Water and heat budgets of a shallow tropical reservoir

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[1] This study is one of the few attempts to close water and heat budgets in tropical lakes and reservoirs on both daily and monthly time scales. A water budget of Kranji Reservoir is constructed for the year of 2007 using data for water level, reservoir gate operation records, and inflow predicted by a catchment rainfall-runoff model. A heat budget of Kranji Reservoir is also constructed for a field deployment period in 2007 using data for surface radiation fluxes measured by a meteorological station, heat fluxes associated with inflows and outflows, and heat content of the water column measured by thermistors. All the components of the water and heat budgets are accounted for on the basis of a complete data set obtained from field measurements and reliable model predictions, including those that were often neglected in the earlier studies, e.g., advective heat. The water budget of Kranji Reservoir is dominated by the discharge and catchment inflow, which are very sensitive to the variations in precipitation. Analysis of the gate operation records in 2007 shows an appreciable amount of the outflow of Kranji Reservoir was released, especially during storm events. The heat budget reveals that net heat flux of this shallow tropical reservoir is dominated by the net surface radiation fluxes and is also highly responsive to variations in stormflow conditions. It is noted that two critical components in the heat budget are latent heat and inflow advective heat, which equal 83% and 71% of net radiation, respectively.


1. Introduction

[2] Constructing and closing a water budget is a useful method to describe the hydrology of lakes and reservoirs [Assouline, 1993] and has been widely applied as such. Water residence time, for example, can be derived from the water budget and used to explain the variability of thermal stratification and primary production in lakes and reservoirs [Monsen et al., 2002; Rueda and Cowen, 2005]. Similarly, a heat budget is important in studying the variability in the thermal structure and mixing dynamics in a lake or reservoir during both shorter and longer time scales. Determining how surface heating and cooling and the advective heat transferred by inflows and outflows change the lake heat content are essential for understanding the vertical and horizontal thermal stratification and mixing in a lake or reservoir [Levis, 1983a; Talling and Lemoalle, 1998].

[3] However, in water budget studies of lakes and reservoirs, there are often constraints of economics and resources for carrying out detailed measurements of each component in the water balance equation. It is not uncommon that unmeasured or neglected terms exist for closing the water budget [Winter, 1981; Assouline, 1993]. Moreover, studies on lake water budgets typically focus on longer time scales such as monthly [e.g., Myrup et al., 1979; Assouline, 1993; LaBaugh et al., 1997] or annual [e.g., Levis, 1983b; Claessens et al., 2006; Shanahan et al., 2008].

[4] Similarly, heat budget studies for lakes and reservoirs are often restricted by unmeasured or inadequate data for evaluating some of the important terms [Myrup et al., 1979]. Earlier studies of lake heat budgets focus primarily on the surface heat fluxes, with one-dimensional vertical heat flux models being applied to numerous lakes for describing the overall heat balance [e.g., Eggers and Tetzlaff, 1978; Spence et al., 2003; Binyamin et al., 2006; Momii and Ito, 2008]. The advective heat associated with inflows and outflows was often considered as a minor source of heat or not measured because of difficulties encountered in assessing this term and thus neglected in the heat budget calculations [e.g., Keijman, 1974; Colomer et al., 1996; Rouse et al., 2003; Binyamin et al., 2006; Momii and Ito, 2008], though Tanny et al. [2011] noted its possible significance. Although the findings of many studies of lake heat budgets show that the input and output of heat energy are dominated by surface heat fluxes including radiation fluxes, latent heat flux and sensible heat flux [e.g., Myrup et al., 1979; Levis, 1983a; Livingstone and Imboden, 1989; Colomer et al., 1996; Oswald and
Rouse, 2004), this may not be so for lakes where the water budget is dominated by inflows and outflows. In such lakes, the advective heat transport is likely to play as important or greater role than the surface heat flux terms in the heat budget.

[5] In a similar way, although the change in heat storage in a lake or reservoir has historically been considered important [e.g., Hutchinson, 1957] when describing the response of lakes to seasonal meteorological variations, its calculation has often been oversimplified or neglected. In some studies of lake heat budgets, the heat storage has been assumed to be equal to the residual of the heat balance calculation [e.g., Rouse et al., 2003; Binyamin et al., 2006]. In studies where lake heat storage change is accounted for via water temperature changes and lake geometry, it is typically calculated using the equilibrium water temperature which is the surface temperature at which the net heat flux is zero [Livingstone and Imboden, 1989] or a depth-averaged water temperature [Keijman, 1974; Eggers and Tetzlaff, 1978; Spence et al., 2003; Oswald and Rouse, 2004; Rouse et al., 2008]. Even the more rigorous method of calculating lake heat content by integrating vertically the heat content of individual water layers can be an oversimplification since it assumes that the lake has a one-dimensional thermal structure, i.e., horizontal homogeneity [Livingstone and Imboden, 1989; Moreno-Ostos et al., 2008]. This method works well on lakes with small horizontal temperature differences while inherent errors may exist for lakes where there are significant horizontal temperature gradients.

[6] Tropical lakes are generally characterized by higher levels of and weaker seasonal variations in solar radiation than are experienced by temperate lakes throughout the year except for periods with high cloud cover [Gunkel and Casillas, 2002; Lewis, 1987; Talling and Lemoalle, 1998]. Compared to temperate deep lakes which have seasonal background stratification, shallow tropical lakes with average depths smaller than 5 m may achieve complete mixing of the whole water column multiple times every year, possibly even mixing diurnally [Lewis, 2000; Talling, 2001]. Examples include Pilkington Bay of Lake Victoria in tropical Africa [MacIntyre et al., 2002] and Lake Calado of the Amazon floodplain [MacIntyre and Melack, 1984]. However, comprehensive studies of water and heat budgets and the effects of different components on the water and heat balance equations of tropical lakes and reservoirs have been very limited. Of the few existing studies, many focus on the seasonal or annual variations in water and heat budgets [e.g., Lewis, 1983b; Tin and Nicholson, 1998; Verburg and Antenucci, 2010] or observed correlations of mixed layer depths with solar isolation and penetrative convection on a daily scale [MacIntyre and Melack, 1988]. Instantaneous flux measurements offer an approach to determine water and heat budgets on a daily basis and such budgets are needed in understanding the short time scale stratification and mixing in shallow tropical lakes [Talling and Lemoalle, 1998]. This study establishes the water and heat budgets of Kranji Reservoir accounting for advective heat via inflows and outflows, and change in heat storage. The observations we report here highlight the importance of the advective term in both the water and heat budgets. The originality of this current study is that it is one of the few attempts made at closing water and heat budgets in a tropical lake or reservoir on the daily time scale incorporating all key components.

