hr) | Accuracy, $uS_{EP}$ ($10^{-6}$ cm/s) |
|---|---|
| 4 | ± 0.34 |
| 6 | ± 0.23 |
| 8 | ±0.17 |
| 10 | ± 0.14 |
| 12 | ± 0.11 |

The accuracy of the computed seepage rate with estimated evaporation depends on test specific measurements of wind speed, pond surface temperature, relative humidity, and air temperature. Therefore a similar general table is not shown for this method.

Upon completion of a test period, backup all data to an external device and carefully review results while leaving the seepage meter system in place. Review results for accuracy, data quality, and compliance with the test control requirements above. Based on this review the engineer shall determine whether to leave the system in place for more testing or to conclude testing and demobilize the seepage meter system.

### 4.5. Cleaning and Decontamination

Clean and decontaminate all PPE and test equipment that has contacted waste, prior to removal from the facility. Remove all gross residue, apply 10% household bleach solution (1 part bleach to 9 parts water), allow the solution to work for at least 20 minutes, and rinse with water. Five gallons of bleach solution and five gallons of water should be sufficient. Seal contaminated disposable materials (gloves, towels, etc.) in a plastic bag prior to removal from the facility and dispose properly. Dry, inspect and properly stow test equipment in a state of readiness for next use.

## 5. Seepage Meter System and Deployment

The seepage meter system shall consist of a power supply, data logger, measurement sensors, and equipment to deploy these instruments. Sensors are deployed at a shore station at waters edge, and at an embankment station on top of the embankment adjacent to the shore station. See Section 4.2 for location requirements.

The sensors and deployment equipment shall be designed and used in a manner to minimize contact with the waste and provide for easy cleaning and decontamination. The instruments and equipment shall be operated in accordance with manufacturer recommendations.

A suitable power supply, data logger, and sensors are necessary to achieve useful accuracy. See Section A4 for sensor and accuracy requirements.

## 5.1. Power Supply

The power supply shall consist of a rechargeable battery and regulator that provide stable, noise free power to the data logger and sensors. It shall have sufficient capacity for at least 36 hours of continuous operation.

## 5.2. Data Logger

The data logger shall continuously measure all sensors and compute the seepage rate and accuracy in accordance with the schedule in Section A3 of the appendix. Measurements and results shall be stored in static memory with sufficient capacity for at least 36 hours of continuous operation. Measurements and results shall be stored in a form that can be readily transferred to a personal computer for reporting, analysis, and post processing as necessary.

## 5.3. Sensors at Shore Station

Sensors at the shore station measure water level displacement in the pond, water level displacement in the evaporation pan in the pond, and pond surface temperature.

### 5.3.1. Water Level Sensor in Pond

This sensor measures water level displacement in the pond with respect to a fixed reference point in the pond. Deploy this sensor in water that is sufficiently deep for measurement, approximately 1-2 m from shore. Ensure that the reference point remains stable throughout the test period.

### 5.3.2. Water Level Sensor in Evaporation Pan in Pond

This sensor assembly measures evaporation from water level displacement in a low profile evaporation pan that is partially submerged in the pond. The water in the pan reaches thermodynamic equilibrium with, but is hydraulically isolated from, the pond.

The sensor and pan assembly shall have a low profile to provide for representative measurement. This means it shall be designed and deployed to minimize disturbance of the hosting aerodynamic and thermodynamic conditions.

- The sensor shall not occupy more than 10 percent of the water surface in the pan. Compensation for this unexposed area shall be made mathematically in the computations of the data logger.
- The pan shall be generally hemispherical, symmetrical about the vertical axis, substantially rigid, and formed with a single thin wall of aluminum or steel.

- The rim of the pan shall not extend more than 1.5 cm above the water surface in the pan or the pond surface at the beginning of the test.
- The sensor and pan assembly shall be deployed in the clear, with the rim of the pan at least 50 cm away from any disturbance or penetration of the pond surface.

Deploy the sensor and pan assembly as above, approximately 2-3 m from shore. The character of the water surface in the pan should generally represent that of the pond surface.

#### 5.3.3. Infrared Radiometer

The infrared radiometer measures surface temperature of the pond for input to the bulk transfer equation for estimation of evaporation. Deploy this sensor approximately 1-2 m from shore and approximately1.5 m above the pond surface. Direct it 45º downward and outward towards pond surface.

### 5.4. Sensors at Embankment Station

Sensors at the embankment station measure wind speed, relative humidity, and air temperature for input to the bulk transfer equation for estimation of evaporation. Relative humidity and air temperature sensors shall be positioned within a suitable solar radiation shield.

