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Wastewater matters: Incorporating wastewater reclamation into a process-based hydrological model (CWatM v1.08)

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Abstract

Wastewater treatment and reuse are increasingly perceived as essential to improve water use efficiency and increase water availability and reliability. Furthermore, wastewater has a significant impact on hydrological signals in urban watersheds. Hydrological modeling has developed over the last few decades to account for the human-water interface. Yet, despite the importance of wastewater treatment and reclamation, it is not yet comprehensively included in large-scale and multi-resolution hydrological models. This paper presents the newly developed wastewater treatment and reclamation module as part of the hydrological Community Water Model (CWatM) and demonstrates its capabilities and advantages in an urban and watershed with intermittent flows. Incorporating wastewater into the model increases model performance by better-representing discharge during the dry period. It allows for representing wastewater reuse in different sectors and takes on a modular approach, allowing for higher control over the wastewater treatment and reclamation process when spatial resolution and data availability allow it. As the current development focuses on water quantity, the water quality dimension of wastewater treatment remains a limitation, which sets the plans of incorporating water quality into the model and developing global input data for wastewater treatment and reclamation.

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1. Introduction

Hydrological modeling has developed over the last few decades to account for the human-water interface (Wada et al., 2017). Recent developments in this field focused on developing higher-resolution global hydrological models (GHMs) by increasing models' spatial resolution, adjusting their datasets, and including a variety of water management options (Abeshu et al., 2023; Hoch et al., 2023; Burek et al., 2020; Hanasaki et al., 2022).

Increasing human interventions in the water cycle and higher spatial resolution modeling have emphasized the need to include water management as an integral part of hydrological models (Hanasaki et al., 2022). Some large-scale hydrological models (LHMs) already account for water management aspects, like water withdrawal and consumption, irrigation management, reservoir operations, water transfers, and desalination (Wada et al., 2017).

Wastewater treatment and reclamation are other management options that are increasingly important in many regions. Currently, treated wastewater is estimated at 188 km^3 per year globally, which is around 52% of effluents generated. Further, approximately 22% (of treated wastewater) is estimated to be reclaimed (Jones, van Vliet, Qadir, & Bierkens, 2021). Thebo et al. (2017) find that around 35.9 mega hectares of irrigated cropland are supported by rivers dominated by wastewater from upstream urban areas, and Van Vliet et al. (2021) indicate that expansion of treated wastewater uses from 1.6 to 4.0 billion m^3 per month can strongly reduce water scarcity levels worldwide.

Specifically, wastewater reuse is a valuable water source for industrial use and irrigation in water-stressed regions. For example, Israel reclaims around 88% of its treated wastewater, mainly for use in the agricultural sector, where it satisfies about 45% of the agricultural water withdrawals (Fridman, Biran, & Kissinger, 2021). Treated wastewater is also used for irrigation in South European, Mediterranean, and North African countries (Angelakis et al., 1999; Bixio et al., 2006). While accepting exacerbated stress on freshwater resources, the European Parliament is working to improve the quality of wastewater treatment in the EU, aiming to increase wastewater reuse (European Parliament, 2024). It follows that prospects of increased utilization of this resource are plausible.

Wastewater collection, treatment, and reclamation are relevant processes for the hydrological modeling of urban catchments and complex water resource systems and are included in different small-scale models (Salvadore, Bronders, & Batelaan, 2015). Large-scale hydrological models often neglect wastewater treatment and reclamation. However, to some extent, few models include wastewater treatment effects on water quality. The Soil & Water Assessment Tool (SWAT) includes septic tanks as an on-site treatment option. It simulates the percolation of wastewater into soils, the interaction between pollutants and the soil media, and bacteria build-up and nutrient uptake (Neitsch, Arnold, Kiniry, & Williams, 2011).

Another example is DynQual, a global water quality model coupled with the PCR-GLOBWB2 hydrological model (Jones et al., 2022). The model includes wastewater treatment processes in water quality simulations while simplifying wastewater treatment and reclamation management. Namely, in DynQual, wastewater is generated, collected, treated, and discharged locally (in a single grid cell).

While these are significant developments, they only partially capture the complex dynamics between human activities and hydrological processes occurring in urbanized catchments or otherwise complex water resource systems.

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This paper introduces a recently developed, customizable wastewater treatment and reclamation module as part of the Community Water Model (CWatM), allowing various modes of simulating wastewater treatment and reclamation processes.

CWatM is a versatile, fully distributed, modular, and open-source hydrological model that simulates natural and human-affected hydrological processes at a daily time step and multiple spatial resolutions ranging from 0.5° to 30 arc-seconds (Burek et al., 2020). CWatM has extensive and publicly available documentation of the source code, the model structure, and model training and tutorials (https://cwatm.iiasa.ac.at/, last access: 11 July 2024). The development of the wastewater treatment and reclamation fits with the modularity and flexibility of CWatM by providing various modus-operandi to enable simulation of wastewater treatment and reclamation on global (0.5°), regional (5 arc minutes), and local (up to 30 arc seconds) scales. This paper aims to introduce this module using a hyper-resolution (resolutions of less than or equal to 1 km^2) case study of an urbanized river basin in a relatively dry climate (the Ayalon River basin in Israel).

The rest of the paper is organized as follows. Section 2 describes the model development; section 3 covers the case study, input data, and scenarios; and section 4 presents the results, followed by discussion and conclusions in sections 5 and 6, respectively.

2. Model development

2.1. The Community Water Model (CWatM)

CWatM is a large-scale distributed hydrological model suitable for implementation at global and regional scales (Burek et al., 2020). It is implemented in the Python programming language and is fully open-source (https://cwatm.iiasa.ac.at). CWatM simulates the main hydrological processes and covers some aspects of the human-water interface. This paper presents the recently developed wastewater treatment module, aiming to enhance CWatM's capacities for addressing human water management. The model is applied to the relatively water-scarce Ayalon River basin in Israel. It uses a spatial resolution of 30 arc-seconds (so-called ~1 km^2 grid) in a geographic coordinate system (WGS84). Groundwater is simulated by the coupled CWatM-MODFLOW6 model (Guillaumot et al., 2022) at a spatial resolution of 500 meters using the UTM36N coordinate system.

2.2. Developing the Wastewater Treatment and Reclamation Module (WRTM)

The wastewater treatment and reclamation module (WRTM) enhances the capacity of CWatM to simulate the human-water interface at hyper-spatial resolution. It introduces wastewater generation, collection, treatment, discharge, storage, and reclamation to CWatM. Figure 1A demonstrates WRTM workflow and sub-modules: (1) pre-treatment; (2) treatment; (3) post-treatment.

