The design of a new device to automate a Class A evaporation pan

D. Caissie

Fisheries and Oceans Canada
Oceans and Science Branch
Diadromous Fish Section
343 Université Avenue
Moncton, NB
E1C 9B6

2011

Canadian Technical Report of Fisheries and Aquatic Sciences 2927

Fisheries and Oceans Canada
Pêches et Océans Canada

Canada

Canadian Technical Report of Fisheries and Aquatic Sciences

Technical reports contain scientific and technical information that contributes to existing knowledge but which is not normally appropriate for primary literature. Technical reports are directed primarily toward a worldwide audience and have an international distribution. No restriction is placed on subject matter and the series reflects the broad interests and policies of Fisheries and Oceans, namely, fisheries and aquatic sciences.

Technical reports may be cited as full publications. The correct citation appears above the abstract of each report. Each report is abstracted in the data base *Aquatic Sciences and Fisheries Abstracts*.

Technical reports are produced regionally but are numbered nationally. Requests for individual reports will be filled by the issuing establishment listed on the front cover and title page.

Numbers 1-456 in this series were issued as Technical Reports of the Fisheries Research Board of Canada. Numbers 457-714 were issued as Department of the Environment, Fisheries and Marine Service, Research and Development Directorate Technical Reports. Numbers 715-924 were issued as Department of Fisheries and Environment, Fisheries and Marine Service Technical Reports. The current series name was changed with report number 925.

Rapport technique canadien des sciences halieutiques et aquatiques

Les rapports techniques contiennent des renseignements scientifiques et techniques qui constituent une contribution aux connaissances actuelles, mais qui ne sont pas normalement appropriés pour la publication dans un journal scientifique. Les rapports techniques sont destinés essentiellement à un public international et ils sont distribués à cet échelon. II n'y a aucune restriction quant au sujet; de fait, la série reflète la vaste gamme des intérêts et des politiques de Pêches et Océans Canada, c'est-à-dire les sciences halieutiques et aquatiques.

Les rapports techniques peuvent être cités comme des publications à part entière. Le titre exact figure au-dessus du résumé de chaque rapport. Les rapports techniques sont résumés dans la base de données *Résumés des sciences aquatiques et halieutiques*.

Les rapports techniques sont produits à l'échelon régional, mais numérotés à l'échelon national. Les demandes de rapports seront satisfaites par l'établissement auteur dont le nom figure sur la couverture et la page du titre.

Les numéros 1 à 456 de cette série ont été publiés à titre de Rapports techniques de l'Office des recherches sur les pêcheries du Canada. Les numéros 457 à 714 sont parus à titre de Rapports techniques de la Direction générale de la recherche et du développe-ment, Service des pêches et de la mer, ministère de l'Environnement. Les numéros 715 à 924 ont été publiés à titre de Rapports techniques du Service des pêches et de la mer, ministère des Pêches et de l'Environnement. Le nom actuel de la série a été établi lors de la parution du numéro 925.

Canadian Technical Report of
Fisheries and Aquatic Sciences 2927

2011

The design of a new device to automate a Class A evaporation pan

by

Daniel Caissie

Fisheries and Oceans Canada
Oceans and Science Branch
Diadromous Fish Section
343 Université Avenue
Moncton, NB
E1C 9B6

Cat. No. Fs. 97-6/2927E ISSN 0706-6457 (Printed version)
Cat. No. F597-6/2927E-PDF ISNN 1488-5379 (on-line version)

Correct citation for this publication:

Caissie, D. 2011. The design of a new device to automate a Class A evaporation pan. Can. Tech. Rep. Fish. Aquat. Sci. 2927: vii + 33p.

TABLE OF CONTENTS

TABLE OF CONTENTS iii

LIST OF TABLES iv

LIST OF FIGURES v

ABSTRACT vi

RÉSUMÉ vii

1.0 INTRODUCTION 1

2.0 MATERIALS AND METHODS 3

- 2.1 Design of a new device to automate a class A evaporation pan 3
- 2.2 Materials and testing of the evaporation pan 5
  - 2.2.1 Materials and detailed functioning of the evaporation pan 5
  - 2.2.2 Testing the evaporation pan 7

3.0 RESULTS AND DISCUSSION 9

- 3.1 Testing of the overflow apparatus 9
- 3.2 Accuracy of the automated evaporation pan 10
- 3.3 Pumping time and power requirement 11
- 3.4 Field testing of the evaporation pan 12

4.0 SUMMARY AND CONCLUSIONS 13

5.0 ACKNOWLEDGMENTS 15

6.0 REFERENCES 16

LIST OF TABLES

1. Testing of the overflow apparatus to bring back the water level to a predetermined level within the evaporation pan................................. 20

2. Testing of the surface tension effect on the overflow apparatus during different evaporation measurement cycles 21

3. Results of the Automatic Evaporation Pan (AEP) operation, predicted vs. observed evaporation, and corresponding errors 22

4. Duration of pumping for different evaporations.. 23

LIST OF FIGURES

1. Design of a new overflow apparatus to bring the water level in the evaporation pan to a predetermined level and to redirect the excess water into the stilling well 24
2. Illustration showing the operation of the new designed AEP with both the overflow apparatus and stilling well 25
3. Illustration of the operation of both the overflow apparatus and the stilling well during an evaporation measurement cycle 26
4. Prototype of the Automatic Evaporation Pan in the lab for testing 27
5. Illustration of the surface tension effect (ΔH) at the top of the overflow apparatus 28
6. Predicted vs. observed evaporation for different evaporation rates using the Automatic Evaporation Pan (AEP) 29
7. Water level settling time for different simulated evaporations for a single fill cycle (0 min = 7:00 am) 30
8. Water level settling time for different simulated evaporations for a double fill cycle (0 min = 7:00 am) 31
9. Installation of the prototype automatic evaporation pan for testing in the field. Figure inset shows the protective casing over the overflow apparatus. 32
10. Field testing of the automated evaporation pan: a) water levels within the stilling well and b) water temperatures in the pan (August 28 to September 1, 2010) 33

ABSTRACT

Caissie, D. 2011. The design of a new device to automate a class A evaporation pan. Can. Tech. Rep. Fish. Aquat. Sci. 2927: vii + 33p.

In the present study, a new device was designed to automate a class A evaporation pan. The accuracy of the refilling/measurement device to automate a class A evaporation pan was studied using simulated evaporations in the laboratory and the pan was also tested in the field under various meteorological conditions. The new design consists of an overflow apparatus which brings back the water in the pan to a predetermined level. The overflow apparatus was designed to redirect any excess water into a stilling well (used to measure the evaporation). The stilling well consists of an upright pipe acting as a cylinder to measure the amount of evaporated water through an amplification factor. Results showed that the overflow apparatus brought back the water level within ±0.1 mm of the predetermined level after each measurement cycle. The device was tested in the laboratory by simulating different evaporation rates (1 to 13 mm). This was done by removing an exact amount of water from the pan (simulated evaporation) and then comparing the amount to the calculated evaporation from the automatic evaporation pan. Results showed very good performances with errors typically less than 0.1 mm. The average absolute error was 0.069 mm whereas the root mean square error was 0.086 mm. These errors are consistent with requirements of the World Meteorological Organisation for the operation of evaporation pans (±0.1 mm). The automatic evaporation pan was also tested in the field for a period of 40 days.

RÉSUMÉ

Caissie, D. 2011. The design of a new device to automate a class A evaporation pan. Can. Tech. Rep. Fish. Aquat. Sci. 0000: vii + 33p.

