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Ponderful
PONDS FOR CLIMATE



Deliverable D3.4

Protocol on Hydrological Modelling

Pond Ecosystems for Resilient Future Landscapes in a Changing Climate

European Commission

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1. Executive Summary

The Protocol on hydrological modelling will be used in understanding the hydrology of the ponds/pondscapes. It presents the methodology to collect the needed data (precipitation, evaporation, water level, surface water discharge) to develop the budget analysis for the ponds. The water budget of the ponds is calculated on a monthly basis, and if all data is collected on a daily basis, they can be used to understand the hydrology of the ponds on a daily basis.

2. Introduction

Hydrological cycle is the continuous movement of water and exchange of the energy influencing climate around the Earth. Hydrological/water cycle (Figure 1) is made of some major components which are evaporation, condensation and precipitation. Evaporation is the process of a liquid changing to a gas, which is driven by the Sun. However, it is mostly influenced by wind, temperature and humidity. Condensation is the process of a gas changing to a liquid. Lastly, precipitation is the direct description of any liquid or solid water which falls to the Earth. As water precipitates, some different processes can be observed. First, soil absorbs some of the water. This water enters the process of transpiration. Transpiration is a process like evaporation where liquid water is turned into water vapor by the plants. Plants push the water toward leaves for photosynthesis and the extra water leaves the plant through stomata. Some of the water pours down as runoff over ground, this is a combined process with channels, rivers and ending into lakes, oceans, etc. Lastly, some of the water absorbed by soil starts to move to the deeper parts of the soil. Water starts seeping and this gives rise to an increase in the groundwater level.

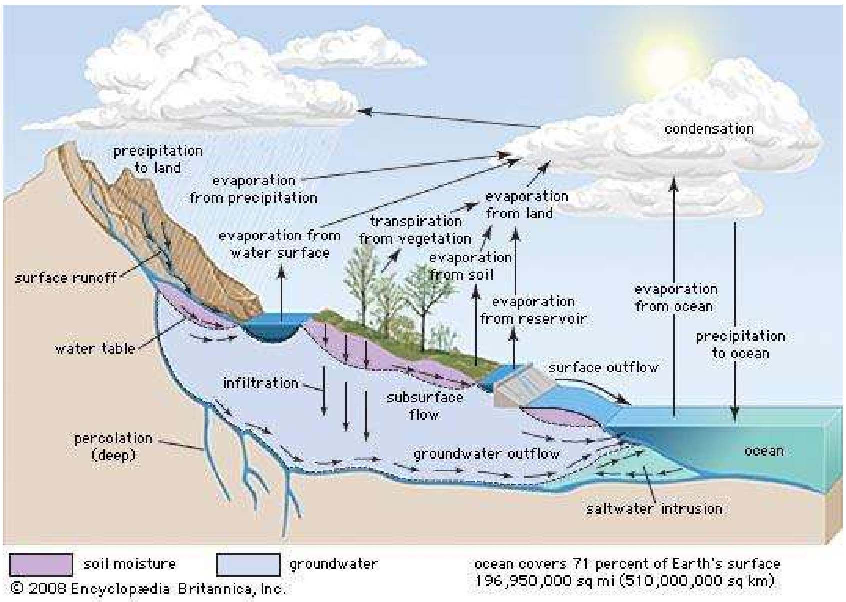

Figure 1. Hydrological Cycle

The components of the hydrological cycle are directly linked with changes in the atmospheric temperature and radiation balance (Inglezakis et al., 2016). According to recent studies, under climate warming, the global terrestrial cryosphere has undergone changes involving glacier retreat, snow reduction and permafrost degradation, all affecting the water cycle (Yongjian et al., 2020). Likewise, rapid population growth and the resultant water consumption have direct effects on the water cycle and relevant budget (Dosdogru et al., 2020).

A basin model simulates hydrologic processes of this cycle in a holistic approach. Therefore, basin-scale modeling of water bodies has great importance for a better understanding of the future of water resources and to create solutions for problems caused by changes in the amount of water. Various models are used to estimate the physical parameters of the basin and streamflow.