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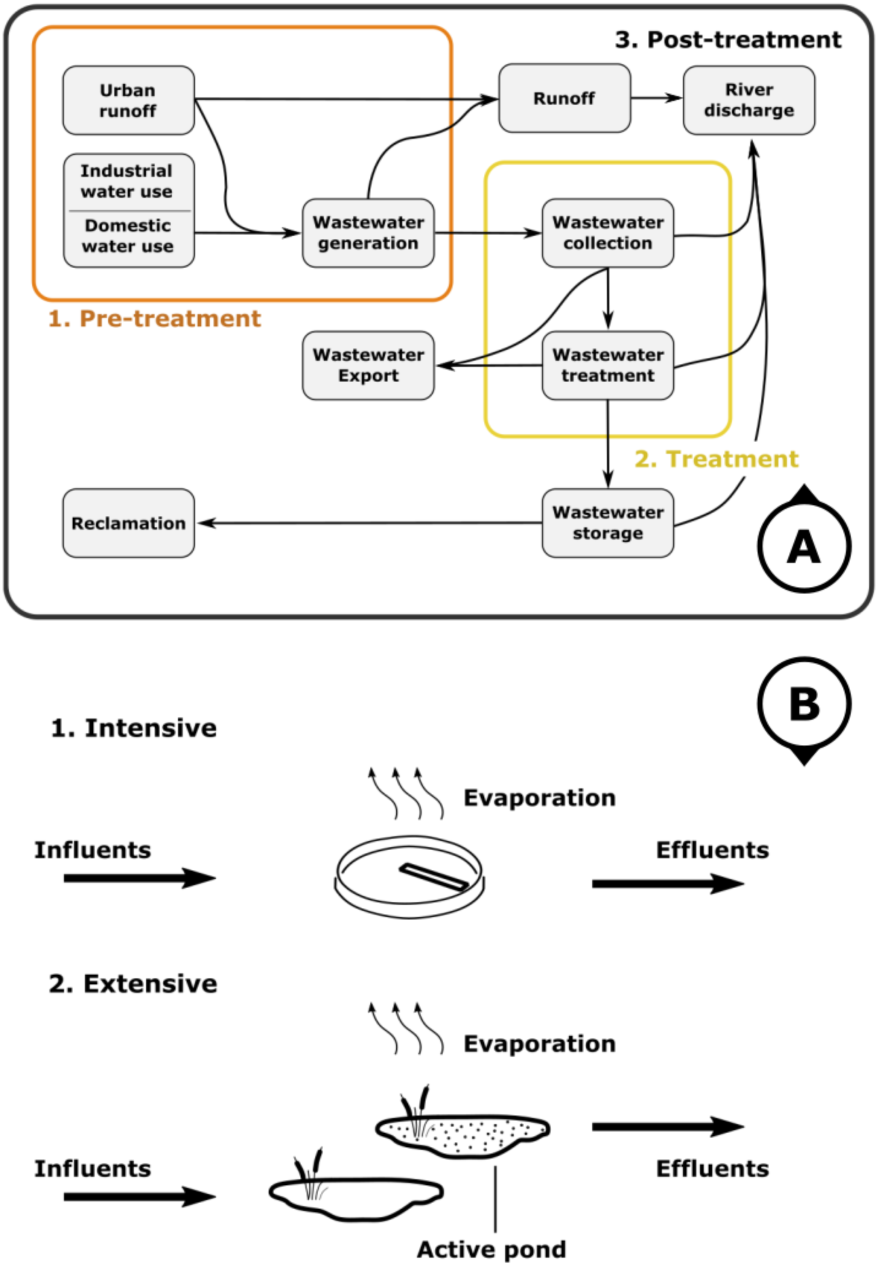

Figure 1: (A) Workflow of the Wastewater Treatment and Reclamation Module, and (B) the main processes and flows in intensive and extensive wastewater treatment systems.

2.2.1. Pre-treatment

The first processes of the wastewater module are the accumulation of wastewater and sealed area runoff in each grid cell (see Equation 1). Wastewater originates from domestic and industrial effluents (Eff^{Dom} and Eff^{Ind}), calculated by multiplying the simulated non-irrigation return flow as the sectoral fraction of the non-irrigation water demand.

Equation 1: Calculating WWTP influents in CwatM-WTRM.

$$Inflow_{j,t} = \sum_{l \in j} \left(Eff_{l,t}^{Dom} \times D_j^{Dom} + Eff_{l,t}^{Ind} \times D_j^{Ind} \right) \times Cs_l + Rf_l \times \alpha$$

Note: j and *t* represent a simulated WWTP and the time step, respectively; *l* indicates a grid cell.

Setting up wastewater treatment plants (WWTP) allows for collecting and treating wastewater from different sectors using a logical variable (e.g., D^{Dom}). The aggregated value of potentially collected effluents is multiplied by a collection share coefficient (*Cs*) representing sewer connection rates and leakages. Finally, any share of the urban runoff (*Rf*) can be added to the collected effluents by applying the α collection coefficient. Thus, it is possible to control the design of the urban stormwater drainage systems, either integrated, partially integrated, or completely separated from the urban sewer system.

2.2.2. Treatment

The treatment phase starts with the collection of influents to WWTP. User-defined collection areas and efficiencies guide this process (see Equation 1). Wastewater treatment plants can hold the following features: the period of operation (e.g., from 2000 to 2010), daily treatment capacity, export share, designed hydraulic retention time (HRT), and minimally allowed HRT. The WWTP inputs use a tabular format (i.e., via an Excel spreadsheet), facilitating the creation of several instances for each WWTP to represent plant upgrades over time (e.g., increased daily capacity, reduction in HRT).

Currently, the module supports two optional wastewater treatment technologies defined by the hydraulic retention time. The two options are intensive and extensive treatment plants, as described in Figure 1b. HRT of intensive WWTP usually does not exceed 24 hours, and a treatment plant is considered extensive if its HRT is two days or above, though setting it to 20 -30 days is recommended (Pescod, 1992).

The main flows within the treatment section are influent, evaporation, and effluent, as described below.

Influent inflows

If daily influent exceeds the plant's daily treatment capacity, excess wastewater is discharged into pre-specified discharge locations. Treatment plants' design often allows inflows to exceed the designed capacity to handle fluctuations, for example, due to rain events. The hydraulic retention time is defined as $HRT = Volume/Inflow$, hence exceeding the designed capacity reduces the retention time, resulting in less effective wastewater treatment (Pescod 1992).

The module accounts for this feature by enabling treatment plants to have peak capacities higher than their designed capacities. The minimally allowed HRT (days) parameter expresses the lowest operational hydraulic retention time a treatment plant can withstand before it refuses inflows. Following the calculation of the hydraulic

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retention time, the maximum daily capacity can be calculated as follows $Inflow_{max} = Volume/HRT_{min}$, whereas volume is fixed. For example, a minimally allowed HRT of 0.8 days implies an increase of 25% in the operational daily capacity.

Evaporation

Surface area evaporation is calculated by multiplying the potential open water evaporation rate with the estimated surface area of the treatment pools, and it is limited by the volume of stored wastewater in the pool.
Calculating the surface area of the treatment pools is different for intensive and extensive systems. The approach divides daily treatment capacity for intensive systems by an estimated treatment pool depth (currently set to six meters).
Extensive systems are modeled as treatment ponds, alternately filling up and treating water (see Figure 1B). Unlike in intensive systems, treatment ponds in extensive systems may remain empty for long periods. Since evaporation is simulated at the pond level, it considers only ponds with positive water storage.