Dans la présente étude, un nouveau dispositif a été conçu pour automatiser un bac d'évaporation de class A. La précision du dispositif de mesure/remplissage du bac d'évaporation a été étudiée en utilisant des évaporations simulées en laboratoire et le bac a été testé sur le terrain pour différentes conditions météorologiques. Le nouveau concept se compose d'un appareil de débordement qui ramène l'eau dans bac à un niveau prédéterminé. L'appareil de débordement a également été conçu pour rediriger tout excès d'eau dans un puits de mesure (utilisé pour mesurer l'évaporation). Le puits de mesure se compose d'un tuyau vertical agissant comme un cylindre pour mesurer la quantité d'eau évaporée par un facteur d'amplification. Les résultats ont montré que l'appareil de débordement ramène le niveau d'eau de ± 0.1 mm du niveau prédéterminé après chaque mesure. Le dispositif a également été testé en laboratoire en simulant différents taux d'évaporation (de 1 à 13 mm). Cela a été fait en retirant une quantité exacte d'eau du bac (évaporation simulée), pour par la suite comparer ce montant à l'évaporation calculée à partir du bac d'évaporation automatique. Les résultats ont montré de très bonnes performances avec des erreurs typiquement inférieures à 0.1 mm. L'erreur absolue moyenne était de 0.069 mm, tandis que l'erreur quadratique moyenne était de 0.086 mm. Ces erreurs sont compatibles avec l'exigence de l'Organisation météorologique mondiale pour le fonctionnement des bacs d'évaporation (± 0.1 mm). Le bac d'évaporation automatique a également été testé sur le terrain pour une période de 40 jours.

1.0 INTRODUCTION

Evaporation has always played a key role in hydrologic and water resource studies. Historically, water resource agencies (e.g., provincial and federal governments) maintained networks of evaporation pans. These data were valuable for water resource management as well as for many other fields of science (Chin and Zhao 1995; Burn and Hesch 2007). For instance, the rate of evaporation has been particularly important in lake studies where it is an essential component of the water budget analysis (Fennessey 2000; Reis and Dias 1998). Evaporation is also very important in stream temperature modeling studies (Caissie *et al.* 2007; Benyahya *et al.* 2010) as well as in agriculture for the estimation of water deficits and irrigation requirements (Phene *et al.* 1992; Phene et al. 1996). The monitoring and the estimation of evaporation have always been challenges because of their complexity in relation to meteorological conditions (Brutsaert 1982). As a result, many studies have relied on empirical equations rather than monitoring evaporation per say.

In fact, a variety of methods have been used to estimate evaporation, ranging from empirical equations (Rosenberry *et al.* 2007), the Bowen ratio (Assouline et al. 2008; Vercauteren *et al.* 2009) and the eddy covariance approach (Armstrong et al. 2008; Tanny *et al.* 2008). However, there will always be a need for direct measurements of evaporation in order to develop, validate and compare methods and equations. One such direct measurement approach is the use of evaporation pans. Evaporation pans have been used extensively in the past and are still used today for a wide range of applications, e.g., global evaporation studies (Brutsaert 2006), local evapotranspiration studies (Xing et al. 2008), reference crop irrigation (Chin and Zhao 1995) and others. The advantage of using evaporation pans is that they are relatively simple and inexpensive in terms of equipment compared to other methods (e.g., eddy covariance). According to Stanhill (2002), the use of evaporation pans is still one of the most practical and cost effective methods for determining irrigation requirements. This is especially true in underdeveloped countries where irrigation and water management are highly important and where relatively cheap methods are often essential. In many parts of the world, evaporation pans have historically been operated manually by technical staff. Although equipment is relatively inexpensive, the cost of human resources have been important and most likely contributed to the demise of some evaporation pan networks. In order to remedy this situation, some attempts have been made to automate the operation of evaporation pans using various techniques and designs (Asrar *et al.* 1982; Van Haveren 1982; Thibault and Savoie 1989; Chow 1994). The design of an automated floating pan to better estimate lake evaporation has also been found in the literature (Masoner *et al.* 2008). Some studies have compared the performance of commercially available evaporation pans to manually operated pans (Bruton et al. 2000; McGinn and McLean 1995). In the case of Bruton et al. (2000), they showed relatively large differences in evaporation estimates between automated and manually operated pans, and attributed this to potential mechanical problems related to sensors. McGinn and McLean (1995) showed differences of approximately 1 mm between commercial and manual pans; however, results were for a very short monitoring period (24 hours).

The above studies have shown that commercially available automated pans have not been without drawbacks and challenges. In particular, one of the challenges of most automated pans is their inability to monitor evaporation with a relatively high level of accuracy. This limitation is primarily related to the accuracy of water level sensors. According to the World Meteorological Organisation (WMO), a precision of ±0.1 mm is required for the operation of evaporation pans. Such precision is currently not obtainable with currently available water level sensors. Most pressure transducers monitor water levels to a precision of approximately ±1 mm, with a few float monitoring systems that are slightly more accurate (±0.2 mm).

A second challenge with automated evaporation pans is their inability to bring back the water level to a predetermined level (e.g., 200 mm) at the end of each measurement cycle (e.g., daily). The re-establishment of water level is important in order to have the same conditions at the start of each day and to be consistent with manually operated pans. As such, the present study will focus on the design of a new device for the measurement and refilling of a class A evaporation pan which will address these issues, i.e., 1) to improve the accuracy of automated evaporation pans and 2) to design a mechanism that will bring back the water level (within the pan) to a predetermined level.

In the present study, the new device to automate a class A evaporation pan will be presented and tested both in the laboratory and in the field. This study has the following specific objectives: 1) to provide information related to the functioning of the new refilling/measurement device, 2) to test the ability of the overflow apparatus to bring back the pan's water level at a predetermine level, 3) to test the accuracy of the evaporation pan based on predetermined extraction of water (i.e., simulation of evaporation) and 4) to test the operation of the automatic pan in the field under various meteorological conditions.

2.0 MATERIALS AND METHODS

2.1 Design of a new device to automate a class A evaporation pan

The purpose of this section is to provide detailed information on the newly designed device to automate a class A evaporation pan. Two new features in the design of the Automated Evaporation Pan (AEP) have been added to improve the operation. The first new feature consists of an "overflow apparatus" where the objectives of the device are twofold. First, the overflow apparatus was designed to bring back the water level to a predetermined level within the pan after each measurement cycle. This is done at a specific time of day (e.g., each morning at 7:00 am). Second, the overflow apparatus was designed to redirect any excess water back into the "stilling well" (described below) to measure the evaporation. The overflow apparatus is shown in Figure 1.

The second feature, to improve the operation of AEPs, is a stilling well which consists of an upright pipe acting as a cylinder to measure the amount of water added or evaporated through amplification. Both the overflow apparatus and the stilling well work together in improving AEPs. Figure 2 shows the basic operation of these two devices. In Figure 2, Δh_1 represents the change in water level due to evaporation. In order to make a measurement of evaporation, water is pumped from the stilling well to the pan until the water overflows back into the pan through the overflow apparatus. When water ceases flowing through the overflow apparatus, the change in water level in the stilling well (Δh_2) represents an amplified value of the evaporated water (Δh_1). The amplification factor is calculated from the ratio of the area between the evaporation pan (A_1) and the stilling well (A_2) given by:

$$Amplification\ Factor = \frac{A_1}{A_2} = \frac{A_{pan}}{A_{Stilling\ well}} \tag{1}$$

In the present design, the stilling well consisted of an 8 in (203.2 mm) diameter pipe with a 47.5 in (1206 mm) diameter evaporation pan. The surface area ratio provides an amplification factor of 35.2. Therefore, a change in the water level in the pan of 1 mm represents a change of 35.2 mm in the stilling well.

Figure 3 provides more details on the operation of the newly designed device. Figure 3a shows the water level in the pan resulting from the evaporation of the previous day. At the start of the evaporation measurement cycle, the water level in the stilling well is brought to a specific level (h_0). Water is then pumped from the stilling well to the pan, as shown in Figure 3b. During the pumping, the water in the stilling well will drop and the water in the pan will rise until the water overflows through the overflow apparatus (Figure 3c). When the overflow is detected, the pumping is ceased and the excess water is returned to the stilling well. When the excess water is no longer flowing, the evaporation can be calculated using the difference in water levels within the stilling well (h_0-h_1) (Figure 3d).

The evaporated water is calculated by the following equation:

$$Pan\ Evaporation = \frac{(h_0 - h_1)}{Amplification\ Factor} \tag{2}$$

where h_0 represents the initial water level, h_1 represents the final water level and the amplification factor is calculated using equation (1).

