HYDROLOGICAL MODELLING OF A RECYCLING FACILITY WITH LANDFILL

HYDROLOGISK MODELLERING AV EN ÅTERVINNINGSANLÄGGNING MED DEPONI


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Abstract
A parsimonious lumped model was developed for simulating a catchment composed of a landfill and recycling facility. The modelling results showed acceptable conformity with the observed values with NSE of 0.54 and R^2 of 0.56 in hourly simulations, though the results were characterized by a general underestimation. The catchment model was coupled with a reservoir model to simulate the leachate storage ponds downstream of the catchment. The time simulated storage of the leachate ponds was aligning with the observed recordings with NSE of 0.96. Simulation of the expected climate change was made to deduce the required expansion of the ponds in future climate and the required additional volumes were calculated to 7,800 m^3 for the current climate to avoid overflow, with 9,100 m^3 for the near term and 10,100 m^3 for the mid- and long-term effects of climate change. It is also recommended to optimize the leachate ponds storage by improving the treatment plant capacity, and/or by continuous control of inflow and outflow. An additional storage volume would probably still be needed.

Keywords: Parsimonious approach; Lumped modelling; Surface water; Landfill; Leachate water; Storage reservoirs.

Sammanfattning
En datasnål, aggregerad modell utvecklades för att simulera lakvattenflöde till en pumpstation vid en återvinningsanläggning med deponi. Modelleringsresultaten överensstämde generellt hyfsat med bra de observerade värdena (NSE=0,54; R^2=0,56), men viss underskattning vid låga flöden noterades. Avrinningsmodellen kopplades till en reservoarmodell för att simulera vattennivå i fördröjningsdammar för lakvatten nedströms avrinningsområdet. Den simulerade fördröjningen i dammarna stämde väl överens med observerade mätningar (NSE=0,96). Resultatet visade att dammarna behöver utvidgas med 7 800 m^3 för att allt vatten ska kunna hanteras med ordinarier reningsrutiner vid nuvarande klimat. I ett framtida klimat kommer det att behövas 9 100 m^3 på kort sikt och 10 100 m^3 för medellång och lång sikt. Det rekommenderas också att man optimerar fördröjningen av lakvatten genom att förbättra reningsverkets kapacitet och/eller genom kontinuerlig mätning och styrning av in- och utflöde. Även med sådana förbättringar, skulle förmodligen ytterligare fördröjningsvolym ändå behövas.

Introduction and site description

As a result of the current environmental laws that were set to monitor the municipal solid waste (MSW) management and landfilling practices, many recycling facilities are facing a challenge in assessing the environmental impact arising from their activities. For each facility, the compliance with the environmental laws is crucial for ensuring renewal of the permits required for continuous operation. One of the major requirements for permit renewals is that the leachate water discharged from the hazardous waste landfills must be collected and stored separately from other water and checked while waiting for final disposal (Nårab Miljörapport, 2020).

The current shift in the global climate and the witnessed consequences of global warming and the subsequent precipitation increase have made it more critical for recycling facilities to cope with the already changing climate. Subsequently, a paradigm shift in thinking about the expected large and extreme events in precipitation, made it crucial for such facilities to prepare and conduct hydrological assessments for their existing infrastructures, and make plans for future expansion as well.

The studied site is a municipal company, Nårab, that handles the cleaning in three municipalities in Scania, Sweden. The company takes care of everything within the collection of waste from households and industries, in addition to the work at the waste facility and the management of recycling centers in the area. A major part of the area consists of an old landfill which is partially closed with a permeable surface. Drainage from this landfill is performed by underground drainage pipes for leachate water collection.

The facility consists of several different surfaces for handling the waste. All the areas are connected to the facility treatment plant, where leachate and surface water from the entire area flows for treatment before it is used for irrigation of surrounding forest areas or pumped to the nearest wastewater treatment plant. The facility treatment plant is old and dimensioned for a smaller area than what exists at its disposal today, and therefore a new assessment of the capacity for the system is needed to be carried out in the current and future climate. A critical part of the system is the leachate storage ponds, as an overflow of such ponds will have a drastic effect on the surrounding environment.

