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 vital for enhancing water use efficiency and ensuring reliable water availability. Wastewater also significantly influences hydrological dynamics within urban watersheds. Although hydrological modeling has advanced to capture human-water interactions, large-scale and multi-resolution models often lack comprehensive integration of wastewater treatment and reclamation processes. This paper presents the new modular 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 improves model performance by better-representing low- and peak-flows during the dry and wet seasons. It allows for representing wastewater reuse in different sectors and exploring different measures for increasing wastewater reclamation, and its effects on the water stress. Modeling of wastewater treatment and reclamation is relevant for other world regions with similar climates or urbanization patterns, or those promoting wastewater reuse policies. The wastewater treatment and reclamation module is able to scale-up by minimizing the data requirments through a simplified workflows. Combined with the availability of recent datasets of wastewater treatment plants and processes, a global application of the module is feasible. 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.

~~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.~~

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.

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~~WTRM)

The wastewater treatment and reclamation module (~~WRTM~~WTRM) enhances the capacity of CWatM to simulate the human-water interface at ~~hyper~~high ~~-~~spatial resolution. It introduces wastewater generation, collection, treatment, discharge, storage, and reclamation to CWatM. Large scale modeling shall utilize the basic setup of the WTRM for which sufficient data is available globally. Case studies for which data availability is higher, may benefit from a set of optional advanced function. The following section disntiguishes between basic and advanced (optional) functionalities. ~~-~~Figure 1~~Figure 1~~A demonstrates ~~WRTM~~WTRM workflow, ~~and~~ split into three sub-~~modules~~processes: (1) pre-treatment; (2) treatment; (3) post-treatment.

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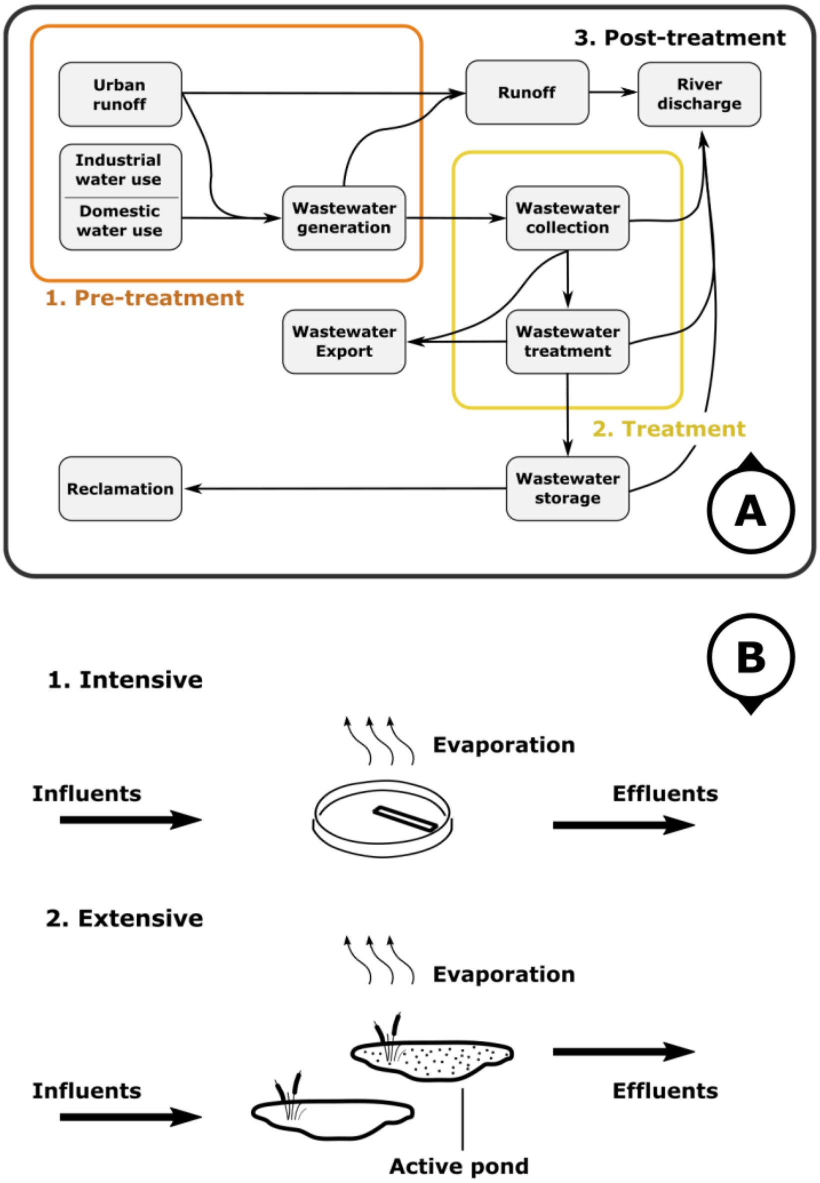

Figure 1: (A) Workflow of the Wastewater Treatment and Reclamation Module, and (B) the main processes and flows in intensive and extensive wastewater treatment systems.

2.2.1. Pre-treatment: wastewater generation and collection

Wastewater generation in CWatM is represented by non-irrigation return flows, which are a function of water availability and allocation scheme, and the ratio between the consumptive and total water withdrawal. The wastewater module estimates domestic and industrial wastewater generation (Eff^{Dom} and Eff^{Ind}) by multiplying the non-irrigation return flows by the realtive sectoral water demand. The next step is wastewater collection and supply into wastewater treatment plants (WWTP) (see Equation 1).
~~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 (~~$\cancel{Eff^{Dom}}$ ~~and~~ $\cancel{Eff^{Ind}}$~~), 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.

WWTP service areas are model input that defines the linkages between location of wastewater generation (individual grid cells, denoted by l) to wastewater treatment plants (denoted by j). Wastewater collection is also a function of the sewer connection rate (Cs_l; where a value of one indicates all wastewater is collected and sent to a WWTP), and can include urban runoff (Rf_l), due to leakage or integrtation of the urban stormwater and wastewater systems. The α coefficient defines the level of systems' integration and ranges between zero (no integration) to one (complete systems-integratuion). The total wastewater collected in all grid cells l associated with a WWTP j are registered as the treatement plant's inflow.