2.2 Materials and testing of the evaporation pan

2.2.1 Materials and detailed functioning of the evaporation pan

Following the conceptual design of the evaporation pan a prototype was built (Figure 4), and both laboratory and field tests were carried out to assess the functionality of the pan. The automated evaporation pan consisted of a stainless steel pan, two small pumps, a source of water, a water level sensor, a datalogger, an overflow apparatus and a stilling well. The water level sensor installed within the stilling well was a precision water level sensor (Model 6541B) from Unidata Pty Ltd (i.e., a float and pulley system with an accuracy of ±0.2 mm). For field testing, an Ott PLS (0-5 psi) water level sensor was used. The pumps used were Jabsco Par-Max 1 water pressure system pumps (4.3 L/min). These low flow marine pumps operate on 12V and were switch ON and OFF using a CR1000 datalogger (Campbell Scientific Corp.) and relay switches (i.e., A21REL-12).

Details on the functioning of the prototype pan are described as follows. During an evaporation measurement cycle, the stilling well is initially filled to a predetermined level h_0 (e.g., 7:00 am) (Figure 3a). A pump (Pump1) takes water from an external source (water in a container) and fills the stilling well until the specific level h_0 is reached. Pump1 is then turned OFF by the datalogger using a water level optical sensor switch installed within the stilling well at h_0. At this stage, the stilling well is filled to its highest level to carry out the evaporation measurement. When the water level in the stilling well is higher than h_0 at 7:00 am (e.g., due to rainfall), the fill procedure is bypassed and Pump1 remains turned OFF. The water level (h_0) is measured over the next 5 minutes and data are recorded by the datalogger. At 7:05 am, a second pump, Pump2, is turned ON and extracts water from the stilling well to fill the pan until overflow occurs (Figure 3b and 3c). When overflow occurs, Pump2 is turned OFF using a second water level optical sensor switch installed within the stilling well at the mouth of the overflow apparatus. When Pump2 is turned OFF, the excess overflow ceases within 30 to 45 minutes (on average) which brings back the water level within the pan to the predetermined level. The changes in water levels in the stilling well are recorded every minute between 7:00 am and 8:00 am and at 15 minute intervals thereafter. The pan evaporation is then calculated using equation (2). It should be noted, that the daily cut-off period (i.e., evaporation between two different days) is when the overflow occurs (generally between 7:06 and 7:12 am). Any evaporation after is monitored the next morning. Also, any evaporation occurring after the cut-off does not affect the reading, as it only stabilises the level within the stilling well faster. The datalogger also measures the duration of pumping for each pump and each cycle in order to estimate the battery power requirement.

It should be noted that the previous section described a one cycle evaporation measurement (daily evaporation less than 9 mm). For days with more than 9 mm of evaporation, the measurement is carried out in two cycles. These measurements are referred to as a double fill measurement. In this situation, the water level within the stilling well drops below a critical level of 100 mm and Pump2 is turned OFF. The stilling well is refilled at 7:11 am and the second cycle is initiated at 7:17 am.

2.2.2 Testing of the evaporation pan

Three specific aspects of the automated pan were tested in the laboratory during the present study, namely 1) the ability of the overflow apparatus to bring back the water level in the pan to a predetermined level, 2) the surface tension effect around the overflow apparatus and 3) the accuracy of the evaporation measurements. Following the laboratory experiments, the AEP was tested in the field for 40 days under different meteorological conditions.

To ensure accurate measurements of evaporation, the overflow apparatus must bring back the water level to a predetermined value. To carry out this experiment, a manual water level gauge by Armfield (Vernier Hook & Point Gauges with a ±0.1 mm precision) was installed near the “mouth” of the overflow to monitor the level during each cycle. Six series of measurements were carried out at approximately one hour intervals. During measurements, three manual gauge readings were taken within a three minute interval to observe the steadiness of the water level and to reduce sampling errors.

The second series of tests consisted of measuring the surface tension effect around the overflow apparatus. The surface tension influences the “contact angle” between a liquid and a solid. The contact angle either elevates or drops the surface of a liquid when in contact with a solid. In the AEP, a surface tension effect is present around the top of overflow apparatus (Figure 5). When the water rises in the pan, the effect is maximal immediately before the overflow occurs. This means that the water level has to be at a higher level to initiate the overflow and then drops back to a normal level after the overflow has ceased. The difference in height (ΔH) was measured to study the influence on the operation of the overflow apparatus. As such, water levels were measured at the moment of overflow and immediately after the overflow ceased. The difference in levels represented the surface tension effect (ΔH).

During the third experiment, the accuracy of the evaporation pan was tested. Prior to each test, a measurement cycle was carried out to fill the pan to a predetermined level and to verify that no evaporation occurred. Then a simulated evaporation was carried out by extracting a measured quantity of water from the pan. The extracted water was weighed using a micro balance (Cole-Parmer Symmetry ECII-4000, ±0.1 g). A ratio of 1167g per 1 mm of simulated evaporation was used to precisely measure the extracted water in terms of evaporation. The ratio was calculated based on the size of the pan and water density. Once the amount of simulated evaporation was extracted from the pan, the pumping cycle was initiated through the datalogger. After each test, the logger time was reset to 7:00 am for another cycle and another amount of water was extracted from the pan to simulate another controlled evaporation.

The calculated amount of evaporated water (equation 2) was compared to the weighed amount (extracted). The calculations of a single fill (< 9 mm) required two water levels and the double fill (> 9 mm) required four water levels (two per cycle).

During the field testing, the automatic pan was installed on a wooden platform and evaporation measurements were carried out daily at 7:00 am. The current design only monitors the evaporation during days without rainfall or rainfall less than the evaporation. During rainfall days exceeding the evaporation, the water in the stilling well rises to a level higher than h_0 (approximately 10 mm higher) and any excess water overflows out of the stilling well (this amount of water was not measured). As such, any surplus water from the pan due to rainfall is evacuated through the overflow of the stilling well. The next morning, as the water level in the stilling well is higher than h_0, the refilling is bypassed; however, the evaporation measurement cycle is carried out.

3.0 RESULTS AND DISCUSSION

3.1 Testing of the overflow apparatus

Testing of the overflow apparatus was carried out and the results of this experiment are presented in Table 1. The three readings during each observation gave the same value; therefore only the mean value was presented. Results show that the water level was set at approximately 202.1 mm and 202.2 mm from the bottom of the pan. The variation in readings was well within the accuracy of the Armfield manual gauge (±0.1 mm) and highly acceptable for the operation of evaporation pans. Therefore, the overflow apparatus was very effective in bringing back the water to a predetermined level.

During the second series of tests, the surface tension effect on the overflow apparatus was measured. A total of 14 observations were carried out and results are presented in Table 2. The difference between the height at the moment when overflow started (initial gauge height) and the height immediately after the overflow ceased (final gauge height) provided the surface tension effect, ΔH (Figure 5). During this experiment, the final water levels (202.5 and 202.6 mm) were slightly higher than in the previous experiment (Table 1) because the overflow apparatus was moved slightly during some adjustments. Nonetheless, the consistency of final levels in Table 2 showed that the overflow apparatus was very effective in bringing back the water to a predetermined level (similar to Table 1). The average surface tension effect was 0.9 mm with a maximum value of 1.7 mm and a minimum of 0.6 mm. Notably, the surface tension effect was less than 2 mm and it does not influence the daily evaporation readings because a measurement cycle is always carried out each morning (with or without any precipitation the previous day). However, the surface tension effect has to be considered in the design and operation of the AEP during days with a net precipitation of 0-2 mm (i.e., precipitation + condensation – evaporation = between 0 and 2 mm). The amount of daily precipitation is generally measured with a precipitation gauge (e.g., tipping bucket) next to the evaporation pan.