Stormwater from considerable clean surfaces (e.g., office area) is handled in a different way and not connected to leachate storage ponds and the treatment plant.

This work aims to map the runoff from the various surfaces and calculate the water balance for the entire area, by constructing a computer model with a lumped representation of the catchment with a parsimonious modelling approach. The model is tested against its ability to model a complex semi-urban catchment with a limited set of parameters, and its robustness for modelling future climate change events and its implications on the existing system at the facility is checked.

Theoretical basis

Conceptual models are used for hydrological modelling due to frequent data limitations, and that it provides the advantage of simulating complex processes with fewer parameters (Willems, 2014). Parsimonious conceptual models emerged as it allows flexibility in changing the model structure from predefined models depending on the catchment in question (Willems, 2014), and that it serves the purpose of the model when the aim is to study the final outflow from the catchment (Coutu et al., 2012).

The main limitation of adopting a conceptual approach is that prior to any input; the structure of the model must be specified, and that usually exists some parameters with no physical meaning (Zoppou, 2001; Wagener et al., 2002). This means that the outcome of the model will be greatly dependent on the system understanding by the modeler. In addition, over parametrization and lack of parameter identifiability, where combinations of different set of parameters or different model structures can produce the same result (Johnston and Pilgrim, 1976; Uhlenbrock et al., 1999; Wagener et al., 2002).

The water balance method is normally the adopted technique for approaching hydrological modelling through landfills (Bengtsson et al., 1994; Johnson et al., 2001; Marques and Hogland, 2003) and there exis ts several modelling techniques for landfills such as the HELP model (Marques and Hogland, 2003; Berger, 2015; Broichsitter et al., 2018). Several other software exists that can be used for hydrological simulation of landfills, like PREFLO, MOBYDEC and FILL (Hogland et al., 2003). Nonetheless, there were other attempts to simplify the flow through landfills to a greater extent by adopting numerical water budget formulas that is based on continuity (Hogland et al., 2003).

Modelling of landfills is normally initiated with precipitation and retained leachate water as the only inputs to the model (Marques and Hogland, 2003). Most of such studies did not factor any additional flows that may contribute to the total flow, such as surface and sub-surface flows from the surrounding area, which is the case in this work. The objective of this work was to study the system integrity at the large and extreme flow events, not to model the flow through the landfill itself. Thus, it was regarded that a parsimonious lumped model is deemed acceptable considering the level of detail required, the available data and resources.

The issue of overparameterization of conceptual models is usually a limitation to the practicality and robustness of any model. Perrin et al. (2003) noted that a four-parameter model is the optimum complexity in relation to the model output, and that adding additional parameters to a model does not significantly improve the model outcome. Jakeman (1993) also noted the possibilities of using a four-parameter model with two flow components distinctions composed of "quick" and "slow" flow. Subsequently, the choice of the model in this work started from a basic reservoir configuration for semi-urban catchment by Coutu et al. (2012), where the model is directed towards a distinction of the reservoirs to fall on the "quick" or "slow" categories.

Methodology

The approach was to simulate the flow through the catchment by adopting a parsimonious lumped model represented by storage reservoirs, in which the time-dependent storage of each reservoir is influencing the outflow from the reservoir, which subsequently aimed to simulate the delay of flow within the catchment.

A preliminary mapping of the area contributing to the observed flow has been performed through field observations, document studies, and by contacts with the facility personnel, in order to locate the flow that is contributing to the observed flow and neglecting other flow lines. By analyzing the areas contributing to the observed flow, it was deduced that there exist three distinct differences between each area group. The flow types in the model have therefore been distributed to three categories, as following:

- Type "h", Hard (asphalted) surfaces drained through surface flow towards the drainage network.
- Type "p", Permeable (soiled) surfaces drained through underground drainage network of perforated pipes.
- Type "d", The old landfill drained through underground drainage network below the landfill.

Precipitation and observed flow data were received from Nårab. The acquired data composed of an hourly value of precipitation in millimeter and observed flow in cubic meter per hour, for the period of approximately two years, from 2019-12-01 to 2021-11-07. Historical hourly temperature data was acquired from the nearest SMHI station (Swedish Meteorological and Hydrological Institute).