Basin-scale models can be classified according to the modeling approaches used (Figure 2). One of the most critical classifications is based on the type: empirical models, conceptual models, and physically-based models (Sitterson et al., 2017). Empirical models are data-driven models, and they involve mathematical equations that define the functional relationships between inputs and outputs by using regression and correlation models whereas conceptual models consist of linked reservoirs, which represent physical elements in a basin and hydrological processes by using semi-empirical equations. On the other hand, physical models are based on spatial distribution and evaluation of parameters describing physical characteristics (Devia, Ganasri, & Dwarakish, 2015). Basin-scale models can further be classified as lumped, semi-distributed, or distributed models. The lumped models simplify basin parameters into a single unit, whereas semi-distributed and distributed models include spatial variability of processes, boundaries, and characteristics of the basin (Daniel et al., 2011). Models can also be classified as deterministic or stochastic. The stochastic model can produce different outputs for a single set of inputs, whereas the deterministic model will give a single output. Deterministic models obtain outputs by known mathematical relations, whereas stochastic models obtain a range of outputs by inputs that are statistically distributed (Melone, et al., 2005). Another classification can be based on whether the model includes time or not. Sorooshian et al. (2007) had classified models as an event-based model in which output is produced for specific periods and as a continuous model in which output is produced for long term continuous periods. An event-based hydrological model focuses on revealing basins response to an individual storm event at a finer scale, whereas a continuous hydrological model reveals both hydrological processes and the cumulative effect of several storm events over a more extended period with both wet and dry conditions (Chu & Steinman, 2009). The main difference between these models is that evapotranspiration and groundwater seepage may be ignored in the event-based model, but the continuous model should include these processes for better reflection of soil drying (Scharffenberg, 2008). The coarse-scale continuous models will require bigger datasets when compared with the fine-scale event-based models (Chu & Steinman, 2009).

There are quite utilizable hydrological software applications which exist to understand the water balance of the water bodies. They can collaborate with soil, water, climate, land use and some spatial information (Jajarmizadeh et al., 2012). It is obvious that there has been a great interest (Middelkoop et al., 2001) and different studies (Botter et al., 2013) for the evaluation of the impacts of human activities and climate change on water balance and hydrological regime. It is also obvious that there are some different situations in understanding water balance and the complicated structures and processes have given rise to the development of lots of models.

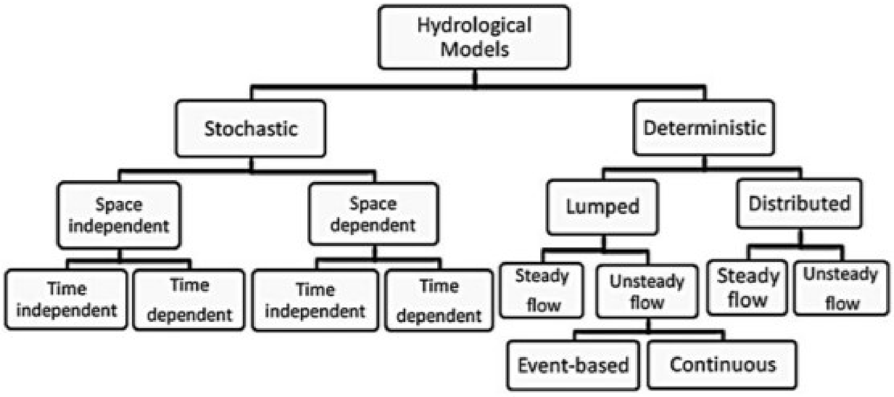

Figure 2. Principles for Classification of Water Balance Models as a Subgroup of Hydrological Models (Chow et al. 1988)

One of the examples for these software applications might be the WEAP[1] (Water Evaluation and Planning) system. It is a free and user-friendly software especially for specific water resources planning and relevant scenarios. Three main operations for WEAP can be counted as:

- Water Balance Database, for supply and demand
- Scenario Generation Tool, for simulations including the runoff, supply, pollution, storage, etc.
- Policy Analysis Tool, for a full range of management options with different scenarios.

Overview of WEAP system can be seen in Figure 3.