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Modelling sector-specific WWTP (e.g., treatment of only industrial wastewater) is an advanced model functionality, ~~Setting up wastewater treatment plants (WWTP) allows for collecting and treating wastewater from different sectors~~and to-date does not fit a global application. It uses ~~using~~ a ~~logical~~ boolean variable (e.g., D^{Dom}), which equales one if the treatment plant recieves a specific wastewater stream (e.g., domestic). A default value of one for both sectors is set in place, in case of missing data. ~~variable (e.g.,~~ $\cancel{D^{Dom}}$~~). 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: Influent, evaporation and effluent

~~The treatment phase starts with the collection of influents to WWTP. User-defined collection areas and efficiencies guide this process (see Equation 1).~~ Simulated ~~W~~wastewater treatment plants ~~can~~ must have the following basic features: location, start year of operation, daily treatment capacity, treatment period (days), and outflow location.
~~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~~ which is associated with ~~by~~ the ~~hydraulic retention~~treatment period ~~time~~. The two options are intensive and extensive treatment plants, as described in Figure 1~~Figure 1~~b. Intensive treatment refers to the conventional wastewater treatment technology charcterized by low residence time and low area requirements. It usually treats water to secondary or tertiary level over less than 24 hours (Pescod, 1992). ~~HRT of intensive WWTP usually does not exceed 24 hours,~~ As CWatM uses a daily timestep, the intensive treatment plant's treatment period is set to one day. Any WWTP with a longer treatment period (i.e., >= 2 days) would be classified as extensive. Extensive treatment refers to natural biological systems, consist of a short primary treatment in a relatively deep anaerobic pond, followed by a longer residence time (20 -40 days) in a shallow facultative pond for secondary treatment (Pescod, 1992). ~~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).~~

An advanced model feature enables exceeding the WWTP daily capacity, by temporarily reducing the hydrological retention time (HRT). This feature is enabled by setting a treatment plant specific minimally allowed HRT, providing WWTP some buffer to handle days with extreme inflows, e.g. due to rain events. Another advanced option is to simualte WWTP closure or upgrades by providing an end-year of operation to a WWTP instance.

~~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).~~

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

Influent inflows

According to the basic model setup, ~~If daily~~ excess ~~influent~~ wastewater ~~exceeds~~ beyond the plant's daily treatment capacity is discharged to the pre-defined outflow location. However, the model holds advanced modelling capabilities enabling higher WWTP to accept larger inflows to handle temporal fluctioations (e.g., due to significant rain events). Inflows higher that the designed capacity shortens the hydrological retention time (HRT, or residence time), resulting in less effective wastewater treatment. The designed retention time is calculated as $HRT_j^{Design} = Volume_j / Inflow_j^{Design}$, where $Volume_j$ is the volume of WWTP j and $Inflow_j^{Design}$ is the daily treatment capacity of WWTP j (Pescod 1992). The daily treatment capacity and treatment time (or designed HRT) are model inputs. ~~, 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

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Formatted: Font: Italic, Complex Script Font: Italic retention time a treatment plant can withstand before it refuses inflows. Following the calculation of the hydraulic 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 pool live storage.~~stored wastewater in the pool.~~

Calculating the surface area of the treatment pools is different for intensive and extensive systems. The surface area of an intensive WWTP is defined as the ratio between the plant volume and the pool depth. For that purpose, a simiplified represention of WWTP treatemnet pool is adopted based on clarifier design (used during both primary and secondary treatment; Pescod, 1992), and the pool depth is estimtaetd at 6 meters (WEF, 2005; see Figure B1). ~~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 natural biological treatment ponds, alternately filling up and treating water. These processes consist of a relatively shot anaerobic treatment in deeper ponds followed by a lonterm (20-40 days) residence in facultative shallow ponds (see Figure 1~~Figure 1~~B; also refer to Pescod, 1992). 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 1.5 meter, as the depth of a facultative pond~~one meter~~; Pescod, 1992). 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~~two; Pescod, 1992).

Effluents

Treated wastewater (effluents)~~Effluents~~ ~~can~~ are ~~be~~ either discharged, ~~exported,~~ or sent to reservoirs for reclamation. The timing of effluent release differs between intensive and extensive systems. Figure 1~~Figure 1~~B shows the main differences between these two types of systems. In intensive systems, influents remain in the treatment plant ~~during~~ throughout 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*.

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~~In an e~~Extensive systems~~,~~ ~~we~~ differentiate between two types of treatment ponds. At each time, there is one treatment pond that receives all inflows, and the other pond is either full or empty~~.~~ Ponds that do not receive inflows and are not empty are considered 'active',~~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., in which ~~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 that had gone through the longest treatment time~~with the longest retention time~~, though they may not be fully treated.

2.2.3. Post-treatment

The basic module has ~~three~~ two post-treatment ~~possibilities~~options: 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.~~

Direct r~~R~~eclamation (e.g., for irrigation purposes) ~~generally occurs~~ is possbile by using CWatM~~the~~ reservoirs operation through the water demand module. This option requires data on the linkages between WWTP and reservoirs. ~~, so treated wastewater is sent to reservoirs that manage water use.~~ The ~~module~~ routine iterates over the list of WWTP-Reservoir links~~all treatment plants~~ and attempts to send treated wastewater to associated reservoirs. In the case of multiple recieving reservoirs, the water are split~~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~~ access water are discharged~~s the remaining water in~~ on~~a~~ predefined ~~discharge~~ outflow locations. Discharge into streams/rivers 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~~ are ~~be~~ discharged if a plant's inflows exceed the plant's peak capacity (see minimally allowed HRT in section 2.2.2~~2.2.2~~).

T~~t~~reated 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.

~~This module provides multiple wastewater storage, conveyance, and reclamation modeling options. For example,~~Indirect reclamation ~~one~~ can be simulated ~~the discharge and dilution of treated wastewater into an~~ by releasing the water into a ~~upstream~~ channel, upstream to a lift area in which river water are abstracted and used, or into a reservoir that is linked to the river network, where effluents are mixed with fresh water. ~~, 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.~~

The module is designed to allow inter-basin transfers of wastewater or treated wastewater, yet this advanced option is not required in the case of a global model. Interbasin transfer of treated wastewater aims to account for cases in which the reclamation areas extends beyond the borders of the simualted river basin. In that case, an WWTP-specific export-share parameters indicate the daily fixed percent of treated wastewater that is transffered for recalamation in other basins. The interbasin transfer of un-treated wastewater represent cases in which treated wastewater collected in one basin are treated in another basin. It occurrs automatically in case a defined service area is not associated with any WWTP located within the simualted basin. ~~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.~~

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~~Figure 2~~). Ayalon is an urbanized river basin partially overlaying the Tel Aviv-Yaffo metropolitan 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.