Equation 2: calculation of the surface area of extensive treatment systems.

$$As_j = \frac{1}{Depth_j} \times \left(VolCap_j \times \frac{TreatTime_j}{TreatPool_j - 1} \right)$$

The surface area of each treatment pool is calculated by dividing the pool's volume by its depth (see Equation 2; *Depth*, currently set to one meter). Each pool volume is derived by multiplying the daily capacity (*VolCap*) with the pool filling time. The latter is a function of the total treatment time (*TreatTime*) and a predefined number of treatment pools (*TreatPool*; currently set to three).

Effluents

Effluents can be discharged, exported, or sent to reservoirs for reclamation. The timing of effluent release differs between intensive and extensive systems. Figure 1B shows the main differences between these two types of systems. Influents remain in the treatment plant during the predefined treatment time in intensive systems. For example, for a treatment time of one timestep, the effluent volume at time *t* equals the influent volume minus evaporation of time *t – 1*.
In an extensive system, we differentiate between two types of treatment ponds. At each time, there is one treatment pond that receives all inflows. All other ponds can be either empty or not. Every pond that is neither a receiving pond nor an empty one is termed an 'active' pond, i.e., where wastewater treatment occurs. Effluents are released from 'active' ponds under any of the following conditions: (a) the predefined treatment time has passed since the 'active' pond stopped receiving inflows; (b) all pools are at full capacity, and more influents should be added into the system. In the latter case, the effluents always originated from the 'active' pond with the longest retention time, though they may not be fully treated.

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2.2.3. Post-treatment

The module has three post-treatment possibilities: river discharge, wastewater export, and reclamation. The module exports untreated and treated wastewater; collected untreated wastewater is exported from the simulated region if the WWTP associated with the collection area does not exist within the model domain. Treated wastewater can be exported to account for cases where reclamation occurs partially or entirely outside the simulated region. In this case, the 'Export share' parameter allows a fixed proportion of the effluents to be sent outside the model domain. In the latter case, the export of treated wastewater occurs immediately after the treatment phase.

Reclamation (e.g., for irrigation purposes) generally occurs using the reservoir module, so treated wastewater is sent to reservoirs that manage water use. The module iterates over all treatment plants and attempts to send treated wastewater to associated reservoirs. In the case of multiple reservoirs, the module divides the water in proportion to the reservoirs' remaining storage (calculated as $remainingStorage_{i,t} = totalVolume_i - liveStorage_{i,t}$). If all related reservoirs are full, the module discharges the remaining water in a predefined discharge location. Discharge is the default behavior if no reservoir is associated with a treatment plant. Further, the user can force discharge for specific WWTP, even if reservoirs are associated with them, by setting the export share to -1. Finally, untreated wastewater can be discharged if a plant's inflows exceed the plant's peak capacity (see minimally allowed HRT in section 2.2.2).

This module provides multiple wastewater storage, conveyance, and reclamation modeling options. For example, one can simulate the discharge and dilution of treated wastewater into an upstream channel, which can be re-captured in a reservoir downstream for reclamation purposes. Additionally, treated wastewater can be managed in a separate reclamation system by establishing a set of artificial, off-stream (type-4) storage reservoirs. A type-4 reservoir is not connected to the river network, thus having no channel-related inflows or outflows. Instead, water inputs include water/wastewater pumping, and water outputs are evaporation and pumping. As each WWTP can be linked to one or more reservoirs or discharge its water directly into a river channel, the model allows for the combination of the two aforementioned approaches.

3. Case study application

Israel is located on the Eastern Coast of the Mediterranean between the latitudes 29°N –34°N and along the 35°E longitude. Its Central coastal and Northern parts are governed by a Mediterranean climate (hot and dry summer), its Eastern parts are arid due to rain shadow from its Central Mountain range, and the Southern parts experience a semi- to hyper-arid climate due to their vicinity to the world's desert belt.

During the 1960s, Israel initiated a country-wide water conveyance system (the 'National Water Carrier') to transfer water southwards from the northern Sea of Galilee, allowing rural development and large-scale irrigation in the semi-arid Negev region (Tal, 2006). Israel's water system is intensively managed today and relies primarily on seawater desalination, treated wastewater reclamation, and groundwater abstraction. Although it is a nationally managed system, significant regional differences exist in sectoral water provision (Fridman et al., 2021).

The Ayalon basin is in central Israel and the West Bank, and stretches 815 km^2 between the western slopes of the Judea Mountains and the Mediterranean Coastal zone. A few kilometers inland, the Ayalon spills into the Yarkon stream (see Figure 2). Ayalon is an urbanized river basin partially overlaying the Tel Aviv-Yaffo metropolitan

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area downstream and the city of Modi'in in its middle segment. Downstream urban areas result in considerable water demand, vast runoff from sealed areas, and a high rate of wastewater generation. Upstream, the landscape of the Ayalon basin is predominantly a rural mosaic of open areas and small settlements. Patches of irrigated agriculture and forests are primarily found in the South-Eastern parts of the basin.

Ayalon is a seasonal river originating in the South-Eastern part of the basin. An artificial 'horseshoe' shaped reservoir ('Mishmar Ayalon') regulates its flows and maintains relatively fast groundwater recharge. Five main tributaries drain the remaining basin and feed the Ayalon River downstream. An artificial cemented canal collects the river water before crossing densely populated urban areas downstream.

3.1. Data sources

This hyper-resolution analysis combines global and local datasets better to represent the case-study hydrologic processes and human-hydrologic interactions (Hanasaki et al., 2022). Table 1 provides an overview of both the global (e.g., meteorological forcings, soil characteristics, topography, and the river network) and the local datasets (e.g., wastewater treatment and reclamation, reservoir networks, aquifer properties, landcover maps, seawater desalination, and water demand).

Table 1: Model inputs from global and local datasets.

Input data	Spatial resolution	Data sources
Global datasets		
Meteorological forcings	0.5° grid; daily Downscaling to 30 arc-seconds	ISIMIP 3a, GSWP3-W5E5 (Lange, Mengel, Treu, & Büchner, 2022) WorldClim (Fick & Hijmans, 2017)
Soil	30 arc-seconds	Dai et al. (2019) Shangguan, Hengl, Jesus, Yuan, & Dai (2017)
Topography	3 arc-seconds	MERIT Digital Elevation Model (Yamazaki et al., 2017)
River network properties flow direction map	30 arc-seconds	MERIT Hydro IHU (Eilander et al., 2020)
Local/modified datasets		
Landcover maps	500 meters	MODIS Global landcover between 2001 - 2019 (Friedl & Sulla-Menashe, 2019), OpenStreetMap (Urba areas, water, and green spaces; available at https://www.openstreetmap.org), Ministry of Agriculture and Rural Development (MOAG, 2022; cultivated land), and Hamaarag (2017; forests' map)