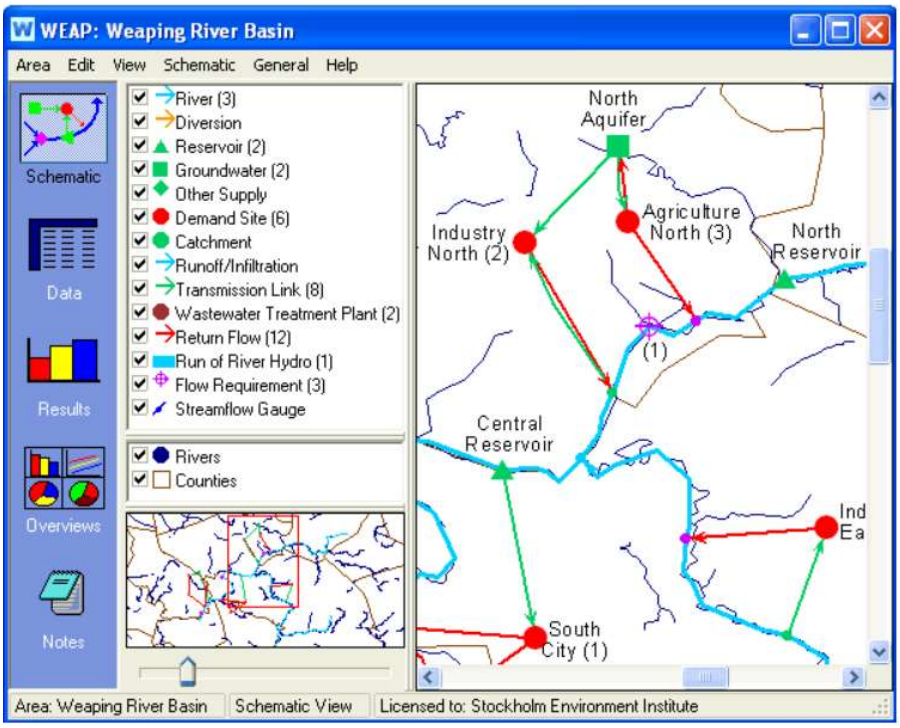

Figure 3. Interface of WEAP System.

The software allows the users to do integrated scenarios including some engineering components (e.g. pumping systems) for present and future. Briefly, users can obtain some scenarios like 'what if population growth and economic development patterns change', 'what if groundwater is more fully exploited' or 'what if the mix of agricultural crops changes'. Another example may be the MIKE Hydro

[1] https://www.weap21.org/index.asp?action=200

Basin.[2] It is a common interface framework of MIKE by DHI with some modules like Basin module and River module.

- Basin module, a considerably flexible model framework for utilizations of management and planning perspectives of water resources within a river basin. It can be utilized for integrated water resources management analysis, scenarios for water shortage, reservoir and hydropower optimization and irrigation performances.
- River module, another framework for 1D river model embedding and executing. It can be utilized for river hydraulics, flood issues, dam break observations, sediment analysis and optimization of hydraulic structures like gates.

Additionally, RIBASIM[3] (River Basin Planning Management) is another integrated tool for water systems and their surroundings. It can be utilized for irrigation improvements, reservoir strategies, drought warning systems, etc.

Lastly, SWAT[4] (Soil and Water Assessment tool) is one of the most popular tools for integrated analysis of water and soil. Land management practices considering lots of perspectives from water, sediment, chemicals etc. can be utilized. Most importantly, SWAT can simulate a hydrological cycle with different time steps via hydrologic response units.

Water balance models can be counted as computational aspects of water movements which means it would be better to consider these models as a subgroup of hydrological models (Abdollahi et al., 2019). Water balance models are widely used popular models to conceive the aspects of water movement for the hydrological cycle. There has been considerable research on the development and application of water balance models since the 1940s (Zaremba & Smoleński, 2000). There are lots of models having different data types and inputs. Some of them are quite complex with huge amounts of inputs while some of them need a few parameters (Sood & Smakhtin, 2015). Briefly, water balance models assume that the system is closed which means there is no gain or loss for the system. The fundamental water balance equation for a pond/lake can be presented in the following form.

$$P \pm E \pm \Delta S \pm Q = 0 \tag{1}$$

where P is the precipitation, E is the evaporation, ΔS is the change in the storage and Q is the inflows/outflows (sign indicates whether it is an outflow or not).

This equation can be enhanced by dividing flows as inflow/outflow or by considering other inputs that may be effective for the specific watershed/wetland/lake or pond like cattle consumption (Duesterhaus et al., 2008) or existing drainage/sewage systems (Riley et al., 2018).

Water resources management systems including larger water bodies and wetlands with necessary scenarios, especially for climate change and restoration purposes (Karakuş et al., 2017), can be also obtained by the use of water balance models. Additionally, some preliminary estimations can be worked out for construction of artificial ponds (e.g. fishponds) which is a very helpful tool to estimate probable water budget of a pond before construction (Teichert-Coddington et al., 1988).
In the literature, hydrology and the relevant water balance for ponds are underestimated despite their important environmental roles (Biggs et al., 2005). It is mostly believed that their functions are to collect the water from rainfall/run-off and store it till it is lost by evaporation (Lehsten et al., 2011). On the other hand, recent studies have shown that this is not the case. They have important contributions to the river networks, and thus to other bigger water bodies connected to the networks (Golus et al., 2017).

