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Hydrological models for climate-based assessments at the watershed scale: A critical review of existing hydrologic and water quality models

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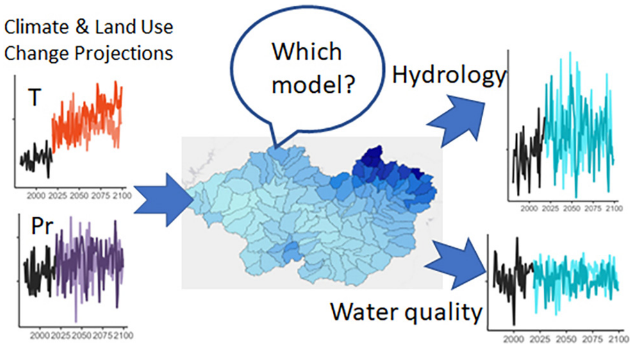
HIGHLIGHTS

- Critical analysis of 21 hydrologic models.
- Consistent criteria to consider functionality, scope, ability to model extreme events.
- Analysis of strengths and limitations of available models.
- Recommendation based on modeling objectives (water supply, water quality).

GRAPHICAL ABSTRACT



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ABSTRACT

Global changes, including climate and land use changes, can result in significant impact to water resources. Planning for these changes requires making projections, even in the face of considerable uncertainties, to make informed management and policy decisions. A number of climate change scenarios and projections at global and regional levels are available that can be used to predict the likely range of outcomes. However, there is a need to translate these projections into potential implications for hydrology and water quality. Since there are dozens of hydrologic models, there is a need to evaluate them critically and to develop guidance regarding selecting the appropriate model for a given objective. We conducted a review of 21 different models commonly used for modeling hydrology (8), water quality (6) or both (7) at the watershed scale. Six of the models are strictly water quality models that depend on a separate model or observed data for hydrology. Seven additional models are useful for estimating hydrology and water quality simultaneously. The models were then evaluated based on ten different criteria, including functionality, scope, ability to model extreme events, data requirements, availability, and technical support, among others. The models were ranked Low, Medium or High in each of the criteria. The results indicate that three hydrologic models, MIKE-SHE, HEC-HMS, and MODHMS, as well as two full hydrology and water quality models, SWAT and WARMF, stand out in terms of functionality, availability, applicability to a wide range of watersheds and scales, ease of implementation, and availability of support. Modelers should carefully select the best model for their application, in part guided by the criteria discussed herein.

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Contents

1. Introduction

In response to changes in our climate, there is a need to consider broad potential impacts on water resources as well as utility infrastructure. A changing climate will result not only in changes in average annual precipitation and air temperature, but also their intra- and interannual variation, potentially increasing the number of wet or dry years (Dore, 2005; Portmann et al., 2009; Trenberth, 2011). Some years will see more intense storms than observed in the past, colder or warmer seasons, or more intense and/or frequent droughts. These changes will affect stream flow and velocity, runoff intensity, snowmelt timing, snow accumulation, flooding, groundwater recharge, evaporation in reservoirs and other water bodies, evapotranspiration from natural and managed landscapes, soil erosion, sediment transport in rivers and other water bodies, river channel scouring, and other hydrologic processes (Jeton et al., 1996; Zhang, 2004; Foody et al., 2004; Zhang and Nearing, 2005; Booij, 2005; Kang and Ramírez, 2007; Fang and Pomeroy, 2007; Abdulla et al., 2009; Angel and Kunkel, 2010; Göncü and Albek, 2010; Jones and Perkins, 2010; Meyers et al., 2010; Belachew et al., 2010; Chang and Jung, 2010; Hay et al., 2011; Son et al., 2011; Battaglin et al., 2011; Walker et al., 2011; Kure et al., 2013; Tripathi et al., 2014; Rasouli et al., 2015; Dams et al., 2015; Gizaw et al., 2017; Bian et al., 2017). On the water demand side, higher temperatures will result in increased water needs for agriculture as well as industrial and municipal uses such as cooling and others (Parker et al., 2008; López-Moreno et al., 2014). Climate change is likely to exacerbate water quality issues such as algal blooms, which are generated by a combination of low and slow flows, higher temperatures, and excess nutrients (Obregon et al., 2011; Park et al., 2013; Tang et al., 2015; Chang et al., 2015; Brown et al., 2016; Robertson et al., 2016; Bosch et al., 2018; Du et al., 2018; Pesce et al., 2018; Shalby et al., 2019; Carr et al., 2019; Rahmati et al., 2019). These algal blooms can affect water quality by altering pH and decreasing dissolved oxygen in the water column, generating toxins, and clogging industrial water intakes. Increased turbidity, due to either increased suspended sediments or algal growth, can also affect many operations, requiring additional treatment. Suspended sediments are also vectors for pollutants and pathogens, mobilizing pollutants that would otherwise remain deep in sediment beds.