Additional sensors at the embankment station measure wind direction and solar radiation for general evaluation and quality assurance of the test. The solar radiation sensor may optionally be deployed at the shore station.

Deploy all sensors at the embankment station approximately 2 m above the top of the embankment.

### 5.5. Calibration (Verification)

The data logger and sensors used in computation of the seepage rate shall have current calibration in accordance with a program approved by the engineer. The calibration program shall specify methods and schedule for the specific data logger and sensors used in the test. The methods and schedule shall consider manufacturer recommendations and conditions of use including temperature range and severity.

## 6. Report

### 6.1. Test Description

Describe the application of this procedure and the actual testing efforts including facility characterization, planning, and test control. Describe the actual seepage meter system, components, and accuracies. Describe any significant departures from this procedure and their potential effect on test results.

### 6.2. Results

Report the computed seepage rate and accuracy at 95% confidence interval, to two significant digits, as $S_{EP} \pm uS_{EP}$ (with measured evaporation) and $S_{EB} \pm uS_{EB}$ (with estimated evaporation).

Include graphical presentation(s) of test data versus time over the entire test period showing:

- Water level displacement in pond $D_C$.
- Measured evaporation $D_{EP}$.
- Estimated evaporation $D_{EB}$.
- Ambient parameters including pond surface temperature $T_S$, wind speed $W_{SE}$, relative humidity $RH$, and air temperature $T_A$.

### 6.3. Analysis and Interpretation

The following analyses will provide for interpretation of results for evaluation of the pond liner.

- Compare the computed seepage rates ($S_{EP}$ with measured evaporation versus $S_{EB}$ with estimated evaporation). Review accuracies, data quality, adherence to test control requirements and potential method and model errors.
- Specify the determined seepage rate $S_D$. This is the one preferred computed seepage rate ($S_{EP}$ or $S_{EB}$) that is likely to best represent the actual rate, for use in evaluation of the pond liner.
- The projected seepage rate $S_P$ is equal to the determined seepage rate $S_D$ times the design pond depth divided by the actual pond depth during testing. Assume the accuracy of the projected seepage rate $S_P$ is the same as that of the determined seepage rate $S_D$.
- Review the projected seepage rate $S_P$ and accuracy with respect to the design seepage rate limit. Consider the number of significant digits of the limit specification and rounding. For example, a limit specification of $\leq 1 \times 10^{-6}$ cm/ may be interpreted to mean $\leq 1.4 \times 10^{-6}$ cm/s rounded to one significant digit.
- Review graph(s) for data quality. The traces of water level displacements should be smooth, continuous, and indicative of natural transients of seepage and evaporation. Sharp changes may indicate disturbance or malfunction, except in cases of condensation, rain, or unexpected inflows or outflows (see below). An extended flat line probably indicates instrument malfunction.
- Review graph(s) with for adherence to the test control requirements of Section 4.
    - A simultaneous rise in waster level displacement in the pond and evaporation pan indicates condensation or rain. This may correlate with a

change in estimated evaporation $D_{EB}$ in the case of condensation (negative evaporation).

- Sharp changes in water level displacement in the pond only, that are not accompanied by similar changes in the evaporation pan, may indicate unexpected inflows or outflows.
- Cyclical changes in water level displacement in the pond only, that are not accompanied by similar changes in the evaporation pan, may indicate tidal effects.
- Initial and final measurements of waster level displacement in the pond shall be taken when wind speed $W_{SE} \leq 4$ m/s.

## 7. References

Ham, J. M. and K. A. Baum. 2009. Measuring seepage from waste lagoons and earthen basins with an overnight water balance test. *Trans. ASABE.* 52(3): 835-844.

Ham, J. M. 2002. Uncertainty analysis of the water balance technique for measuring seepage from animal waste lagoons. *J. Environ. Qual.* 31(4): 1370‑1379.

Ham, J. M. 1999. Measuring evaporation and seepage losses from lagoons used to contain animal waste. *Trans. ASAE* 42(5): 1303‑1312.

## 8. Bibliography

Glanville, T.D., S. Baker, S.W. Melvin, and M. M. Agua, 2001. Measurement of leakage from earthen manure structures in Iowa. *Trans.* ASAE 44(6): 1609-1616.

Ham, J. M., and R. S. Senock. 1992. On the measurement of soil surface temperature. *SSSA J.* 56(2): 370‑377.

Buck, A. L. 1981. New equations for computing vapor pressure and enhancement factor. *J. Appl. Meterol. 20(12): 1527-1532.*

Murray, F. W., 1967: On the computation of saturation vapor pressure. *J. Appl. Meteor.,* 6, 203-204.