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Municipal and industrial water demand	Municipality	Israel Central Bureau of Statistics (ICBS, 2022). A Random Forest regression imputed missing data for different localities and specific years. Palestinian Central Bureau of Statistics (PCBS, 2022).
Wastewater treatment plants' location and treatment levels, collection areas, and wastewater generation coefficients	Municipality	A national dataset was compiled mainly relying on a report by the Israel National Reserve Authority (INRA, 2016) and data from PCBS (2022a).
Desalination	National	Annual desalination capacity between 2005 - 2019 (Gov.il, N.D.). A basin-scale desalination is allocated proportionally to the relative domestic water demand. For example, the national supply of desalinated seawater in 2005 and 2015 was 20 and 503.4 MCM, respectively. In the same years, the Ayalon desalinated seawater supply is estimated at 3.4 and 88 MCM.
Reservoirs	-	Manually identify and digitize reservoirs based on aerial photography and satellite imagery. Depth and volume were assumed based on fieldwork and engagement with water managers.
Groundwater basin and aquifers	Various resolutions	Aquifer maps were taken from Israel Hydrological Services (2014), and porosity and permeability were taken from Melloul et al. (2006) for the coastal basin and from Wollmann, Calvo, & Burg (2009) for the mountain basin.

Groundwater basins and aquifers

This case study uses the coupled CWatM-Modflow model to account for the interface between surface and groundwater hydrology and groundwater dynamics (Guillaumot et al., 2022). The Ayalon River basin lies above two principal groundwater aquifers. The west mountain aquifer is part of the larger Yarkon-Taninim aquifer system and has two partially separated sub-aquifers reaching a thickness of 600 meters. It comprises carbonate sedimentary rocks and has a relatively high but non-homogenous hydraulic conductivity (Wollmann, Calvo, & Burg, 2009). The slopes of the West Judea mountains function as recharge zones, and the top layers in the Western

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foothills are made of chalk and marl and act as an aquitard, confining the Western Mountain aquifer (see Figure A1). To the west, the relatively shallow Coastal aquifer (thickness up to 200 meters) mixes a sandstone aquifer with clay lens, resulting in varying hydraulic conductivity (Melloul, Albert, & Collin, 2006). Data on groundwater abstraction volumes and locations, as well as the water table changes, was unavailable.

Reservoirs

We have manually identified and digitized reservoirs in the Ayalon basin using multiple data sources, including georeferenced aerial photography, visual inspection of satellite imagery, fieldwork, and interviews with local water management experts. The biggest reservoir in the Ayalon basin is Mishmar Ayalon (7.5 MCM; Figure 2), a seasonal water storage fed by the upstream section of the Ayalon River and regulates downstream flows. The Natuf reservoir is located on a prior quarry site northeast of the basin (4.3 MCM) and contributes to groundwater recharge. Four smaller reservoirs constitute the wastewater irrigation infrastructure and have a total designed storage of 634,200 m^3. This reclamation system extends beyond the basin's borders, for which we account by exporting a fraction of the treated wastewater.

Wastewater in the Ayalon basin

Two primary wastewater treatment plants collect wastewater generated in the main cities, and small-scale treatment plants collect those generated in the rural sector. The *Shafdan* WWTP treats all wastewater generated in the Tel Aviv-Jaffa metropolitan area in the adjacent Sorek basin, which is out of the scope of this analysis. Later, they were exported to the North-Western Negev for irrigation purposes (Fridman et al., 2021). The Ayalon WWTP is the most significant facility in the basin, with a daily capacity of 81,000 m^3. It collects treated wastewater from the cities of Lod and Modi'in (see Figure 2) and their surroundings. An extensive treatment plant has been in place since 1995, but development and population growth have exceeded its capacity, increasing sewer discharge frequency into the stream. An intensive activated sludge treatment plant with a daily capacity of 54,000 m^3 started operating in 2003. Its capacity was increased in 2019. Almost ten small-scale wastewater treatment plants in the Ayalon basin are treating sewers at a settlement scale with a total daily capacity of 12,298 m^3.

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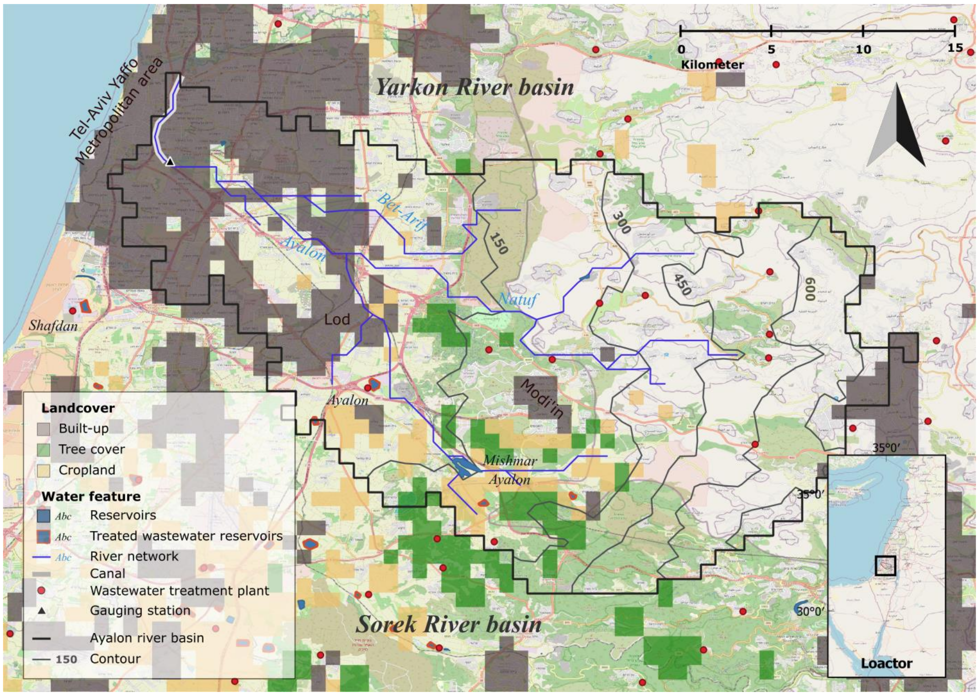

Figure 2: the Ayalon River basin case study: land cover and major water features. Partially uses data from © OpenStreetMap contributors 2022. Distributed under the Open Data Commons Open Database License (ODbL) v1.0.

3.2. Setting modeling scenarios and model parameters

In this analysis, we simulate the Ayalon basin hydrology and wastewater treatment and reclamation under different scenarios, aiming to explore the effects of the wastewater treatment module's different modes of operation on model calibration and basin-scale water resource management. Table 2 describes the four scenarios. We use scenario S2 for model calibration, which resulted in an urban runoff collection share of 46% of the urban runoff. We explore two different reclamation schemes, using a buffer of four grid cells around the reservoirs (S2) or predefined reclamation zones (S3).