[7] This paper is organized as follows. A description of Kranji Reservoir and field measurements from 2007 are presented in section 2. Section 3 describes the water balance and heat budget models. The data collected during 2007 is presented in section 4, along with the measured dam and pumping outflows. Section 5 discusses the results of water budget for Kranji Reservoir during the field deployment and for the whole year of 2007. Section 6 presents the results of heat budget for Kranji Reservoir during a field deployment in 2007 and discusses the effects of advective heat fluxes, as well as the stream temperature responses to precipitation and storm events. Some of the remaining challenges in further refining the heat budget are enumerated in section 7, and a summary of findings of this study is also discussed in this section.

2. Study Site and Methods

2.1. Study Site

[8] Kranji Reservoir (1°25′N, 103°43′E) is located at the northwest corner of Singapore. It is a former river, which was dammed at its mouth in 1972 to form a freshwater storage reservoir. It is one of the reservoirs for water supply in Singapore. The total area of the Kranji catchment is about 5.6 × 10^5 m^2 and maximum volume of 1.6 × 10^7 m^3. The length of main channel of Kranji Reservoir is about 4 km with maximum depth of about 20 m and average depth of about 5 m. There are four major tributaries flowing into Kranji Reservoir, which are Sungei Kangkar, Sungei Tengah, Sungei Peng Siang and Sungei Pang Sua. Sungei Pang Sua was diverted into Kranji Reservoir at the end of 2005. Kranji Reservoir is almost entirely fed by dry weather flow and storm runoff from the four tributaries and direct precipitation on the reservoir. A map of Kranji Reservoir and its catchment is shown in Figure 1a.

2.2. Field Measurements

[9] An extensive array of hydrodynamic moorings was deployed in Kranji Reservoir from 10 April (year day 100) to 14 June (year day 165) in 2007. The moored instrumentation included Seabird SBE39 temperature loggers (one SBE39 each at M1, M2 and M3 and thermistor chains of multiple SBE39s at other locations), two 1200 KHz and one 600 KHz RDI/Teledyne acoustic Doppler current profilers (ADCP). Table 1 summarizes the deployed instruments and their setup in each mooring station. The locations of the eight mooring stations and the instruments deployed are shown in the contour map of Kranji Reservoir (see Figure 1b). The bathymetry of Kranji Reservoir was digitized from a survey map of Kranji Reservoir.

[10] A meteorological station was located on the water close to M5 in the Kranji Reservoir during the field deployment period in 2007 (hereafter, Met station 1). The sensors of Met station 1 were installed at 1.5 m above water surface, recording air temperature, relative humidity, wind speed and direction, shortwave radiation, net radiation, as well as rainfall rate at 15 min intervals. Unfortunately, there was a short gap of about 10 days in the data recorded at the station from 6 May (year day 126) to 15 May 2007
because of an equipment malfunction. The meteorological data with the exception of the rainfall data was filtered with a fourth-order low-pass Butterworth filter with a cutoff time scale of 2 h.

2.3. Inflow and Outflow

We have measured the inflow in the main channel of Kranji Reservoir during the 2007 field deployment period using the ADCP at M5 as M5 was located in the middle of the main channel and included inflow from all the four tributaries. In contrast the flow at M4 did not include tributary inflow from Sungei Pang sua and M6 was located near the shore of the main channel (see Figure 1b). The ADCP measured at 4 min interval and recorded velocities in 0.2 m bins. The inflow is also modeled by an established hydrological and hydraulic model which will be discussed later in section 3.1. The outflow of Kranji Reservoir has two components, i.e., daily discharge through the Kranji Gate at the Kranji Dam and transfer to Choa Chu Kang (CCK) Water Work by pumping. The Kranji Gate is a roller gate, which opens up when the water level rises during rainfall events.

Figure 1. (a) Kranji Reservoir and its catchment. (b) Contour map of Kranji Reservoir showing the four important inflows, the Kranji Dam, and locations of field deployment stations in the 2007 April to June field experiment: thermistor loggers (M1 to M8) and acoustic Doppler current profilers (ADCPs; M4, M5, and M6). The solid black lines between adjacent moorings define the boundaries of different blocks used in the calculation of lake heat content of Kranji Reservoir in section 3.2.3. (c) Locator map of Kranji Reservoir in Singapore showing the water body and its catchment.
2.4. Water Level

[12] The water level of Kranji Reservoir was measured at the Kranji Gate before and after each gate operation. It was also measured at M5 and M6 using the internal pressure sensors of ADCP during the field deployment period in 2007. The depths measured by ADCPs were further corrected by the barometric pressure measured by a Seabird 26plus located about 8 km away at Nanyang Technological University.

3. Model Description

3.1. Water Balance Model

[13] In order to calculate the water balance and assess the importance of each of the components in the water budget, a simple water balance equation is used:

\[
\frac{\Delta V}{\Delta t} = Qin + P - Q_{out} - E
\]

(1)

where \(\Delta V/\Delta t\) is the storage change of Kranji Reservoir calculated by the water level change over a certain time period, \(Q_{in}\) is the total tributary inflows into the main channel, \(Q_{out}\) is the total outflow from the reservoir including the discharge through the Kranji Gate and pumping transfer to CCK Water Work. \(P\) is the precipitation on the lake surface and \(E\) is the evaporation over the lake. Table 2 summarizes the variables used in the water balance model and methods to obtain them. We have not explicitly included possible water leakage through the bottom of the gate, the dam bed and seepage into the sediments in the water balance. Rather, these small effects are implicitly lumped into the much larger outflow component since the dam outflow is computed directly by the observed daily water level change in the reservoir. To balance the model, we calculated the total input and output terms and then the corresponding water imbalance percentages over different time scales.

3.1.1. Inflow Model: Approach 1

[14] The XP Storm water & Wastewater Management Model [XP Software Inc., 2005] was established and calibrated to predict the direct runoff from the four main catchments in the Kranji Catchment [Lo et al., 2008]. The simulated total runoff hydrographs (time interval of 15 min) were compared with the measured hydrographs at several gauging stations in the Kranji catchment and the approach works well. The model was calibrated over both single and continuous stormflow events [Tan et al., 2008]. We configured XP-SWMM and ran it for the whole year of 2007.