The catchment was modelled as a set of three flow lines, representing the three flow types, where each flow line is composed of subsequent routing reservoirs (Figure 2) in which the flow from precipitation represents the input. The output from each flow line is dependent on the storage in each reservoir. For each flow line, three non-linear reservoirs were used to simulate the flow. Precedent to the routing reservoirs, a soil model was developed to account for soil moisture process.

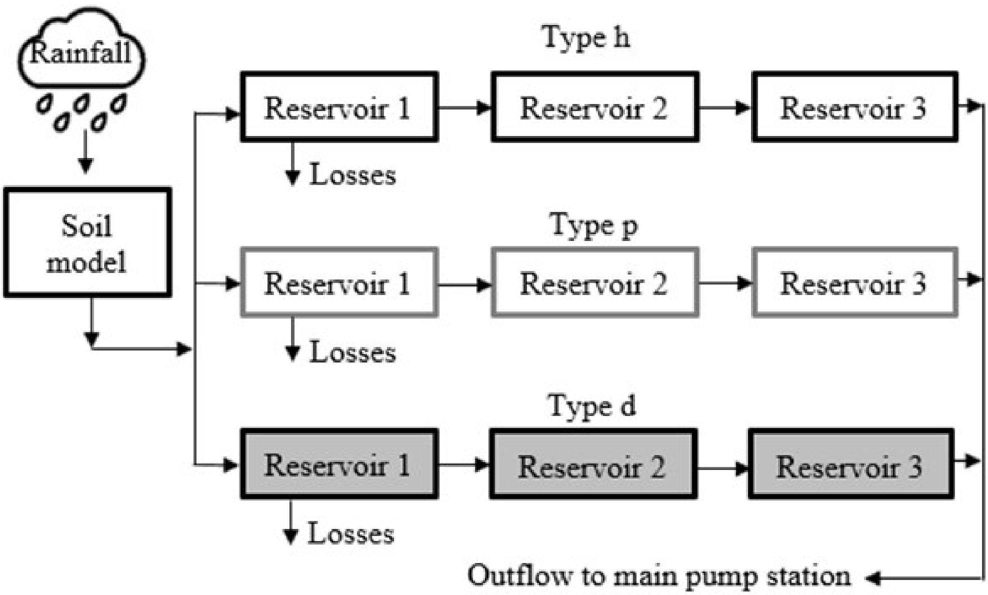

Figure 2. *Schematic diagram of the catchment model.*

Model construction

The general equation for the flow from each reservoir (Wagener et al., 2002) were as following:

$$\frac{dS}{dt} = Q_{[i+1]} - Q_{[i]} \qquad (1)$$

$$Q = aS^n \qquad (2)$$

Where $Q_{[i]}$ and $Q_{[i+1]}$ is the outflow from the reservoir at time-step i and $i+1$, S is reservoir storage, a is reservoir discharge rate, and n is the discharge linearity.

It can be noticed that a and n are the only parameters to be calibrated in the above equations (1) and (2).

In the first reservoir of each flow line, a fraction of the flow is diverted from the outflow to account for losses such as infiltration or evaporation:

$$L = b(S - S_c)^m \qquad (3)$$

where L is the lost flow, b, and m are discharge rate and reservoir linearity respectively. The losses flow from the reservoir is dependent on the critical storage of the reservoir, *Sc,* in which the losses equation is activated when the reservoir storage goes above the critical storage. *Sc* is a model parameter to be calibrated for each first reservoir of the three flow types.

Subsequently, the output flow of the model is the simulated total flow from each flow line, as:

$$Q_{total} = Q_h + Q_p + Q_d \qquad (4)$$

where Q_h, Q_p, and Q_d are the outflow from each flow line for hard, permeable surfaces and the old landfill, respectively.