3.2 Accuracy of the automated evaporation pan

The third set of observations consisted of testing the accuracy of the automated evaporation pan. The experiment was carried out to determine how effective the AEP was at measuring a known amount of daily evaporation (in our case a known amount of extracted water, i.e., simulated evaporation). In total, 20 observations were carried out for the experiment and test values ranged from 1 to 13 mm (Table 3). Single and double fill cycles were required depending on the amount of simulated evaporation. For instance, double fill cycles were required for evaporation greater than 9 mm. Results showed that 75% of observations (15 of 20 observations) were within the ±0.1 mm error value suggested by the WMO. The average mean error for the 20 observations was calculated at +0.023 mm and the root mean square error (RMSE) was calculated at 0.086 mm. Both the absolute and relative errors were presented (Table 3). The average absolute error was 0.069 mm with a maximum of 0.195 mm (at 4.5 mm) and a minimum of 0.004 mm (at 10 mm). The average relative error was 1.64% with a maximum value of 5.08% (at 1 mm) and a minimum of 0.04% (at 10 mm). With a mean absolute error less than 0.1 mm and a relative error less than 2%, results of the AEP were deemed very good for the estimation of daily evaporation. Figure 6 shows a plot of predicted vs. observed evaporations as well as the line of perfect fit. The figure shows a good agreement between both observed and predicted values with a slight positive bias at 4-5 mm and a slight negative bias around 6-7 mm.

Figures 7 and 8 show the water level in the stilling well for single and double fill evaporation cycles during a period of 60 minutes (between 7:00 and 8:00 am). No consistent pattern was observed other than the water level was stable and very close to its final value after 30 to 45 minutes. In the case of the double fill cycles, the first cycle was initiated at 7:05 am and by 7:08 am, the water level had reached a minimum value of close to 100 mm. The refill was initiated at 7:11 am and was completed at 7:14 am. The second cycle was initiated at 7:17 am and the water level was stable within the same timeframe than for the single fill. The different water levels were used in the calculation of evaporation.

3.3 Pumping time and power requirement

The results provide an approximation of the duration of pumping and power requirement for each evaporation measurement. The duration of pumping for the 20 observations for Pump1 and Pump2 were collected and listed in Table 4. The pumping time for observation 13 (at 7 mm) was not available due a program malfunction. For instance, Table 4 provides the average pumping time for single and double fill cycles, and for Pump1 and Pump2. The average pumping time for single fill was 91 seconds for Pump1 and 161 seconds for Pump2. The duration of pumping for double fill averaged 195 seconds for Pump1 and 284 seconds for Pump2. Both pumps use approximately 2 Amps while in operation. This means that, on average, these pumps used less than 0.2 Amp-hour (for a total pumping time of 360 s) during each cycle of daily evaporation. Therefore, the average daily power requirement is approximately 0.2 Amp-hour.

3.4 Field testing of the evaporation pan

Following the laboratory testing, the prototype was tested in the field under different meteorological conditions for a period of 40 days (August 15, 2010 to September 25, 2010). Figure 9 shows the installation of the AEP on a wooden platform in the field. In the field, the overflow apparatus was covered with a 4" (102 mm) PVC pipe (with a cap on top), to minimize the wind effect around the device. Figure 10a shows changes in water levels within the stilling well during a typical operation of the AEP (between August 23 and September 1, 2010). This was a period with precipitation on August 25 (2.4 mm) and 26 (14.2 mm) and relatively warm air temperatures. Minimum air temperature occurred on August 28 at 9.5°C and maximum air temperature occurred on September 1 at 34.1°C. It should be noted that the time axis on Figure 10a is not to scale (as shown on Figure) to amplify the duration of refilling and evaporation measurement (1 hour, between 7:00 and 8:00 am) compared to the remainder of the day (23 hours). During the 10-day period, the daily evaporation measurements varied between 0.16 mm and 3.1 mm. The refill level h_0 was at 435 mm and the stilling well overflow level was at 445 mm (in the evening of September 26 and early September 27). The figure shows the operation of the pan for days with and without rainfall. For example, during the first day with rain (August 25; 2.4 mm) the water level increased within the stilling well in the morning (8 mm) and early August 26 (75 mm), immediately before the refill at 7:00 am. The refill occurred on August 26 and the evaporation was calculated at 0.16 mm. The day after, a significant amount of rain was present (August 26; 14.2 mm) and the level in the stilling well reached the overflow level of 445 mm (at 4:00 pm). The morning of August 27, as the level was higher than h_0 (435 mm), the refill was bypassed and the measurement cycle was nevertheless carried out (with an evaporation of 0.45 mm). The water surplus was 13.75 mm (14.2 mm - 0.45 mm). There will be situations where the level in the stilling well will not stabilizes between 7-8 am (conditions not experienced during the field observation) and the water level will reach the stilling well overflow level (due to rainfall during the same period, i.e., between 7-8 am). During such events, neither the evaporation nor the surplus of water can be calculated for those days.

Figure 10b shows the time series of water temperature measured every 15 min (bottom and surface) in the evaporation pan. Results show no significant difference between bottom and surface water temperature, therefore the water is well mixed throughout the pan.

4.0 SUMMARY AND CONCLUSIONS

The measurement of evaporation remains a key component of the overall understanding of the hydrologic cycle. Evaporation also plays a crucial role in many studies where direct monitoring is essential (e.g., lake water budget, crop irrigation, etc). The equipment and the monitoring of evaporation have evolved significantly over the years (Shuttleworth 2007); however, evaporation pans are still widely used. Many projects and studies are small scale and, as such, expensive equipment and technologies are usually not an option. Therefore, there is a need to rely on less expensive technologies and evaporation pans remain a very important monitoring device in many applications (Stanhill 2001). This is especially true in developing countries where less expensive technologies are sometimes the only option.

In the present study, a new device to automate a class A evaporation pan was designed, described and tested to determine the relative accuracy in the estimation of daily evaporation. Results revealed that this newly designed automatic evaporation pan (AEP), with overflow apparatus and stilling well, performed very well. The overflow apparatus has the objective of bringing back the water level to a predetermined level. Results showed that the water level was within ±0.1 mm of the predetermined level which is highly acceptable. The overflow apparatus also has the objective of redirecting any excess water back into the stilling well in order to estimate the evaporation. Results showed that this process takes approximately 30 to 45 min between 7:00 am and 8:00 am. Although the water level stabilises in 30 to 45 min, the daily cut-off occurs immediately after the overflow. As such, any evaporation (between 7-8 am) after the cut-off will stabilise the water level within the stilling well faster without affecting the evaporation measurement the next day.

The automatic evaporation pan (AEP) was tested by simulating different evaporation rates (1 to 13 mm). This was done by removing an exact amount of water from the pan (simulated evaporation) and then comparing the amount to the calculated evaporation from the AEP. Results showed very good performances with errors typically less than 0.1 mm. The average absolute error was 0.069 mm whereas the root mean square error was 0.086 mm. These errors are consistent with the requirement from the World Meteorological Organisation for the operation of evaporation pans (±0.1 mm). The AEP was also tested in the field under various meteorological conditions and the unit performed well with and without rainfall. However, the current design has the limitation of not being able to monitor evaporation (or surplus of water) for days when significant rainfall is present between 7-8 am (which would prevent the stabilisation of the level within the stilling well).

Given the good results and performance of the AEP, important considerations should, nevertheless, be considered when setting up the equipment. One important consideration of the AEP is the levelling of the overflow apparatus. The levelling of the overflow apparatus was important to reduce the water settling time to a minimum. The minimum water level in the stilling well (in our case 100 mm) is a function of the water level sensor. This limitation was due to the transducer which modified the surface area (amplification factor) below this level.

In conclusion, the automated evaporation pan, when tested in the laboratory and in the field, performed very well. The newly designed AEP has the advantage of being less expensive than other evaporation monitoring devices including manually operated pans. The AEP operates on 12V and has a low power requirement. As such, it also provides an opportunity for continuous monitoring in remote settings as well as for real time data acquisition.

5.0 ACKNOWLEGEMENTS

This study was partially funded by NSERC and their support was greatly appreciated. I want to thank the following people for their contribution during this study: Luc LeBlanc for carrying out the laboratory experiments, Donald J. Snodgrass (Campbell Scientific Canada Corp.) for his help with sensors and some programming, Nassir El-Jabi (Université de Moncton) for providing the class A evaporation pan and Mysore G. Satish (Dalhousie University) for the fabrication of the overflow apparatus. I also want to thank Dr. Gerrit Hoogenboom (AgWeatherNet and Washington State University) for comments on an earlier draft of the manuscript and Drs. Chris Spence and Newell Hedstrom (Environment Canada), Dr. Lien Chow (Agriculture and Agri-Food Canada), Cindy Breau and Peter Hardie (Fisheries and Oceans Canada) for reviewing the manuscript.