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3.1. Data sources

The CWatM provides global datasets at 0.5 degree and 5 arc-minutes as described in Burek et al. (2020). This ~~hyper~~high-resolution analysis combines global and local data sources to ~~sets~~ better ~~to~~ represent the case-study hydrologic processes and human-hydrologic interactions (Hanasaki et al., 2022). Table 1~~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). A complete documentation of the dataset associated with this publication is available at https://doi.org/10.5281/zenodo.12752967.

Table 1: Model inputs from global and local datasets. Unless explicitly indicated, all datasets were resampled to 30 arc-seconds or converted to a raster format.

Input data	Spatial (temporal) resolution	Data sources and comments on data processing
Global datasets		
Meteorological forcings	0.5° grid~~;~~ (daily) Downscaling to 30 arc-seconds (multi-annual monthly average)	ISIMIP 3a, GSWP3-W5E5 (Lange, Mengel, Treu, & Büchner, 2022) WorldClim (Fick & Hijmans, 2017)
Soil	30 arc-seconds grid (fixed value)	Dai et al. (2019) Shangguan, Hengl, Jesus, Yuan, & Dai (2017)
Topography	3 arc-seconds grid (fixed value)	MERIT Digital Elevation Model (Yamazaki et al., 2017)
River network properties flow direction map	30 arc-seconds grid (fixed value)	MERIT Hydro IHU (Eilander et al., 2020)
Local/modified datasets		
Landcover maps	500 meters grid (annual)	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)
Municipal and industrial water demand	~~Municipality~~Local governement borders, polygons (annual)	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' data base: WWTP location & outflow location ~~and~~ treatment levels & years of operation ~~, collection~~ serivce areas, connection rate, and wastewater generation coefficients	~~Municipality~~ Point data (fixed value) Tabular format (by year) Local governement borders, polygons (fixed value)	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 value (annual)	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	Digitzed polygons (fixed value)~~-~~	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 Aquifer borders Aquifer properties – coastal/mountain	~~Various resolutions~~ Digitzed polygons (fixed value) Digitzed polygons (fixed value)	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 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~~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~~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.

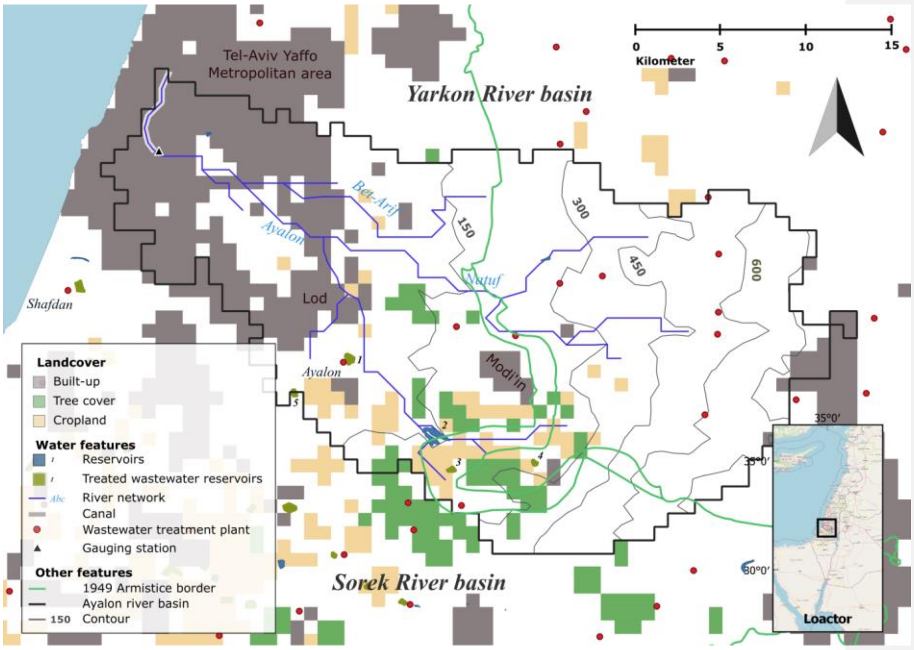

Figure 2: the Ayalon River basin case study: land cover and major water features. Partially uses data from © OpenStreetMap contributors 2022. Distributed under the Open Data Commons Open Database License (ODbL) v1.0. Marked reservoirs: (1) Ayalon; (2) Mishmar Ayalon; (3) Ta`oz; (4) Mesilat Zion; (5) Mazli'akh.

3.2. Setting ~~modeling~~ calibration scenarios and model parameters

In this analysis, we simulate the Ayalon basin hydrology and wastewater treatment and reclamation under ~~different~~ three 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. In the first scenario (S0) we disable the wastewater treatement and reclamation module. The second (S1) and third (S2) include wastewater treatment and reclamation without and with urban runoff collection, respectively. The share of urban runoff flowing into the sewers is set as a calibartion parameter in S2. Additional calibration parameters 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).

Apart from calibration scenarios, we set three more wastewater reclamation scenarios by expanding the irrigated agriculture area (by 5%) and increasing storage volume (by 5%) for two reservoirs for which command areas are defined: Ayalon and Mazlikh. One scenarion include both expansion and increased storage, and each of the two others scenarios include either expansion or increased storage.

~~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~~

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~~**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~~

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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~~Figure 2~~) over the period ~~January~~ August 1^{st}, 2001~~3~~, to July 30^{th}, 20006~~10~~, and validated over the period August 1^{st}, 20007~~10~~ to December 31^{st}, 2019. We ~~have~~ further~~also~~ compared the simulated evapotranspiration with multiple ~~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).We use the Kling-Guphta Efficiency (KGE) and Nush-Sutcliffe equilibria (NSE) coefficients to measure model performance.