[2] https://www.mikepoweredbydhi.com/products/mike-hydro-basin
[3] https://www.deltares.nl/en/software/ribasim/
[4] https://swat.tamu.edu/

3. Method

A simple size-based definition of ponds was developed in the early 1990s and subsequently widely adopted. According to size-based definition, ponds are defined as water bodies between 1m^2 and 2 ha in areas that may be permanent or seasonal, including man-made or natural water bodies. Since the size is small from a hydrological point of view, the modelling becomes more challenging due to the availability of the data in the hydrological cycle. Within the PONDERFUL project, a simple water balance model for the selected ponds will be set and necessary observations from the field (water level/pressure, inflows and outflows, etc.) will be carried out with an appropriate time interval. Likewise, it is important to understand the type of ponds and the relevant possible hydrological function of the different types of ponds.

Ponds have different characteristics according to ecological and hydrological concepts. They can be artificial or natural. The artificial ones can be for the following purposes:

- Fishponds which are the most popular artificial ponds. It is quite crucial to monitor pH levels, nutrient levels, dissolved oxygen content, temperature, and water hardness in these ponds.
- Wildlife Ponds
- Mini Ponds
- Swimming Ponds
- Retention and Irrigation Ponds

However, the main goal is to understand the hydrology of natural ponds. Natural ponds also have some subgroups and relevant hydrology. They may have quite different positions from an ecological perspective also. There may be some different classifications according to different perspectives. From hydrological point of view, natural ponds can be classified as 'ephemeral', 'kettle', 'spring fed' and 'meadow-stream'.

Ephemeral ponds are isolated and mostly small ponds. They are isolated because they are mostly formed due to snowmelt and some rain. Most of the time their basins are close, and they do not have a connection with larger water bodies or basins. (Figure 4). This is the main reason that they dry up within a few months. They are seasonal and dependent on the snow/rain (Means, 2018).

Figure 4. Overview of an Ephemeral Pond. (Reith, 2019)

Kettle ponds are considerably old ponds formed when glaciers retreat from surface depressions. Glaciers melt slowly and form these ponds with some sediments. In some regions, they are one of the richest and most diverse ecosystems in wetlands (Pätzig et al., 2012). Kettle ponds which do not have groundwater connections are generally dry in the warm summer months (Figure 5).

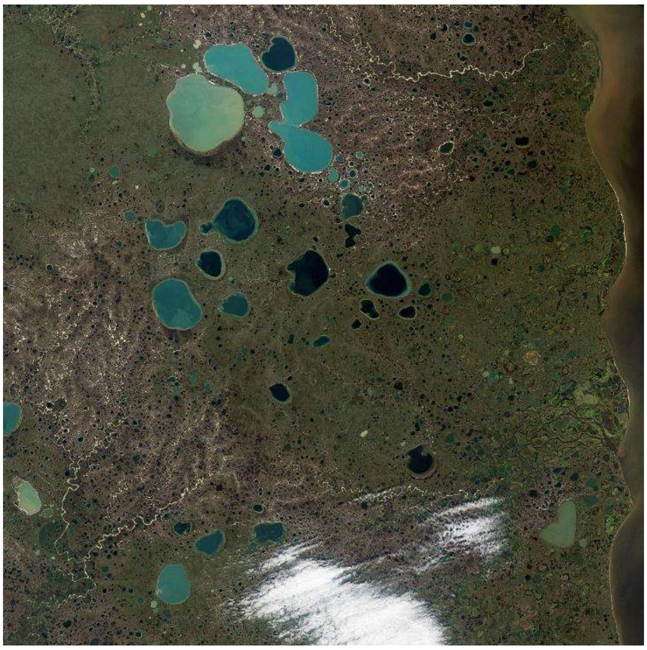

Figure 5. Example of Neighboring Kettle Ponds (Becker & Amer, 2017)

As the name suggests, spring-fed ponds are ponds formed by underground springs. The flow goes to the surface and starts to fill some depression on the surface (Figure 6). Mostly, these kinds of ponds are clean and include water with rich minerals.

Figure 6. Overview of a Spring-Fed Pond((Guide to Different Types of Pond (Natural & Man-Made), 2018).

Meadow – Stream Ponds are ponds formed by rivers/streams. They are mostly formed as a part of the stream system (Figure 7). These dynamic flows give rise to highly rich and valuable water and food sources for animals, they have direct connections with larger water bodies on the surface. Considerably rich ecosystems exist in these ponds.

Figure 7. Example of Stream Ponds for PONDERFUL.