Table 2: Description of scenarios and features

Scenario	Wastewater treatment	Urban runoff collection share	Wastewater reclamation
S0: No wastewater	Off	0%	-
S1: No urban runoff collection	On	0%	Irrigation around reclamation reservoirs
S2: With urban runoff collection	On	46%	Irrigation around reclamation reservoirs
S3: Extended irrigation	On	46%	Irrigation in pre-determined reclamation areas

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Additional parameters used for calibration are associated with evapotranspiration rates of irrigated croplands and grassland, soil depth adjustment, within grid-cell soil moisture spatial distribution, soil hydraulic conductivity and water content at saturation, Manning's roughness coefficient, riverbed exchange rate, urban evaporation coefficient, and urban infiltration coefficient. The emphasis on the urban landscape is due to the relatively high share of built-up areas in the Ayalon basin (see Figure 2).

4. Results

4.1. Model validation

We have calibrated the Ayalon case study against the daily average discharge at the Ayalon-Ezra gauging station (34.794° E, 32.04° N; Figure 2) over the period January 1st, 2003, to July 30th, 2010, and validated over the period August 1st, 2010 to December 31st, 2019. We have also compared the simulated evapotranspiration with a satellite-derived product (Mu, Maosheng, Running, & Numerical Terradynamic Simulation Group, 2014) and the simulated monthly influent flows into the Ayalon WWTP with observed data between 2016 -2019 (Ayalon Cities Association, 2021).

The simulation reproduces daily discharge in the Ayalon basin with a KGE of 0.69 and NSE of 0.74. Both validation periods perform relatively well, showing a slight decrease in performance in the latest period ($KGE_{2010-2014}$ = 0.67, $KGE_{2015-2019}$ = 0.5). The mean observed and simulated discharge at the outlet are 0.81 and 0.89 $m^3 s^{-1}$ (see Table 3), respectively. The average simulated discharge is slightly higher than the observations, but the opposite occurs during high-flow days (Figure 3).

Regarding evapotranspiration, both the observed and simulated data show clear seasonal patterns, where evapotranspiration is high during the summer, demonstrating overall steady interannual levels (see Figure B1). The model overestimates the evapotranspiration during the late spring and early summer (April – June), presumably due to the under-representation of plant mortality in unmanaged open areas (represented as grassland in the model). Nevertheless, during mid-summer, simulated evapotranspiration is higher than the observations. Evaluating for model performance results in a relatively low KGE (0.33) and NSE (0.35).

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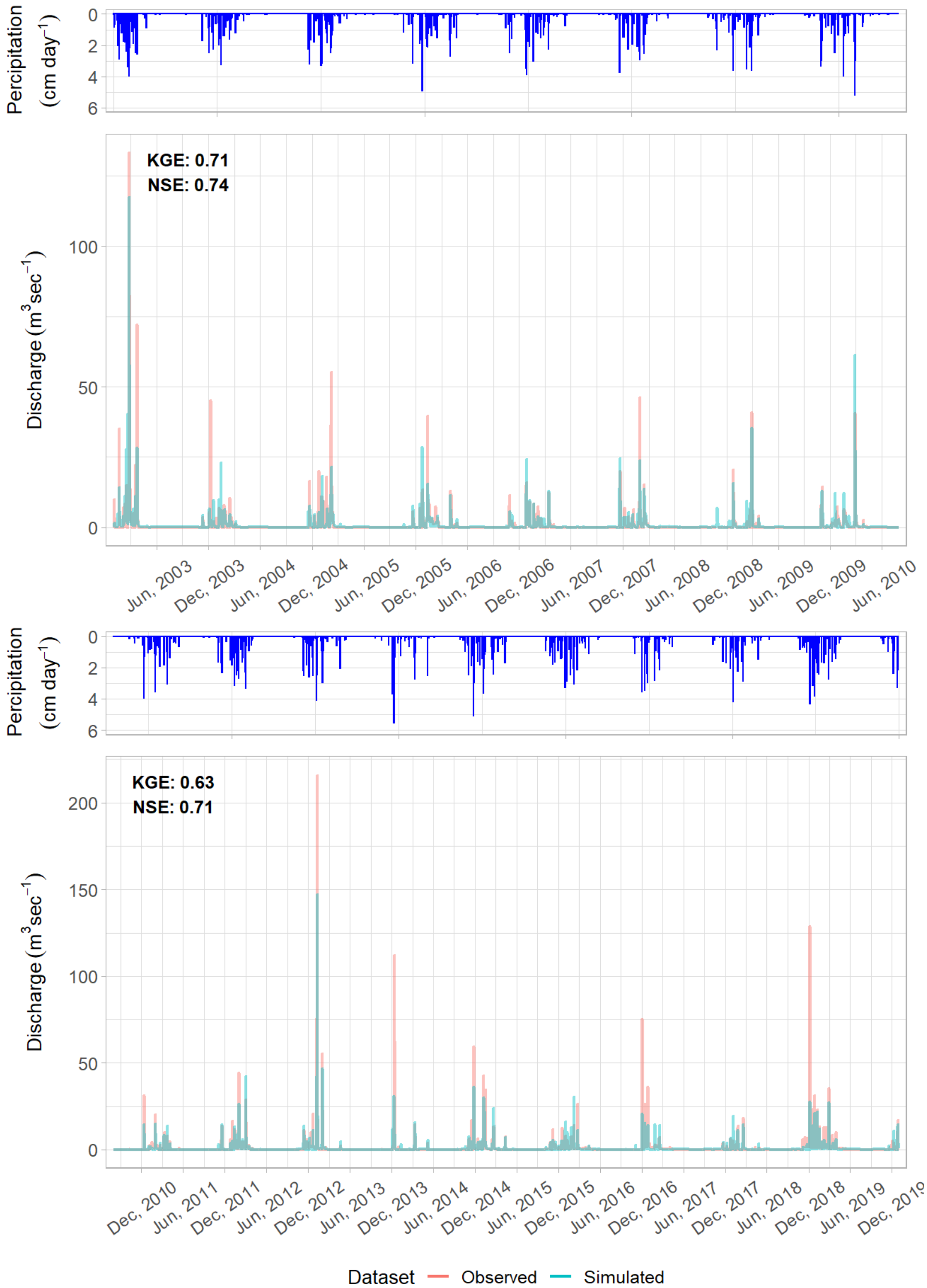

Figure 3: comparison of the observed and simulated discharge at the outlet during the calibration and validation periods.

Modeling the intermittent Ayalon River case study is challenging, mainly due to its arid climate and small basin area. Under these conditions, even a low deviation in the absolute simulated discharge results in a high relative error. It follows that diverting return flows (i.e., sewers) away from the river was a crucial step in the Ayalon model calibration. Introducing wastewater treatment and reclamation into CWatM enables the simulation of actual water dynamics in the Ayalon basin, resulting in a better-performing model. The KGE values of scenarios S0-S3 are -1.13, 0.25, 0.61, and 0.62, and the percentage differences between the simulated and observed average discharge are 201%, 60%, 9.8%, and 7.5%, respectively (see Table 3). The improvement from including the wastewater treatment and reclamation module (scenario S1) is associated with reducing the dry season's baseflow from an average of 1.21 $m^3 s^{-1}$ to 0.15 $m^3 s^{-1}$. The effects of urban runoff collection were mainly evident in the wet season's discharge, which was reduced from an average of 2.46 $m^3 s^{-1}$ (scenario S1) to 1.67 $m^3 s^{-1}$ (scenario S2). The collection of urban runoff into the sewer systems reduces flows downstream to urban areas and allows for the capture, to some extent, of the inflow dynamics into the Ayalon wastewater treatment plant (see Figure 5). Finally, the extended irrigation in scenario S3 results in reduced discharge of treated wastewater into the river channel and improved model performance.