3.1.2. Inflow Model: Approach 2

[15] For the field deployment period in 2007, the total tributary inflow can also be calculated from the ADCP measurements of depth-averaged velocities at M5. A mean velocity correction was used to transform the depth-averaged flow velocity to the mean flow velocity. We transformed the depth-averaged flow velocity to mean velocity following Wilkerson and McGahan [2005] and assuming a straight trapezoidal channel:

\[
V_0 = V_Z \left( \frac{1}{(1 + 0.104Z) - (0.125Z) \exp \left( \frac{2.24Z - 0.582}{Y_2} \right)} \right)
\]

(2)

Here \(V_0\) is the mean velocity, \(V_Z\) is the depth-averaged velocity at the centerline of the channel, \(Z\) is the cotangent

Table 1. Instruments Used at Each Mooring Site During Field Deployment in 2007*a

<table>
<thead>
<tr>
<th>Moorings</th>
<th>Latitude (°N)</th>
<th>Longitude (°E)</th>
<th>Depth (m)</th>
<th>Instruments</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>M1</td>
<td>1°24.740'</td>
<td>103°42.986'</td>
<td>1.7</td>
<td>Thermistor</td>
<td>1 mab</td>
</tr>
<tr>
<td>M2</td>
<td>1°23.776'</td>
<td>103°43.516'</td>
<td>1.7</td>
<td>Thermistor</td>
<td>1 mab</td>
</tr>
<tr>
<td>M3</td>
<td>1°23.958'</td>
<td>103°43.973'</td>
<td>1.1</td>
<td>Thermistor</td>
<td>0.5 mab</td>
</tr>
<tr>
<td>M4</td>
<td>1°24.807'</td>
<td>103°43.755'</td>
<td>6.1</td>
<td>Thermistor chain;</td>
<td>1, 2, 3, 4, 5, 6 mab;</td>
</tr>
<tr>
<td>M5</td>
<td>1°25.155'</td>
<td>103°44.223'</td>
<td>8.4</td>
<td>1200 KHz RDI ADCP</td>
<td>0.72–5.32 mab, 0.2 m bins</td>
</tr>
<tr>
<td>M6</td>
<td>1°25.868'</td>
<td>103°44.636'</td>
<td>13.3</td>
<td>Thermistor chain;</td>
<td>2, 4, 6, 7, 8, 9, 10, 11, 12 mab;</td>
</tr>
<tr>
<td>M7</td>
<td>1°26.160'</td>
<td>103°44.433'</td>
<td>7.9</td>
<td>600 KHz RDI ADCP</td>
<td>1.61–11.11 mab, 0.5-m bins</td>
</tr>
<tr>
<td>M8</td>
<td>1°24.883'</td>
<td>103°44.473'</td>
<td>2.3</td>
<td>Thermistor chain;</td>
<td>1, 3, 5, 6 mab</td>
</tr>
</tbody>
</table>

*aThe time interval and estimated accuracy of the thermistors are 30 s and 0.002°C respectively. The time interval of acoustic Doppler current profilers (ADCPs) is 4 min, and estimated accuracies are 0.64 cm s\(^{-1}\) at M4 and M5 and 0.46 cm s\(^{-1}\) at M6. In the details column, mab denotes meters above the reservoir bottom.

Table 2. Variables Used in the Water Balance Model and Methods to Obtain Them

<table>
<thead>
<tr>
<th>Variable</th>
<th>Definition</th>
<th>Methods</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\Delta V/\Delta t)</td>
<td>Storage change calculated by water level change</td>
<td>Method 1, water level change measured by internal pressure sensors of ADCP; method 2, water level change measured by Kranji Gate operations*a</td>
</tr>
<tr>
<td>(P)</td>
<td>Precipitation</td>
<td>Measured by rain gauge at Met Station 1</td>
</tr>
<tr>
<td>(Q_{in})</td>
<td>Total tributary inflows</td>
<td>Method 1, simulated by XP-SWMM; method 2, calculated from the velocities measured by ADCP</td>
</tr>
<tr>
<td>(Q_{out})</td>
<td>Total outflow</td>
<td>Measured by Kranji Gate and pumping operations</td>
</tr>
<tr>
<td>(E)</td>
<td>Evaporation</td>
<td>Used monthly average evaporation data for 12 years of MacRitchie Reservoir, another reservoir in Singapore as available from the Public Utilities Board</td>
</tr>
</tbody>
</table>

*aAn average of the two pressure measurements by ADCPs at M5 and M6 was used for better accuracy and to account for spatial variability in method 1.
of bank slope, \( z - z_{\text{toe}} \) is the lateral distance from the toe of slope to the point of interest (for centerline it is \(-B/2\), where \( B \) is the bottom width of the channel) and \( Y \) is the flow depth over the channel bed. Thus the inflow is calculated as \( Q_{\text{in}} = V_0 \times A_c \), where \( A_c \) is the cross sectional area.

[16] This approach using ADCP is applicable to periods of storm events when the flow is dominated by inflows from tributaries. The flow is driven by weak winds with flow velocities unresolved by the ADCP on daily time scales during dry periods. The inflow for these periods is generated using XP-SWMM.

### 3.1.3. Outflow Model

[17] The tributary inflows during storm periods of the 2007 field deployment are estimated from the two approaches above. The calculated outflow from both approaches is compared to the measured outflow in order to evaluate the two inflow approaches. The following water balance equation is used:

\[
Q_{\text{out}} = Q_{\text{in}} - A_1 \frac{dh}{dt} \quad (3)
\]

where it is assumed that the rainfall and evaporation can be neglected in the calculation of outflow and the reservoir surface changes are in phase. \( Q_{\text{out}} \) is the calculated outflow, \( Q_{\text{in}} \) is the tributary inflows calculated from the two approaches, \( h \) is the average water level measured by ADCP at mooring stations M5 and M6, and \( A_1 \) is the area of reservoir surface from M5 to the Kranji Gate.