In addition to water supply organizations and their related infrastructure, electric power utilities may be significantly affected by these changes in climate, and in particular in precipitation. The electric power industry is a major user of water resources, for cooling systems, hydropower, and even for washing solar panels (Keller et al., 2010; Averyt et al., 2011). Major implications of climate change for many power utilities will be the availability of water resources for power generation, (Kopytkovskiy et al., 2015) changes in demand patterns, and wildfire frequency. Increasing water temperatures in waterbodies will affect cooling capacity of the intake water (Cristea and Burges, 2010; van Vliet et al., 2013; Jeznach and Tobiason, 2015; Truitt, 2018), and may also constrain discharge temperatures. Higher frequency of large storm events may overwhelm the design capacity of storm management and ash pond infrastructure, potentially leading to water quality exceedances and accidental releases (Waters et al., 2003; Kim et al., 2015, 2017; Thakali et al., 2016; Choi et al., 2017; Bahrami et al., 2019). Climate change will also affect the extent of flooded areas and sea levels as well as streambank erosion rates, which could affect infrastructure (Rosenberg et al., 2010; Das and Simonovic, 2013; Zahmatkesh et al., 2015). Utilities may need to consider relocating pipelines, transmission lines and towers, substations, water storage facilities and other operations that may be within these low-lying areas.

2. Models that estimate impacts to water resources

Water resource managers, as well as many public and private institutions such as flood control districts and power companies, have a need to predict future water availability and water quality at the watershed scale using sophisticated tools. Numerical models employed to manage water resources can be categorized in several ways. One approach is to differentiate between hydrologic and water quality models: (1) hydrology only models that do not consider water quality, except in a few cases sediment transport; (2) water quality only models that rely on an external model for hydrology; and (3) hydrology and water quality models. There are important trade-offs to consider. Hydrology-only models typically have more sophisticated representations of hydrologic processes; these may be simplified in models that also consider water quality since that implies a large set of additional equations. However, some of the water quality models considered here have a rather sophisticated representation of the hydrologic system.

Models also differ in the approach for representing processes, from empirical models that are based on regression equations, to analytical models that use differential equations to provide a continuous or semi-continuous representation of processes, to models based on energy and mass conservation approaches. Almost all models rely on a combination of approaches, but models differ in their degree of reliance on empirical, analytical, or "first-principles" representation.

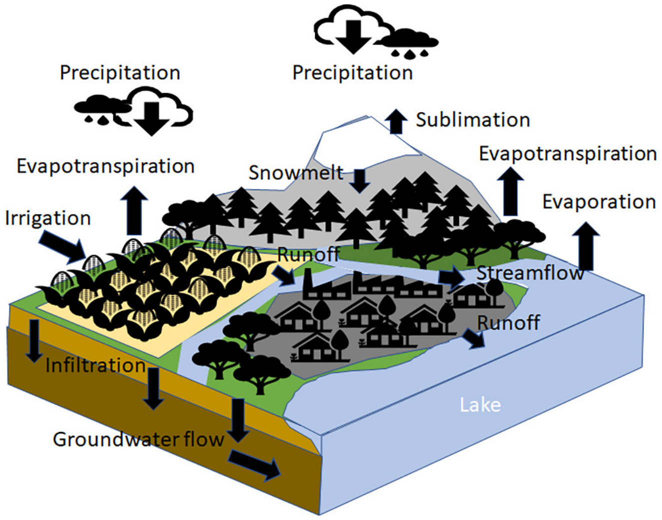

Fig. 1. Hydrologic processes considered in most models. Some models also include explicit representation of human activities that modify the hydrology, such as irrigation, reservoir operation, and groundwater pumping.

Hydrologic models considered in this review include the processes represented in Fig. 1. The completeness in the representation of the hydrologic system is one of the criteria used to evaluate these models. Models can differ substantially in terms of their representation of snow and groundwater complexity and processes, and even in the equations that are considered for common processes, such as evapotranspiration and infiltration. There can also be significant differences in the representation of hydrologic processes within a stream channel. Differences in process representation can result in differences in prediction of hydrographs (i.e., the shape of the wave of water moving after a storm event) and stream velocities, and also streambank erosion and transport of different classes of sediments (e.g., clays, silts, sands, gravels, and even large rocks), and their subsequent deposition as flow velocities decrease.

In terms of water quality, models can consider a heat balance to estimate water temperatures, model conservative chemicals (i.e., those that lack significant reactions with other media, such as chloride, sodium, calcium, and other generally inert and non-sorbing ions), reactive chemicals (e.g., organic chemicals that degrade and sorb onto soils and sediments), and elements with more complex biogeochemical cycles, such as those of nitrogen, phosphorus, oxygen, carbon, and mercury. Water quality models differ in their ability to represent important processes such as atmospheric deposition, loading of chemicals to various land uses (e.g., pesticides and fertilizers), discharge from point and non-point sources into water bodies, and in-stream processes (Fig. 2).