Table 3: Model performance under different scenarios

Scenario	KGE	NSE	Annual mean discharge (% relative to observed)	Dry season's mean discharge (% relative to observed)	Wet season's mean discharge (% relative to observed)
Observed	-	-	0.81 ± 4.9 (-)	0.04 ± 0.38 (-)	1.59 ± 6.9 (-)
S0: No wastewater	-1.13	0.59	2.44 ± 5.2 (201%)	1.21 ± 0.61 (2900%)	3.68 ± 7.1 (131%)
S1: No urban runoff collection	0.25	0.64	1.3 ± 5.06 (60%)	0.15 ± 0.56 (275%)	2.46 ± 6.9 (55%)
S2: With urban runoff collection	0.61	0.7	0.89 ± 3.87 (9.8%)	0.12 ± 0.36 (200%)	1.67 ± 5.35 (5%)
S3: Extended irrigation	0.62	0.7	0.87 ± 3.87 (7.4%)	0.1 ± 0.35 (150%)	1.65 ± 5.35 (3.7%)

4.2. Component and flows of the wastewater module

The wastewater flows between the different model components are illustrated in Figure 4 using the water circle concept (Smilovic et al., 2024). Wastewater treatment plants' inflows consist of domestic or industrial wastewater and are optionally combined with urban runoff (e.g., in dual-purpose urban drainage systems). In the Ayalon basin case study, the largest share (66%) of the influents is being treated in the *Shafdan* WWTP outside of the basin of interest (i.e., Sewer exported; see also Figure 2), and approximately 16% are sent to reclamation reservoirs from local treatment plants. The remaining share includes the discharge of treated wastewater (6%) and sewer overflow (6%).

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In Israel, treated wastewater is operated separately from potable water, and reclamation reservoirs do not receive stream inflows; instead, they only store treated wastewater. Roughly half the reservoirs' inflows in the Ayalon basin are of treated wastewater. A large share of the total inflows is lost to evaporation, and approximately 6% is reclaimed for irrigation.

According to the second scenario (S2), the Ayalon basin water supply heavily relies on groundwater abstraction (50%) and desalinated seawater (48%). In comparison, wastewater reclamation only plays a minor role (approximately 2% of the water use). Nevertheless, treated wastewater satisfies about 26% of the basin's effective irrigation. Wastewater reclamation in other basins also relies on sewers generated in the Ayalon basin, as all the sewers of the Tel-Aviv metropolitan areas are treated in the *Shafdan* WWTP and used for irrigation in the South of Israel (Fridman et al., 2021).

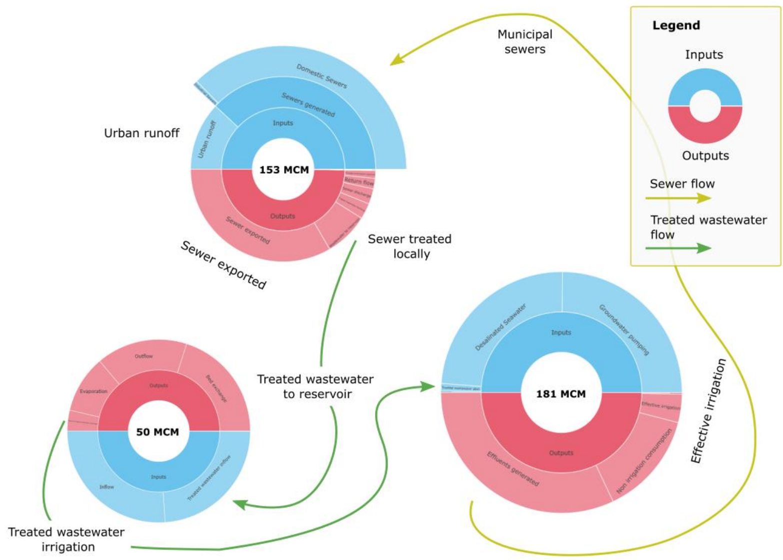

Figure 4: Average annual sewer and treated wastewater flows within and between CWatM modules, based on a simulation for the Ayalon River Basin, Israel, from 1/1/2001 -31/12/2010.

4.3. Modelling wastewater and urban stormwater collection systems

CWatM supports two main hydrological processes of urban areas, namely surface runoff and return flows (e.g., sewer discharge). Managing these flows utilized either separated or combined collection and drainage systems. In Israel, two separate systems operate to collect urban wastewater and stormwater. However, stormwater leakage into the sewers frequently occurs due to illegal connections of urban drainage to the sewers.

The runoff collection coefficient allows the user to control the magnitude of systems integration. One combined system would have a coefficient of one, implying all urban runoff flows into the sewers collection system, and a coefficient of zero suggests two completely separated systems. The calibrated model ended up with a coefficient of 0.46, implying that 46% of urban runoff flows into the sewers.

Although the runoff collection coefficient significantly increased model performance, it may lead to slightly overestimating the discharge. Validating the model against wastewater collection data for the Ayalon WWTP also

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supports the notion that the runoff collection coefficient should have been lower. On average, between 2016 and 2019, the Ayalon WWTP accepted 1,780 +/- 85 thousand m^3 sewers every month. The average inflows in the scenarios without and with urban runoff collection are 1,562 +/- 119 and 1,682 +/- 195 thousand m^3 per month, respectively. Overall, the model underestimates the inflow to the Ayalon WWTP, as shown in the top panel of Figure 5, during the dry months (e.g., April to June). The monthly variation of inflows is partially captured (bottom panel of Figure 5), yet irregularities are missed (e.g., May to August 2017) since water demand inputs into the model are annual.

Rain events during the wet season often result in increased inflows into the wastewater treatment plants (e.g., during December 2016 or January 2018). This increase is only visible in scenarios that include urban runoff collection. The calibrated model overestimates peak flows (see Figure 5 bottom panel), implying that a lower urban runoff collection coefficient is required.

Figure 5: Observed VS. simulated monthly wastewater inflows into the Ayalon WWTP with and without urban runoff collection using absolute values (top chart) and annually detrended values (bottom chart).

4.4. Modelling wastewater reclamation

Wastewater treatment and reclamation may significantly affect water management, particularly for complex water resource systems in water-scarce countries. Israel is a water-scarce country that reclaims wastewater, utilizes desalination water, and transfers water between river basins to mitigate water stress. As Israel manages water nationally, analyzing water resources on a basin scale aligns differently from Israel's actual state of water resources. Instead, the following scenarios aim to illustrate the relevance of the WRTM module to water resource management, as it can be applied to one or multiple basins.