### 3.1.4. Uncertainties in the Water Balance Model

[18] The uncertainty for each of the terms in the water budget can be estimated. The outflow measured by Kranji Gate uses a simple method of multiplying the surface area by the observed water level decrease after the release of water from each large rainfall event. The uncertainties come from three sources: (1) this method assumes that the water level decrease measured at the gate represents the whole reservoir, (2) it assumes the surface area is constant, and (3) there is error in the water level measurements. As the water level changes have little spatial variations in Kranji Reservoir (measured by ADCPs at M5 and M6, data not shown) and the reservoir surface area has small variations, the uncertainties from sources 1 and 2 are negligible. The water level measured manually at Kranji Gate is compared to measurements of the more accurate ADCPs and the maximum difference obtained is 0.1 m, about 2% of the average water depth of Kranji Reservoir. Thus we assumed, very conservatively that the uncertainty of the discharge through gate to be 10 times larger at 20% which is sufficient to account for the three sources of error listed above. The pumping to CCK Water Work is more accurate as it is measured at the CCK Water Work except for the last three months in 2007 when there was no available data. The uncertainty level of the first nine months is estimated to be the standard deviation of daily pumping data (computed to be 10%) while the uncertainty level of the last three months is assumed to be very conservatively 100% which is more than sufficient to account for any variations in pumping volume. The accuracy of the rain gauge is 1% and since the precipitation is much smaller than the outflow and tributary inflows, the uncertainty of precipitation can be neglected. The uncertainty of total tributary inflows simulated by XP-SWMM is assumed to be 20%, which is taken as the mean runoff volume error of earlier verification results of XP-SWMM [Lo et al., 2008]. Lastly the uncertainty of evaporation is assumed to be 30%, which is sufficient to account for errors associated with using the monthly average evaporation data for 12 years of MacRitchie Reservoir, a reservoir within 20 km of Kranji.

### 3.2. Heat Budget Model

[19] A simple heat budget equation can be expressed as

\[
\Delta H = H_{\text{surf}} - H_{\text{rain}} + H_{\text{in}} - H_{\text{out}} \quad (4)
\]

where \( \Delta H \) is the heat content change of Kranji Reservoir and \( H_{\text{surf}} \) is the total net surface heat flux, \( H_{\text{in}} \) is the heat flux arising from tributary inflows into the main channel and \( H_{\text{out}} \) is the heat flux of the total outflow from the reservoir. Last, \( H_{\text{rain}} \) is the effective sensible heat flux of rainfall, a small contribution of which a positive value indicates loss of heat from water surface to the atmosphere [Gosnell et al., 1995]. \( H_{\text{rain}} \) is calculated as

\[
H_{\text{rain}} = C_w R(T_a - T_r) \quad (5)
\]

where \( C_w \) is the specific heat of water, \( R \) is the rainfall rate, and \( T_a \) and \( T_r \) are the water surface and mean rain temperature, respectively [Gosnell et al., 1995]. We used the measured air temperature \( T_a \) to represent \( T_r \) because of lack of rain temperature measurements. This method underestimates \( H_{\text{rain}} \) compared to using wet bulb temperature for \( T_r \). However, as the mean relative humidity at Kranji Reservoir is 84% (see section 4) this error can be neglected because the Web bulb temperature is close to the dry bulb temperature. Table 3 summarizes the variables used in the heat budget model, methods to obtain them and their mean values and uncertainties.

#### 3.2.1. Surface Heat Fluxes

#### 3.2.1.1. Net Radiation

[20] The net radiation of Kranji Reservoir, defined as the sum of incoming shortwave radiation and net longwave radiation, was measured by Met station 1 near M5.

#### 3.2.1.2. Sensible Heat Flux

[21] Sensible heat flux is due to convection and takes place at the surface of Kranji Reservoir. It is calculated using the standard bulk formula [Hicks, 1972]:

\[
Q_s = \rho_A C_p C_i U_{10} (T_s - T_a) \quad (6)
\]

where \( \rho_A \) is the density of air, \( C_p \) is the specific heat of air (1012 J kg\(^{-1}\) °C\(^{-1}\)), \( C_i \) is the bulk transfer coefficient for sensible heat, \( U_{10} \) is the wind speed at 10 m above the water surface, \( T_s \) is the measured water surface temperature and \( T_a \) is the measured air temperature at 10 m above the water surface. The air density is calculated as \( \rho_A = \frac{p}{R_d T_a} \), where \( p \) is the air pressure, \( R_d \) the gas constant for dry air is 287.05 J kg\(^{-1}\) °K\(^{-1}\), and \( T_a = T + (0.61q) \) is the virtual temperature with \( q \) being the specific humidity [Garratt, 1992]. The measured water surface temperature at M5 is
used to specify \( T_r \). For neutrally stable boundary layers it is recommended \( C_s = 1.45 \times 10^{-7} \) [Hicks, 1972]. However, as the atmospheric boundary layer over tropical lakes is often found to be unstable [e.g., MacIntyre et al., 2002; Verburg and Antenucci, 2010] and the fact that the daily average air temperature is always lower than the water surface temperature in Kranji Reservoir (see discussion in section 6 and Figure 7b), the atmospheric boundary layer over Kranji Reservoir is mostly unstable. We corrected for atmospheric stability following the procedure by Fairall et al. [1996] and its implementation using the Matlab Air-Sea Toolbox Version 2 from Pawlowicz et al. [2001]. In the correction, the air shear velocity is calculated as \( u_s = \left( C_D \frac{U_{10}^2}{\kappa} \right)^{1/2} = \frac{U_{10}}{\ln(z_0)} \), and the surface roughness length \( z_0 \) is defined through a Charnock constant \( \alpha = \frac{\nu}{\kappa} \) [Guan and Xie, 2004]. Here \( C_D \) is the drag coefficient, \( U_{10} \) is the wind speed measured at height \( z \) and \( \kappa \) is the von Kármán constant which equals 0.4. The Charnock constant has a range of reported values from 0.010 to 0.035 [Garratt, 1992] and it is larger at shorter fetch and shallower water depth. Considering the short fetch of Kranji Reservoir (~4 km for winds aligned with the channel main axis) and comparing with studies of lakes with similar fetch and water depth [e.g., Vickers and Mahrt, 1997], a reasonable range of 0.018 (for fetch-limited coastal regions) to 0.035 (large lake) from Garratt [1992] is adopted for the present calculations.

### 3.2.1.3. Latent Heat Flux

Latent heat flux due to evaporation at the surface of Kranji Reservoir is calculated using [Hicks, 1972]

\[
Q_L = \rho_L L_E \left( q_e - q_a \right)
\]

where \( \rho_L \) is the density of air, \( L_E \) is the latent heat of evaporation, \( C_L \) is the bulk transfer coefficient for latent heat, \( U_{10} \) is the wind speed at 10 m above the water surface, \( q_e \) is the saturation specific humidity (kg H₂O kg⁻¹ air) at the measured water surface temperature \( T_w \) and \( q_a \) is the specific humidity of atmosphere at 10 m above the water surface. We corrected for the effects of atmospheric stability on the mass transfer coefficients, similar to the correction for sensible heat flux.