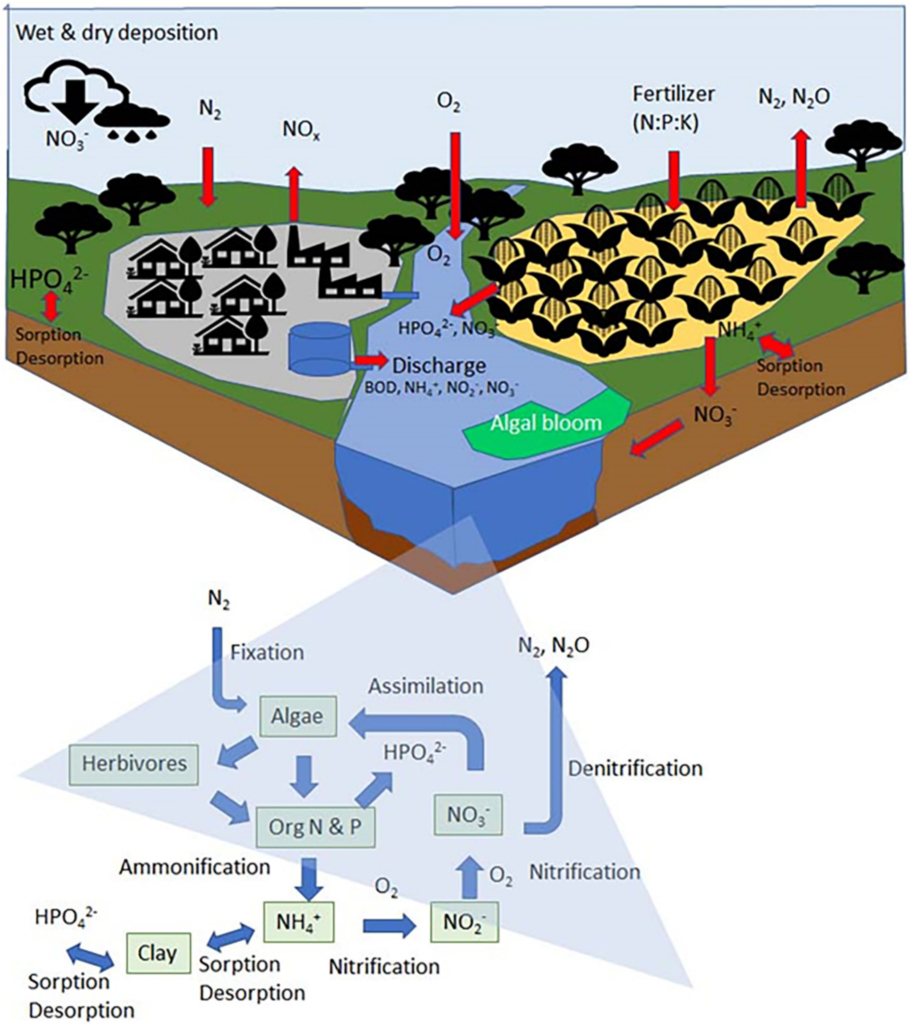

Fig. 2. Typical nutrient processes and their interactions represented in water quality models. Some models also include explicit representation of biogeochemical processes on the terrestrial landscape and soils, as well as human activities that modify these fluxes.

There are several previous studies available that compare different models, which serve to better understand the strengths and weaknesses of these models, as well as to compare performance in terms of ability to match observed results (Devia et al., 2015; Kauffeldt et al., 2016; Kour et al., 2016; Gao et al., 2018; Pandi et al., 2021). Comparative studies have also been performed to evaluate differences in predicted hydrological implications of a changing climate (Surfleet et al., 2012; Xie and Lian, 2013; Golmohammadi et al., 2014; Dams et al., 2015; Karlsson et al., 2016; Tsai et al., 2017; Zhang et al., 2018). In addition, a few studies have reviewed a large number of models (Xu, 1999; Beckers et al., 2009; Devia et al., 2015; Kauffeldt et al., 2016; TetraTech Inc., 2018). These have generally considered either hydrologic models only or water quality models (with and without hydrology). The best studies have defined criteria for evaluating the models, thus providing a more substantiated comparison of models. Since assigning values to various criteria is subjective and depends on how criteria are defined, a qualitative assessment is preferred. In this review we have followed this approach, ranking the models in terms of Low, Medium or High within the various categories. In some cases, the boundaries are grey, resulting in a mixed ranking (e.g., Low to Medium).

Two reviews were particularly useful as a basis for the current review. The first one was conducted by the Forum for Research and Extension in Natural Resources in 2009 (Beckers et al., 2009). The authors reviewed 27 models, focusing only on hydrology, even though a few of the models can also model water quality. Well-defined criteria were used to evaluate the models, particularly with respect to model functionality (i.e., completeness and level of representation of different hydrologic processes). The authors communicated with several of the model developers to clarify issues, and integrated perspectives from select modelers. Many of the models reviewed by that study are included here, with updates that have occurred since the 2009 review. Some of the less common models, or those that are no longer updated, were not considered here.