6.0 REFERENCES:

Armstrong, R.N., J.W. Pomeroy and L.W. Martz. 2008. Evaluation of three evaporation estimation methods in a Canadian prairie landscape. Hydrological Processes 22: 2801-2815.

Asrar, G., R.J. Kunze and D.E. Linvill. 1982. *Automating a class A evaporation pan for semi-continuous recording*. Agricultural Meteorology 25: 275-281.

Assouline, S., S.W. Tyler, J. Tanny, S. Cohen, E. Bou-Zeid, M.B. Parlange and GG Katul. 2008. *Evaporation from three water bodies of different sizes and climates: measurements and scaling analysis*. Advances in Water Resources 31: 160-172.

Benyahya, L., D. Caissie, N. El-Jabi and M.G. Satish. 2010. *Comparison of microclimate vs. remote meteorological data and results applied to a water temperature model (Miramichi River, Canada)*. Journal of Hydrology 380: 247–259.

Bruton, J.M., G. Hoogenboom and R.W. McClendon. 2000. *A comparison of automatically and manually collected pan evaporation data*. Transactions of the ASAE (American Society of Agricultural Engineers) 43(5): 1097-1101.

Brutsaert, W. 2006. *Indications of increasing land surface evaporation during the second half of the 20th century*. Geophysical Research Letters 33, L20403, doi:10.1029/2006GL027532.

Brutsaert, W. 1982. Evaporation into the atmosphere. Dordrecht, Holland: D. Reidel Publishing Company. 299p.

Burn, D.H. and N.M. Hesch. 2007. *Trends in evaporation for the Canadian Prairies*. Journal of Hydrology 336: 61-73.

Caissie, D., M.G. Satish, and N. El-Jabi. 2007. *Predicting water temperatures using a deterministic model: Application on Miramichi River catchments (New Brunswick, Canada)*. Journal of Hydrology 336: 303-315.

Chin, D.A. and S. Zhao. 1995. *Evaluation of evaporation-pan networks*. Journal of Irrigation and Drainage Engineering 121(5): 338-346.

Chow, T.L. 1994. *Design and performance of a fully automated evaporation pan*. Agricultural and Forest Meteorology, 68: 187-200.

Fennessey, N.M. 2000. *Estimating average monthly lake evaporation in the northeast United States*. Journal of the American Water Resources Association 36(4): 759-769.

Masoner, J.R., D.I. Stannard and S.C. Christenson. 2008. Differences in evaporation between a floating pan and class A pan on land. Journal of the American Water Resources Association 44(3): 552-561.

McGinn, S.M. and H.D.J. McLean. 1995. *Monitoring free-water evaporation at automated weather stations*. Journal of Atmospheric and Oceanic Technology 12: 1363-1366.

Phene, C.J., D.A. Clark and G.E. Cardon. 1996. *Real-time calculation of crop evapotranspiration using an automated pan evaporation system*. In: Proc. Evapotranspiration and Irrigation Scheduling Conf., Nov. 3-6, San Antonio, Texas, ASAE, St. Joseph, Michigan. pp.189-194.

Phene, C.J., W.R. DeTar, and D.A. Clark. 1992. *Real-time irrigation scheduling of cotton with an automated pan evaporation system.* Applied Engineer in Agriculture 8(6): 787-793

Reis, R.J. and N.L. Dias. 1998. *Multi-season lake evaporation: energy-budget estimates and CRLE model assessment with limited meteorological observations*. Journal of Hydrology 208:135-147.

Rosenberry, D.O., T.C. Winter, D.C. Buso and G.E. Likens. 2007. *Comparison of 15 evaporation methods applied to a small mountain lake in the northeastern USA*. Journal of Hydrology 340: 149-166.

Shuttleworth, W.J. 2007. *Putting the "vap" into evaporation*. Hydrology & Earth System Sciences 11(1): 210-244.

Stanhill, G. 2002. *Is the Class A evaporation pan still the most practical and accurate meteorological method for determining irrigation water requirements?* Agriculture and Forest Meteorology 112: 233-236.

Tanny, J., S. Cohen, S. Assouline, F. Lange, A. Grava, D. Berger, B. Teltch and M.B. Parlange. 2008. *Evaporation from a small water reservoir: Direct measurements and estimates*. Journal of Hydrology 351: 218-229.

Thibault, G. and P. Savoie. 1989. *Automatic filling and emptying of a water evaporation pan*. Computers and Electronics in Agriculture 3: 327-333.

Van Haveren, B.P. 1982. *An automated recording system for evaporation pans*. Water Resources Bulletin 18(3): 533-536.

Vercauteren, N., E. Bou-Zeid, H. Huwald, M.B. Parlange and W. Brutsaert. 2009. *Estimation of wet surface evaporation from sensible heat flux measurements*. Water Resources Research 45, W06424, doi:10.1029/2008WR007544.

Xing, Z., L. Chow, F.-R. Meng, H.W. Rees, J. Monteith and S. Lionel. 2008. *Testing reference evapotranspiration estimation methods using evaporation pan and modeling in Maritime Region of Canada*. Journal of Irrigation and Drainage Engineering 134(4): 417-424

Table 1. Testing of the overflow apparatus to bring back the water level to a predetermined level within the evaporation pan.

Observation	Mean level of three readings (mm)
1	202.1
2	202.2
3	202.1
4	202.2
5	202.2
6	202.2
Mean =	202.2

Table 2. Testing of the surface tension effect on the overflow apparatus during different evaporation measurement cycles.

Observation	Initial gauge height (mm)	Final gauge height (mm)	Surface tension effect, ΔH (mm)
1	204.2	202.5	1.7
2	203.9	202.6	1.3
3	203.4	202.6	0.8
4	203.3	202.6	0.7
5	203.6	202.6	1.0
6	203.4	202.6	0.8
7	203.4	202.6	0.8
8	203.3	202.5	0.8
9	203.3	202.6	0.7
10	203.5	202.5	1.0
11	203.2	202.5	0.7
12	203.6	202.5	1.1
13	203.2	202.5	0.7
14	203.1	202.5	0.6
		Mean =	0.9

Table 3. Results of the Automatic Evaporation Pan (AEP) operation, predicted vs. observed evaporation, and corresponding errors.

Obs	Evaporation (mm)	Observed[1] evaporation (mm)	Predicted[2] evaporation (mm)	Single / double fill (S/D)	Error (mm)	Absolute error (mm)	Relative error (%)
1	1	0.97	1.02	S	0.049	0.049	5.08
2	1.5	1.50	1.54	S	0.041	0.041	2.72
3	2	1.97	1.94	S	-0.024	0.024	1.23
4	2.5	2.50	2.55	S	0.047	0.047	1.88
5	3	2.96	2.99	S	0.030	0.030	1.01
6	3.5	3.50	3.57	S	0.071	0.071	2.04
7	4	3.99	4.14	S	0.143	0.143	3.59
8	4.5	4.50	4.69	S	0.195	0.195	4.32
9	5	4.92	5.00	S	0.080	0.080	1.63
10	5.5	5.50	5.55	S	0.055	0.055	0.99
11	6	5.95	5.85	S	-0.101	0.101	1.70
12	6.5	6.50	6.34	S	-0.164	0.164	2.52
13	7	7.00	6.88	S	-0.116	0.116	1.66
14	7.5	7.50	7.49	S	-0.012	0.012	0.16
15	8	8.01	7.99	S	-0.022	0.022	0.27
16	9	9.00	9.06	D	0.060	0.060	0.67
17	10	10.00	10.00	D	-0.004	0.004	0.04
18	11	11.00	10.99	D	-0.016	0.016	0.15
19	12	12.00	12.05	D	0.048	0.048	0.40
20	13	13.01	13.11	D	0.099	0.099	0.76
				Mean =	**0.023**	**0.069**	**1.64**
				RMSE[3] =	**0.086**		

[1] - Observed evaporation was obtained by weighing the extracted water using a micro balance.

[2] - Predicted evaporation was obtained by the automatic evaporation pan.

[3] - Root mean square error.

Table 4. Duration of pumping for different evaporations.