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The S2 (wastewater and urban runoff collection) scenario have resulted with the ~~simulation~~ best performing model (KGE = 0.76; NSE = 0.72 during training), followed by S1 (wastewater without urban runoff collection; KGE = 0.27; NSE = 0.61), and S0 (KGE = -0.4; NSE = 0.57). ~~reproduces daily discharge in the Ayalon basin with a KGE of 0.69 and NSE of 0.74. Both~~ Model performance is lower during the validation periods ~~-~~across all scenarios. The complete implementation in S2 yields the best performing model during the validation periods ~~perform relatively well, showing a slight decrease in performance in the latest period~~ (~~KGE_{2010}~~$KGE_{2006\text{-}\cancel{2014}\,2013}$ = 0.69~~7~~, ~~KGE_{2015}~~$KGE_{2014\text{-}2019}$ = 0.55). ~~The~~ Over the complete simulation period (1995 -2019), the mean observed ~~and simulated~~ discharge at the outlet ~~are~~ is 0.81 $m^3 s^{-1}$, and it was best matched by the simulated discharge in scenario S2 ~~and~~ (0.87~~9~~ $m^3 s^{-1}$; ~~(~~see Table 2~~Table 3~~)~~, respectively~~. The full implementation scenario (S2) best matchs the observed discharge during most of the days in the dry (April-September) and the wet sesaons ~~The average simulated discharge is slightly higher than the observations, but the opposite occurs during high-flow days~~ (Figure 3~~Figure 3~~). In some occasions the model overestimates discharge, or simulates flow events during the dry period (e.g., during late April 2003, see Figure 3). This is often associated with mismatch between forcing data (e.g., precipitation) to actual precipitation (see **Error! Reference source not found.** and **Error! Reference source not found.**).

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~~Regarding~~ The simualtions were further compared with different remote-sensing derived evapotranspiration (RS-ET) time-series. All scenarios are able to capture seasonal dynamics quite well, but overestimate ET during early spring (around March-April; except from SMAP, see **Error! Reference source not found.**). The 'No wastewater' (S0) scenario highly over-estimate ET, whereas the other two (S1, S2) scenarios better aligns with the RS-ET data, particularly after 2015. There are differences between RS-ET datasets associated with process, forcings, and parameterization errors (Zhang et al., 2016); some are shown in **Error! Reference source not found.**. GLDAS v2.1 shows the lowest KGE across scenarios, and SMAP indicates the highest (see **Error! Reference source not found.**). These findings are consistent with an intercomparison of RS-ET datasets (Kim et al., 2023). Furthermore, the fitness to RS-ET time-series improves when incroporating additional features of the wastewater module across the all datasets. The average KGE is -0.68 (S0), -0.27 (S1), and -0.17 (S2).

~~, 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).~~

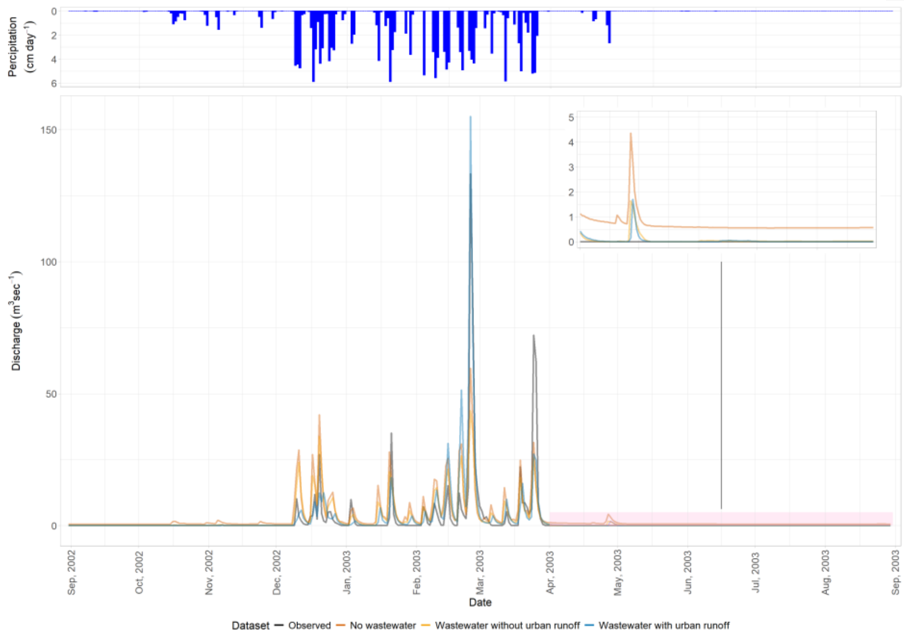

Figure 3: comparison of the observed and simulated discharge at the outlet across scenarios during ~~the~~ a selected year (September 2002 -September 2003).~~calibration and validation periods.~~

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~~ small deviation in the absolute simulated discharge results in a high relative error. It follows that diverting return flows (i.e., ~~sewers~~sewage) away from the river was a crucial step in the Ayalon model calibration. Introducing wastewater treatment and reclamation into CWatM enables ~~the~~

~~simulation~~ simulating ~~of~~ actual water dynamics in the Ayalon basin, resulting in a better-performing model. The KGE values of scenarios S0-S2~~3~~ between 1995-2019 are -0.75~~1.13~~, 0.~~25~~17, and 0.66~~1, and 0.62~~, and the percentage differences between the simulated and observed average discharge are ~~201~~162%, ~~60~~62%, and ~~9.8~~4.1%, ~~and 7.5%,~~ respectively (see Table 2~~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~~0.07 $m^3 s^{-1}$ to 0.06~~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~~53 $m^3 s^{-1}$ (scenario S1) to 1.~~67~~68 $m^3 s^{-1}$ (scenario S2). The collection of urban runoff into the sewers ~~systems~~ reduces flows downstream to urban areas and ~~allows~~ fits~~for the capture~~, to some extent, of the inflow dynamics into the Ayalon wastewater treatment plant (see Figure 5~~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 2~~3~~: Model performance under different scenarios over the complete simulation (1995 -2019). The dry season occurs during the month April-September.

Scenario	KGE (during calibration)	NSE (during calibration)	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~~ -0.75 (-0.4)	0.5~~5~~9 (0.55)	2.12~~44~~ ± 5.1~~2~~ (216~~201~~%)	~~1.21~~0.7 ± 0.~~61~~85 (~~2900~~1650%)	3.~~68~~54 ± ~~7.1~~6.92 (12~~31~~%)
S1: ~~No urban runoff collection~~Wastewater without urban runoff collection	~~0.25~~0.17 (0.27)	0.~~64~~62 (0.61)	1.3 ± ~~5.06~~4.36 (~~60~~62%)	0.~~15~~09 ± 0.65~~6~~ (~~275~~125%)	2.~~46~~53 ± ~~6~~5.9 (~~55~~59%)
S2: ~~With urban runoff collection~~Wastewater with urban runoff collection	0.~~61~~66 (0.76)	0.7 (0.72)	0.~~89~~87 ± ~~3.87~~4.1 (~~9.8~~7%)	0.~~06~~12 ± 0.~~36~~42 (~~200~~50%)	1.~~67~~68 ± 5.~~35~~67 (~~5~~6%)
~~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~~Figure 4~~ using the water circle concept, a simplified representation of the water cycle (Smilovic et al., 2024). Wastewater treatment plants' inflows mostly consist of domestic sewage~~or industrial wastewater and are optionally combined~~ mixed with urban

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runoff (e.g., in dual-purpose urban drainage systems). In the Ayalon basin case study, the largest share (~~66~~68%) of the influents is being treated in the *Shafdan* WWTP outside of the basin of interest (i.e., ~~Sewer~~ Sewage exported; also see ~~also~~ Figure 2~~Figure 2~~), and approximately ~~16~~14% are sent to reservoirs for reclamation~~reclamation reservoirs from local treatment plants~~. The remaining share includes the discharge of treated wastewater (~~6~~4%) and ~~sewer~~ raw sewage ~~overflow~~ (~~6~~8%).

