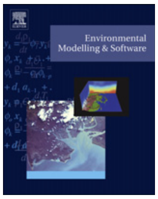
ARTICLE IN PRESS

Environmental Modelling & Software xxx (2011) 1–12

Contents lists available at ScienceDirect

Environmental Modelling & Software

journal homepage: www.elsevier.com/locate/envsoft



A computationally efficient open-source water resource system simulator – Application to London and the Thames Basin

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ARTICLE INFO

Article history:
Received 18 December 2010
Received in revised form
18 June 2011
Accepted 16 July 2011
Available online xxx

Keywords:
Water management models
Conjunctive use water resource systems
Decision support systems (DSS)
Simulation models
Open-source

ABSTRACT

Interactive River-Aquifer Simulation-2010 (IRAS-2010) is a generalized water resource system simulation model. IRAS-2010 is a new release of IRAS previously released by Cornell University in 1995. Given hydrological inflows, evaporation rates, water allocation rules, reservoir release rules, consumptive water demands and minimum environmental flows, IRAS-2010 estimates flows, surface water and groundwater storage, water use, energy use, and operating costs throughout the water resource network at each user-defined time-step. Multi-reservoir release rule curves, streamflow routing, regional groundwater flow, ecological flows, hydropower, pumping, desalination, and other features can be represented. The IRAS-2010 model is linked to a generic user-interface called HydroPlatform; both model and user-interface are open-source. We present an IRAS-2010 model of London's conjunctive use water resource system that satisfactorily emulates a more sophisticated model currently used by regulators. Results from daily and weekly time-step models are compared. IRAS-2010's fast run times make it appropriate for workshop settings and advanced planning methods that require many model evaluations. Model limitations, benefits, project organization and future plans are outlined.

Software availability

Name of software: IRAS-2010
Developers and Contact Address: Evgenii Matrosov and Julien Harou, University College London. Gower Street, London, UK WC1E 6BT, Pete Loucks, Cornell University. Ithaca, NY 14853
Year first available: March, 2011
Hardware Required: Windows, Linux or Apple computer
Software required: a Fortran compiler to modify source code
Program Language: Fortran 77 and 90
Program Size: 450 Kb
Availability: www.hydroplatform.org
Cost: free under general public license (GPL)

1. Introduction

Water resource simulation models help water managers plan, design and operate water systems (Loucks et al., 1981; Loucks and van Beek, 2005). Such models use user-defined operating and allocation rules to predict flow and storage of water throughout the water resource node-link network (Letcher et al., 2007; Maass et al., 1962) over time. They help predict how different management rules and infrastructure configurations react to adverse conditions such as droughts, flooding or long-term change. Simulation models are frequently used in integrated assessments (Jakeman and Letcher, 2003) and can be embedded in decision support systems (e.g. Lautenbach et al., 2009) or linked to optimization models (e.g. Ahrends et al., 2008).

This paper describes the generalized IRAS-2010 water resource management simulation model and its application to the Thames basin water system in south east England. The first parts of this paper describe IRAS-2010's history, functionality, equations and simulation procedure. Next an IRAS-2010 model of the Thames water resource system is described. Results of the IRAS-2010 Thames model are compared to those of a calibrated planning model of similar resolution maintained by the Environment Agency (EA) of England and Wales. Finally, limitations and advantages of IRAS-2010 and future development are discussed. Before describing IRAS-2010 we summarize below the main approaches to simulating water resource systems.

1.1. Approaches to water management simulation

Two main computational approaches exist for simulating water resource management: 'rule-based' and 'optimization-driven'

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doi:10.1016/j.envsoft.2011.07.013

Please cite this article in press as: Matrosov, E.S., et al., A computationally efficient open-source water resource system simulator – Application to London and the Thames Basin, Environmental Modelling & Software (2011), doi:10.1016/j.envsoft.2011.07.013

simulation. Rule-based models use procedural or object-oriented computer code where programming instructions sequentially define how water is managed using for example “if then else” statements and iterative instructions (‘loops’). Iterative solution procedures are used to represent the interconnections between water requirements and management rules at different locations, often moving from upstream to downstream to route flows and track storage throughout the system. Such ‘ad hoc’ algorithms are challenging to build but have the potential to reproduce management mechanisms with high fidelity. Examples of generalized rule-based models available with user-interfaces include RIBASIM (WL Deflt Hydraulics, 2004), WRAP (Wurbs, 2005b), HEC-ResSim (Klipsch and Hurst, 2007), WaterWare (Cetinkaya et al., 2008), AQUATOR (Oxford Scientific Software, 2008) and WARGI-SIM (Sechi and Sulis, 2009). IRAS-2010 and AQUATOR, the models considered in this paper, are both rule-based simulation models. Table 1 summarizes selected defining features of a representative set of rule-based simulators including whether they allow scripting and whether their time-steps are fixed or user-selected. Scripting allows customizing actions of particular nodes or links in a network using a generalized programming language rather than modifying source code. Scripting increases flexibility but requires more skillful users.

Optimization-driven simulation models solve a distinct optimization model at each simulated time-step to route flows, track storages and allocate water through the network. This method is popular because of its relative ease of use and flexibility; optimization-driven allocation takes some of the burden off the programmer whose code no longer has to consider every conceivable system state or outcome. However, some complex rules may be difficult to represent using optimization and model results may not be easy to replicate in practice. Examples of such models with user-interfaces include WATHNET (Kuczera, 1992), AQUATOOL (Andreu et al., 1996), OASIS (Randall et al., 1997), MISER (Fowler et al., 1999), MODSIM (Labadie and Baldo, 2000), RIVERWARE (Zagona et al., 2001), MIKE BASIN (Jha and Das Gupta, 2003), CALSIM (Draper et al., 2004), REALM (Perera et al., 2005) and WEAP (Yates et al., 2005). Further information on the optimization-driven simulation approach is given by Labadie (2004) and descriptions of modeling systems that use it can be found in Wurbs (2005a).

Since each approach has advantages and limitations, the institutional and water management context often determines which modeling type is most suitable for a particular application. For example a model seeking to predict water trading will benefit from an optimization engine, whereas rule-based models are well-suited for modeling actual system operating procedures (e.g. reservoir release tables) and predicting their performance under certain conditions.

1.2. IRAS-2010 history

The original IRAS (Interactive River-Aquifer Simulation) program (Loucks et al., 1995) was developed at Cornell University and the International Institute for Applied Systems Analysis and released in 1995. IRAS was used in several published and unpublished studies around the world as a tool for addressing regional, national and international water basin management (Loucks and Bain, 2002; Loucks et al., 1995; Salewicz and Nakayama, 2004). Using IRAS Brandgo and Rodrigues (2000) conducted a study of the downstream effects in Portugal of reservoir storage capacity increases on Spain’s Guadiana river.

IRAS-2010 is a new code based on the 1995 version. Improvements include (1) an improved calculation algorithm for water deficits, (2) the ability to associate demand link diversions to any demand node, (3) more flexible reservoir group balance rules, (4) demand restrictions during water supply shortfalls, (5) long-term water demand changes, (6) energy costs and hydropower revenues, (7) more detailed aquifer interactions, (8) calculation of channel dimensions and flow velocity, (9) performance measure output, (10) support for batch runs (e.g. for stochastic climate change studies), (11) addition of text-based input and output files and leap year support. More information on these changes is found in section 4 and Table 3.

IRAS-2010’s Fortran source code was optimized for speed by reducing file manipulation, caching data, and transforming input data into a structured binary format. Using data structures gives users the possibility to modify network parameters without having to re-read input files, increasing the efficiency of multiple run simulations for stochastic simulations. The resulting modeling system produces fast models; for example the London water resource system model described below runs in 1 second on a 3.5 GHz computer when using a weekly time-step over an 85-year time horizon.

1.3. IRAS-2010 functionality

IRAS-2010 is a rule-based water resource management simulator that models water flows and storages, single and joint reservoir releases, time-varying water consumption, hydropower production and pumping energy use. Salient IRAS-2010 features include computational speed, the ability to realistically represent a wide range of water management actions and conditions, and a customizable user-interface and online open-source code management (www.hydroplatform.org).