### 3.2.2. Advection Heat Fluxes

The advective heat flux resulting from the summed tributary inflows is calculated by

\[
H_{in} = \sum_{i=1}^{4} \rho C_w Q_i T_i
\]

where \( Q_i \) and \( T_i \) are the flow rate and water temperature for each of the four tributaries of Kranji Reservoir. \( Q_i \) was predicted by the XP-SWMM model (see section 3.1) and \( T_i \) was measured by thermistors located in each of the four tributaries (at M1, M2, M3 and M8, see Table 1 for details). The outflow heat flux is calculated as

\[
H_{out} = \rho C_w Q_{out} T_{out}
\]

where \( Q_{out} \) and \( T_{out} \) are the flow rate and water temperature of the outflow. \( Q_{out} \) was predicted by the XP-SWMM model and \( T_{out} \) was measured by thermistor at M7.

### 3.2.3. Lake Heat Content

The lake heat content is calculated as

\[
H = \sum_{i=1}^{8} \rho C_v V_i T_i
\]

where \( V_i \) and \( T_i \) are the volume and water temperature of eight different blocks of water in the reservoir with temperature measured by the eight moorings M1 to M8. The boundaries between every adjacent block are defined on the basis of the lake bathymetry with the water temperature profile of each mooring representing the nearby waters with similar water depths (see Figure 1b for the defined boundaries of the eight blocks of water in Kranji Reservoir).
4. Observations

[25] The meteorological measurements during the field deployment period in 2007 are presented in Figure 2. Diurnal cycles of wind speed, solar radiation, air temperature and relative humidity are readily apparent. The wind speed had an average value of 1.27 m s$^{-1}$ and the maximum value of 6.64 m s$^{-1}$. The wind speed was generally higher in the afternoon when it blows from northeast and lower in the nighttime hours. For most of the days, incoming solar radiation peaked between 500 W m$^{-2}$ and 1000 W m$^{-2}$. The air temperature underwent a cooling period from year day 116 to 120 and increased again afterward. The relative humidity varied from about 50% (minimum observed was 48%) to nearly 100% daily and had a mean value of 84%. The deployment was during the intermonsoonal period of Singapore’s climate which had occasional intense thunderstorm events, with larger events occurring between year day 110 to 120.

[26] The inflow was measured by the ADCP at M5 in the main channel of Kranji Reservoir during the field deployment period in 2007. The water temperature measured by thermistors, and the water depth and velocity aligned with the axis of the main channel as measured by the ADCP at M5 are shown in Figure 3. A large inflow event from year day 113 to 120 of 2007 was observed when water temperature dropped by around 2.5$^\circ$C and water depth rose by 0.3 m (see Figures 3b and 3c). The mean velocity along the main channel at M5 during the field deployment period in 2007 was only 0.001 m s$^{-1}$ while the magnitude of peak velocity during the inflow event was around 0.05 m s$^{-1}$ (see Figure 3a). The resulting flow was as large as 100 m$^3$ s$^{-1}$ during inflow event. Mean flows in the main channel of Kranji Reservoir were observed to be positive, which indicates that the flow was transported from tributaries to the dam. The large fluctuations of water depth (see Figure 3c) were due to the catchment inflow draining into the reservoir and the dam release.

[27] The pumping and gate opening data of Kranji Reservoir in 2007 were obtained from Public Utilities Board (PUB), Singapore and processed for the field deployment period in 2007. Analysis of gate opening data showed that there were 34 gate opening events during the 59 day mooring deployment with release events ranging from 1 h to 6 h and averaging 3 h and 15 min. The total discharge through the Kranji gate opening was $1.6 \times 10^7$ m$^3$ from year day 103 to 162 of 2007. The total rainfall was 490 mm during the same period. During each gate opening event, the water level is reduced to a constant level. The average flow rate during the gate openings was 40 m$^3$ s$^{-1}$; the maximum

Figure 2. Meteorological data of (a) wind speed, (b) wind direction, (c) shortwave radiation, (d) air temperature, (e) relative humidity, and (f) rainfall depth. The time interval of meteorological data is every 15 min for Figures 2a and 2c–2e, every 2 h for Figure 2b, and daily for Figure 2f. The blank area between year days 126 and 135 of 2007 indicates the period when the equipment malfunction occurred.
flow rate was $4.0 \times 10^2$ m$^3$ s$^{-1}$ on year day 116. Analysis of pumping to CCK Water Work shows that there was no pumping to CCK Water Work from year day 103 to 106, while there was daily pumping from year day 107 to 162. The total of outflow through pumping to CCK Water Work was $3.0 \times 10^6$ m$^3$ during this period. The average flow rate was 0.60 m$^3$ s$^{-1}$, while the maximum flow rate was 5.8 m$^3$ s$^{-1}$ on year day 108. The pumping outflow was roughly uniform after year day 108.

A comparison of the water level measurements at the Kranji Gate and measured by ADCP during the field deployment period in 2007 is plotted in Figure 4. The general trend of the water level variations is fairly consistent between the two measurements.

5. Water Budget of Kranji Reservoir

The daily tributary inflows calculated by XP-SWMM exhibits a strong linear relationship with the daily rainfall averaged over the five rain gauges in the Kranji Catchment ($R^2 = 0.93$, plot not shown). The outflow calculated by the two approaches for tributary inflow (i.e., XP-SWMM predictions and ADCP velocity measurements, as described in the inflow model of section 3.1) compare well between each other not only on year day 116, the day with the largest inflow event (see Figure 5a), but also for a longer period of ten days (year day 110 to 120) with several storm events (see Figure 5b, with $R^2 = 0.66$). The peaks of the hydrographs predicted by the two approaches and the time to peaks both match well while the peaks of dam outflow measured by Kranji Gate are generally less than the predictions of the two approaches except on year day 110. This is expected: the dam outflow data measured by Kranji Gate only has the start and end time of gate opening and the water depth change during this period. The dam outflow is estimated as dividing the total volume of outgoing water (calculated by the water depth change multiplied by reservoir surface area) by the time of gate opening. The resulting dam outflow has lower peaks but close to total volume compared to the outflow predicted by the two methods because of the lack of detailed information between the gate opening and closing. The outflows calculated by the two approaches are within 20% of difference between each
Figure 4. Water level variations measured by averaging the ADCP measurements at M5 and M6 and by Kranji Gate. $H'$ denotes the perturbations of water level, i.e., water level measurements minus the mean water level during the field deployment period.