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~~About 46% of the reservoirs' inflows in the Ayalon basin are of treated wastewater. A large share of the total inflows is lost to evaporation (16%), and approximately ~~6%~~8% is reclaimed for irrigation.

~~According to the second scenario (S2),~~ As shown in Figure 4, ~~t~~the Ayalon basin water supply heavily relie~~d~~s on groundwater abstraction (~~50~~96%). However, it has been slowly replaced by ~~and~~ desalinated seawater~~,~~, reaching an average share of 60% per year between 2015-2019.~~(48%)~~. In comparison, wastewater reclamation only plays a minor role (approximately 2% of the water use). Nevertheless, treated wastewater satisfies about ~~26~~10% of the basin's effective irrigation. Wastewater reclamation in other basins also relies on ~~sewers~~ sewage generated in the Ayalon basin, as all the ~~sewers~~ wastewater ~~of~~ from the Tel-Aviv metropolitan area~~s~~ ~~are~~ is treated in the *Shafdan* WWTP and used for irrigation in the South of Israel (Fridman et al., 2021).

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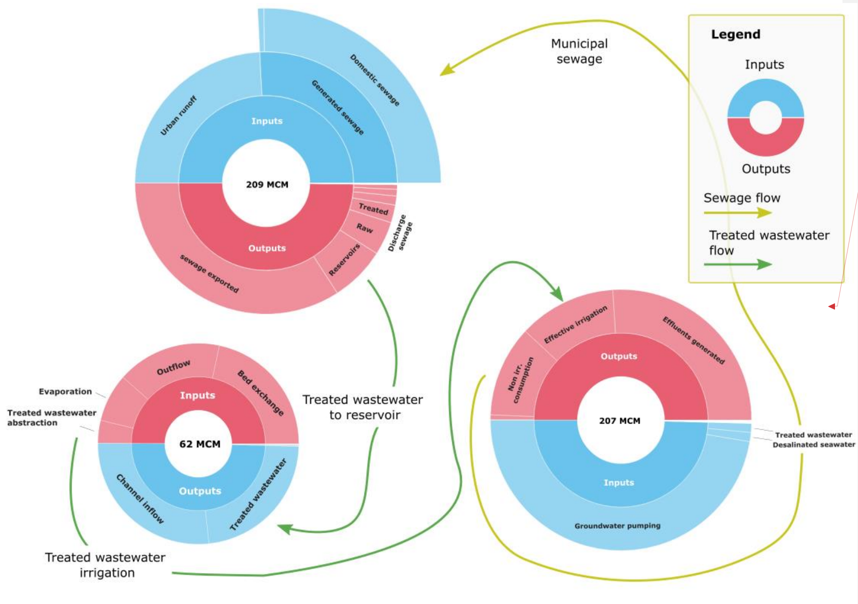

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Figure 4: Average annual ~~sewer~~ sewage and treated wastewater flows within and between CWatM modules, based on a simulation for the Ayalon River Basin, Israel, from 1/1/2001 -30~~1~~/07~~12~~/20~~1~~06.

4.3. Modelling wastewater and urban stormwater collection systems

CWatM ~~supports~~ includes two main hydrological processes ~~of~~ for urban areas:~~, namely~~ ~~surface runoff and~~ return flows (e.g., sewage~~er~~ ~~discharge~~generation) and urban runoff. ~~Managing T~~these flows ~~utilized~~ are managed by either separated or combined collection and drainage systems. In Israel, two ~~separate~~ systems are operated separately to collect urban wastewater and stormwater. However, stormwater frequently ~~leakage~~ leaks 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 0.78~~46~~, implying that ~~46~~78% of urban runoff flows into the sewers.

The advantages of the ~~Although the~~ runoff collection coefficient are shown in Figure 5, comparing the monthly inflows to the Ayalon WWTP against the simulated inflows with (S2) and without (S1) urban runoff collection. ~~significantly increased model performance, it may lead to slightly overestimating the discharge. Validating the model against wastewater collection data for the Ayalon WWTP also 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~~ 86 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~~1,699 +/- ~~195~~ 203 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~~Figure 5~~, during the dry months (e.g., April to June), which is probably due to the use of annual water withdrawal inputs, that do not capture seasonality.~~.~~ ~~The~~ In fact, seasonality is only captured by the 'Wastewater with urban runoff' (S2) scenario, as a direct result of urban runoff collection. Another factor limiting WWTP inflows is the minimally allowed HRT presented in section 2.2.2. As one percent in change in the parameter value results on average in 0.23% change in the WWTP inflows (see Supplementary Information and **Error! Reference source not found.**). ~~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 scenario that includes urban runoff collection (S2) ~~calibrated model~~ can simulate these peaks, though it slightly overestimates ~~peak flows~~theme, whereas no peaks are simualted for scenario S1 in which no urban runoff is collected (see Figure 5~~Figure 5~~ bottom panel). While it may be that the runoff collection paramters was set at value that is too high, overestimating the peak flows can also be the result of errors in precipitation data (see **Error! Reference source not found.**). The wasterwater with urban runoff collection (S2) scenario out perfromes the scenario without wastewater collection based on multiple parametrs (showing lower bias, and higher NSE and correlation; see **Error! Reference source not found.**). ~~, implying that a lower urban runoff collection coefficient is required.~~