# APPENDIX--MEASUREMENT AND PROCESSING

## Table of Contents



## A1. Definitions and Conventions

Measurement variables, units, and required accuracies are defined in Sections A4.

"Required Accuracy" means the maximum composite uncertainty of a measurement at 95% confidence interval as recorded in the data logger over the anticipated temperature range of the test. The composite uncertainty includes all uncertainties involved in the measurement including that of the sensor, signal conditioning, and data logger.

Sensor location, position, and physical requirements are described in Section 5 of the text.

Computations are defined in Sections A5 and A6.

A negative value means displacement in the downward direction. For example:

- A water level displacement in the pond $D_C \leq 0$ means the water level in the pond has changed downward.
- A water level displacement in the evaporation pan in the pond $D_{EP} < 0$ means the water level in the pan has changed downward.
- A seepage rate $S_{EP} < 0$ means seepage that is downward or outward through the pond liner.

References are listed in Section 7 of the text.

## A2. Test Initiation

Set up the power supply, data logger, and sensors in accordance with Section 5 of the text.

Position the water level sensors at the approximate center of their working range.

Allow ample time for all sensors to stabilize and equilibrate to the test environment.

Reset $\Delta t$, $D_C$, $D_{EP}$, and $D_{EB}$ to zero in the data logger to start the test.

## A3. Measurement and Processing Schedule

The data logger shall operate according to the following schedule:

**1-Second Interval**

Measure and record into ring (volatile) memory:

$D_C$, $D_{EP}$, $T_S$, $W_{SE}$, $W_D$, $RH$, $T_A$, $SF$, $V_P$, and $T_P$.

**1-Minute Interval**

Record time $t$.

Compute and record elapsed time $\Delta t$.

From 1-second measurements, compute and record 1-minute averages:

$D_C$, $D_{EP}$, $T_S$, $W_{SE}$, $W_D$, $RH$, $T_A$, $SF$, $V_P$, and $T_P$.

Compute and record into static memory the standard deviation $s$ of 1-minute averages:

$sD_C$, $sD_{EP}$, $sT_S$, $sW_{SB}$, $sW_D$, $sRH$, and $sT_A$.

**10-Minute Interval**

Record time $t$.

Compute and record elapsed time $\Delta t$.

From 1-second measurements, compute and record 10-minute averages:

$D_C$, $D_{EP}$, $T_S$, $W_{SB}$, $W_D$, $RH$, $T_A$, $SF$, $V_P$, and $T_P$.

Compute and record standard deviation $s$ of 10-minute averages:

$sD_C$, $sD_{EP}$, $sT_S$, $sW_{SB}$, $sW_D$, $sRH$, and $sT_A$.

From requisite 10-minute averages compute and record seepage rates and accuracies:

$S_{EP}$, $S_{EB}$, $uS_{EP}$, and $uS_{EB}$.

**30-Minute Intervals:**

Same as 10-minute intervals respectively.

## A4. Measurement

Following the method of Ham and Baum (2009) as specified herein.

### A4.1. Shore Station

Measure and record the flowing variables at the shore station.

| Variable | Unit | Required Accuracy | Description | Source (Sensor) |
|---|---|---|---|---|
| $D_C$ | mm | $uD \leq 0.035$ mm | Water level displacement in containment structure (pond), cumulative since start of test. | Water level sensor in pond. |
| $D_{EP}$ | mm | | Water level displacement in evaporation pan in pond (aka measured evaporation), cumulative since start of test. | Water level sensor in evaporation pan in pond. |
| $T_S$ | ºC | $uT_S \leq 0.4$ ºC | Pond surface temperature. | Infrared radiometer. |

### A4.2. Embankment Station

Measure the following variables at the embankment station.

| Variable | Unit | Required Accuracy | Description | Source (Sensor) |
|---|---|---|---|---|
| $W_{SE}$ | m/s | $uW_{SE} \leq 0.3$ m/s | Wind speed. | Anemometer. |
| $W_D$ | Deg azimuth | N/a | Wind direction. For evaluation and QA of test. | |
| $RH$ | % | $uRH \leq 2\%$ | Relative humidity. | Relative humidity sensor. |
| $T_A$ | ºC | $uT_A \leq 0.2$ ºC | Air temperature. | Air temperature sensor. |
| $SF$ | W/m² | N/a | Solar flux (radiation). For evaluation and QA of test. | Pyranometer. |

## A4.3. Data Logger

Measure the following variables in the data logger.