An IRAS-2010 model represents the system as a network composed of nodes and links of various types. Nodes can be natural lakes, reservoirs, aquifers, wetlands, gauge sites with time-series of inflows, demand sites, consumption sites, and confluence or

Table 1
Selected benefits and limitations of a representative group of rule-based water resource simulation modeling systems.

Model	Selected characteristic features
IRAS-2010	Free and open-source; Computationally efficient; Multi-reservoir operating rules; Flow routing; Geographic interface implemented in a separate customizable open-source model platform named ‘HydroPlatform’; Time-step is user-selected between 1 and 365 days
AQUATOR	Flexible generalized scripting at nodes and links using the VBA language; Simplified modeling of groundwater flow or storage not included; Time-step is daily
RIBASIM	Wide variety of features (lay-out, demand and control nodes) and several link types; Links to DELWAQ water quality model and HYMOS hydrological model; Geographic interface; Many international case-studies; Time-step is user-selected between monthly and daily
WRAP	Represents priority-based water allocation; Calculates supply reliability performance measures; Time-step is user-selected between monthly and daily
HEC-ResSim	Includes generalized scripting using the Jython language for reservoir rules allowing complex rules including flood control operations; Operational focus rather than long-term planning; Multiple routing methods; Geographic interface; Incorporates time-series generated by sister hydrologic model HEC-HMS; Public domain (free); Time-step is user-selected between daily and 15-mimute intervals
WaterWare	Includes native rainfall runoff, water quality, and irrigation demand models; Web-interface with user-management which allows running models on servers and clusters; Link to heuristic optimization procedures for calibration and management; Time-step is daily
WARGI-SIM	Links with WARGI-OPT, an optimization model; Time-step is user-selected between seasons and hours

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divergence sites. Nodes can be combinations of certain node types, for instance demand/consumption nodes have properties of both. Demand nodes have either flow or storage demand targets. When demand nodes experience a deficit they call for water from links or supplemental reservoir releases.

Links represent unidirectional or bidirectional natural or engineered flow paths between two surface and/or groundwater nodes. IRAS-2010 has three types of unidirectional links: 'diversion', 'demand' or 'natural' links. Diversion links represent canals or pipelines and require diversion functions to indicate how much water is abstracted (Fig. 5). A demand link transmits water to a demand node whose allocation comes from either surface storage (reservoirs) or river reaches. Simple hydrologic river flow routing routines and loss functions can be activated on unidirectional links. Bidirectional links model flow to or from aquifers (along 'groundwater' links) or flow to and from wetlands (along 'surface' links). Storage nodes representing reservoirs, lakes, aquifers or wetlands use rating tables to define surface area, elevation, seepage and release as a function of storage volume. Lakes release water according to rating tables and reservoirs use rating tables to define minimum and maximum release rates within user-defined storage zones. Evaporation and rainfall rates can be associated with surface storage nodes. Wetlands and aquifers use volume-head tables defined on their bidirectional links to determine the direction of flow. Additionally, simplified aquifer–aquifer and aquifer-surface water interactions can be represented.

IRAS-2010 estimates hydropower and pumping energy production or requirements on relevant nodes. Demand modeling features include annual demand growth, storage-level triggered water demand reductions and flexible scalar, seasonal or time-series specification of water demands. This allows simulating realistic water use restrictions and customized water demand change patterns.

All IRAS-2010 parameters can vary seasonally and annually. Designated 'gauge' sites (locations having a time-series of natural unregulated flows) can use flow factors to modify the flow (e.g. for scenario analysis or climate change impact modeling).

IRAS-2010 generates a results file with time-series of all modeled state variables at each network location and time-step. A performance summary file currently outputs a variety of scalar indicators for different nodes types and could be adapted to include further performance metrics. Reliability, resilience and vulnerability performance indicators adapted from Hashimoto et al. (1982) are calculated at storage nodes. These indicators show how many times user-defined storage thresholds were violated and their average and maximum duration. Another reliability indicator gives an average annual reliability probability for each threshold. Energy use or production resulting from pumping or hydropower is summarized and includes energy costs or revenue calculated from user-defined energy prices. Generic energy and costs can be included at any network location by specifying energy requirements per unit of water. Finally two water supply indices, Shortage Index (SI) and Stability Degree (SD) (Hsu et al., 2008) are quantified at each water demand.

2. IRAS-2010 computer program

IRAS-2010 is programmed in Fortran using procedural programming, meaning it organizes tasks into subroutines. All model functionality is included in subroutines; custom scripting of specific network elements is not possible. It is an open-source code distributed under a general public license (GPL) with an online code management website (accessed from www.hydroplatform.org). IRAS-2010 does not have its own user-interface; instead it is available as an add-in within HydroPlatform, an open-source generic user-interface and data manager for water models (Harou et al., 2010). The HydroPlatform add-in builds IRAS-2010 input files and can launch the executable. Alternatively the IRAS-2010 executable runs as a stand-alone program if IRAS-2010 input files exist in the same folder.

IRAS-2010 runs on a yearly loop. The year is divided into time-steps, each having a user-specified number of days. For example, a week long time step uses 7 days, and a monthly time-step uses 30 days. IRAS-2010's internal algorithms break each time-step into subtime steps. The simulation procedure loops summarized in Fig. 2 are run for each subtime step. The user-defined number of sub time steps defaults to 20. The more subtime steps there are, the more precise calculations become especially when reservoir rules, aquifers and wetlands or demand and source nodes are part of the network and looped flows exist (Loucks et al., 1995). However, including more subtime steps results in increased run times. The user must therefore consider the trade-off between increased precision with more subtime steps and the corresponding longer run times.

IRAS-2010 supports inputs in any units. The user must provide conversion factors that convert user input units into internal IRAS-2010 units (Table 2).

3. IRAS-2010 equations

3.1. Hydrologic routing in unidirectional surface links

When the time-step of simulation is shorter than the time it takes for flow to travel through a river or canal reach, it may be necessary to use hydrologic routing techniques to account for water conveyance travel time. IRAS-2010 can perform hydrologic flow routing using two methods. The first method relates the outflow at link *l*, $Qout_l$, in user flow units to the water volume in the link, V_l, using the following equation:

$$Qout_l = aV_l^b \tag{1}$$

where *a* and *b* are user calibrated routing parameters specific to the link and user flow units. The outflow, $Qout_l$, depends on the detention storage in the link.

The second method is the cascading reservoirs method; it splits the link into a user-defined number of cascading sub-links (*sl*) whose outflows, $Qout_{sl}$, are related to their inflows, Qin_{sl}, according to:

$$Qout_{sl} = (a * Qin_{sl} + b * V_{sl})^c \tag{2}$$

where V_{sl} is the sub-link volume and *a*, *b*, and *c* are user calibrated routing parameters. The input of the next reservoir in the sequence is the output of the previous one.

3.2. Link cross section geometry

If routing is enabled, flow depth [m], width [m] and velocity [m/subtime step] can be calculated. Width can then be used for link loss calculations.

Table 2
IRAS-2010 internal units.

Parameter	Nodes	Links
Length	m	m
Area	m^2	m^2
Volume	Million m^3 (Mm^3)	Million m^3 (Mm^3)
Flow and Seepage	Mm^3/day	Mm^3/day
Evaporation/Rainfall/Link Loss	m/day	m/day
Power	KW	–
Hydraulic Conductivity (K)	–	m/day

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Table 3
New developments in IRAS-2010 (item numbers correspond to those described in Section 1.2).

(1) There is an option to bypass the future sub-time step extrapolation algorithm to calculate the demand deficit for nodes that only receive diverted flow and no natural flow (no ‘passive’ water).
(2) The demand link associated to a demand node no longer needs to be directly upstream of the node to request diversion to satisfy its deficit.
(3) Reservoir groups can be balanced on either the total group storage or on only the independent reservoir’s storage and refill triggers for dependent reservoirs can be set.
(4) Flow demand of demand nodes can be reduced depending on the storage of an associated reservoir to simulate demand restrictions in times of supply shortfall.
(5) Flow demand can be set to increase annually by a user-defined percentage or a time-series of demand can be used to represent complex demand fluctuations.
(6) For links that cannot use IRAS-2010’s pumping energy or hydropower algorithms (e.g. desalination energy) energy requirements per unit of water can be defined. Energy prices can also be defined to calculate variable operating costs.
(7) Darcy’s equation can be used to simulate simplified inter-aquifer and aquifer-surface water interactions.
(8) If routing is enabled, channel depth, width and flow velocity can be calculated.
(9) An output file with several performance measures evaluated at storage and flow demand nodes, energy consumption and production as well as associated energy cost and revenue is generated at the end of the simulation.
(10) Multiple runs using monthly flow factors to perturb flow time-series is possible.
(11) IRAS-2010 now uses text-based input files and supports leap years.