The soil moisture was represented by an equation reflecting the wetness index of the soil known as Catchment Wetness Index (CWI) (Wagener et al., 2002; Croke and Jakeman, 2008), which calculates the portion of the rainfall that gets translated to an effective rainfall, depending on the wetness index of the previous time-step. The effective rainfall $u_{[i]}$ was hereby calculated as following:

$$u_{[i]} = [c(\emptyset_{[i]} - I_s)]^p \, r_{[i]} \qquad (5)$$

where $r_{[i]}$ is the observed precipitation at time-step *i*. *c, Is*, and *p* are parameters representing mass balance, soil moisture index threshold and non-linear response terms, respectively. $\emptyset_{[i]}$ is the soil moisture index at time-step i, calculated as following:

$$\emptyset_{[i]} = r_{[i]} + \left(1 - \frac{1}{t_{[i]}}\right)\emptyset_{[i-1]} \quad (6)$$

where $t_{[i]}$ is the drying rate at time-step i, calculated by:

$$t_{[i]} = t_w \, exp\left(0.062 f\left(T_r - T_{[i]}\right)\right) \quad (7)$$

where t_w is the reference drying rate, f is the temperature modulation, T_r is the reference temperature and $T_{[i]}$ is the air temperature at time-step i.

Thus, the parameters to be calibrated in the above equations (5, 6 & 7) is c, p, I_s, t_w, f, and Tr.

The original equations described by Jakeman et. al (1990) was meant to directly relate the transfer from rainfall $r_{[i]}$ to effective rainfall $u_{[i]}$ by the parameter c which is thereafter calculated explicitly (i.e., $I_s = 0$ and $p = 1$). Nonetheless, the form used in this model is a more general form to allow the non-linear simulation of the moisture indexes through the parameter p and the incorporation of a moisture threshold I_s, thus requiring model calibration with the two parameters (Croke and Jakeman, 2008).

Calibration and validation

The model performance has been assessed by using a set of objective functions, which in essence aggregate the difference between the observed and simulated flow (Wagener et al., 2002). The model was calibrated manually and automatically until it produced the maximum fitting (i.e., lowest residual) according to the current model structure. Preliminary calibration of the model was crucial for the automated calibration to progress in the right direction. Numerous interventions were made after visual inspection of the interim automated calibration results. It was recommended by Willems (2014) that the calibration to be a combination of manual and automatic steps that intertwine some user interventions, which is confirmed in this report.

The results of the calibration were gauged visually and by analyzing the results of several objective functions. The objective functions used for calibration (Wagener et al., 2002; Kalin and Hantush, 2006; Coutu et al., 2012) are as following in Table 1:

Table 1. *A summary of the used objective functions with the ideal value.*

Indicator	Ideal value
Nash-Sutcliffe Efficiency Model (NSE)	1
Normalized Bias (NB)	0
Coeff. of Determination (R^2)	1
Deviation of Runoff Volume (DV)	1

The model was calibrated during the period of 2019-12-01 to 2021-05-07 (approx. 1.5 year), and subsequently validated for the period of 2021-05-08 to 2021-11-07 (approx. 0.5 year).

Results of the catchment simulation

The calibration of the model was performed from 2019-12-01 to 2021-05-07 (532 days) with hourly time-steps. The results of the calibration for this period are summarized in the following Table 2:

Table 2. *Results of the model calibration by simulation at time-step = 1 h.*

Indicator	Calibration	Validation	Ideal value
NSE	0.54	0.54	1
NB	0.01	0.09	0
R^2	0.54	0.56	1
DV	0.99	0.90	1

Accumulating the hourly time-series to daily values, the results of the calibration are summarized as shown in Table 3:

Table 3. *Results of the model calibration by simulation at time-step = 1 day.*

Indicator	Calibration	Validation	Ideal value
NSE	0.69	0.69	1
NB	0.01	0.01	0
R^2	0.69	0.74	1
DV	0.99	0.90	1

Moriasi et al. (2015) noted that the models are considered acceptable if NSE > 0.50 and $R^2 > 0.60$