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Table 4 summarizes the annual average key water sources and uses across the four scenarios. On average, the annual total natural and alternative water use in the Ayalon basin is estimated at 89 million cubic meters (MCM), of which almost 7.5% is used for irrigation (6.6 MCM).

Table 4: Key indicators of water use and supply for all four scenarios (annual average in the Ayalon basin between 1/1/2001 to 31/12/2019)

Variable	S0	S1	S2	S3
Irrigation consumption (MCM)	6.6	6.6	6.6	6.6
Treated wastewater irrigation (MCM)	0	1.7	1.8	3.7
Treated wastewater irrigation (exported; MCM)	0	39	51.1	51.1
Groundwater pumping (MCM)	49.4	48.6	48.6	46.7
Sea desalination (MCM)	38.9	38.9	38.9	38.9
Total natural and alternative water (MCM)	88.3	89.3	89.3	89.3
Share treated wastewater irrigation (%)	0%	26%	27%	56%
Share treated wastewater of total natural and alternative water (%)	0%	2%	2%	4%

Note: Total natural and alternative water includes groundwater pumping, sea desalination, and treated wastewater irrigation. Wastewater used outside the basin is excluded.

The water supply in the Ayalon basin heavily relies on desalination and groundwater pumping, accounting for 96% -98% of the total water use across all scenarios. Considering only irrigation water, wastewater reclamation satisfies 26% to 56% of the basin scale withdrawal for irrigation, depending on scenarios. Introducing wastewater reclamation into CWatM was initially based on irrigation buffer; irrigation with reclaimed wastewater is allowed within a fixed distance from the reservoirs. In the 'extended irrigation' scenario (S3), the reservoirs are linked with designated command areas, which reduces the overlap between irrigation areas and increases the irrigation water withdrawn from each reservoir. Under this scenario, wastewater reclamation accounts for 56% of the total irrigation and 4% of the total water withdrawal. Reclaimed wastewater as an alternative source for crop irrigation reduces the pressure on the groundwater resources by 1.6% – 5.5%, as groundwater pumping reduces from 49.9 MCM to 46.7 MCM in scenario S3, relative to the baseline scenario. In practice, the total volume of wastewater reclamation is much higher since approximately 51 MCM of wastewater is collected in the Ayalon basin, treated in the nearby *Shafdan* WWTP (in a nearby basin), and reclaimed for irrigation approximately 80 kilometers southwards.

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5. Discussion

Wastewater treatment and reclamation play a crucial role in the hydrological modeling of urban watersheds, especially in low-discharge/intermittent rivers.

Discharges from wastewater treatment plants often dominate urban watersheds' hydrological signals, increasing low-flows, flashiness, and the frequency of medium and high-flow events (Coxon et al., 2024). The effect of wastewater on stream hydrological signals would become more pronounced in intermittent streams, challenging model calibration. Acknowledging this fact, one may compromise on model performance in urban watersheds, yet including wastewater treatment and reclamation in the modeling allows for increased model performance as it better represents local water management processes. The example provided in this paper demonstrates this point by showing a significant increase in model performance due to including wastewater treatment and reclamation in the modeling.

To our knowledge, only a few existing hydrological models account for wastewater treatment and reclamation. Dyn-Qual, for example, simplifies the treatment process and only allows for indirect reclamation, i.e., treated water is discharged into rivers and can be abstracted downstream. SWAT model represents wastewater treatment by including pit latrines, yet both models focus on the water quality and missing critical operations associated with water quantity (e.g., supplying treated wastewater directly to reservoirs or fields). Although addressing the highly relevant topic of water quality, the representation of wastewater processes in these two models would not contribute to model calibration in urban or intermittent watersheds.

The importance of including wastewater treatment and reclamation in hyper-resolution (i.e., ~1km) hydrological modeling is also aligned with recent findings, as these models are susceptible to the effects of human activity on the water cycle and often require better representation of these processes and more precise data (Hanasaki et al., 2022). The Ayalon case study relies on local knowledge and data to better represent the in-situ water process and human intervention in the water cycle, which is further emphasized by the inclusion of local knowledge about the leakage of urban stormwater into the sewer collection system (scenario S2), and more accurate data covering the actual command-areas utilizing treated wastewater (scenario S3).

The wastewater treatment module is designed to foster synergies across multiple model features to better represent the human dimension of the water cycle.

The community water model (CWatM) development is an ongoing effort to provide open-source and readily available modeling tools for basin-scale and large-scale hydrological simulation, and it focuses on the complex and diverse set of interactions between human and water systems. The WRTM development relied significantly on currently available and developing model features. It follows that the case study described in this paper uses three additional water management options and can potentially utilize others. CWatM's soruce-sector abstraction fraction and reservoir operation options play a pivotal role in modeling the treated wastewater reclamation. The scope of the WTRM includes wastewater generation, collection, treatment, and discharge into a channel or reservoir. Reclamation occurs as a part of the model's water demand routine when channel water is pumped downstream to the treatment plant discharge point or treated wastewater from a reservoir is used to satisfy water demand in their surroundings.

Defining reservoirs' command areas that represent, for example, the irrigation areas served by each modeled reservoir allows higher control over the simulated reclamation. As a result, the model can better utilize the existing treated wastewater stock by avoiding overlaps between command areas. Using the source-sector abstraction fraction option also enables significant control over potential water use by defining the potential water mix of different sectors (e.g., irrigation or industrial). For example, defining the irrigation abstraction fraction of treated wastewater to 100% enables water demand to be fully satisfied by treated wastewater in case a sufficient volume of water is available. The treated wastewater in the Ayalon case study is used for crop irrigation, urban landscape irrigation, and thermal power plant cooling. As data on water demand for urban landscape irrigation and thermal power plant cooling was unavailable, this paper only accounts for reclamation by irrigation.

While relying mainly on existing model processes, representing the water supply networks in the Ayalon case study required additional development. Water distribution in Israel is pursued via two separate distribution networks for freshwater and reclaimed water. To account for this, an off-stream-network reservoir was introduced to CWatM (also called a type-4 reservoir). The inflows into this reservoir consist only of water transfers, and the outflows are limited to abstraction and evaporation losses. The water levels in these reservoirs are not affected directly by river flows and runoff, and they can maintain a traceable stock of treated wastewater over the long run.

The flexibility in the module design is a key concept for developing versatile LHM, that is fit for both continental and global simulations and hyper-resolution local simulations. It also allows for the adjustment of modeling practices to data availability.