The second review was an assessment of surface water quality models by Tetra Tech, Inc., for the US Environmental Protection Agency (USEPA) Water Modeling Workgroup, conducted in September 2018(Allen et al., 2018). The authors considered 18 models, including water quality only with several that also have a hydrologic model built in. Some of the models considered land processes as well as water quality in rivers and lakes, while several were "waterbody only" models that do not represent terrestrial processes. These require a separate model for estimating loads from terrestrial compartments to water bodies. While the review did not set out to rank the models, it provided a very recent enumeration of water quality models and provided some of their attributes.

The objective of this current review was to evaluate 21 hydrologic and water quality models (Table 1) using the following approach:

1) Identify hydrological and water quality models that can be used to assess the potential effects of climate change (including extreme events), land use change, and other large-scale changes (e.g., Best Management Practices, renewable power generation), at the watershed scale, on flows and water quality parameters of relevance to water resources and infrastructure managers;
2) Develop an approach to evaluate the models, including a description of input information needed for each of the models identified, as well as possible sources of the inputs;
3) Provide a high-level evaluation of the strengths and weaknesses of each model. Note that the modeler should select the model based primarily on the intended application (Table 1), using the evaluation as a secondary factor.

3. Criteria for evaluating models

Although model evaluation involves some subjectivity and depends on the objectives of the modeling project (e.g., screening vs. detailed, only hydrologic vs. full water quality), the specifics of a region (e.g., cold climate, frequent prolonged droughts, importance of groundwater), and scale (i.e., small vs very large watershed), there are some criteria that can be considered to develop a more objective selection process. Some of these criteria, like model functionality, are important for all modeling projects while others depend on resources and experience using models (e.g., data availability, complexity). Ideally, a model would be easy to implement, data would be readily available, it would have full functionality, be freely available, and have unlimited support. However, all of the models reviewed are complex and require significant amounts of data, and many have some limitations in terms of functionality. Thus, the final selection of a model will depend on the needs and resources available for a project. The following criteria, explained in more detail in the Supporting Information, were employed to evaluate the models:

- Model functionality: Completeness in the representation of hydrologic and water quality processes
- Model complexity
- Applicability to climatic and physiographic settings, and scale(s) at which model is applicable

Table 1
Models considered in this review.

Model	Type	Major application	Reference
CRHM	Hydrology	Cold regions hydrology	(Pomeroy et al., 2007)
DHSVM	Hydrology	Ecohydrology	(Wigmosta et al., 1994; Wigmosta et al., 2002)
HEC-HMS	Hydrology	Watershed and waterbody hydrology	(USACE, 2000)
MODHMS	Hydrology	Surface & groundwater interactions	(HydroGeoLogic, 2000)
PRMS/MMS	Hydrology	Surface & shallow groundwater, and stream routing	(Leavesley et al., 2010)
RHESSys	Hydrology	Ecohydrology	(Tague and Band, 2004)
VIC	Hydrology	Land surface modeling, needs additional stream routing model	(Liang et al., 1994).
WaSIM-ETH	Hydrology	Hydrology in alpine regions	(Schulla, 1997)
WATFLOOD	Hydrology	Flooding conditions	(Bingeman et al., 2006)
WEPP	Hydrology	Erosion from storm events	(Flanagan and Livingston, 1995; Flanagan et al., 2007)
AQUATOX	Water quality	In-stream water quality	(Park et al., 2008)
CE-QUAL-ICM	Water quality	3-D modeling of eutrophication	(Cerco and Cole, 1995)
CE-QUAL-W2	Water quality	2-D version of CE-QUAL-ICM	(Cole and Wells, 2003)
QUAL2Kw	Water quality	1-D river water quality model	(Brown and Barnwell, 1987; Pelletier et al., 2006)
SWMM	Water quality	Stormwater management within land surface, no stream modeling	(Metcalf et al., 1971; Huber and Dickinson, 1992)
WASP	Water quality	In-stream water quality	(Di Toro et al., 1983)
ACRU4	Hydrology & water quality	Agricultural operations	(Schulze, 1995)
EFDC	Hydrology & water quality	Complex hydrodynamics in waterbodies, fate & transport of sediments and pollutants	(Hamrick, 1992)
HSPF	Hydrology & water quality	Management of runoff and chemicals, urban & agriculture practices	(Johanson et al., 1980)
MIKE-SHE	Hydrology & water quality	Surface & groundwater interactions, can add water quality modules	(Abbott et al., 1986; Bathurst, 1986).
SWAT	Hydrology & water quality	Management of runoff and chemicals, focus on agricultural practices	(Neitsch et al., 2002; Arnold and Fohrer, 2005; Gassman et al., 2007; Santhi et al., 2014)
WARMF	Hydrology & water quality	Management of runoff and chemicals, urban & agriculture practices	(Chen et al., 2000)