Figure 5. Comparison of outflows calculated by the two inflow approaches and measured by Kranji Gate (a) on year day 116 and (b) during year days 110 to 120 of 2007 ($R^2 = 0.66$; significant at 99% confidence level).
other and with the discharge measured at the Kranji Gate. The possible causes of differences between the two methods are the uncertainties in converting ADCP velocity measurements at one specific location to the mean velocity at the M5 cross section and that the flow rate predicted by the XP-SWMM method represents an average across the channel width which may further have some time lag in transporting the storm flows to the outlet.

The water budget for the whole year of 2007 was next analyzed. The XP-SWMM model was configured and run for the 2007 calendar year and model results were used as the total tributary inflows. The resulting monthly water budget of Kranji Reservoir in 2007 is plotted in Figure 6a. The inputs of the tributary inflows and the precipitation on the water surface are plotted as positive values, while the outputs comprising discharge through the Kranji Gate,

![Figure 6](image)

**Figure 6.** (a) Monthly water budget of Kranji Reservoir in 2007, in which the inflow term is predicted by XP-SWMM while all the other terms are measured data. The inputs are plotted as positive values, and the outputs are plotted as negative values. (b) Monthly water imbalance of Kranji Reservoir in 2007 and (c) daily water imbalance of Kranji Reservoir for the field deployment period from year days 103–162 in 2007.
pumping to CCK Water Work and evaporation are plotted as negative values. As the Kranji Gate opens up during rainfall events thus keeping the water level almost constant over the longer term, the monthly reservoir volume change, or $\Delta V$ is estimated to be zero. The uncertainty in the total water budget is calculated to be 22% by adopting the method of error propagation [Emery and Thomson, 2004] and on the basis of the uncertainty estimates of individual water budget components as described in section 3.1.

[31] On the basis of the 2007 monthly water budget of Kranji Reservoir in Figure 6a, the total input including tributary inflow and precipitation over the whole of 2007 is $7.6 \times 10^7$ m$^3$ while the total output including dam outflow, pumping outflow and evaporation is $7.0 \times 10^7$ m$^3$. The percentage of water imbalance between the total inputs and outputs in the annual water budget is 8.2%, well within the uncertainty level of 22%. The water budget is dominated by discharge (67% of the annual total output), and catchment inflow (83% of the annual total input), which are sensitive to variations in precipitation.

[32] The daily water imbalance calculated from the total water input and output on a daily basis is plotted in Figure 6c for the field deployment period from year day 103 to 162 in 2007. Over the field deployment period, the total input including tributary inflow and precipitation is $1.1 \times 10^7$ m$^3$ while the total output including dam outflow, pumping outflow and evaporation is $1.0 \times 10^7$ m$^3$. The much smaller daily water imbalance (max of $3.6 \times 10^5$ m$^3$) indicates that the total input and total output match well on the daily time scale. The total input exceeds the total output by about 7.9% over the deployment period. For the storm period from year day 110 to 120, total input including tributary inflow and precipitation is $3.2 \times 10^6$ m$^3$ while the total output including dam outflow, pumping outflow and evaporation is $3.8 \times 10^6$ m$^3$. The total input is 14% less than the total output. Thus the water budget model overestimates the total input in the period without intensive storm events and underestimates the total input during the storm period. However, these differences are well within the 22% uncertainty level of the overall water budget and thus the daily water balance closes within the uncertainty limits.

6. Heat Budget of Kranji Reservoir

[33] The various surface heat fluxes that make up the surface heat budget of Kranji Reservoir during the field deployment period in 2007 are shown in Figure 7a. The

![Figure 7](image_url)

Figure 7. (a) Daily surface heat budget of Kranji Reservoir (positive when downward) and (b) daily average air temperature and water surface temperature for the field deployment period from year days 103-162 in 2007.
uncertainties of each surface heat flux was small as calculated by the method of standard error propagation [Emery and Thomson, 2004] with estimated values shown in Table 3. Of the surface heat fluxes, the net radiation and latent heat flux are the dominant components. Large variations of all the three surface heat fluxes are observed for the two month record. The daily average water surface temperature measured by thermistors and air temperature measured by Met station 1 is shown in Figure 7b. The daily average water surface temperature is always warmer than the air temperature by 1°C–4°C during the field deployment period. Thus the lake transferred energy to the air and the calculated sensible heat flux was negative (heat loss to the atmosphere).

In several earlier studies [e.g., Myrup et al., 1979], the lake heat content was calculated by using an average vertical temperature profile for the whole lake. In Kranji Reservoir, however, horizontal temperature differences along the main channel are substantial and comparable to vertical variations. For example, Figure 8 shows the vertical temperature profiles at the four mooring stations in the main channel of Kranji Reservoir on year day 116. The reservoir was well mixed in the early morning at all the locations. Cold inflows from the tributaries plunged into deeper parts of the junction (M4) from 13:00 LT and formed much larger vertical temperature differences in M4 and M5 than in M6 and M7. The Kranji Reservoir system is sometimes multidimensional in behavior where significant variations in temperature in the along and cross-reservoir directions are driven by cold inflow events, differential heating and potential reservoir releases (as above). As discussed in section 3.2.3, the lake heat content of Kranji Reservoir is hence calculated by integrating the heat content of eight different blocks of water in the reservoir represented by moorings M1 to M8, instead of using a uniform vertical temperature profile. The heat content change of Kranji Reservoir during the field deployment period in 2007 since year day 103 calculated by using the vertical temperature profiles at M4, M5, and M6 is plotted in Figure 9. Notable differences exist in the heat content change calculated by vertical temperature profiles at different stations. The reservoir underwent cooling periods from cold tributaries inflows during year day 113 to 123 and was then warmed again toward the end of the field deployment.