The important point to mention here is conceiving all the possible contributions for the hydrology of a pond regardless of the type. The contribution of groundwater, surface flow, rainfall, runoff and other hydrological components must be determined carefully and evaluated with some methods. Different possible contributors for different ponds can be seen in Figure 8. If the groundwater and surface water do not feed the pond, the main contributor is the precipitation (Figure 8a), if the groundwater feeds the pond there may be inflow from groundwater, if there is outflow it must be considered in the budget analysis (Figure 8b). The pond can be fed by groundwater and surface water where the inputs and outputs must be considered in the budget analysis of the pond (Figure 8c).

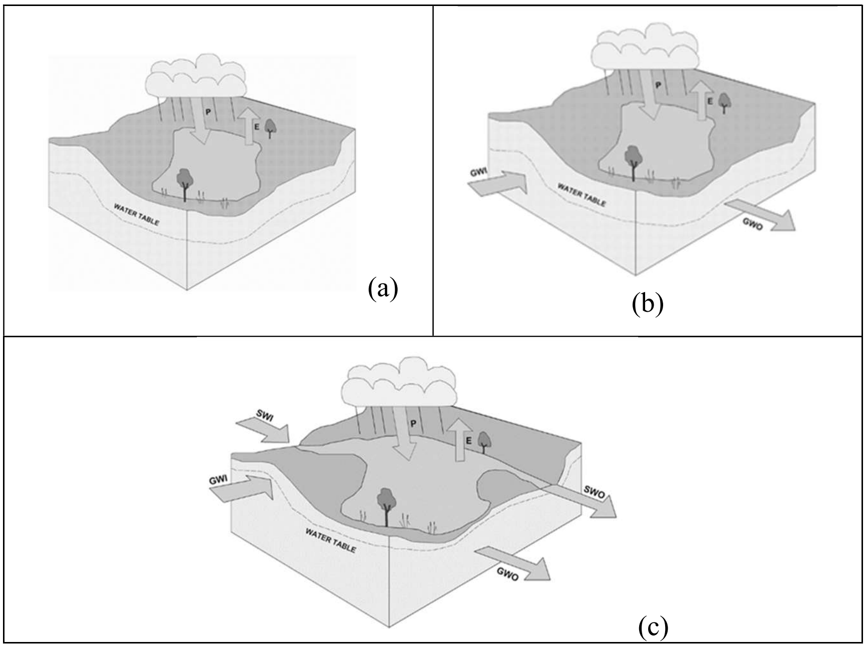

Figure 8. Different Hydrological Contributors of Ponds due to Surface Flow and Water Table. (Golus et al., 2017)

The system of a pond can be conceptualized (Figure 9) and the water budget equation can be enhanced as follows.

$$(P - E) + \Delta SWF + \Delta GWF - \Delta S = 0 \quad (2)$$

Where ΔSWF is the change in surface water flows and ΔGWF is the change in groundwater flows.

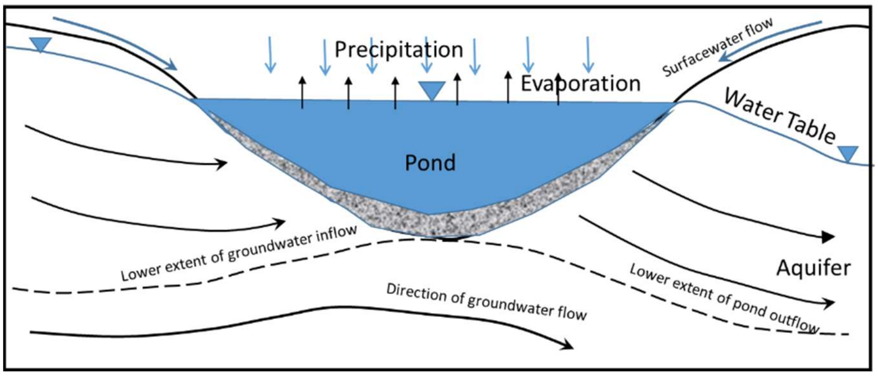

Figure 9. Hydrological System of a Pond.