| Variable | Unit | Required Accuracy | Description | Source |
|---|---|---|---|---|
| *t* | yy mm dd hh mm ss | $ut \leq 6$ ppm (negligible in accuracy computations) | Date and time of measurement record. | Data logger. |
| *dt* | s | | Elapsed time, incremental (interval duration). | |
| *Δt* | m | | Elapsed time, cumulative, at given time $t_f$ since start of test at time $t_i$. (aka test duration). | |
| *s* | N/a | N/a | Standard deviation of average measurement. For evaluation and QA of test. | |
| $V_P$ | V | N/a | Voltage of power supply. For evaluation and QA of test. | |
| $T_P$ | ºC | N/a | Panel temperature of data logger. For evaluation and QA of test. | |

# A5. Computation of Seepage Rate

Compute the seepage rate using the **water balance equation** following the method of Ham & Baum (2009) as specified herein.

## A5.1. With Measured Evaporation

$S_{EP}$ (cm/s) is the seepage rate computed with water level displacement in the pond $Dc$ and measured evaporation from water level displacement in the evaporation pan $D_{EP}$ :

$$S_{EP} = (D_C - D_{EP})/10/(\Delta t \bullet 60)$$

## A5.2. With Estimated Evaporation

$S_{EB}$ (cm/s) is the seepage rate computed with water level displacement in the pond $D_C$ and the estimated evaporation from the pond $D_{EB}$ using integration of the **bulk transfer equation**:

$$S_{EB} = (D_E - D_{EB})/10/(\Delta t \bullet 60)$$

Where:

$D_{EP}$ (mm) is the estimated evaporation using integration of the bulk transfer equation over elapsed time *Δt.*

$$D_{EB} = \sum_{ti}^{tf} E_B dt$$

Where $E_B$ (mm/s) is the estimated evaporation rate computed using the bulk transfer equation:

$$E_B = -C_E W_{SP} \frac{0.622}{R_D(273.15 + T_S)}\left(e_{SS} - \frac{RH}{100}e_{SA}\right)$$

Where:

$C_E$ (dimensionless) is the aerodynamic transfer coefficient = 2.5 x $10^{-3}$.

$W_{SP}$ (m/s) is the estimated wind speed at 1 m above pond surface based on wind speed at the embankment station:

$W_{SP} = k_W W_{SE}$

Where $k_W$ (dimensionless) is an empirical coefficient = 0.75 in normal cases.

$R_d$ (J $kg^{-1}$ $K^{-1}$) is the gas constant = 287.04.

$e_{SS}$ (Pa) is the saturation vapor pressure at the pond surface and $e_{SA}$ (Pa) is the saturation vapor pressure at 1 m above the pond surface. Following Buck (1981):

$$e_{SS} = 0.61378\exp\left(\frac{17.502T_S}{240.97 + T_S}\right)$$

$$e_{SA} = 0.61378\exp\left(\frac{17.502T_A}{240.97 + T_A}\right)$$

# A6. Computation of Accuracy

Compute the accuracy of the seepage rate at 95% confidence interval using the **root sum square equation** following the method of Ham (2002) as specified herein.

## A6.1. With Measured Evaporation

$$uS_{EP} = \left(uD_C^{\ 2} + uD_{EP}^{\ 2}\right)^{1/2} / (\Delta t \bullet 60)$$

## A6.2. With Estimated Evaporation

$$uS_{EB} = \left(uD_C^{\ 2} + uD_{EB}^{\ 2}\right)^{1/2} / (\Delta t \bullet 60)$$

Where:

$uD_{EB}$ is the cumulative uncertainty of the estimated evaporation using partial differentiation of the bulk transfer equation:

$$uD_{EB} = \sum_{t_i}^{t_f} uE_B dt$$

Where $uE_B$ is computed from the root sum square equation with inputs from the accuracy of each input variable times the partial differential of the estimated evaporation with respect to that variable.

$$uE_B = \left[\begin{array}{l}\left(uC_E\frac{\partial E_B}{\partial C_E}\right)^2 + \left(uW_{SP}\frac{\partial E_B}{\partial W_{SP}}\right)^2 + \left(uT_S\frac{\partial E_B}{\partial T_S}\right)^2 \\ + \left(uRH\frac{\partial E_B}{\partial RH}\right)^2 + \left(uT_a\frac{\partial E_B}{\partial T_A}\right)^2\end{array}\right]^{1/2}$$

Where $uC_E$ is the uncertainty of the aerodynamic transfer coefficient = 1.5 x $10^{-4}$.