The average individual components in the heat budget of Kranji Reservoir as calculated from methods discussed in section 3 and the associated uncertainties are summarized in Table 4 for the field deployment in 2007. The average net surface heat flux as the sum of net radiation, latent heat and sensible heat is within the range of [4.93, 8.83] W m⁻², with the lower bound using Charnock constant of 0.035 and the upper bound using Charnock constant of 0.018 (see section 3.2.1). On average 83% of the energy goes from net radiation into latent heat of evaporation. The inflow advective heat flux also represents a large component, at 71% of the net radiation. The average net advective heat flux, obtained by dividing the net advective heat by the reservoir surface area, is −4.00 W m⁻² and average rain heat flux is −2.67 W m⁻². The predicted average lake heat content change of Kranji Reservoir calculated as

![Figure 8](image-url)  
**Figure 8.** Vertical temperature profiles of Kranji Reservoir at (a) M4, (b) M5, (c) M6, and (d) M7 on year day 116 in 2007.
the sum of the surface heat flux, rain heat flux and advective heat flux is within the range of $\left[ -1.74, 2.16 \right]$ W m$^{-2}$ for the two different Charnock constants used. The heat imbalance between this predicted lake heat content change and the measured lake heat content change which averages 1.28 W m$^{-2}$ over the field deployment period is within the range of $\left[ -3.02, 0.88 \right]$ W m$^{-2}$. The percentage of heat imbalance is 2%, well within the uncertainties limits of the calculated component terms. Although the heat budget of Kranji Reservoir is dominated by the surface heat fluxes (Table 4), the net advective heat flux cannot be neglected, since it is similar in magnitude to the net surface heat flux.

A daily heat budget was computed for the first 23 days of the 2007 field deployment; this time period is focused upon since there was a gap in meteorological measurements from year day 126 onward. The measured lake heat content starting from year day 103 and the predicted lake heat content as computed by the sum of surface heat fluxes, advective heat fluxes and the lake heat content are plotted in Figure 10a. Figure 10 includes sensible and latent heat calculated using the range of Charnock constant of $\left[ 0.018, 0.035 \right]$. The predicted lake heat content is higher than the measured lake heat content from year day 104 to year day 116 and lower than the measured for the final ten days. A large fraction of the daily heat imbalance is attributable to the water budget imbalance (see Figure 10b). The predicted daily lake heat content can be corrected by the daily heat imbalance due to water budget imbalance (Figure 10c). This correction was computed by taking the water imbalance and accounting for its heat content at 00:00 LT daily using the mean measured water temperature in four tributaries since the water budget imbalance mainly comes from the discrepancy between total inflow and outflow (see section 5 for discussion on the daily water budget). As indicated in Figure 10c, the measured lake heat content and the corrected lake heat content predictions generally match well, not only in the overall trend during the 23 days but also exhibiting similar the day-to-day variations. The comparison in the last 5 days is not as good as the first 18 days as also can be seen in Figure 10b where water budget imbalance does not compensate for the heat imbalance as well as the first 18 days. However even the largest daily heat imbalance (on year day 125) is 4% of the heat content, well within the accuracy of the water budget closure which is 10% over the field deployment period.

Table 4. Components of Average Daily Heat Budget of Kranji Reservoir With Uncertainties Over the Field Deployment Period From Year Days 103–162 in 2007*

<table>
<thead>
<tr>
<th>Component</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Net radiation (W m$^{-2}$)</td>
<td>91.06 ± 0.28</td>
</tr>
<tr>
<td>Latent heat (W m$^{-2}$)</td>
<td>$\left[ -77.64, -74.05 \right]$ ± 0.66</td>
</tr>
<tr>
<td>Sensible heat (W m$^{-2}$)</td>
<td>$\left[ -8.49, -8.18 \right]$ ± 0.06</td>
</tr>
<tr>
<td>Net surface heat flux (W m$^{-2}$)</td>
<td>$\left[ 4.93, 8.83 \right]$ ± 0.72</td>
</tr>
<tr>
<td>Heat flux of inflow (W m$^{-2}$)</td>
<td>64.35 ± 6.4</td>
</tr>
<tr>
<td>Heat flux of outflow (W m$^{-2}$)</td>
<td>$\left[ -68.35, 6.8 \right]$</td>
</tr>
<tr>
<td>Net advective heat flux (W m$^{-2}$)</td>
<td>$\left[ -4.00, 9.3 \right]$</td>
</tr>
<tr>
<td>Rain heat flux (W m$^{-2}$)</td>
<td>-2.67</td>
</tr>
<tr>
<td>Predicted lake heat content change (W m$^{-2}$)</td>
<td>$\left[ -1.74, 2.16 \right]$ ± 9.3</td>
</tr>
<tr>
<td>Measured lake heat content change (W m$^{-2}$)</td>
<td>1.28</td>
</tr>
<tr>
<td>Imbalance between measured and predicted lake heat content (W m$^{-2}$)</td>
<td>$\left[ -3.02, 0.88 \right]$ ± 9.3</td>
</tr>
<tr>
<td>Imbalance percentage (%)</td>
<td>2 ± 6</td>
</tr>
</tbody>
</table>

*aThe lower and upper values of latent and sensible heat use a Charnock constant of 0.035 and 0.018. The imbalance percentage is computed using the imbalance divided by the total input heat flux.*
The daily heat budget has a larger imbalance than the average heat budget over the field deployment period which has a low imbalance percentage of 2% (see Table 4). This is because the uncertainties of the daily average component terms are much larger than the uncertainties of the component terms averaged over the whole field deployment period. The heat imbalance becomes smaller and falls within the range of uncertainties when averaging with the two month’s data.

7. Discussion and Summary

We have compared the Bowen ratio, the ratio of sensible to latent heat flux for Kranji Reservoir with reported values from some other tropical lakes and reservoirs as well as lakes in temperate region. This comparison is summarized in Table 5. The Bowen ratio is usually used to compare the heat losses by convection and evaporation [Bowen, 1926] and also used in heat budget calculations if

![Figure 10.](image)

(a) Comparison of predicted lake heat content (sum of surface heat fluxes, advective heat fluxes updated every 15 min) using a range of the Charnock constant ($\alpha$) from 0.018 to 0.035 and measured lake heat content at 00:00 LT daily, (b) comparison of heat imbalance between predicted and measured lake heat content at 00:00 LT daily and heat imbalance due to daily water budget imbalance, and (c) comparison of measured and predicted daily lake heat content after being corrected for water imbalance from year days 103 to 126 in 2007 ($R^2 = 0.65$ when $\alpha = 0.018$ and $R^2 = 0.59$ when $\alpha = 0.035$; both significant at the 99% confidence level).
one of the components is missing. \cite{Assouline2008}. Kranji Reservoir has a small Bowen ratio, daily mean of 0.11, standard deviation 0.04. This value is comparable to other Mediterranean and tropical lakes and reservoirs, e.g., Eshkol Reservoir in Israel, which has a shallow depth of 3.5 m and is in the Mediterranean climate \cite{Assouline2008}. Lake Tanganyika \cite{Verburg2010} and Lake Victoria \cite{Yin1998} in tropical Africa. It is much smaller than lakes in the temperate region, e.g., Great Lakes in North America \cite{Lofgren2000}. The small value is consistent with heat budget analysis of Kranji Reservoir, which shows that on average 83% of the energy from net radiation is converted into latent heat of evaporation.