3.1. Monitoring the water level

The surface water level can be measured with a pressure sensor (e.g. HOBOX). This data logger is utilizable for recording water levels and temperatures in shallow wells, streams, lakes and freshwater wetlands. There are different types and models of water level loggers for different purposes. However, the following three models can be utilized in monitoring the water level in the ponds in PONDERFUL:

- The HOBO U20L-04, which can take measurements between 0 – 4 meters. Accuracy is 0.1% and resolution is <0.014 kPa (0.002 psi), 0.14 cm (0.005 ft) water.
- The HOBO U20L-01, which can take measurements between 0 – 9 meters. Accuracy is 0.1% and resolution is <0.02 kPa (0.003 psi), 0.21 cm (0.007 ft) water.
- The HOBO U20L-02, which can take measurements between 0 – 30.6 meters. Accuracy is 0.1% and resolution is <0.04 kPa (0.006 psi), 0.41 cm (0.013 ft) water.

Their operational ranges are between -20° to 50°C (-4° to 122°F) and they have a battery life of 5 years with 1 minute or greater logging interval. Lastly, their dimensions are 3.18 cm (1.25 inches) diameter, 15.24 cm (6.0 inches) length; mounting hole 6.3 mm (0.25 inches) diameter.

The data logger is placed on the bed of the pond at the deepest part of the water body. A borehole or anchor system can be installed to keep the logger stable. The collected pressure values are corrected with the atmospheric pressure measured within the pond. The data are downloaded during the field visits once every two weeks.

Figure 10. HOBO Water Level Data Logger.

The data logger must be installed with HOBOware[5] software. After installing the program, the user can select the outputs like temperature, relative humidity, pressure (pressure is the appropriate choice for water level observations) (Figure 11).

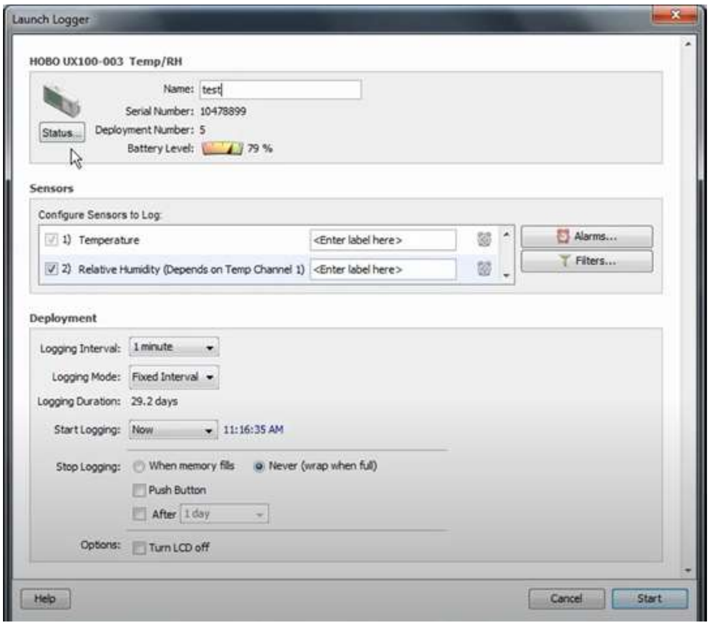

Figure 11. HOBOware Logger Launching.

In this interface, users can select the logging interval and the relevant logging duration so that the saved data can be exported without any data loss. Then, the outputs can be plotted in the software. An example plot can be seen in Figure 12 for temperature, relative humidity, dew point and time.