Before these link calculations begin, the link’s surface area and width at the link’s lower banks’ capacity is calculated (Fig. 1) (Matrosov, 2009). Calculation of flow width, depth and velocity begins by averaging the volume of the link at the beginning of the subtime step and the volume at the end of the subtime step, $\overline{V}_l$, to account for routing and losses. Using the link’s average volume and the flow rate through the link, Q_l [now in m^3/subtime step] the residence time of the link, T_l [subtime steps] is

$$T_l = \frac{\overline{V}_l}{Q_l} \tag{3}$$

The velocity of the flow in the link is then its length, l_l [m] divided by its residence time:

$$Velocity_l = \frac{l_l}{T_l} \tag{4}$$

The area, A_l [m^2], of the link is calculated using the link volume:

$$A_l = \frac{\overline{V}_1}{l_l} \tag{5}$$

Equations to calculate reach geometries in either case are found in Matrosov (2009).

3.3. Unidirectional surface link losses

Losses in unidirectional surface links can be calculated by three methods. The simplest method uses a loss rate vs. flow rating table while the other two methods determine link loss by using a loss rate, lr_l [m/day], and the link’s surface area:

$$Qloss_l = lr_l * W_l * l_l \tag{6}$$

where W_l [m] is the average width of the flow channel at the water level and l_l [m] the length of the link. The second method interpolates W_l from a user-defined W_l vs. flow rating table while the third obtains W_l from link cross section calculations which are described in section 3.2.

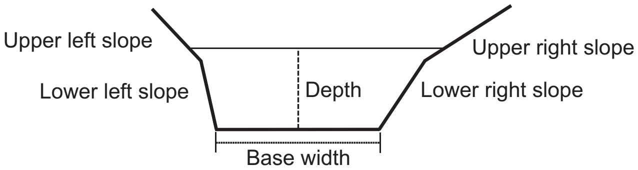

Fig. 1. Reach cross section geometry considered in IRAS-2010 showing slopes of various angles.

3.4. Bidirectional groundwater links

Bidirectional groundwater links can employ user-defined flow tables to define the direction and magnitude of flow based on piezometric head on either side of the link. Additional methods exist for calculating the flow through groundwater (gw) bidirectional links based on Darcy’s law:

$$Qgw_l = K_l * A_l * \frac{(y_1 - y_2)}{l_l} \tag{7}$$

where Qgw_l refers to the flow in the groundwater link l, K_l is the hydraulic conductivity [m/day], A_l is the area through which the flow occurs [m^2], y_1 and y_2 [m] are groundwater level elevations read from rating tables, and l_l [m] is the length over which the flow occurs. Subscripts 1 and 2 denote the nodes at either side of the groundwater link. A positive Qgw_l denotes flow to node 2 while a negative flow is a flow to node 1. Groundwater flow can be estimated between aquifers, between a storage node and an aquifer or between a surface water link and an aquifer.

3.5. Hydropower and pumping

Hydropower power generation and pumping energy usage calculation begins by determining the head difference, ΔH [m] between the nodes: $\Delta H = y_1 - y_2$ where y_1 and y_2 [m] are input and output node elevations respectively. Elevation at storage nodes is calculated dynamically from storage-elevation rating tables. If flow through bidirectional links is directed towards the output node, hydropower is produced, if it is flowing towards the input node then pumping energy is consumed.

For hydropower, the head is redefined if the turbine elevation is higher than that of the downstream node:

$$\Delta H_{hp} = \min\{\Delta H, y_1 - y_{turbine}\} \tag{8}$$

The power produced, P [W], is calculated using the general hydropower equation including plant efficiency:

$$P = g * \rho * Q_l * \Delta H_{hp} * \ efficiency \tag{9}$$

where g [m^2/s] is the gravity constant, ρ the density of water and Q_l [m^3/s] the flow through the link.

The energy produced, E [Wh] is power multiplied by the number of hours in a subtime step:

$$E = g * \rho * Q_l * \Delta H * efficiency * hours\ per\ subtime\ step \tag{10}$$

For this calculation the flow through the link, Q_l, should be in m^3/s. Because the program’s internal flow units are in Mm^3/subtime step, Q_l is converted (Matrosov, 2009) leading to:

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$$E = 2725 * \rho * Q_l \left(\frac{Mm^3}{\text{subtime step}} \right) \Delta H * \ \textit{efficiency} \tag{11}$$

Details on unit conversions can be found in Matrosov (2009). This is the energy that the plant should theoretically produce per subtime step. The actual energy produced is subject to its capacity at its rated head, *hCap* [Wh], and the plant factor (*pf*) which is the fraction of the time the plant is enabled:

$$E_{max} = hCap * pf * hours\ per\ subtime\ step \tag{12}$$

If $E > E_{\max}$ then $E_{\max}$ becomes the energy produced in the subtime step by the plant. If pumping is performed on the link energy is consumed and equation (11) is instead divided by the efficiency.

4. IRAS-2010 simulation algorithm

At each subtime step IRAS-2010 executes a series of instructions organized into four loops to calculate storages, flows, allocations and consumptions (Fig. 2). The first loop calculates the demand targets and deficits at demand nodes and determines reservoir releases required to satisfy these deficits. Lake outflows and seepage losses are also calculated in this loop. The second loop calculates inflows and outflows of all non-aquifer and non-wetland nodes by propagating surface storage releases and natural flows from gauge nodes downstream along all unidirectional links. Flow through bidirectional links connected to non-aquifer and non-wetland nodes are also determined in this loop. The third loop calculates the remaining bidirectional link flows and the fourth loop updates wetland and aquifer storages.

4.1. Loop I – releases and losses from surface storage

The first loop calculates demand deficits of demand nodes and releases and losses from surface storage nodes.

Lake releases are calculated according to storage-volume rating tables. Reservoir releases can be demand-driven target releases or supply-driven using reservoir rules and balancing functions. IRAS-2010 makes several passes through the network calculating each release type independently before final outflow calculations are performed.

The first pass determines demand-driven release targets for reservoirs. IRAS-2010 first determines the demand deficit for each demand node. Demand deficits can either be in volume units or flow units depending on if the demand node is a storage or flow node. For storage demand nodes IRAS-2010 computes the subtime step (*st*) deficit [Mm^3] as follows:

$$Deficit^{st}_{dn} = vTarget^{st}_{dn} - V^{st}_{dn} \tag{13}$$

where *dn* is the demand node index, *st* is the subtime step index, *vTarget* [Mm^3] is the target storage for the demand node and V^{st}_{dn} [Mm^3] is the real-time subtime step storage.

Targets for flow demand nodes [Mm^3/st] must consider ‘passive’ water that enters a node without upstream managed releases or abstractions. Passive water is taken into account by extrapolating how much water would reach demand nodes over a time-step. No managed water allocations or releases are made to demand nodes using this method at the first subtime step. This allows the algorithm to estimate how much natural flow would have reached the demand node at the end of the time-step without managed allocations and releases. If the algorithm determines that the demand node will experience a deficit it estimates how much water should be released from reservoir nodes and/or allocated to the node in the next subtime step by calculating the next subtime step’s deficit with equations (14) and (15). This extrapolation procedure is repeated until the end of the time-step taking into account managed releases from previous subtime steps to determine how water should be allocated in each subtime step.

At each subtime step (except the first) the extrapolation estimates demand deficit by predicting the total end of time-step (*t*) inflow, $Qexpected^{st}_{dn}$ [Mm^3]:

$$Qexpected^{st}_{dn} = \sum_{1}^{st} Qin^{st}_{dn} - \sum_{1}^{st} Deficit^{st}_{dn} * \frac{(tst - st + 1)}{(st - 1)} \tag{14}$$

where the first term is the total inflow into the node up to the current subtime step and the second term is the sum of all the subtime step deficits (calculated below) from earlier subtime steps and *tst* is the total number of subtime steps in the time-step.