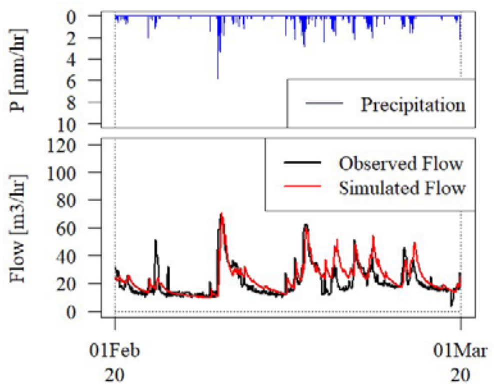

Figure 3. *Main simulation result (time-step = 1 h) during the period of 2020-02-01 to 2020-02-28 (calibration)*

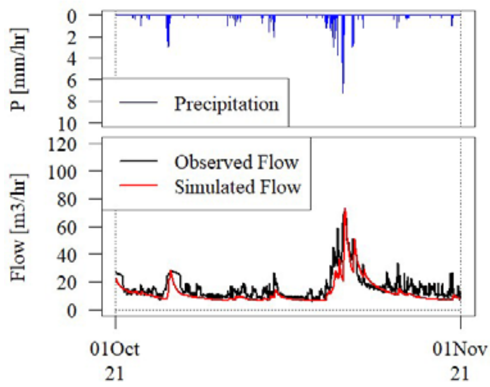

Figure 4. *Main simulation result (time-step = 1 h) during the period of 2021-10-01 to 2021-10-31 (validation)*

for watershed-scale models that is daily simulated. It can be shown that the model has produced acceptable results for the daily accumulated simulations and "fair" for hourly simulations.

It must be noted that the complexity of the catchment could not capture all flow dynamics for hourly simulations, since the catchment includes multiple pumping stations that influence the flow (preceding the main pump station). Monthly records from the facility show that these pumping stations operate for certain hours each month and there is no sound way to track or record the changes to modify the model accordingly. Moreover, the dynamics in the outflow from the old landfill will not normally be expected to be captured in a parsimonious model.

Figure 3&4 shows the simulated and observed flow for two months during the calibration and validation period, respectively. Figure 5 shows the observed and simulated flow after accumulating the hourly time-series to daily values.

Assessment of the routing reservoirs

In order to assess the flow types, i.e., flow from hard surfaces, permeable surfaces, and old landfill; a separate plot was made for each reservoir (Figure 6).

Figure 6 shows that the outflow from each reservoir is matching the preliminary assumptions in terms of the flow delay degree. The hard surfaces are characterized with quicker response for peak flows *(Q_h)*, while the permeable surfaces are delayed as expected from drainage through underground perforated pipes *(Q_p)*. The flow from the old landfill is considered stable through the simulation around 6 m^3/h *(Q_d)*, which confirms work done by Bengtsson et. al (1994), who noted that landfills of considerable old age are characterized by a constant flow over time.

Climate change

A study was conducted to simulate the effect of expected increased precipitation and temperature caused by climate change. Subsequently, three scenarios were studied based on the most recent report by the Intergovernmental Panel on Climate Change (IPCC) (IPCC AR6 WG1, 2021). The three scenarios are outlined in Table 4, where T is increased temperature in degree Celsius and P is percentual increase in precipitation.

Table 4. *Climate change scenarios (IPCC AR6 WG1, 2021)*

Scenario	Period	T (°C)	P (%)
1.0	Near term (2021–2040)	1.5	10
2.0	Mid-term (2041–2060)	2	15
3.0	Long term (2061–2100)	4	25

Precipitation is increased uniformly from the observed (recorded) precipitation values. It is not taken in consideration any change in the frequen-

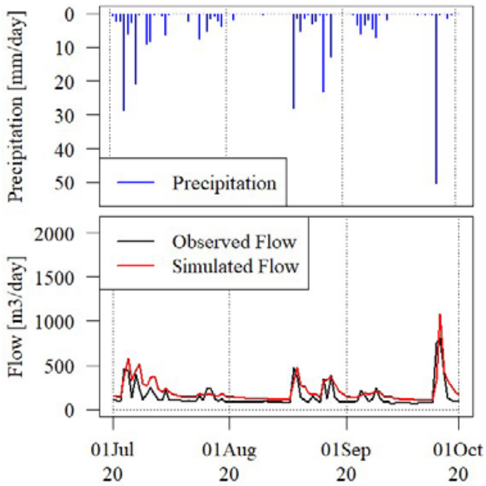

Figure 5. *Main simulation result (time-step = 1 day) during the period of 2020-07-01 to 2020-09-30.*