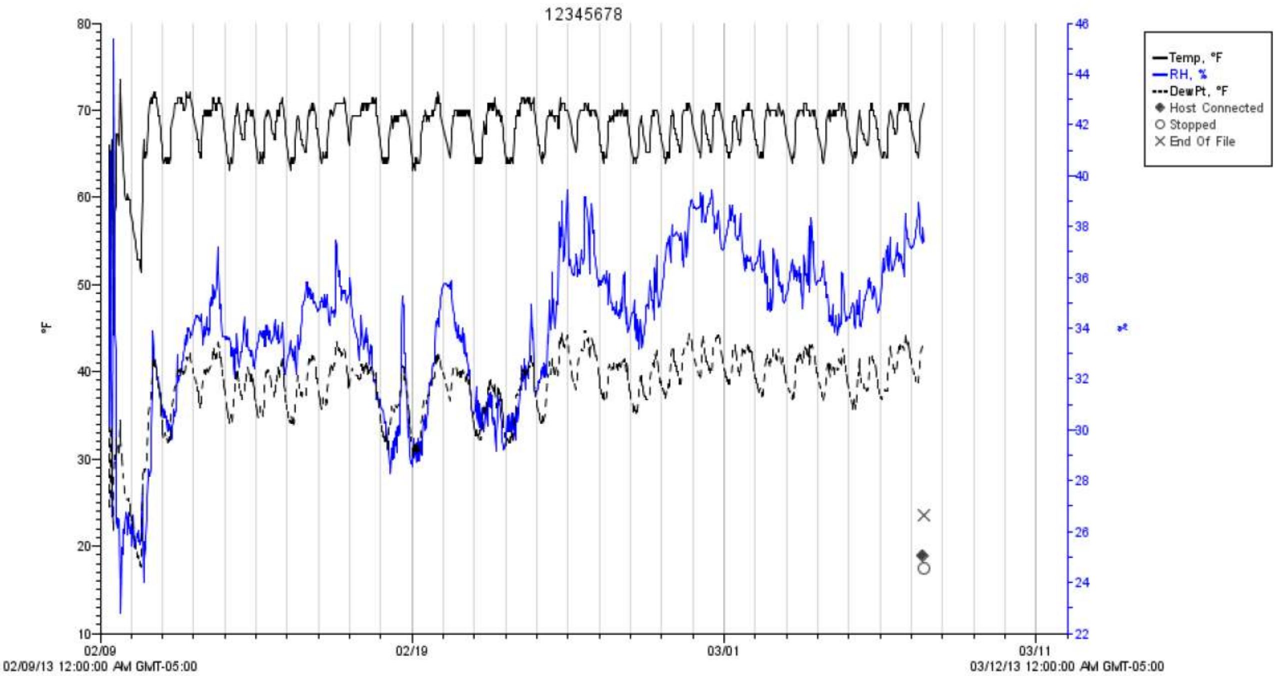

Figure 12. Example Plot from HOBOware Software.(Corporation, 2020)

[5] https://www.onsetcomp.com/hoboware-free-download/

3.2 Collecting meteorological data

Daily Precipitation and temperature values observed at the closest meteorological station must be obtained. Evaporation values can be calculated by using the Penman-Monteith equation.

$$\lambda ET = \frac{\Delta(R_n - G) + \rho_a c_p \frac{(e_s - e_a)}{r_a}}{\Delta + \gamma(1 + \frac{r_s}{r_a})} \quad (3)$$

where λ is the latent heat for water vaporization, R_n is the net radiation, G is the soil heat flux, $(e_s - e_a)$ represents the vapor pressure deficit of the air, ρ_a is the mean air density at constant pressure, c_p is the specific heat of the air, Δ represents the slope of the saturation vapor pressure temperature relationship, γ is the psychrometric constant, r_s and r_a are the bulk surface and aerodynamic resistances.

If the data needed for the evaporation calculation by using the Penman-Monteith equation are not available, the Thornthwaite equation can be used (Eq. 4).

$$PET = 16(\frac{L}{12})(\frac{N}{30})(\frac{10T_d}{I})^{\alpha} \quad (4)$$

where PET is the estimated potential evapotranspiration (mm/month),

T_d is the average daily temperature in Celsius (use ‘0’, if it is negative),
N is the number of days in month being considered,
L is the average day length (hours) of the month being considered,
$\propto = (6.75 * 10^{-7})I^3 - (7.71 * 10^{-5})I^2 + (1.792 * 10^{-2})I + 0.49239,$
and I = $\sum_{i=1}^{12} \left(\frac{T_{m_i}}{5}\right)^{1.514}$ is the heat index with 12 months mean temperatures.

3.3 Surface water contribution

The surface water contribution to the pond must be obtained. If there is any water recharging into the pond, discharge must be measured. This can be done by current meters. A current meter is a (very) sensitive (and fragile) instrument which provides an estimate of the stream velocity at a point. Having selected a suitable site, a tape measure across the river is laid orthogonal to the flow direction (Figure 13). The tape is secured on both banks of the river. Then intervals for measurement of velocity across the cross-section are selected (0.5 m interval is recommended). At each interval the river depth and the river velocity are measured. The measurement must be repeated for other intervals along the cross-section. Once the survey is completed, the discharge can be computed as a summation of velocity multiplied by area for each interval.

Figure 13. An Example of Current Meter Utilization (Meals & Tech, 2008).