The subtime step deficit [Mm^3/st] is the total time-step target demand, $qTarget^{t}_{dn}$ [Mm^3/t] less any demand reductions, the total real-time inflow and the expected inflow divided by the total subtime steps left in the time-step,

$$Deficit^{st}_{dn} = \frac{qTarget^{st}_{dn} - qTarget^{t}_{dn} * f_{Red} - \sum_{1}^{st} \mathrm{Qin}^{st}_{dn} - Qexpected^{st}_{dn}}{(tst - st + 1)} \tag{15}$$

where f_{Red} is a demand reduction factor.

If passive water does not enter a demand node, $Deficit^{st}_{dn}$ can be calculated without the extrapolation procedure described above. This method calculates the sub-time step deficit by:

$$Deficit^{st}_{dn} = \frac{qTarget^{t}_{dn}}{tst} \tag{16}$$

If $Deficit^{st}_{dn}$ for any given node is greater than 0, then a supplemental release, Release [Mm^3] from demand source nodes is calculated according to:

$$Release^{st}_{i,dem} = \sum_{l}^{dn} x_i * Deficit^{st}_{dn}$$

where *i* is the source reservoir node and x_i the deficit fraction. The supplemental release is a demand-driven release target for reservoir *i*. Demand driven releases are denoted by the subscript ‘*dem*’.

After the demand-driven release calculation, supply-driven releases are calculated using updated reservoir volumes considering demand-driven releases. Group reservoirs use reservoir rules

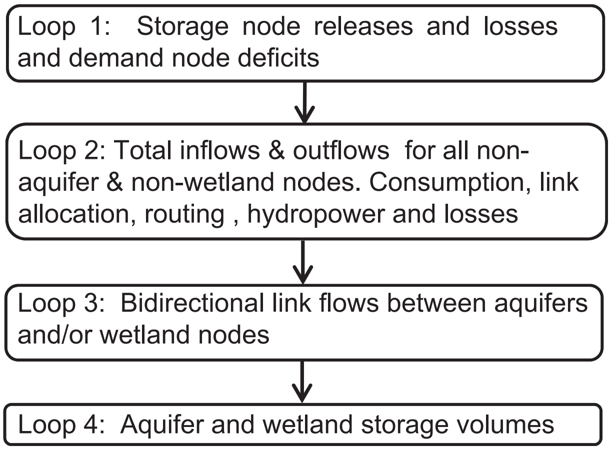

Fig. 2. The IRAS-2010 simulation algorithm is divided into four loops that are run at each subtime step. Adapted from Loucks et al. (1995).

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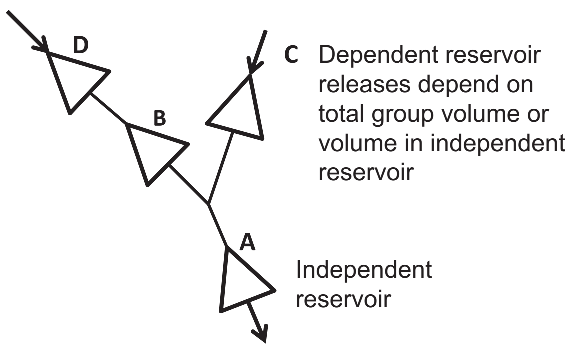
and balancing functions to determine their subtime step supply-driven releases while lakes use rating tables. Single reservoir releases use either the rule-based method or rating tables.

An example reservoir group is seen in Fig. 3. The independent reservoir in the group uses a reservoir rule function (Fig. 4) to determine releases while the dependent reservoirs use balance functions to calculate release as a function of their own storage volumes and either the total group storage (first column in Fig. 3) or the volume of the independent reservoir (second column).

Reservoir rule tables are split into seasonal storage zones (Fig. 4). Two such seasons can be seen in gray in Fig. 4. Each season has unique release rates even if they are on the same point on the plot. Each corner has a corresponding rule release rate (not necessarily proportional to volume). For example, the corner shared between the two gray seasonal storage zones in the figure can have different release rates. Both the beginning and the end of the season(s) have a minimum and maximum release rate at the minimum and maximum storages of the zone (z) (BRmin(z,s), BRmax(z,s), ERmin(z,s), ERmax(z,s) respectively). Their release rates can be seen on the corners of zone N. Linear interpolation is used to find the rule release rate based on the seasonal zone, the day in the year and the total group volume. The releases interpolated from the release functions become the rule based output of the independent reservoir. This is seen in the figure where the rule release for point n interpolated at day D_n and group volume V_n in seasonal storage zone N.

Releases from dependent reservoirs occur when dependent reservoir volume is greater than the volume specified by the balance table. Abstraction to dependent reservoirs is not limited by balance tables as they can still refill passively. To limit managed abstraction, dependent reservoirs can be assigned a refill trigger which can prevent the reservoir from abstracting water from divergence nodes until the storage of the independent reservoir in the group reaches a certain level.

Reservoir supply-driven and demand-driven releases combined constitute target release. Target release may be modified subject to minimum and maximum release rates. Once storage releases are calculated, the effects of rainfall, evaporation and seepage on surface storage nodes are calculated.



Total Storage Volume	Target Storage Volume in Reservoir A	B	C	D
10	5	0	5	0
20	10	0	10	0
60	30	5	20	5
100	30	25	25	20
200	30	45	60	65

Fig. 3. Reservoir group with one independent reservoir (A) and three dependent reservoirs whose releases are controlled by a balance table (in user-defined volume units) giving the ideal storage level in each reservoir as a function of total group storage volumes. Adapted from Loucks et al. (1995).

4.2. Loop II – inflow and outflow of surface nodes

Loop II calculates node inflows and outflows for all non-aquifer and non-wetland nodes. This is done by propagating natural flow and storage node releases downstream while obeying allocation rules on unidirectional links. Flow through bidirectional links connected to any node calculated in this loop is also calculated. Bidirectional links connecting two aquifers or wetlands are not calculated here.

The allocation calculation process proceeds by order of outgoing link type (outgoing links are those that exit the node, link types are described in section 1.3). Allocation calculation order in outflow links of the same type follows input file declaration order. Allocations to bidirectional links are made first followed by consumption on the node itself (which is treated as an allocation) then allocations to demand links, diversion links and finally natural links. If there is not enough water to cover all allocations, lower priority network elements do not receive allocations.

Allocations to bidirectional links are calculated according to equation (7) or user-defined bidirectional flow tables. Consumption at nodes is a fixed proportion of available water. Demand links have an associated demand node either directly downstream or the link has been designated as the supply link of a demand node. In either case, subject to water availability, an amount equal to the demand node's previously described subtime step's deficit, $Deficit_{dn}^{st}$, is allocated. Allocation to demand

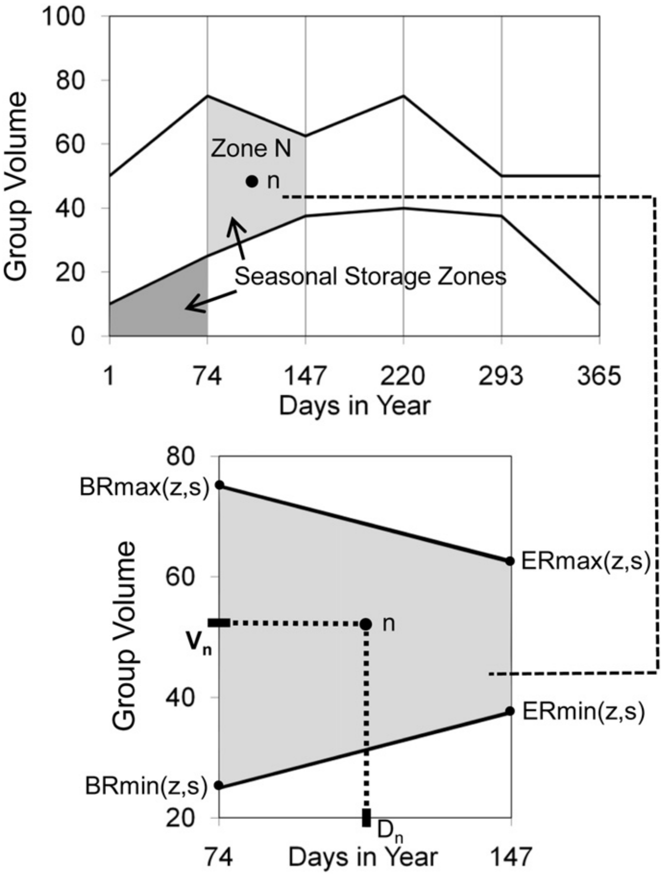


Fig. 4. Reservoir release rule function for independent reservoirs in user-defined volume units (e.g. reservoir A in Fig. 3). Release rates are a function of total reservoir group storage and the day within the year. Rule release is calculated using linear interpolation between the release rates defined at the four corners of a seasonal zone (as seen for point n inside seasonal zone N). Adapted from Loucks et al. (1995).