- Ability to represent future watershed conditions in a long-term planning and/or climate change context
- Ability to model extreme events
- Ability to provide outputs relevant to various needs
- Data sets needed to implement the model regionally are available
- Available sensitivity analysis
- General availability and support

4. High-level evaluation

Evaluation of the models based on the criteria was done at a high level, meaning that it was based on a broad overview of the features and capabilities of the model, information was easily accessible online (e.g., technical descriptions, manuals, publications), as well as evaluation of some of the characteristics in previous studies. In a number of instances, as indicated, the classification (Low, Medium, High) was subjective since it depended on a number of non-quantifiable factors (e.g., complexity of a model). A more detailed explanation of the criteria used for scoring each aspect is presented in the Supporting Information.

For a quick visual comparison, scores and brief notes are presented in Table 2. In addition, the basis for the scores and notes are summarized in the following paragraphs.

5. Functionality: completeness in the representation of hydrologic and water quality processes

Most of the Hydrologic (Hydro) models considered (Table 2) scored High in terms of functionality, since they represent all important hydrologic processes well and, in many cases, have several equations that can be selected by the user (Table S3). The EFDC model is used for modeling hydrodynamics within a waterbody, for which it excels, but does not explicitly model watershed processes, which is an important limitation. Thus, EFDC is considered within the water quality models since it can simulate various water quality processes. The VIC model only considers landscape and soil hydrology, and must be coupled with a stream routing model for a full simulation of the hydrology in a watershed. The PRMS and WaSIM-ETH models have simplified representations of groundwater processes, which is a limitation if groundwater storage is significant in the region of interest. CRHM and WEPP do not consider channel routing, which is an important limitation for modeling flow velocities in river channels. MIKE-SHE is discussed in the third category (hydrologic and water quality models) but would rank High if considered only in terms of hydrologic process modeling. In fact, MIKE-SHE, DHSVM, HEC-HMS, and MODHMS are some of the best models for hydrologic processes that are widely used by the hydrology community.

The Water Quality (WQ) only models (Table 3) are scored Medium in terms of functionality, since naturally any one of them requires two models, a Hydro and a WQ model, to use them, or observed hydrology at sufficient resolution (Table S4). None of these models consider watershed processes, so an additional model needs to be considered to generate pollutant loading that reaches waterbodies. The exception is SWMM, which only models the urban landscape, but does not model the receiving waterbodies. QUAL2Kw can only be implemented for rivers, not lakes nor estuaries.

For Hydro and WQ models (Table 3), three models stand out as High, namely HSPF, SWAT, and WARMF, since they can model watershed hydrology and chemical loading, as well as predicting concentrations in receiving water bodies. They are useful for a wide array of chemicals and require no extra effort from the user to run these chemicals. MIKE-SHE is an excellent Hydro model and it does have a WQ module (ECO model), but it requires some additional effort from the user to implement the ECO model for chemicals of interest. EFDC can be used to simulate WQ in two and three dimensions within the waterbody. RHESSys is a very good Hydro model designed to study ecohydrology, but is limited in its ability to model WQ beyond dissolved organic carbon and total nitrogen. It is thus classified as a Hydro model. ACRU4 is mostly useful for modeling contamination from fertilizers in agricultural settings and thus it scores Medium.

Table 2
Overall scores for hydrologic models. Note that most hydrologic models provide several more outputs, such as soil moisture, evapotranspiration, and snow water equivalents.

Model	Functionality	Simplicity	Applicability	Scale	Represent future	Extreme events	Outputs	Available Data	Available sensitivity	General availability
Hydrology only										
CRHM	M No channel routing	L	H Good for cold	M/H	M Land use change?	H Flooding drought	M Flow	L	H Several	M Free by request, support?
DHSVM	H	L	H	H	M Land use change?	H Flooding drought	H Flow and sediments	M may need interpolation	H Several	L Free, no support
HEC-HMS	H	M	H	M/H	M Land use change?	H Flooding drought	H Flow and sediments	M	H Several	H Free, support
MODHMS	H SW & GW	L	H	M/H	M Land use change?	H Flooding drought	M Flow	L needs detailed soil	L Not explicit	M $, support
PRMS/MMS	M Simplified GW	M	H	M	M Land use change?	H Flooding drought	M Flow	H	H Several	M $, support
RHESSys	M Simplified GW	M	H	L/M	M Land use change?	H Flooding, drought	L/M Flow and N	M	H Several	M Free, no support
VIC	M No channel routing	M	H	H	M	L	M	H	H	H
WaSIM-ETH	M Simplified GW	M	H	M/H	M Land use change?	H Flooding drought	M Flow	M	H Several	H Free, support
WATFLOOD	H	M	H	H	M Land use change?	H Flooding drought	M Flow	H	H Several	M Free, support?
WEPP	M No channel routing	M	M	L/M	M Land use change?	M Flooding	L Sediment	M Observed sediment	H Several	M Free, support?