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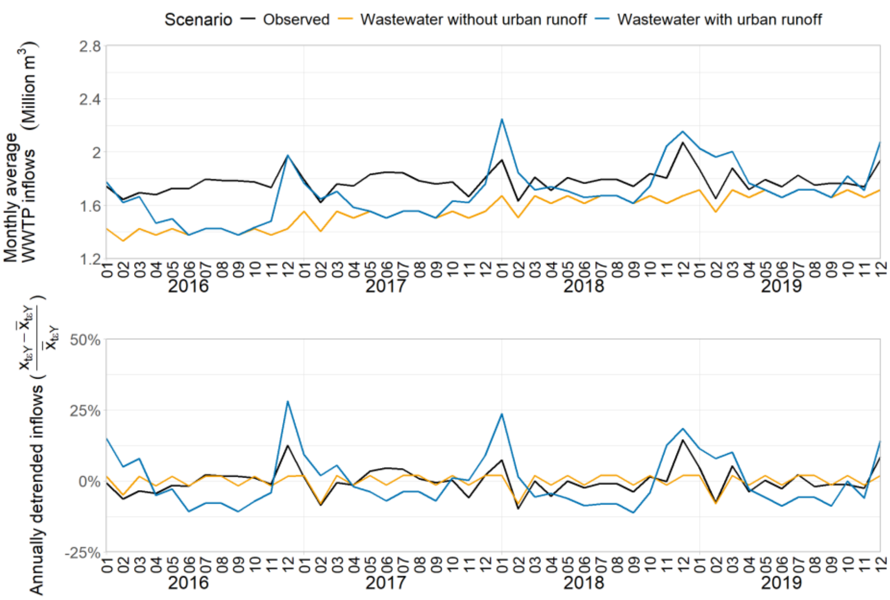

Figure 5: Observed VS. simulated monthly wastewater inflows into the Ayalon WWTP with and without urban runoff collection using absolute values (top chart) and annually detrended values (bottom chart).

4.4. Modelling of wastewater reclamation potential and impacts

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~~WTRM module to water resource management.~~, as it can be applied to one or multiple basins.~~

Until the early 2000's, the Ayalon river basin's water supply has been mostly relying on groundwater abstraction. As a result of population growth and the expansion of the Ayalon WWTP's daily treartment capacity in 2003 (from 22,000 to 54,000 m3/day), the simulated wastewater recalmation has nearly doubled increasing from 1.5 million m^3 in the year 2000 to 2.7 million m^3 in 2005. At the same year, desalinated seawater has been supplied for the first time, satisfying approximately 3% of the total water demand in the basin. Over the years, the role desalination increased accounting for around 47% of the water supply. The share of treated wastewater had slighlty increased reaching 2.7% (approximately 3 million m^3), compared with 1.5% in 2000. Most importantly, avoided groundwater pumping in 2010 further enhanced Israel's water security by reducing the pressures on aquifers, and the avoided seawater desalination reduced energy-for-water use and water production costs (Fridman et al., 2021).

Focusing on the Ayalon WWTP's reclamation projects (see **Error! Reference source not found.**), **Error! Not a valid bookmark self-reference.** presents the multiannual average aboslute and relative wastewater reclamation (for irrigation) between 2000 -2010. Overall, there is a little difference between the baseline and agricultural

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expansion scenarios, showing slight increase in the reclamation volume, but a slight decrease in the relative wastewater irrgiation (relative to irrigation demand). These findings point out a balanced propotion between storage and water demand. Small access storage is kept, allowing additional irrigation as a response to increased water requirements. The two scenarios that include increasing storage demonstrate higher wastewater reclamation volume (of 4.7% -4.9%) and relative irrigation increaseing from 17.3% to 17.8-18.1%. The share of wastewater reclmation out of the total irrigation demand increases from around 13% to 18% in 2000 and 2003 respectively, and reach almost 25% in 2006 (see **Error! Reference source not found.**). These changes are associated with an increased capcaity of the Ayalon WWTP in 2003, and with precipitation variability, e.g., lower irrgiation requirements during wet years thoiugh fixed supply of treated wastewater. As this recalmation project extends southwards, outside of the Ayalon River basin, the model also estimates further reclamation of almost 2 million m^3 (i.e., treated wastewater sent for reclamation outside of the basin). In addition, more than 50 million m^3 are collected and treated in the *Shafdan* WWTP located southwest of the Ayalon river basin (see Figure 2), and are almost entirely reclaimed.

Table 3: Average and standard deviation of the absolute and relative wastewater reclamation in the reclamation project of the Ayalon WWTP between 2000-2010.

Scenario	Wastewater reclamation, thousands m^3 (share increase relative to baseline)	Wastewater irrigation (% of total irrigation)
Wastewater and urban runoff collection (Baseline)	2,423.4±536.8 (-)	17.3±4.1%
Agricultural expansion and increased reservoir capacity	2,543.1±514.4 (4.9%)	17.7±4%
Increased reservoir capacity	2,536.7±515.3 (4.7%)	18.1±3.9%
Agricultural expansion	2,447.2±507.4 (1%)	17±4%

~~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~~

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~~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.~~

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., recalmation through ~~supplying treated wastewater directly to~~ reservoirs or directly to 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~~high-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). It follows that the WTRM complements the recent shift towards high resolution modeling at global (van Jaarsveld et al., 2024) and more local scales (e.g., CWatM implementation in Bureganland Austria; Bhima River Basin, India; North China; Guillaumot et al., 2022; Yang 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~~utilizes multiple features of CWatM, providing tools to conduct policy-relevant analysis on the topic of water resoruce mangement and wastewater treatment and reclamation. ~~designed to foster synergies across multiple model features to better represent the human dimension of the water cycle.~~

Wastewater is increasingly perceived as an untapped resource and is marked as a potential source of water to reduce water stress or drought risk. Hydrological models, such as CWatM, are often used to inform decision-making and policies for enhancing water resource management and can benefit from WTRM capabilities.

The WTRM interacts with different existing modules and routines in CWatM. The analysis described in this manuscript demonstrates such interactions with three additional processes. The source-sector abstraction fraction and reservoir operation options are pivotal in modeling the treated wastewater reclamation. The former can define the desired water mix, restricting wastewater reclamation by some sectors (e.g., forbidding households from using treated wastewater). The reservoir operations options are used during the direct reclamation.

Indirect reclamation is enabled when treated wastewater is released into a river channel or a reservoir, diluted, and is later abstracted downstream, and direct reclamation is mediated through a designated reservoir, disconnected from the river network (type-4 reservoirs). 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. Abstraction from reservoirs takes place either within a certain buffer (i.e., defined by the number of grid cells) from the reservoir or within the area of an associated command area (area served by the reservoir with regards to water supply). Combined with the source-sector abstraction fraction, the modeling of the Ayalon basin has limited the use of treated wastewater for irrigation and livestock to a smaller extent. Other existing uses, like urban landscaping or cooling of thermal powerplants, were ignored, as data was not available.