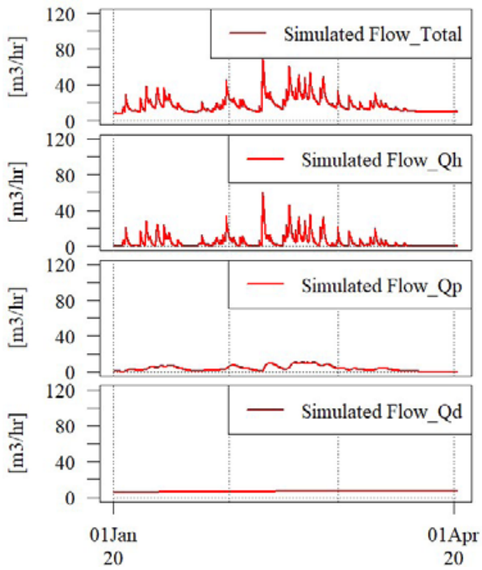

Figure 6. *Simulated flow from each flow type routing reservoir between the period of 2020-01-01 to 2020-03-31.*

cy of the heavy rains (large events) that may arise from the expected global warming as indicated in the IPCC report.

The simulation with future climate is a balance of increased flow due to precipitation, with increased evaporation due to the elevated temperature. In addition, the current treatment routine is depending on temperature, which affects the capacity of the treatment plant.

Leachate ponds simulation

The flow from the catchment (through the main pump station, where the main flow meter is located) is directed towards two leachate storage ponds (Lakdamm 1&2) showed in Figure 1, where the ponds are currently used for aeration and treatment of the leachate and reject water prior to pumping to the treatment plant. In order to simulate the fluctuating volume of the storage ponds, a water balance based on continuity has been developed as following:

$$\frac{dV}{dt} = Q_{in} - Q_{out} \qquad (8)$$

$$Q_{in} = Q_{total} + P(A) \qquad (9)$$

$$Q_{out} = Q_{treat} + E(A) + Inf \qquad (10)$$

Where *V* is the volume of the storage ponds, Q_{in} is the inflow, Q_{out} is the outflow, *P* is precipitation (mm/1000), A is the surface area of the ponds (m^2), Q_{treat} is the flow to the treatment plant, *E* is evaporation (mm/1000), and *Inf* is the infiltration to the sub-ground layers as the ponds were not lined at the bottom at the time of construction. Evaporation and infiltration are simplified by normalizing the yearly values to hourly values. This simplification was deemed acceptable due to the small value of the evaporation and infiltration losses compared to the inflow and outflow to/from the pond by pumping.

The inflow to the ponds is the flow from the catchment through the main pump station, and the outflow Q_{treat} is depending on the pumping periods which is subsequently dependent on the design capacity of the treatment plant. The pumping to the treatment plant is dependent on the air