\cite{40} Our measurements also show that, the advective heat flux is an important component of the overall heat budget and thus cannot be neglected. Even though the tributary inflows of the whole year of 2007 can be predicted by XP-SWMM, we cannot construct an accurate heat budget for 2007 because of the limited period of tributary surface temperature measurements. As a side note, measurements of the stream temperature in Pangsu Channel suggest challenges in further refining the heat budget during storm events. The stream temperature had negative correlations with precipitation magnitude, event inflow volume, as well as mean and peak inflow rates (not shown) while it had positive correlations with air temperature and solar radiation (not shown). However, all the relationships are not significant with small $R^2$ and the data show large deviations from the derived linear fits. From this limited data, it would thus be difficult to predict stream temperature from rainfall, inflow and/or meteorological measurements as any derived linear regression model is likely to be inadequate for explaining a large fraction of the variations.

\cite{41} This study has not considered the spatial differences in meteorological data such as rainfall, wind speed and direction, and air temperature as only measurements in Met station 1 were used in formulating the water and heat budgets for the 2007 field deployment period. Spatial variability of rainfall over distance as short as 1 km has been noted in prior studies \cite{Singh1997, Chauhey1999} as an important factor contributing to the uncertainties of runoff generations. Analysis of precipitation data measured by the five rain gauges located in the Kranji Catchment further indicates that the correlation between two rain gauges has an inverse relationship to the distance between them (not shown). Future studies on water and heat budgets need to take into account the variability of meteorological conditions of the reservoir since it can be a large source of uncertainty.

\cite{41} In summary, the water budget of Kranji Reservoir is dominated by the discharge and catchment inflow, which are very sensitive to the variations in precipitation. Outflow calculated by the two approaches of using XP-SWMM calculations and ACDP measurements for the inflows compare favorably with the outflow measured by Kranji Gate during periods of storm events. XP-SWMM is demonstrated to be useful in predictions of water budgets for reservoirs with flow driven by rainfall. The deduced water budget for the entire year 2007 is closed to within 10%. The heat budget of Kranji Reservoir is dominated by the surface heat flux but the advective heat flux can also be very important. Both the water and heat budgets close to within the uncertainty associated with the different terms in the balance equations on both daily and longer time scales. The water budget closes to within 10% and the heat budget within 2% during the two months of detailed field measurements. All the components in the water and heat budgets are accounted for on the basis of a complete data set obtained from field measurements and reliable model predictions, including those that have often been neglected in the earlier studies, e.g., advective heat. For lakes or reservoirs with frequent and large storm events like Kranji Reservoir, similar approaches of using gauged stream temperature and measured or predicted stream runoff to compute advective heat can be adopted. The lake heat content of Kranji Reservoir is calculated by integrating the heat content of different blocks of water in the reservoir represented by deployed moorings instead of the widely adopted methods of using a uniform vertical temperature profile or an equilibrium water temperature. In the same way, for lakes with significant horizontal temperature gradients, this offers a significant advantage in closing the heat and water budgets.

\textbf{Table 5. Comparison of Bowen Ratio in Lakes and Reservoirs}

<table>
<thead>
<tr>
<th>Lakes</th>
<th>Latitude</th>
<th>Bowen Ratio$^a$</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kranji Reservoir</td>
<td>1°25′N</td>
<td>0.11 ± 0.04</td>
<td>This work</td>
</tr>
<tr>
<td>Eshkol Reservoir</td>
<td>32°42′N</td>
<td>0.079 ± 0.125</td>
<td>Assouline et al. \cite{2008}</td>
</tr>
<tr>
<td>Lake Tanganyika in East Africa</td>
<td>3°–9°S</td>
<td>0.06</td>
<td>Verburg and Antenucci \cite{2010}</td>
</tr>
<tr>
<td>Lake Victoria in East Africa</td>
<td>0°N–3°S</td>
<td>0.15</td>
<td>Yin and Nicholson \cite{1998}</td>
</tr>
<tr>
<td>Tropical lakes in Africa</td>
<td>8°N–9°S</td>
<td>0.15–0.20</td>
<td>Vallet-Coquilomb et al. \cite{2001}</td>
</tr>
<tr>
<td>Lake Valencia in Venezuela</td>
<td>10°N</td>
<td>0.14 ± 0.11$^b$</td>
<td>Lewis \cite{1983}</td>
</tr>
<tr>
<td>North American Great Lakes</td>
<td>41°–49°N</td>
<td>0.37–1.1$^c$</td>
<td>Lofgren and Zhu \cite{2000}</td>
</tr>
</tbody>
</table>

$^a$Mean ± standard deviation, if reported.

$^b$Estimated from Table 4 of Lewis \cite{1983}.

$^c$Estimated from Table 1 of Lofgren and Zhu \cite{2000}.

\textbf{Notation}

\begin{align*}
\Delta V/\Delta t & \quad \text{storage change calculated by water level change.} \\
P & \quad \text{precipitation.} \\
E & \quad \text{evaporation.} \\
Q_{in} & \quad \text{total tributary inflows.} \\
Q_{out} & \quad \text{total outflow.} \\
Q_i & \quad \text{flow rate for each of the four tributaries of Kranji Reservoir.} \\
V_i & \quad \text{volume of eight different blocks of water in Kranji reservoir.} \\
T_{out} & \quad \text{water temperature of the outflow.} \\
V_0 & \quad \text{mean velocity along the channel.} \\
V_z & \quad \text{depth-averaged velocity at the centerline of the channel.}
\end{align*}
$Z$, cotangent of bank slope  
$B$, bottom width of the channel.  
$Y$, flow depth over the channel bed.  
$A_c$, cross-sectional area.  
$A_{k1}$, surface area from M5 to the Kranji Gate of Kranji Reservoir.  
$h$, average water level measured by ADCP at mooring stations M5 and M6.  
$T_o$, air temperature at 10 m above water surface.  
$T_r$, mean rain temperature.  
$T_v$, water temperature.  
$T_a$, virtual temperature.  
$R$, rainfall rate.  
$\rho _A$, air density.  
$U_{10}$, wind speed at 10 m above water surface.  
$C_p$, specific heat of air.  
$C_w$, specific heat of water.  
$C_d$, bulk transfer coefficient for sensible heat and latent heat.

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References


XP Software Inc. (2005), XP-SWMM users’ manual, Portland, Oreg.