links can be limited to a defined link flow capacity. Diversion links use functions similar to consumption functions. The water originally available (before demand and consumption allocations were performed) at the initial node of a diversion link is used to calculate the diversion amount. An example of diversion allocation functions can be seen in Fig. 5. Diversion links can also have a limited flow capacity.

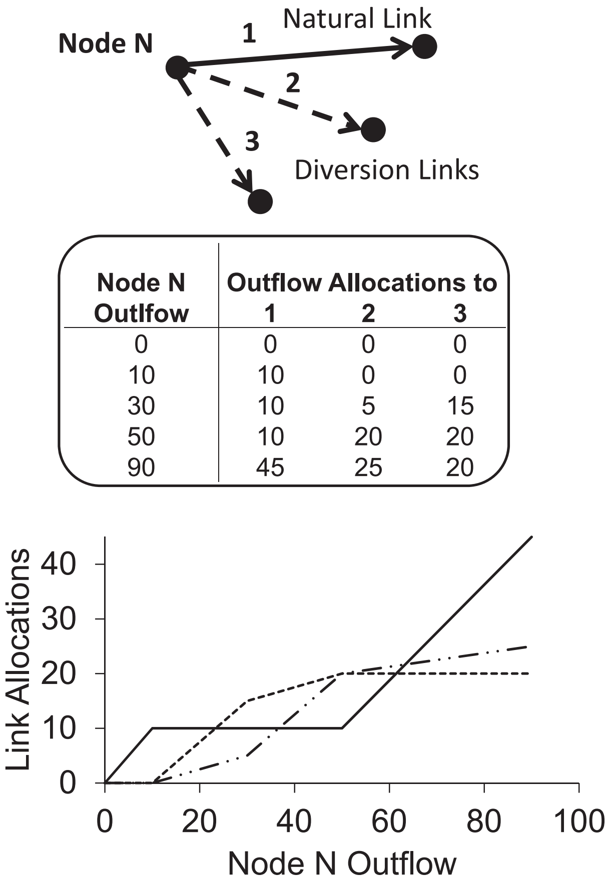
Once demand and diversion table allocations have taken place, any remaining water is distributed equally to all natural links. Natural links are links without a defined flow capacity. If a demand or diversion link does not have a defined capacity it is also considered a natural link and more water can be allocated to it at this step. Return flows from a consumption node can be modeled as allocated flow to an outgoing link.

Hydropower generation or pumping energy requirements and routing defined on links are calculated in this loop.

4.3. Loops III & IV – remaining bidirectional link flows

The third loop in the subtime step computes the remaining uncalculated flows including flows through bidirectional links connecting groundwater or wetland nodes and calculates pumping energy requirements. The fourth loop updates the aquifer and wetland node storages by taking into account the flow through bidirectional links.

This four-loop process is repeated for every subtime step of each time-step until the end of the simulation.



Node N Outlfow	Outflow Allocations to		
	1	2	3
0	0	0	0
10	10	0	0
30	10	5	15
50	10	20	20
90	45	25	20

Fig. 5. Diversion links and example table showing flow allocation to diversion links as a function of the total amount of water leaving node N. The plot below the table provides a visualization of the diversion functions (in user-defined flow units). Adapted from Loucks et al. (1995).

4.4. Summary of IRAS-2010 improvements

An understanding of the IRAS-2010 solution algorithm is useful to understand the changes introduced in this version. These are summarized in Table 3.

5. Thames basin application

To demonstrate the effectiveness of IRAS-2010, a model of the Thames water resource system (Fig. 6) was built. Input data was obtained from an existing Thames water resource system model maintained by the Environment Agency (EA) of England and Wales. The EA's Thames model uses a water resource simulation software package developed for the UK water industry context named AQUATOR (Oxford Scientific Software, 2008). Both Thames models have similar spatial resolution and use a daily simulation time-step over the historical time horizon (1920–2005). A schematic of the IRAS-2010 network as it appears in the current release of Hydro-Platform is displayed in Fig. 7.

5.1. Thames water resource system

The River Thames is one of England's major rivers, and provides about two thirds of London's water supply (Environment Agency, 2009). It flows eastward 346 km to the North Sea through some of England's most urbanized areas including London. Over 13 million people live within its 16,133 km^2 catchment area. Surface water accounts for roughly 60% of water supplies and groundwater 40% in the Thames basin. The water supply is managed by two private water companies: Thames Water Utilities Limited (TWUL) and Veolia Three Valleys Water (VTVW). Thames Water owns thirteen reservoirs in the north-east of London by the Lee river and a group of reservoirs south-west of London supplied by the Thames. The Thames basin has two conjunctive-use schemes. The North London Artificial Recharge Scheme (NLARS) recharges excess treated water to an aquifer for later use during dry periods. The West Berkshire Ground Water Scheme (WBGW) is available for intensive use during droughts. TWUL recently built a desalination plant at Beckton and is proposing to build a new Upper Thames Reservoir (UTR) near Abingdon.

5.2. Thames IRAS-2010 model components

5.2.1. Inflows

Surface water enters the system at Day's Weir on the River Thames and at Feildes Weir on the River Lee. Inflows are publicly available daily historical flow rates obtained from the National River Flow Archive[1] (NFRA). London's groundwater use is modeled as an aggregate inflow into the London demand node. An aggregate inflow node called the Lower Thames (the 'LT+UTR_Trig' node in Fig. 7) represents the aggregate inflow into the Thames between Day's Weir and Teddington and is obtained by subtracting the daily historical flows at Teddington from those at node Day's Weir. This simplification produces negligible error because the small distance between the two nodes allows the routing of daily flows to be ignored.

5.2.2. Water consumption nodes

There are five consumption nodes representing regions that consume water. Some of these water demands vary on a monthly basis to simulate seasonal demand variations. All consumption nodes are fed by surface storage with the exception of a VTVW

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[1] http://www.ceh.ac.uk/data/nrfa/index.html