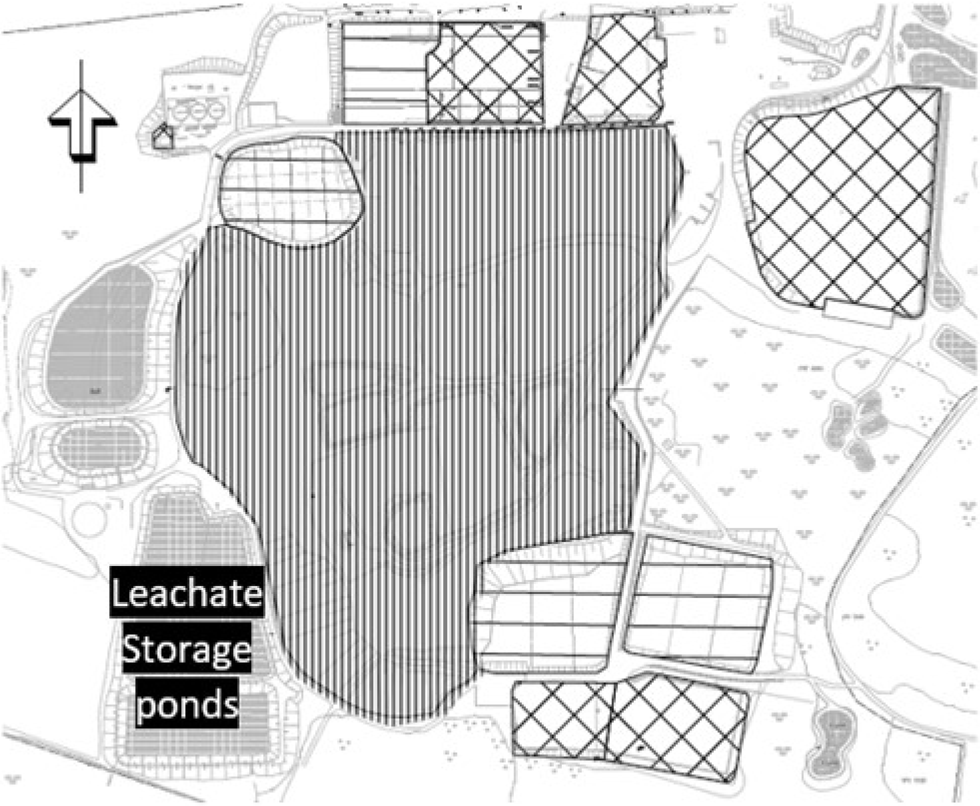

Figure 1. *Catchment area contributing to the observed flow (Hard surfaces: cross hatch, Permeable surfaces: horizontal hatch, and the old landfill in vertical hatch). The flow from these areas is directed to the leachate storage ponds noted in the figure.*

temperature as there exists a maximum capacity of the heaters within in the treatment plant. Generally, more water is pumped to the treatment plant during hot periods compared to cold periods with the following routine: When $T_m \geq 5$ °C, the station is pumping $Q_{treat} = 50$ m^3/h during work hours [08:00 to 17:00] and when $T_m < 5$ °C, the station is pumping $Q_{treat} = 50$ m^3/h only during the hours [08:00 to 10:00] and during the winter months (Dec-Feb) regardless of the air temperature. T_m is the daily mean temperature.

The water level has reached the overflow levels twice during the observed period, i.e., in March 2020 and May 2020 (Figure 7, observed storage). During these periods the pumping was increased to the maximum capacity by the facility personnel (Figure 7, pumping from reservoirs), most probably to prevent overflow, overriding the pumping routine related to temperature. The year 2020 is chosen for further assessment as it includes this extreme case of threatening ponds overflow.

The leachate ponds storage has been simulated with the expected increase in precipitation and temperature as per the climate change scenarios mentioned in Table 4. The input flow to the model is the output from the catchment simulations. The increased precipitation also affects the ponds directly via direct precipitation. Since the outflow to the treatment plant is dependent on the temperature, pumping is subsequently increased with increased temperature. Thus, both the inflow to and outflow from the ponds are increased depending on the increased precipitation and temperature. The analysis of the required additional volume (future expansion of the ponds) is hereby based on the additional storage from the simulation done at the future climate, compared to the storage simulated at the current climate.

During the current climate, an additional storage volume of 7,800 m^3 is needed to avoid overflow of the ponds, provided there is no override to pump larger flow during the cold periods. Considering future climate, instead an additional storage volume of 9,100 m^3 is needed during the near term, and 10,100 m^3 is needed to detain the additional inflow during the mid- and long-term climate change. The most extreme climate change is not the worst case, as the increased temperature will allow more pumping from the ponds to the treatment plant.

Discussion

A parsimonious lumped model was constructed to simulate flow from a catchment composed of a recycling facility and landfill. The model gave acceptable results in terms of the fitting of the simulated flow with the observed flow. The catchment simulation was coupled with a reservoir model for the leachate storage ponds downstream the catchment outflow. The simulation showed a great degree of compliance with the observed values with NSE of 0.96.