Observation	Evaporation (mm)	Pump1 time (sec.)	Pump2 time (sec.)
1	1	136	84
2	1.5	150	124
3	2	22	124
4	2.5	88	122
5	3	42	148
6	3.5	56	222
7	4	82	130
8	4.5	10	160
9	5	90	190
10	5.5	94	164
11	6	82	174
12	6.5	112	184
13	7	N/A	N/A
14	7.5	134	207
15	8	172	216
16*	9	188	234
17*	10	180	254
18*	11	200	300
19*	12	220	304
20*	13	188	328
	Mean[1] =	**91**	**161**
	Mean[2] =	**195**	**284**

* These tests represented a double fill.

[1] - Mean pumping time of single fill.

[2] - Mean pumping time of double fill.

Figure 1. Design of a new overflow apparatus to bring the water level in the evaporation pan to a predetermined level and to redirect the excess water into the stilling well.

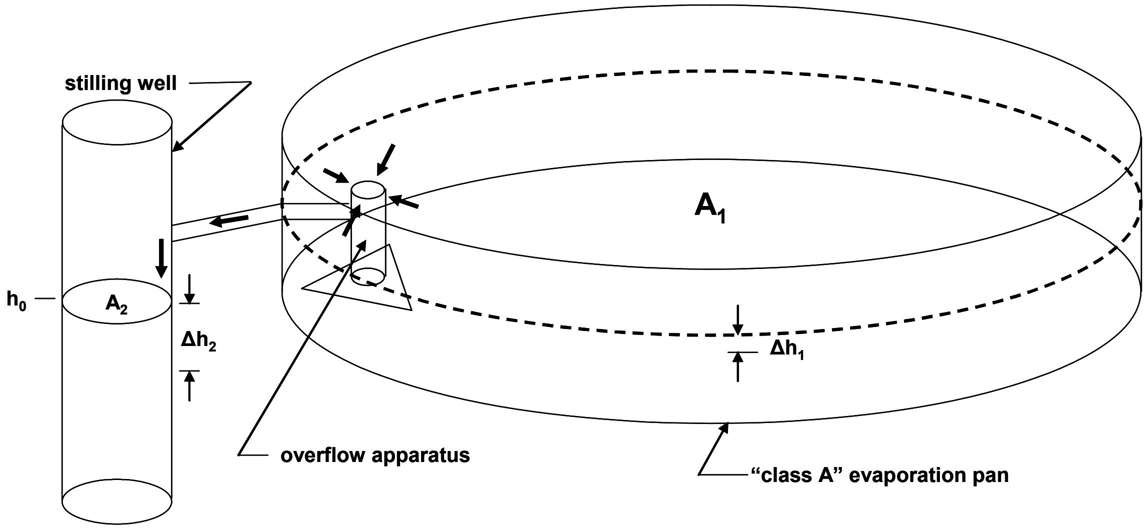
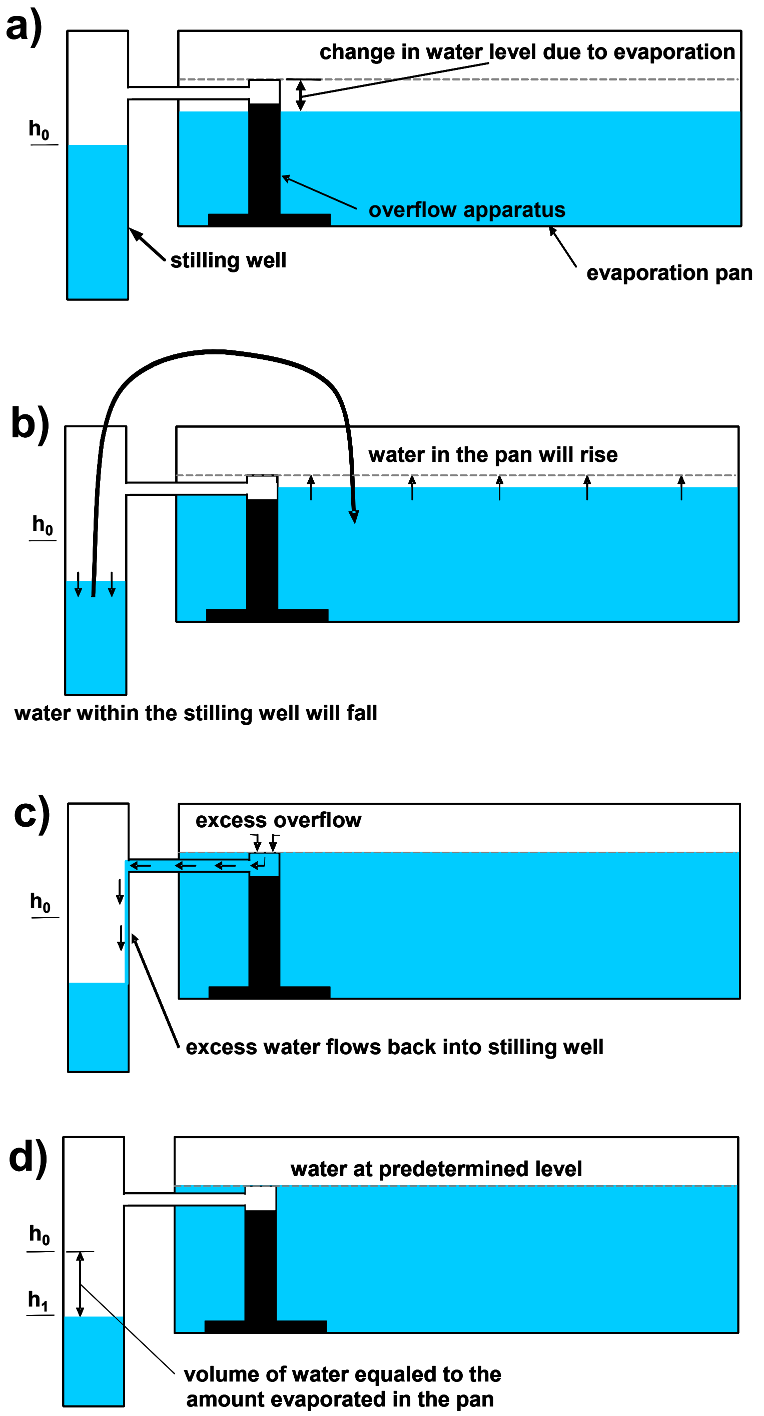


Figure 2. Illustration showing the operation of the new AEP with both the overflow apparatus and stilling well.



$$\text{Evaporation} = (h_0 - h_1) / \text{factor}$$

Figure 3. Illustration of the operation of both the overflow apparatus and the stilling well during an evaporation measurement cycle.

Figure 4. Prototype of the Automatic Evaporation Pan in the lab for testing.

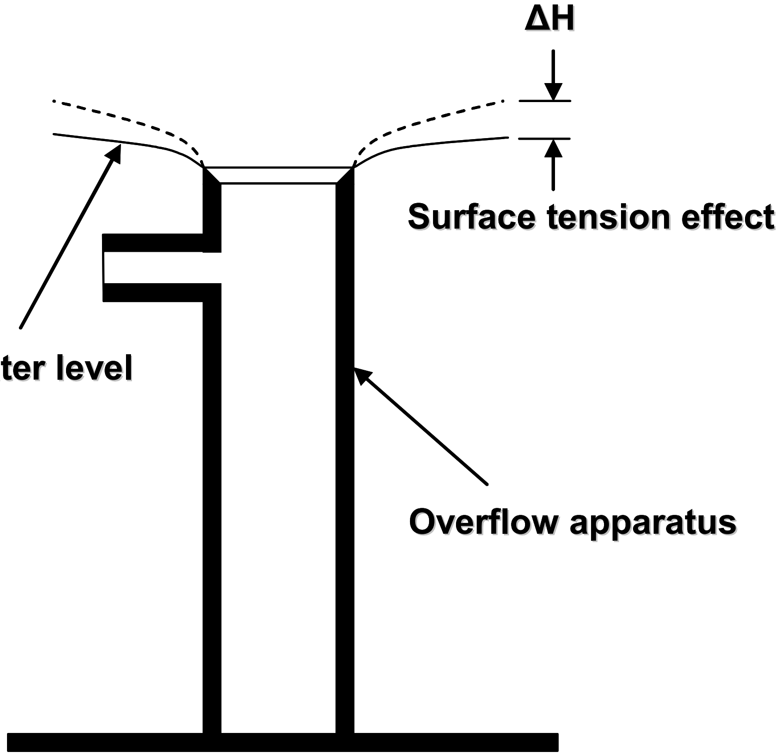


Figure 5. Illustration of the surface tension effect (ΔH) at the top of the overflow apparatus.