Table 3
Overall scores for water quality models.

Model	Functionality	Simplicity	Applicability	Scale	Represent future	Extreme events	Outputs	Available Data	Available sensitivity	General availability
Water Quality only										
AQUATOX	M Needs hydro	M	L Only water body	L/M	M Land use change?	L, Low flow conditions	L WQ limited	M Need loading	M Few	H Free, support
CE-QUAL-ICM	M Needs hydro	L (3D)	L Only water body	H high resolution	M Land use change?	M Flooding drought	L/M WQ limited	L Need loading, bathymetry	L Not explicit	M Free, support?
CE-QUAL-W2	M Needs hydro	M (2D)	L Only water body	M variable grid	M Land use change?	H Flooding drought, low flow conditions	M Good WQ	M Need loading	H Several	H Free, support
QUAL2Kw	L/M River only	M (1D)	L Only water body	L/M	M Land use change?	M Drought, low flow conditions	M Good WQ	M Need loading	H Several	M Free, support?
SWMM	L/M Urban stormwater only	H/M	L No waterbody, only urban	L	M Land use change?	H Flooding drought, low flow conditions	M Produces loading and storm flows	H	H Several	H Free, support
WASP	M Needs hydro	M	L Only water body	M/H	M Land use change?	L Low flow conditions	H Excellent WQ	L/M Need loading, bathymetry	M Few	M Free, support?
Hydrology and water quality										
ACRU4	M No snow, ag pollutants	M	M No snow	L/M	M Land use change?	M Flooding drought	M Flow, ag WQ	M Need loading	L Not explicit	L $, support remote
EFDC	M No watershed processes	L	M No watershed	M/H	M Land use change?	H Flooding drought	M No runoff	2D M 3D L bathymetry	H Several	M Free, support?
HSPF	H	L	H	M/H	M Land use change?	H Flooding drought low flow conditions	H Flow, full WQ, sediments	M Need loading	H Several	H Free, support
MIKE-SHE	H needs ECO model for WQ, SW & GW	L	H	H	M Land use change?	H Flooding drought low flow conditions	H Flow, full WQ, sediments	M Need loading	H Several	M $$$, support
SWAT	H	L	H	M/H	H Land use change OK	H Flooding drought low flow conditions	H Flow, full WQ, sediments	H Loading calculated	H Several	H Free, support
WARMF	H	L	H	M/H	H Land use change OK	H Flooding drought low flow conditions	H Flow, full WQ, sediments	M Need loading	M Few	H Free, support

6. Model complexity

As indicated above, all the models considered in this review are quite complex with dozens of equations, in some cases more than a hundred parameters, and parameter values that need to be estimated for every grid cell, Hydrologic Response Unit (HRU), or catchment. In addition, meteorological data need to be of high resolution, both temporally and spatially. For the water quality models, chemical loading also needs to be estimated and distributed across the watershed and in time. Nevertheless, models differ to some extent in their level of complexity as well as the tools that help the user import parameter values sets, interpolate meteorology, and access the parameter values and selection of equations. A simpler model that can represent the system adequately may be more desirable than one with high complexity. On the other hand, a simpler model may not represent a broader set of circumstances.

In terms of the Hydro models, several models score High in complexity, including CRHM, DHSVM, HEC-HMS, MODHMS, WATFLOOD, and MIKE-SHE. These models all have choices for equations to represent hydrologic processes which is very useful for an advanced modeler but requires considerably more effort in implementing the model. In addition, they represent more elements of the hydrologic process which makes them more complex. Some have very good tools (e.g., graphical user interface, interpolation, data import), which helps to reduce an already complex effort. The other models (PRMS, WaSIM-ETH, WEPP, VIC) are less complex, in part because they have fewer hydrologic processes and simpler representation of the system (e.g., groundwater) or choices for the user.

Most of the WQ only models (Table 3) are scored Medium for complexity because they do not require information and equations to model hydrology but, of course, they do depend on some means of determining hydrology which could be from observed flows or from modeling. CE-QUAL-ICM is the only model in this category of High complexity because of the 3-D nature of the inputs and the more complex representation of internal flows within a waterbody. SWWM is of Low to Medium complexity since it requires few inputs, is limited to urban land use, and has an accessible graphical user interface.

All of the full Hydro and WQ models (Table 3) scored High for complexity except ACRU4 since it is limited to agricultural uses and has fewer hydrologic processes. Some of these models have very accessible graphical user interfaces (e.g., SWAT, WARMF) which helps the user make choices, view parameter values, implement the model, and review output.

In the matrix (Tables 2 and 3), the inverse of complexity (i.e., simplicity, but these are not simple models) is displayed.