Utilizing these modules and processes, the manuscript explores the potential effects of increased storage of wastewater reclamation reservoirs and of expanding irrigated agriculture areas. It focuses on the command areas associated with two reclamation reservoirs (as indicated in **Error! Reference source not found.**), indicating a high share of irrigation with treated wastewater (~17%). The module variables could be utilized for exploring a wide variety of water management instruments, including using treated wastewater to mitigate drought risk (conveying and storing treated wastewater in high drought risk areas), to recharge the aquifer (controlling reservoir infiltration rate), or explore pathways for agricultural expansion/intensification. Wastewater reclamation can also have economic or environmental benefits. The Ayalon case study is relevant for both due to potentially avoided seawater desalination, which is more expensive and requires more energy. Economic, resource intensity, and emission data from different sources (e.g., life cycle assessments; see Liao et al., 2020; Meron et al., 2020) could complement such analysis, applying a Nexus perspective.

~~**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.**~~

Flexible model design and available global datasets provide a robust starting point for simulating wastewater treatment and reclamation scenarios at global scale and coarser resolutions. Some data gaps remain and provide opportunities for scientific engagement.

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. The need for better representing wastewater treatement and reclamation in global, regional and local hydrological modeling is linked to its increasing potential as a water resource. The WTRM provides a diverse set of tools for including wastewater treatment and reclamation into hydrological modeling. So far, the manuscript has focused on the module's advanced mode of operation, suitable for data-abundant regions, or for local case studies, where data collection efforts are feasible. Yet, applying the WTRM at coarser (e.g., 5 arc-minutes) spatial resolution globaly, or in data-scarce region, requires a simplified workflow and a global data inventory.

Following the CWatM modular and flexible structure, the WTRM was developed with that notion in mind, facilitating a simple mode of operation with minimal data requirements, but including advanced procecsses when data is available. The results presented and discussed show a significant incerase in model performance as a result of a simpler implementation of the module (i.e., without urban runoff colleciton), which together with the reclmation scenarios, point on the potential impact of upscaling the analysis to cover other urbanized watersheds, and water stressed regions. Recent development of different global datasets provide an opportunity for upscaling this analysis, though, these data would have to undertake some processing to fit CWatM data structure. Hydrowaste (Ehalt Macedo et al., 2022) is a global WWTP dataset describign plants' location, treatment level, operational status, population served, overflow discharge point, and daily capacity. It was recently used to deteremine the impact of droughts on water quality (Graham et al., 2024), and to account for the global

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microplastic fiber pollution from laundary (Wang et al., 2024). Second, Jones et al. (2021) compiled a global gridded dataset (at a 5 arc minuts resolution) describing wastewater generation volumes, and collection, treatement, and reclamation rates. The data has already been used to force global studies on water quality (2021). These two datasets provide sufficient global data at a spatial resolution of 5 arc minutes, to accommodate six out of the seven mandatory variables required to setup a simple simlation (see Table 4). However, data is lacking for the year of establishment (or start of operation) of a WWTP, which could be assumed by utlizing auxliary time-series data, like drinking water sanitation and hygiene (WASH) available from the joint monitor program (JMP, at https://washdata.org), or sectoral outputs from monetary input-output tables (e.g., https://worldmrio.com). These data could cast temporal trends of increased sanitation coverage or sectoral economic activity. Two additional challenges are indicated in Table 4, associated with the treatment days and service (wastewater collcetion) area. Following Ehalt Macedo et al. (2022), the latter can be traced back from the WWTP to serve the nearest, most likely upstream, popualtion centers. Treatment days are associated with the WWTP classification into intensive and extensive, which in turn can be associated with location and economic factor (like GDP pet capita or electirfication status). The availability of such data at national, sub-national, and grid scale, deems the classification of WWTP as intensive or extensive feasible.

As advanced simulations are not pursued globally, data sources for their requried variables are not seeked. Reclamation and reserovirs conenction are an excpetion, stemming from the large imapct of simulating reclmation on model performance and water resource management analysis. The reclamation rates estimated by Jones et al., (2022) can be used for that purpose. However, as it does not linked to any specific WWTP or reservoir, as required by the WTRM, it would require some pre-processing and simplifying assumptions. Some on-going efforts to identify potential wastewater reclamaiton for specific WWTP can support this processing (Fridman et al., 2023), yet both data sources would invlove high uncertainties at the grid scale. Two other approaches could be taken to assess different reclamation scenarios, including indirect reclamation from waterbodies (e.g., river and lakes), or simulating on-site type-4 reservoirs with command areaa set as fixed buffers. Such recalmation scenarios, could also explore reclamtion by other non-agricultural sectors.

Table 4: model variables for simple and advanced simulations, and potential data sources. Note: * indicates varaible is not available but could be concluded by utlizing auxiliary data; ** indicates variable is not available but could be estiamted based on published methods; * indicates available data is highly uncertain at grid scale, and can be used to inform scenarios.**

Model variable	Simulation mode	Description	Potential Data source
Location	Simple	Geographic location (longitude, latitude) of WWTP	Ehalt Macedo et al., 2022
From year	Simple	First year of a WWTP operation; as an advanced option one may include the last year of operation (i.e., closing of a treatment plant), or several instances (i.e., upgrade).	Not available*
Volume	Simple	Daily capacity of the WWTP in cubic meter	Ehalt Macedo et al., 2022
Treatment days	Simple	Duration of treatment in days (retention time by design), is associated to treatment technology intensive (1 days),	Ehalt Macedo et al., 2022*

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		extensive (approximately 30 days), as described in the manuscript.	
Collection (service) area	Simple	Service area of different WWTP, e.g., gridcells with water consumption which are connected to a given WWTP.	Ehalt Macedo et al., 2022**
Collection share	Simple	Share of sewage generated, collected and sent to WWTP i.e., rate of connection to WWTP.	Jones et al., 2021
Overflow	Simple	Geographic location (longitude, latitude) of the discharge point from WWTP into waterbodies (rivers, lakes, ocean).	Ehalt Macedo et al., 2022
Export share	Advanced	Share of treated wastewater used outside of the basin (do not apply to global simulations).	-
Contributing sectors	Advanced	Sectors from which wastewater are treated in a given WWTP (domestic/industrial/both),	-
Min_HRT	Advanced	Minimally allowed hydrological retention time as a fraction between 0 -1. Indicating how much additional water can be accepted per day on top of the daily capcity, e.g., in case of rain events, or high water consumption	-
Reclamation and WWTP connection to reservoirs	Advanced	Links between WWTP and reservoirs and the rules for reuse of wastewater by different sectors	Jones et al., 2021***

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~~**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

Wastewater largely affects the hydrology in urbanized watersheds, particularly in water stressed regions. Wastewater reuse can potentially ease the pressure on natural water soruces and reduce drought risk. Yet, widely used large scale hydrological models do not account for wastewater treatment and recalamtion. The recent ongoing trend towards higher spatial resolutions, further emphaszie the need to include local data and processes into hydrological modeling.