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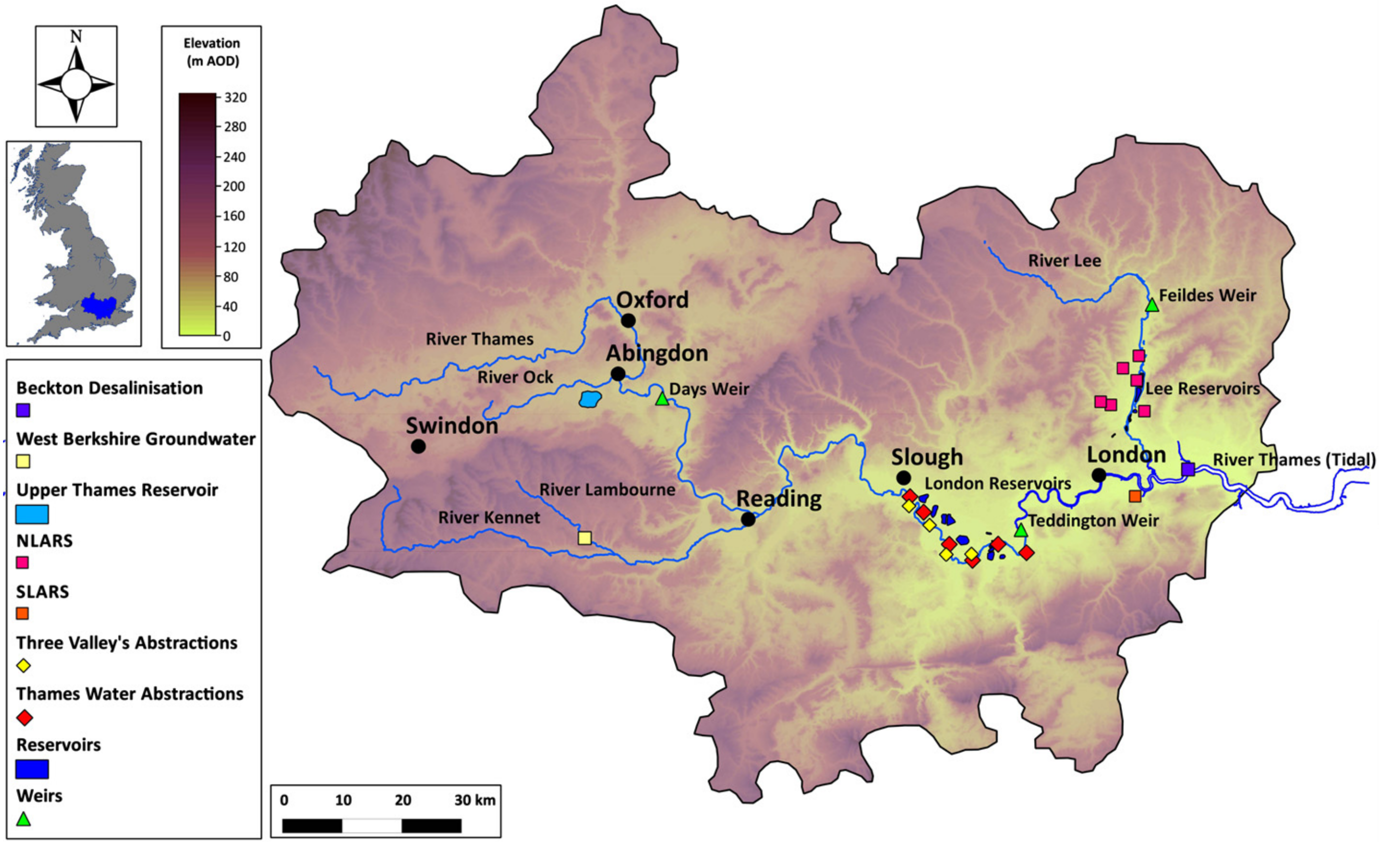

Fig. 6. The Thames river basin featuring major urban centers with the river Thames and its main tributaries. Rivers originate in the highlands to the west and north. Thames Water and Veolia reservoirs are seen to the west of London and in the Lee valley. The UTR is seen to the south-west of Abingdon. The WGBW is found on the river Kennet in the south-west while NLARS is situated in the Lee valley and SLARS south-east of London. The desalination plant is located on the Thames estuary east of London.

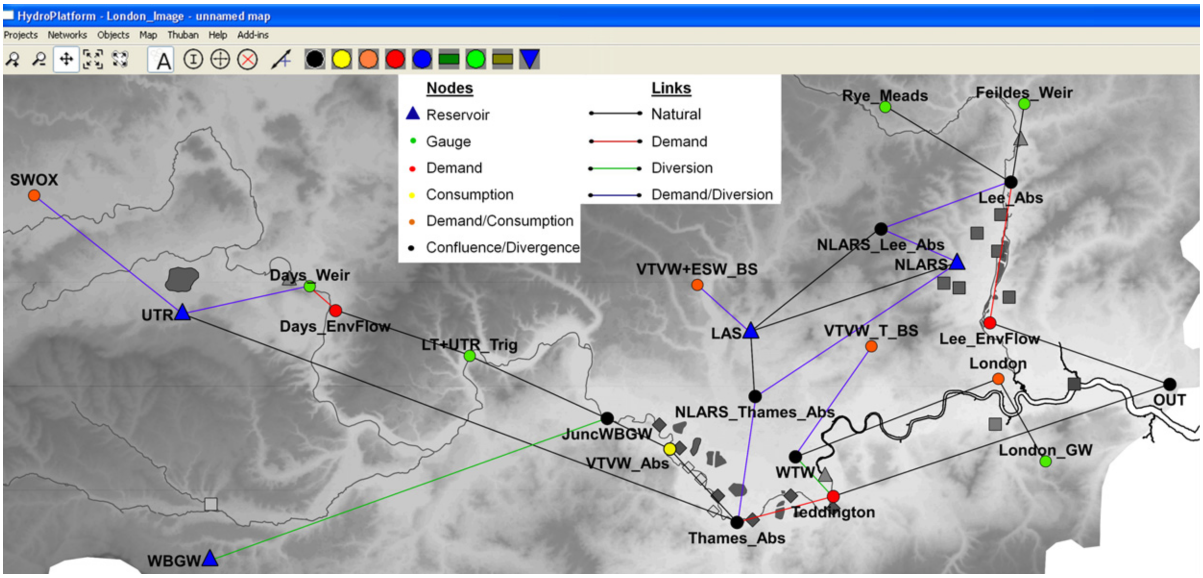

Fig. 7. Thames IRAS-2010 model network in current HydroPlatform interface featuring 5 'gauge' nodes with time-series inflows (Days_Weir, LT+UTR_Trig, Feildes_Weir, Rye-Meads and London_GW), 5 flow ‘consumption’ and ‘demand/consumption’ nodes representing urban demand centers or bulk-supply (BS) transfers to other water companies (London, SWOX, VTVW_Abs, VTVW_T_BS, and VTVW+ESW_BS), and 3 minimum environmental flow ‘demand’ nodes (Days_EnvFlow, Lee_EnvFlow and Teddington). The Lee Valley and Thames reservoirs are aggregated into LAS. LAS and UTR are reservoir nodes and storage ‘demand’ nodes so that they abstract water when not full. The NLARS and WBGW conjunctive use schemes are modeled as reservoir nodes; NLARS is also a storage demand node to receive abstracted water from the Thames and Lee rivers. Leakage from the aggregated Water Treatment Works (WTW) node is represented by a link connecting WTW to Teddington.

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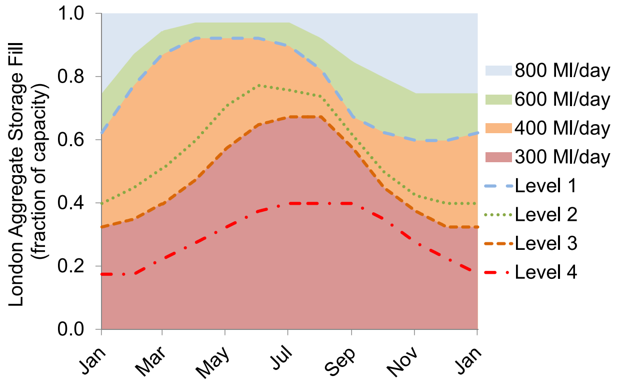

Fig. 8. Lower Thames Control Diagram (LTCD) showing how London demand reduction thresholds (Level 1 – Level 4) and minimum environmental flow rates at Teddington are a function of London's aggregate storage reserves.

reservoir abstraction (VTVW_Abs) which is supplied directly from the Thames and the London demand/consumption node which is supplemented by groundwater (London_GW). Demand reductions representing water use restrictions are triggered by the Lower Thames Control Diagram (LTCD) (Fig. 8) when storage (levels 1 through 4) is low. Different storage levels of the LTCD determine environmental flows at Teddington (Fig. 8).

5.2.3. *Storage nodes*

The 'London Aggregate Storage' (LAS) reservoir represents the London-area Thames and Lee River reservoirs. Water is diverted to LAS first from the Lee River and then from the Thames subject to downstream environmental minimum flows and maximum daily abstraction limitations. NLARS is connected directly to LAS and releases water when LAS level goes below the Teddington 800/600 Ml/day line seen in Fig. 8. NLARS is refilled by abstractions from the links connecting the LAS to the Thames and Lee; abstraction is limited to 40 Ml/day. In reality, NLARS is refilled using treated water from London's main distribution network. This water is supplied by the water treatment works which obtain water from the Lee and the Thames. Such an abstraction and refill system would require a loop flow where the LAS both receives and releases water to and from NLARS. This is impossible using IRAS-2010; instead NLARS abstracts water destined for LAS.