7. Applicability to climatic and physiographic settings

Almost all the models considered for this review have High applicability in terms of climatic and physiographic settings, and have been applied in many regions around the world. Some of these models have been developed with specific climatic conditions in mind. For example, the CRHM model was specifically developed for cold regions and thus excels in its depiction of snow and glacial processes. Some models have been designed for very mountainous terrain (e.g., WaSIM-ETH). Models with Medium applicability include EFDC and CE-QUAL-ICM which are great models for understanding hydrodynamic processes within a complex, 3-D waterbody but do not represent the watershed and therefore are not as applicable to understanding the full extent of climate and land use change at the watershed scale.

The WQ only models all are limited in their applicability since they do not represent the watershed, except SWMM which does represent the watershed but not water bodies. Therefore, these models are in general less applicable to understand the full extent of climate and land use change at the watershed scale. All of the full Hydro and WQ models except ACRU4 are High in applicability. ACRU4 does not represent snow which could be important in many parts of the world.

8. Scale(s) at which model is applicable

Most of the models considered, in all three categories, fall within the Medium level for scale, able to model from small to medium watersheds. A few stand out in their ability to model large systems and there is evidence in the literature regarding their use in these systems. These include CRHM, EFDC, HEC-HMS, MODHMS, WaSIM-ETH, CE-QUAL-ICM, HSPF, MIKE-SHE, SWAT, VIC, WASP, and WARMF. It should be noted that although these models can be used for very large watersheds or waterbodies (EFDC), there is a trade-off in ability to model a small region within the large system accurately. A few models are best used at small scales, such as AQUATOX and SWMM, since they were developed with this in mind and extrapolation to larger areas is likely to result in significant inaccuracies. In the case of AQUATOX, different reaches in a river can be modeled with different AQUATOX modeling runs which requires additional work and the need to externally connect the output information from one reach to the input of the next.

9. Ability to represent future watershed conditions in a long-term planning and/or climate change context

All the models reviewed here have been used in climate change assessments, some extensively (e.g., SWAT) and others only for very few published studies (e.g., MODHMS, QUAL2Kw). Most of the Hydro and full Hydro and WQ models can be implemented to model land-use change. For most of those that can model land use change, however, this implies setting up two or more models, each with a different land use, and externally creating files to transfer outputs from earlier land use to future land use. Therefore, these models are scored Medium. Only two models are scored High given their ability to more seamlessly model two different land-use periods. SWAT can do this within a single simulation by simply specifying the historical and future land use. WARMF can model two different land use periods with two scenarios within the same model run and can generate output files from the historical scenario that will be the initial conditions for the future scenario.

10. Ability to model extreme events

Most of the models in this review have been used to model periods of flooding or prolonged drought. As discussed in the Supporting Information, modeling extreme events involves trade-offs between accuracy and sensitivity. There were several published studies using the various Hydro models for flooding, drought, or both, except for WEPP which due to its focus on sediment transport has only been used to study flooding. Thus, Hydro models (except WEPP) were scored High in terms of their ability to model extreme events. Since VIC does not model the channel, it does not model flooding, but it can be coupled to routing models that simulate flooding. For WQ models, in general, the additional ability to model low flow conditions is important since, under those circumstances, concentrations may peak due to the reduced volume to dilute chemical loads. WQ models that can estimate concentrations during floods, droughts, and low-flow events include CE-QUAL-W2, SWMM, HSPF, MIKE-SHE (with ECO), SWAT, and WARMF and thus score High. CE-QUAL-ICM, ACRU4, RHESSys score Medium since there is no evidence that they model low-flow conditions explicitly. AQUATOX does not model droughts or floods and thus scores Low.

11. Ability to provide outputs relevant to various needs

Three Hydro models (DHSVM, HEC-HMS and MIKE-SHE) generate estimates of runoff and stream flow, stream velocity, hydrograph peaks and flooding, sediment transport, and reservoir and groundwater levels and thus score High. Seven other Hydro models (CRHM, MODHMS, PRMS, RHESSys, WaSIM-ETH, WATFLOOD, VIC) do not model sediment transport and/or generate limited information on reservoir and groundwater levels and are scored Medium. WEPP does model sediment transport but generates limited information on stream hydrology and lake and groundwater levels resulting in a Low score.

In terms of the WQ models, the WQ only models are naturally limited to only model WQ, requiring modeled or observed hydrology so in general score Low to Medium; some of them (CE-QUAL-W2, QUAL2Kw, WASP) generate a wide range of WQ estimates and score Medium. AQUATOX considers many toxic compounds, but does not model N and DO, and thus scores Low to Medium.

In the full Hydro and WQ models category, four (HSPF, MIKE-SHE + ECO, SWAT, and WARMF) score High since they model a wide range of WQ parameters in addition to hydrology. WARMF stands out from all of these in its ability to model the complex chemistry of mercury processes and concentrations. ACRU4 and RHESSys score Low to Medium given their limited range of WQ parameters.