~~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 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 module, completely integrated into the large-scale multi-resolution Community Water Model. It provides a range of operational modes to balance between modelling needs and data availability worldwide. A high-resolution case study of an urbanized and water stressed watershed illustrated the WTRM added value in terms of enhanced model performance and the inclusion of additional water soruces, such as reclaimed wastewater. The role played by wastewater in water resource managmenet planning, can now be included in hydrological simualtions, which are often used to inform such policies. Recently published global datastets were mapped to model variables, indicateing that global modeling ar coraser (5 arc minutes) spatial resultion is also feasble. Some remaining data gaps, including the lack of time-series or missing information on recalamtion projects, would require some assumptions and additional processing of input data. It follows that the compilation of a global input dataset is on desired future development. As wastewater is naturally associated with water quality, this aspect remains a limitation within the scope of the current development and ~~will~~would also be addressed in future developments. ~~The module can benefit from forming a global dataset and additional wastewater treatment technologies.~~

~~el 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.~~

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.

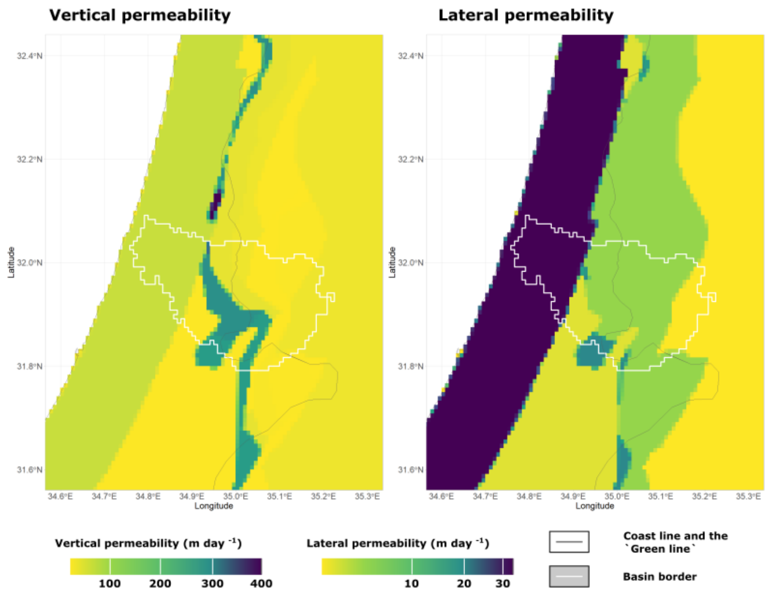

Figure A1: Vertical and lateral permeability in the YARTAN and Coastal aquifers in the Ayalon basin and its surroundings.

Appendix B

The treatment pool depth in an intensive WWTP represents the depth of a clarifier through which sewage flows at different treatment stages. The ratios between the clarifier's depth and diameter are relatively fixed, with the aim of optimizing sewers' biological treatment (e.g., bio-film development). A standard design for a clarifier is a relatively deep pool with a sloped bottom, as demonstrated in Figure B1. In the WTRM, the pool depth is only used to calculate the water surface area and simulate evaporation losses, and therefore, we find a simplified representation of the treatment pool with a flat bottom sufficient. In Figure B1, we convert the sloped bottom clarifier dimensions (WEF, 2005) to the equivalent pool depth in a flat clarifier, maintaining the pool's volume. This results in an approximate depth of 6.6 meters, which, based on data collected for the Ayalon case study, was rounded to 6 meters. We allow modelers to change the pool depth of either intensive, extensive, or both treatment systems by using the following settings in the settings file: 'pooldepth_intensive', 'pooldepth_extensive'. The default settings are hard coded as 6 and 1.5 meters, as described in this manuscript. In addition, to calculate the evaporation from extensive WWTP, we allow users to change the default value of two treatment pools by adding the 'poolsExtensive' to the settings file.

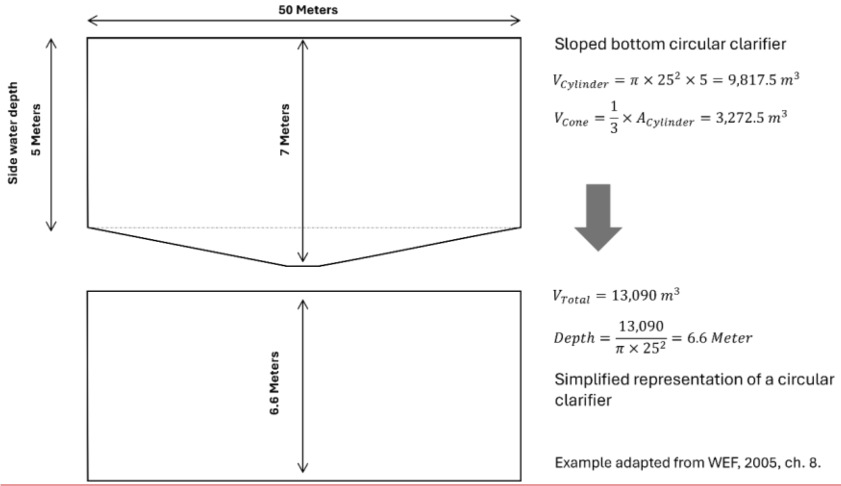

Figure B1: A simplified approach to estimate wastewater treatment pools depth in an intensive WWTP.

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.~~

The complete model (CWatM-Israel v1.06.1) used to conduct the simulations presented in this manuscript is available from https://doi.org/10.5281/zenodo.13990296 (last accessed: 25/10/2024). The input data used for this publication can be downloaded from https://zenodo.org/doi/10.5281/zenodo.13990451 (last accessed: 25/10/2024). The Community Water Model (CWatM) manual can be accessed via https://github.com/iiasa/CWatM.

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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