In order to evaluate the flow correctly, the x-sections of the channels must be determined carefully. The velocities at different points at the x-sections must be observed. These velocities can be estimated from different points due to the chosen method for calculations which are mentioned below. 'Velocity-Area' methods can be very useful and easy to apply (Herschy, 1993). In these methods, some different observation techniques can be chosen as follows:

- The 0.6 depth method, velocity measurements are taken at a single point at 0.6 of the depth from the surface and this observed value is assumed as a mean value of that section. It's a fast method and reliable (Herschy, 1993).
- The 0.2 and 0.8 method, velocities should be observed at two points from the surface which are 0.2 and 0.8 of the depth from the surface and their averages are assumed as mean velocity of that section (Meals & Tech, 2008).
- Six-point method, velocity measurements are taken at 0.2, 0.4, 0.6 and 0.8 of the depth below the surface and mean velocity of that section can be found as:

$$V_{mean} = 0.1^* (V_{surface} + 2^*V_{0.2} + 2^*V_{0.4} + 2^*V_{0.6} + 2^*V_{0.8} + V_{bed}) \quad (5)$$

Additionally, sections can be evaluated by using different methods. However, the mid-section method might be easy to apply for the discharge calculations (Figure 14).

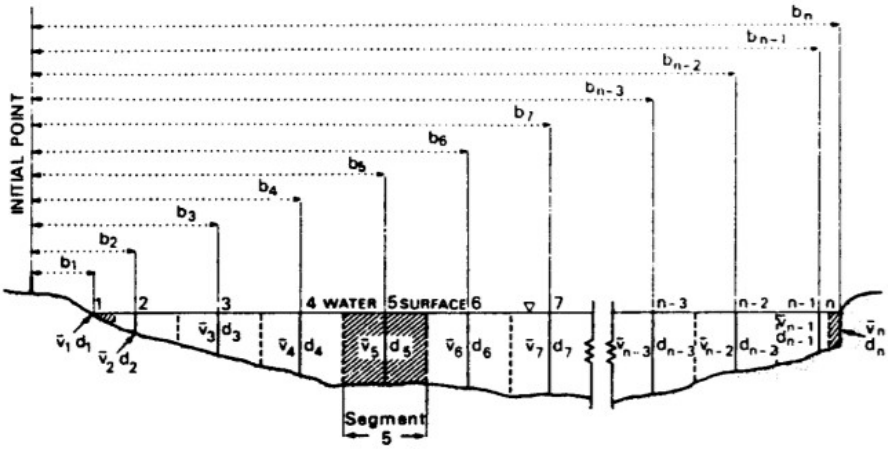

Figure 14. Mid-Section Method.

In the light of these observations, flow can be calculated by the mid-section method as:

$$Q_n = V_n \left(\frac{b_n - b_{n-1}}{2}\right) d_n \tag{6}$$

where V_n is the mean velocity,

d_n is the depth of flow at that vertical,

(b_n, b_{n-1}) are distances from an initial point on the bank to verticals.

Additionally, the mean-section method can also be employed which is the method to evaluate flow by using the successive verticals (Figure 15).

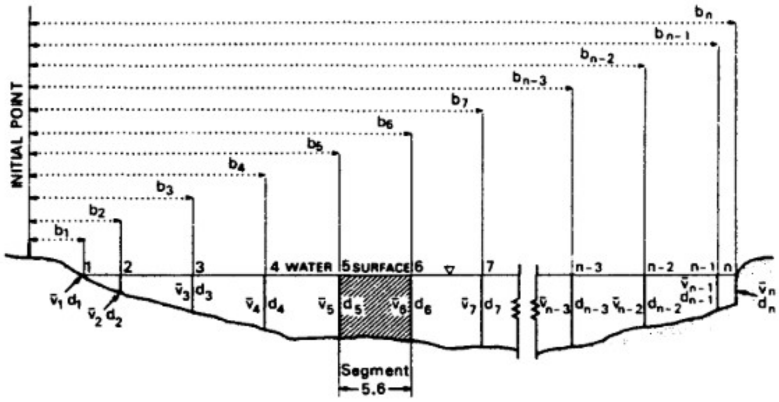

Figure 15. Mean Section Method.

$$Q_{n,n+1} = (\frac{V_n + V_{n+1}}{2}\left(\frac{d_n + d_{n+1}}{2}\right)(b_{n+1} - b_n) \tag{7}$$

where $Q_{n,n+1}$ is the discharge through $n, n+1$,

V_n, V_{n+1} are the mean velocities,

b_{n+1}, b_n are the distances from the initial point,

d_n, d_{n+1} are the depth of flow at that vertical

4. Conclusions

The hydrological budget analysis can be performed after collecting all the related data. The hydrological modelling depending on the simple water budget analysis will be performed on a monthly basis. Depending on the availability of the data, the budget calculation can be done on a daily basis. After collecting all needed data, it is possible to model the behaviour of the pond/pondscape. This will let us understand the hydrology of the temporary and permanent ponds, how they are connected with groundwater and control runoff from the catchment. The developed model can be used to simulate the surface area fluctuations resulting from projected climate change model results and land use changes.

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