The Community Water Model, as well as other large-scale hydrological models (Hanasaki et al., 2022; Hoch et al., 2023), is shifting towards a multi-resolution modeling framework, allowing users to work on a global scale with coarser resolutions and on a local scale with higher resolutions. As shown in this paper (as well as in Hanasaki et al., 2022), higher (or hyper-) resolution hydrological modeling requires better data and representation of the crucial process in the area of interest as the representation of this process may still be necessary at larger scales (e.g., continental, global), such data may not be fully available. To address this issue, the development of the WRTM adopted a modular approach, allowing modeling with minimal data requirements at higher scales and coarser resolutions but providing additional features to improve the simulation, which can be triggered if data exists. This is demonstrated by the already significant improvement in model performance due to simply including wastewater treatment and reclamation (scenario S1), whereas additional, but relatively smaller, improvements are associated with the inclusion of local knowledge used for triggering optional model features. The use of local knowledge and data is not restricted only to urban stormwater leakage or better representing the irrigation command areas but also to represent the increased capacity and change of treatment technology in the main WWTP (Ayalon) in the river basin. At the current development stage, the optional features include the possibility to restrict wastewater influents into specific plants (e.g., setting separated treatment plants for industrial sewers), export a fixed share of the treated wastewater, allowing leakage from the urban stormwater management system to the wastewater collection system, and provide increased operational capacity to handle peak flows (e.g., with the minimum HRT parameter).

6. Conclusions

The recent progress of large-scale hydrological models toward hyper-resolution requires a better representation of local processes and data. The representation of wastewater treatment and reclamation remains a gap across

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most models, and it has significant implications for model performance in intermittent rivers and urban watersheds.

This paper introduces a novel wastewater treatment and reclamation model development within a large-scale multi-resolution hydrological model. It demonstrates its added value in terms of enhanced model performance and the inclusion of essential processes, such as wastewater reclamation. Further, it introduces a recommended development framework that relies on a diverse set of existing features and aims to achieve high flexibility, so it is less restricted by data availability and can be easily customized to different spatial resolutions.

As wastewater is naturally associated with water quality, this aspect remains a limitation within the scope of the current development and will be addressed in future developments. The module can benefit from forming a global dataset and additional wastewater treatment technologies.

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7. Appendices

Appendix A

Figure A1 describes the vertical and lateral permeability of the YARTAN and coastal aquifers in Israel. The coastal aquifer forms a relatively narrow stripe stretching North to the South. Next, the western mountain aquifer is located towards the east, showing a relatively diverse permeability. The YARTAN groundwater basin includes the western mountain aquifer but extends far beyond the borders of the Ayalon River basin.

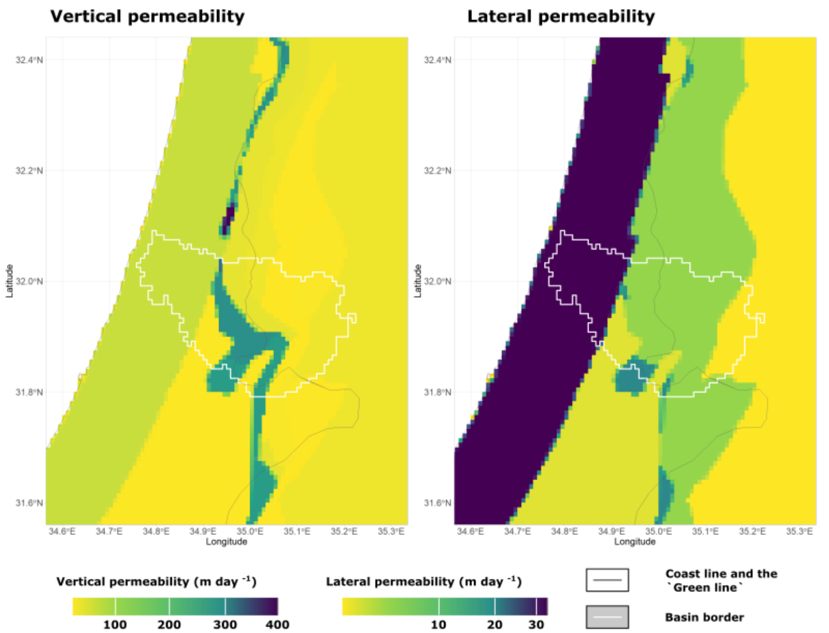

Figure A1: Vertical and lateral permeability in the YARTAN and Coastal aquifers in the Ayalon basin and its surroundings.

Appendix B

Figure B1 compares the simulated evapotranspiration with observed data derived from the MODIS sensor.

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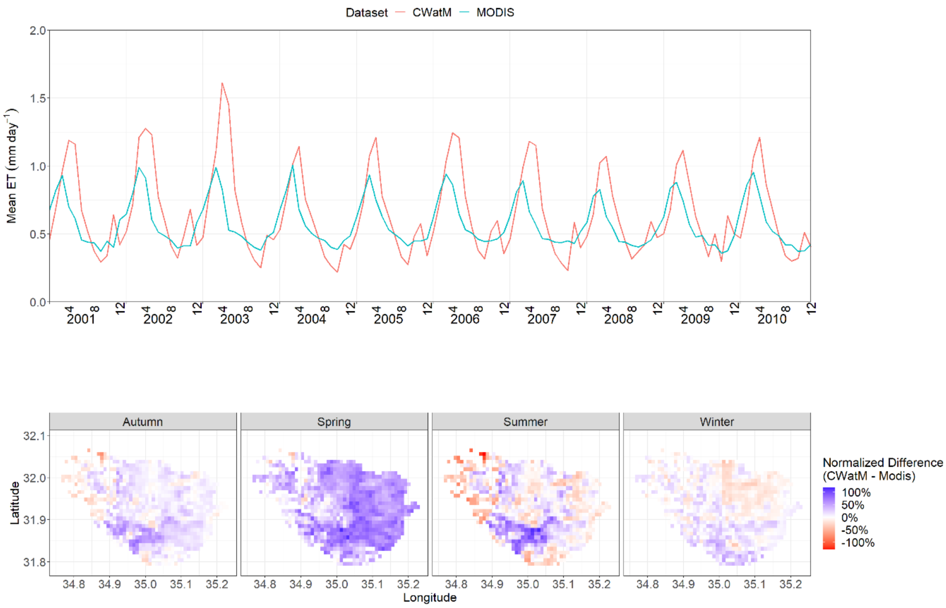

Figure B1: Comparing observed and simulated monthly terrestrial evapotranspiration (top) and seasonal gridded normalized difference for 2005.

8. Code and Data Availability

CwatM source code is publicly available on GitHub under the following repository: https://github.com/iiasa/CWatM; the most recent version is currently available under the development branch and will be included in the next public release.

The data used for this case study is available at: https://zenodo.org/doi/10.5281/zenodo.12752966, and the model used for running the simulations had some additional modifications for the Israel case study and can be found at: https://github.com/dof1985/CWatM-Israel.

9. Author contributions

DF, MS, and PB developed the module code (Wastewater treatment and reclamation), and prepared model input and observation datasets. DF, MS, and PB have prepared model inputs. DF performed the simulations and associated post-processing, and prepared the paper with contributions from MS, PB, ST, and TK. MS, ST, and TK acquired the funding and were in charge of project administration and supervision.

10. Competing interests

The contact author has declared that none of the authors has any competing interests.

11. Disclaimer

Any opinions, findings, and conclusions or recommendations expressed in this material do not necessarily reflect the views of the funding organizations..

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