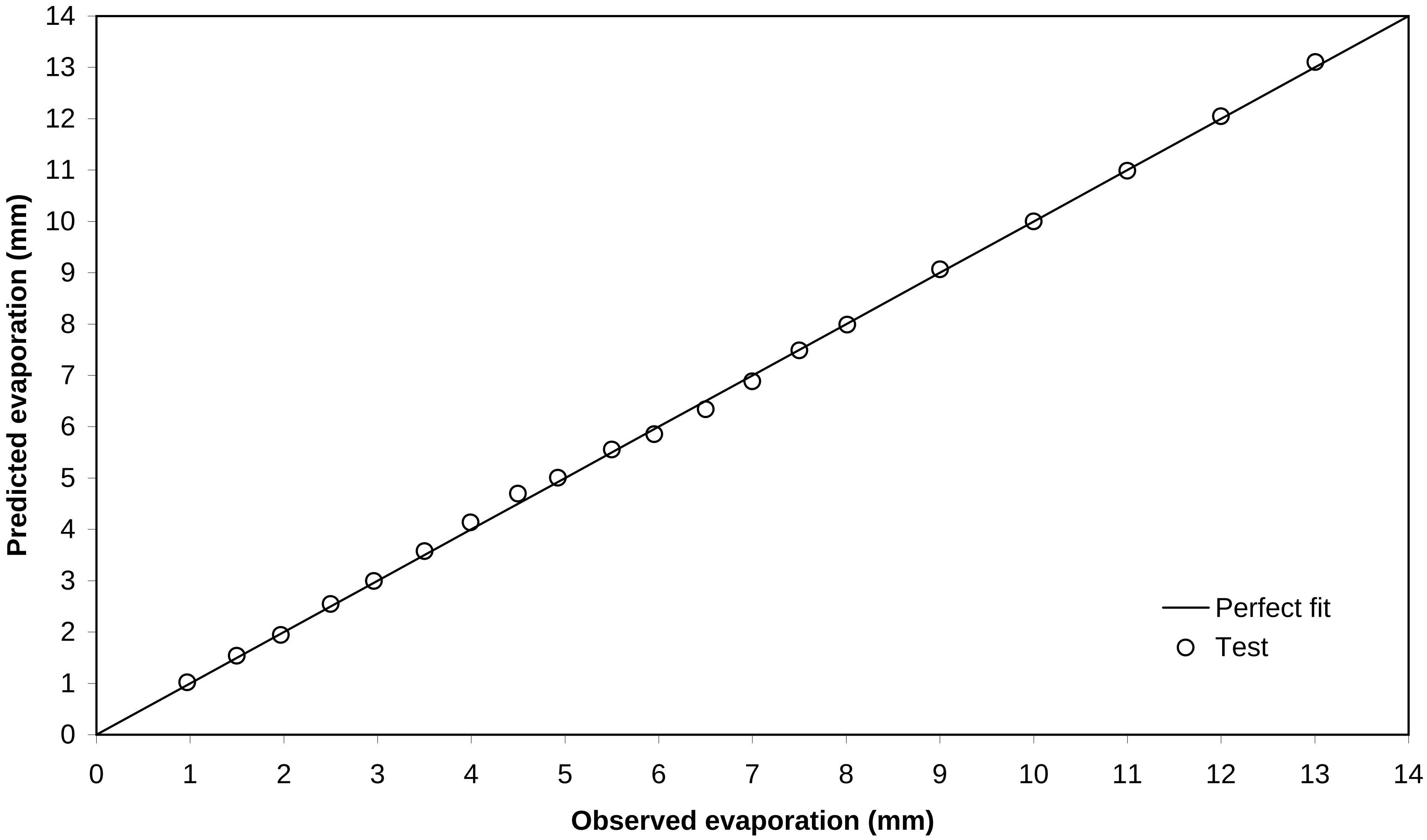


Figure 6. Predicted vs. observed evaporation for different evaporation rates using the Automatic Evaporation Pan (AEP).

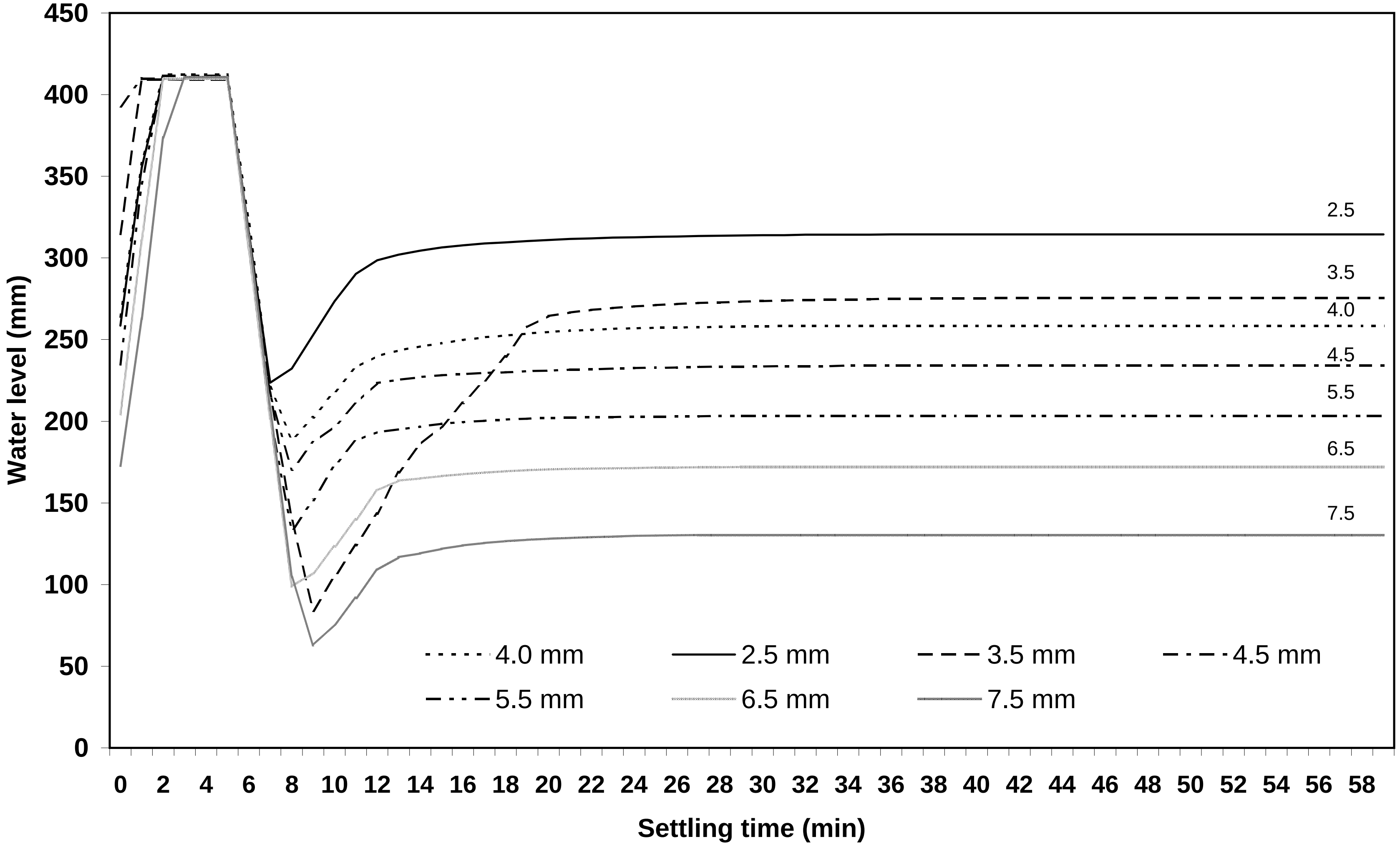


Figure 7. Water level settling time for different simulated evaporations for a single fill cycle (0 min = 7:00 am).