Because NLARS is closer to the Lee abstractions, diversion from the Thames to NLARS is limited to 35% of total abstraction. NLARS refills only when LAS is 99% or more full. Because NLARS is an engineered storage system it is modeled by both AQUATOR and IRAS-2010 as a reservoir even though it is an aquifer storage. WBGW is also modeled as a reservoir with a maximum storage with an inflow time-series representing natural recharge. Its release to the Thames is activated when LAS goes below the Level 2 line (Fig. 8).

The IRAS-2010 model includes the proposed Upper Thames Reservoir (UTR). The UTR supplies water to a consumption site and to the Thames when activated. Release to the Thames is activated when flow downstream (at the 'LT+UTR_Trig' node which is a combined gauge and demand node) goes below 3000 Ml/day. UTR Thames abstraction is limited by a downstream minimum environmental flow and a daily abstraction limit.

5.2.4. *Water treatment works*

Water Treatment Works (WTW) are modeled as a divergence node that feed the London demand node and a demand node representing a water transfer to another water company. A part of WTW inflows leaks out into the environment during treatment. Most of this leakage makes its way through seepage to the Thames as most of the WTWs are located near the river. This seepage is modeled as a link into Teddington and contributes to Teddinton's minimum environmental flow. Some WTWs are located near the Lee and do not contribute to Teddington's flow. This part of the leakage is modeled as losses from this link.

5.2.5. *Teddington*

Teddington weir has a minimum environmental flow between 300 and 800 Ml/day set by the LTCD which limits abstraction from the Thames.

5.3. *Differences between IRAS-2010 and AQUATOR Thames models*

AQUATOR allows custom scripting of individual network elements which provides a level of customization not available in the procedural IRAS-2010 code. AQUATOR uses custom scripting to allow both NLARS and LAS to release water to one another. AQUATOR's scripting also allows UTR to abstract from the Thames only when UTR is not releasing water, but this had little effect on the model since a minimum environmental flow downstream of the abstraction served as the main abstraction limit. In the AQUATOR Thames model the WBGW refills instantaneously once LAS reaches its full capacity while in IRAS-2010 it is refilled with a more realistic daily inflow.

6. IRAS-2010 results

IRAS-2010 results are compared with AQUATOR results and historical gauged river flows (from NFRA) when possible. Historical

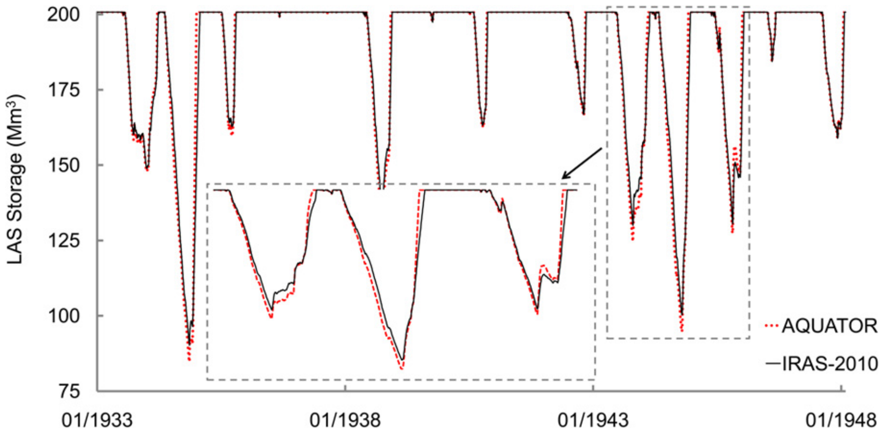

Fig. 9. London Aggregate Storage (LAS) simulated by the IRAS-2010 and AQUATOR models.

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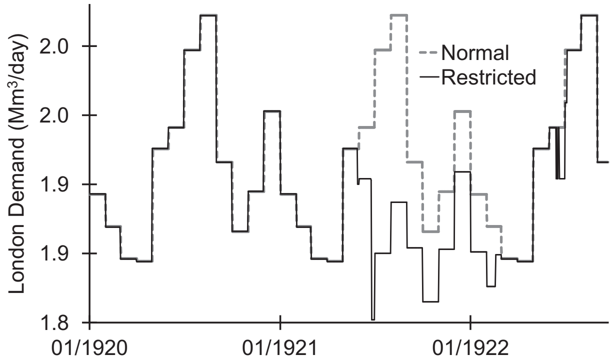

Fig. 10. London demand during a drought event compared to normal demand levels as modeled by IRAS-2010.

data on managed flows, abstractions and storages are not in the public domain in England and Wales which means for example we cannot compare historical and modeled reservoir use. Therefore IRAS-2010 results are compared to those calculated by an AQUATOR Thames model built by EA regulators who are familiar with the system's operation.

LAS over an 85 year period is displayed in Fig. 9. IRAS-2010 and AQUATOR show similar storage levels except for drought periods when LAS levels went lower in AQUATOR than in IRAS-2010. These discrepancies are a result of small differences in storage levels in LAS at the beginning of the droughts in the two models putting LAS storage on different points on the LTCD in each model. This results in demand reductions going into effect at different times and also affects the timing of NLARS and WBGW activation resulting in growing discrepancies in the LAS storage during the drought. The inset in Fig. 9 shows storage differences are minor during the years 1943–1945.

Fig. 10 shows London consumption results for a three-year period including a dry spell between 1921 and 1922. During this drought demand reductions were activated and demand is compared to normal demands.

Fig. 11 shows flow at Teddington weir after all Thames abstractions have been made and after additions from the WTW. Abstraction to LAS directly upstream of this node is limited by the minimum environmental flow at Teddington which is dictated by the LTCD. AQUATOR and IRAS-2010 show the same flows through Teddington but show discrepancies with historical flows (obtained from NRFA). Given the simplifications of these screening models including lack of routing and stream–aquifer interaction these results are deemed satisfactory. Both models show that during late 2003 only the minimum environmental flow was left in Teddington. This is mirrored in the historical flow time-series, albeit with some noise.

Fig. 12a shows a strong correlation between IRAS-2010 Teddington flow rates and historical flows.

Pumping energy consumed during abstraction from NLARS during a drought event is displayed in Fig. 13. As groundwater levels drop more energy is required.

6.1. *IRAS-2010 weekly model*

The IRAS-2010 Thames Basin model was run with a weekly time-step to investigate how a coarser time-step affects results. The weekly time-step and bi-weekly LTCD step function approximation reduced run time to 1 second on a 3.5 GHz desktop compared to 15 seconds for the daily time step and daily LTCD version. The correlation plot (Fig. 12 b) comparing storage under the daily and weekly time-steps shows the coarser time-step closely resembles daily results. The highest density of deviation between the two models occurs when the LAS is nearly full. This is a result of a sub time-step lag that will be discussed in the next section.

7. Discussion

7.1. *Limitations*

Although IRAS-2010 closely emulates the EA's AQUATOR model results, limitations do exist. IRAS-2010 lacks scripting capabilities that would allow users to customize individual network object behavior. Lack of scripting increases ease of use but it also means some complex relationships between model components are more difficult to represent. In procedural programs like IRAS-2010, such special behavior needs to be programmed into the standard subroutines used for all nodes. Some features scripted in the AQUATOR model could be programmed into IRAS-2010 subroutines but they would not be as flexible.

IRAS-2010 currently has no direct way to define which storage node or link serves as a higher priority contributor to a demand node. The order in which links connecting to a demand node are defined in IRAS-2010 sets the priority in most but not all instances. Higher priority links contribute the greatest part to a demand node, but some water is still drawn from lower priority links. This happens in the Thames IRAS-2010 model when some water is taken from the Thames even though the Lee could have satisfied the LAS storage deficit.