Subsequent simulations of the future expected climate change for the short-, mid-, and long-term expected changes showed that the storage ponds are insufficient and that the expected increased precipitation will cause the leachate ponds to overflow unless an expansion is made as per the values recommended in this study. The recommended additional volume on top of the current volume (40,000 m^3) is 7,800 m^3 for the current climate to avoid overflow, 9,100 m^3 for the near term and 10,100 m^3 for the mid- and long-term effects of climate change. The recommendations are based on the extreme flow in year 2020 and increased precipitation and temperature representing future

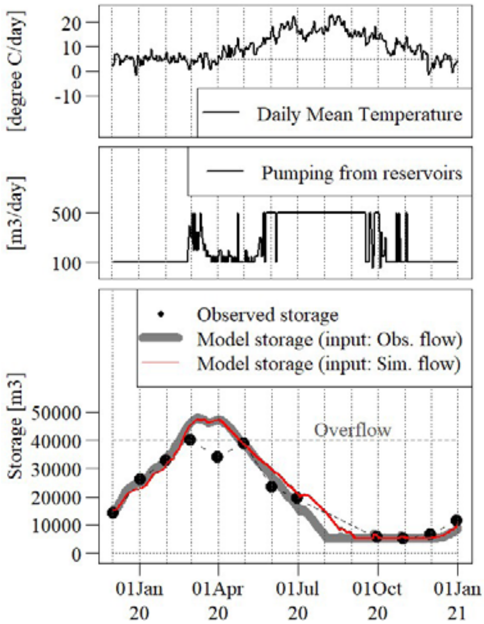

Figure 7. *Simulation of the leachate ponds storage.*

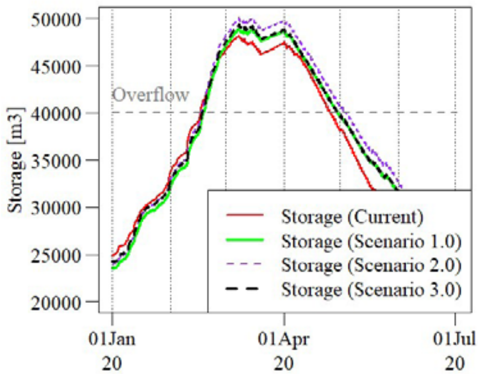

Figure 8. *Climate change simulation of the leachate ponds.*

climate. No statistical analysis was done in order to verify the return period of the extreme flow in 2020. The need for additional volume in the storage ponds is also affected by the capacity of the treatment plant. An additional capacity would allow additional outflow from the ponds. In addition, by incorporating a system for online monitoring of the ponds storage while synchronizing with the pumping periods, storage in the ponds could be optimized.

It was noted that the hourly model did not successfully capture all the peak flows in the observed values and there is an underestimation of peaks. Nonetheless, the daily accumulated values of the simulated flow showed an acceptable fitting of peak flows with the daily accumulated observed flow time-series. Thus, combining the drainage network complexity with the intertwining hydraulic structures in a lumped representation can open possibilities for simulations when the available calibration data is not sufficient for including more complexity or when a detailed hydraulic model is neither needed nor available.

Simulation of a complex system such as old age landfills is earlier proved to be possible by lumped conceptual models. The complexity in the flow dynamics through the landfill layers can be "dampened" by a lumped representation of the landfill itself and the connected drainage network. Simulation of flow from the landfill showed a considerable stable outflow with delayed fluctuations, which was expected (Bengtsson et al., 1994). Simulation of the old landfill with the connected semi-urban catchment, that usually surrounds landfills within recycling facilities, can be simulated in a lumped conceptual model and produce a fair hourly result and daily results that match the observations to a great extent.

Separate analysis of the routing reservoirs represented the expected flows from hard and permeable surfaces as well as from the old landfill. That indicates that system understanding is a key factor in the construction of a lumped model. For simulation of the storage in ponds, it can be noted that the attenuation effect of the storage ponds did "flatten" the residuals between the observed and simulated flow that resulted to this conformity.

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