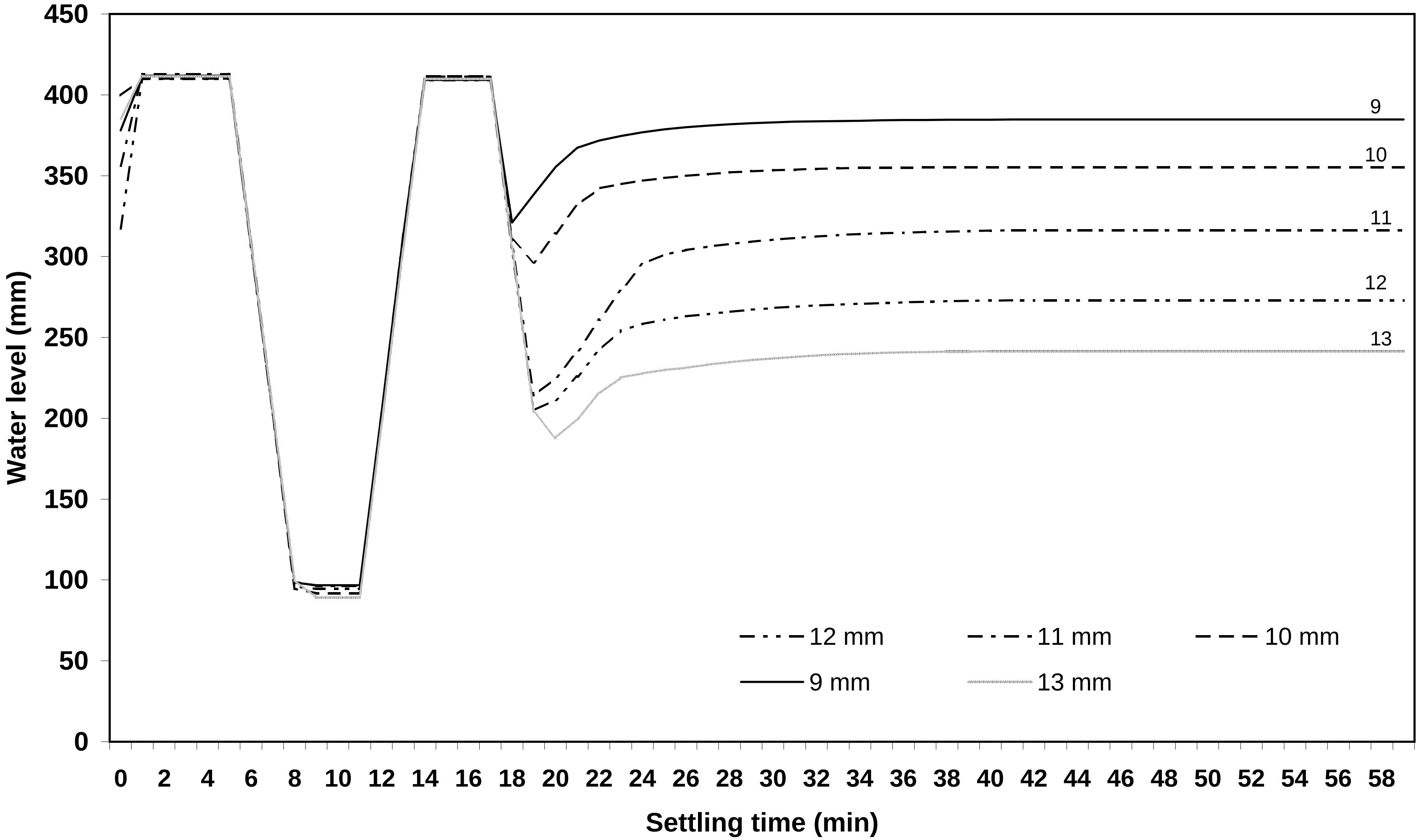


Figure 8. Water level settling time for different simulated evaporations for a double fill cycle (0 min = 7:00 am).

Figure 9. Installation of the prototype automatic evaporation pan for testing in the field. Figure inset shows the protective casing over the overflow apparatus.

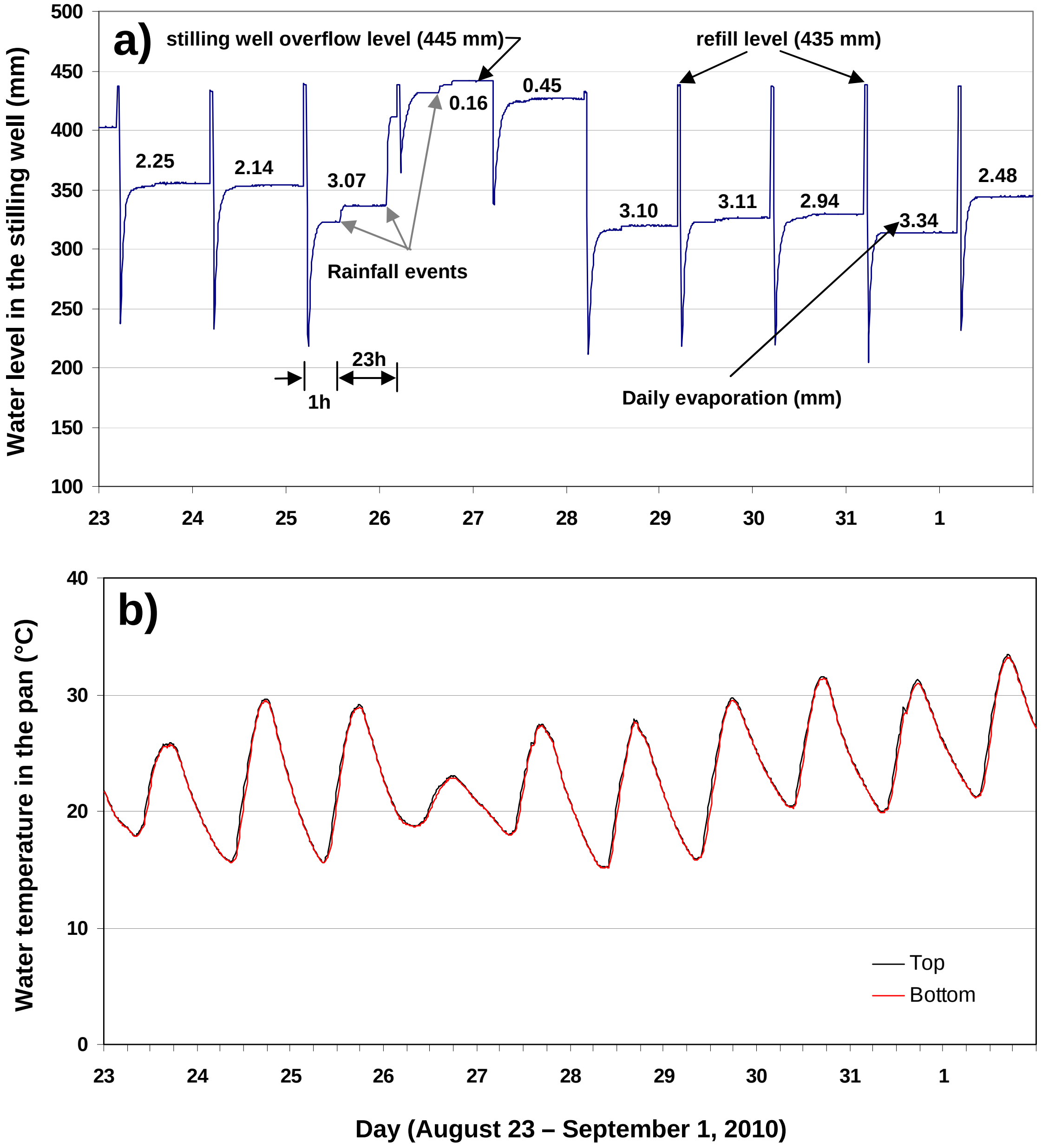


Figure 10. Field testing of the automated evaporation pan: a) water levels within the stilling well and b) water temperatures in the pan (August 23 to September 1, 2010).