Another minor current limitation occurs when a reservoir provides significant flow to a downstream flow demand node. The subtime-step lag in the demand deficit calculation means at the end of a time-step reservoir volume is missing roughly one subtime step release equivalent. This limitation becomes less apparent with smaller subtime steps. This and other known minor computational issues will likely be corrected or mitigated over time.

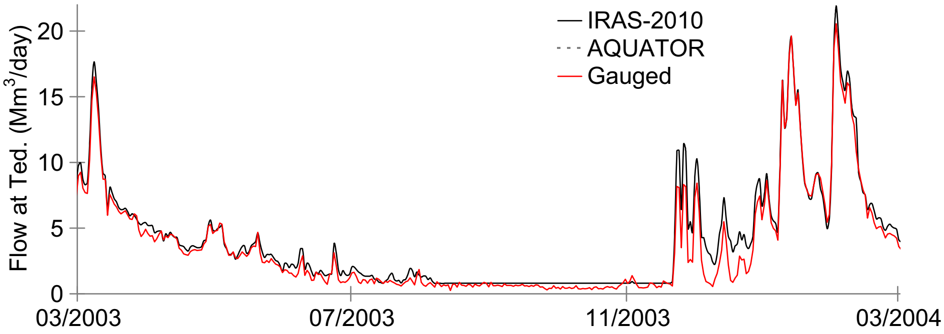

Fig. 11. Flow rates at Teddington (Ted.) calculated by IRAS-2010 and AQUATOR plotted against gauged flows.

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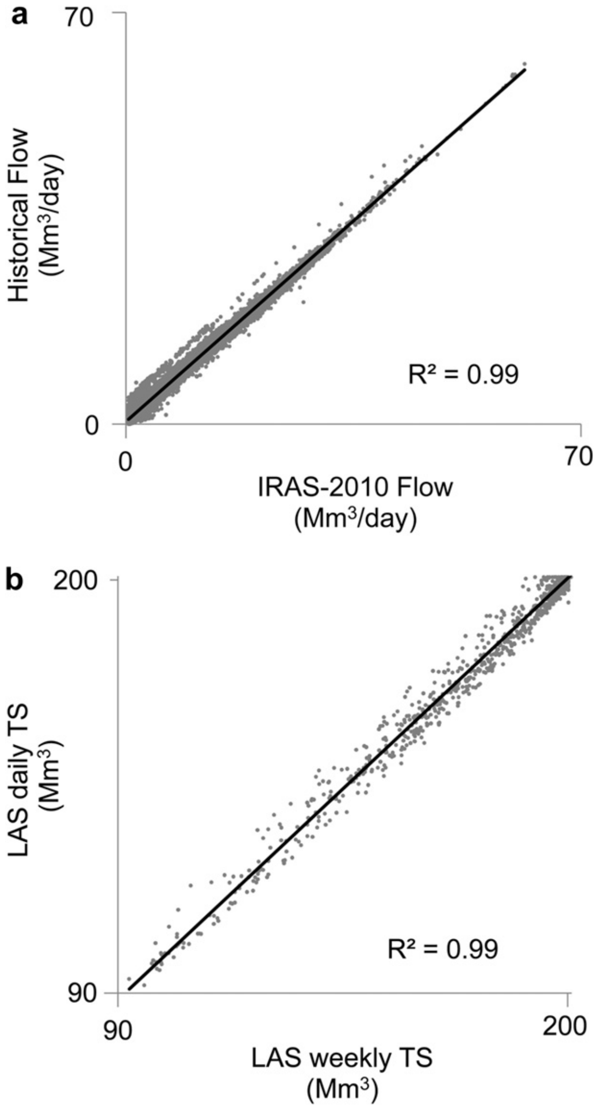

Fig. 12. a) Teddington historical and IRAS-2010 flow correlation and b) Weekly and Daily Time Step (TS) correlation plot for LAS.

7.2. Benefits

Despite these limitations the flow time-series produced by the IRAS-2010 Thames model compares well to gauged Thames flows at Teddington weir and the model closely emulates flows estimated by an existing calibrated system model used by regulators. IRAS-2010 is straight forward to configure and requires no advanced scripting skills. The availability of a separate customizable open-source user-interface (HydroPlatform) is useful for those who would want to customize a decision support system (DSS) for a particular IRAS-2010 model.

IRAS-2010 is computationally efficient making it an attractive model for planning methods that require multiple runs or for collaborative workshops where quick feedback on effects of proposed system changes is useful. The IRAS-2010 Thames model using a weekly time step over an 85 year time horizon runs in 1 second on a 3.5 Ghz computer. The user-selected time-step and ability to implement hydrological routing increase the tool's flexibility. The use of multiplicative flow factors is useful for climate change studies that multiply historical flows by perturbation factors meant to represent possible climate change. IRAS-2010 can easily be run by wrapper codes that automate multiple runs by modifying IRAS-2010's input files.

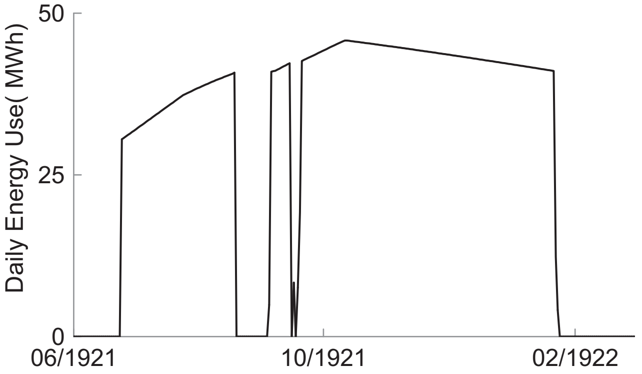

Fig. 13. Pumping energy use from NLARS conjunctive use scheme during the drought between 1921 and 1922.

7.3. Future work

As an open-source project IRAS-2010 will be updated to improve performance and add features. The ability to add priorities on links leading to demand sites and improving the storage demand node deficit calculation would be useful improvements to name a few. Water quality routines included in IRAS have not yet been implemented in IRAS-2010. Making the code Open-MI compliant (Gregersen et al., 2007) would facilitate its use in integrated studies.

8. Conclusions

IRAS-2010 is an effective computationally efficient generalized open-source computer program to simulate water resource systems. IRAS-2010 estimates flow and storage of water in natural (rivers, lakes, wetlands, aquifers) and engineered (reservoirs, canals, water abstractions, consumptive use, hydropower, etc.) water resource systems. It tracks flows, storages, water supply status, operating costs, energy production and use, and environmental performance throughout the network at each time-step.

An application to the Thames River and London's conjunctive use water supply system shows IRAS-2010 closely emulates a water resource simulation model maintained by the Environment Agency of England and Wales. Relatively little information was lost in the transition from a daily to a weekly time-step resulting in a quick and accurate screening tool. IRAS-2010's main limitation as a procedural code is that all model behavior must be programmed into general source code subroutines; customizing the behavior of specific network elements using a scripting language isn't possible. Its computational efficiency makes it appropriate for stochastic applications, where many model runs are required, or for interactive use in a workshop context. Promising fields of application include climate change impact and adaptation studies and modeling with stakeholders. IRAS-2010 is free and open-source software allowing the water management modeling community to further diversify its subroutines, improve performance, and identify and fix errors. A HydroPlatform add-in links IRAS-2010 to a customizable user-interface. The model and user-interface will continue to be improved over time to suit the needs of water managers and researchers.

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Acknowledgements

The authors thank the Environment Agency for supplying the Thames model and providing support and thank Oxford Scientific Software for granting them an AQUATOR license and for their assistance. Funding was provided by the UCL Bridging the Gaps program and the EPSRC Adaptation and Resilience to Climate Change (ARCC-Water) project. The authors would like to thank past IRAS researchers for their contributions including but not limited to Marshall Taylor, Peter French, Huicheng Zhou, and Guy Pegram. The authors are grateful to Junjie Kang for his contribution to IRAS-2010's computational efficiency and to Ashley Woods for producing the Thames and HydroPlatform figures. Joe Kasprzyk and two reviewers provided comments that improved the paper.

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Please cite this article in press as: Matrosov, E.S., et al., A computationally efficient open-source water resource system simulator – Application to London and the Thames Basin, Environmental Modelling & Software (2011), doi:10.1016/j.envsoft.2011.07.013