12. Available data sets to implement the model regionally

In general, the more complex a model, the greater the data needs, either input or observed data, and in many cases both. For example, CRHM requires observed snowpack and glacier extent, which are not common datasets, in addition to more information to accurately model melting rates. WEPP requires observed sediment loading, which is not typically collected at the daily level. Hydro models which use generally available datasets include PRMS, VIC, and WATFLOOD, and thus score High in terms of data availability. Most of the other Hydro models score Medium, except CRHM (needs snow and glacier data), MODHMS (needs detailed 3D soil data). These three models score Low due to their substantial data needs.

For the WQ only models, CE-QUAL-ICM scores Low since it requires both chemical loading data and bathymetry, SWMM scores High since the required datasets are generally available, and the other models score Medium since they require external chemical loading data. For the full Hydro and WQ models, only SWAT scores High, since it has internal information to estimate chemical loading, although the user may still need to verify that the information is applicable for their region of study. All the other models score Medium since chemical loading information needs to be estimated externally from datasets not easily available at the regional scale. EFDC in three-dimensions needs bathymetric data, so it is also scored Medium.

13. Available sensitivity analysis

Having available sensitivity analyses can help to better understand how a model will behave when certain parameter values are adjusted. Conducting sensitivity and uncertainty analyses requires an external shell program that can run thousands of simulations, modifying parameter values for each run according to different approaches. Few models provide a generic shell, so most modelers rely on existing sensitivity analyses to better understand the model. For SWAT, the SWAT-CUP framework allows relatively easy sensitivity and uncertainty analyses, which sets it apart from most other watershed models (Arnold et al., 2012). Sensitivity analyses have been performed for almost all these models and are available in the literature (Table S2). Most of the models scored High since there are several sensitivity analyses covering a wide range of aspects related to the parameters that have the most influence on hydrology or water quality; some include sensitivity to different climate scenarios (Table S2). Two models scored Medium (AQUATOX and WARMF) since only a few studies have been conducted for these models. No studies were found for two models (CE-QUAL-ICM and ACRU4), at least in the published or searchable literature, and thus scored Low.

14. General availability and support

Most of the reviewed models are available for free, and several of them are explicitly and actively supported with updates and user groups. Many of the models considered in the review were developed and are hosted by academic/research groups. Some do provide some support, others don't, unless one is part of the research network. Models that scored High are HEC-HMS, WaSIM-ETH, AQUATOX, CE-QUAL-W2, SWMM, HSPF, VIC, SWAT, and WARMF since they are free and there is good support. Models that scored Medium due to uncertain support include CRHM, EFDC, WATFLOOD, WEPP, CE-QUAL-ICM, QUAL2Kw, and RHESSys. Models that scored Medium because there is a cost to acquire them, even though there is support, are MODHMS, PRMS, and MIKE-SHE. DHSVM scored Low because there was no evident support. ACRU4 scored Low because there is a cost to acquire the model, although there is some support.

15. High-level ranking of models

There are a few models that stand-out in terms of their number of High scores (Tables 2 and 3). The matrix in Table 2 presents the scores of each hydrologic model (L, M, H) with a color code, where High is green, Medium is orange, and Low is Red. A model with mostly green boxes is generally a better option than one with more orange or red boxes. Table 3 presents the scores for the water quality models, with and without a hydrologic model. However, it is important to remember that there is subjectivity to the scores, and for some applications a particular model may not score as high but might still be the best for that objective.

For the Hydro models, HEC-HMS is one of the best choices despite its complexity. If there is a need to model groundwater in detail, MODHMS should also be considered. WaSIM-ETH is also a very good choice if only flow output is needed. Most of the other Hydro models also score High in many of the categories but the limited outputs may be an issue.

The WQ only models have many limitations and thus in general they are not used as much, unless one has a simpler system and one of these models is sufficient. In terms of the full Hydro + WQ models, HSPF, SWAT, and WARMF gathered the most “High” scores, although they are all very complex models given their nature. The user interface and overall user friendliness of SWAT and WARMF make them the best choices, compared to HSPF which suffers from an outdated user experience. In practice, SWAT is the model used the most for full Hydro + WQ studies due to the strong support from USEPA for regulatory purposes (e.g., Total Maximum Daily Loads), large user base, and ease of accessibility.

16. Conclusions

Based on a high-level evaluation, a number of models stand-out in terms of their applicability for assessments of climate change implications for water resources. The results indicate that three hydrologic models, HEC-HMS, MODHMS, and MIKE-SHE, as well as two full hydrology and water quality models, SWAT and WARMF, stand out in terms of functionality, availability, applicability to a wide range of watersheds and scales, ease of implementation, and availability of support. MIKE-SHE can also be used for water quality with the addition of the ECO module, although it does require a higher level of effort and cost compared to SWAT and WARMF. As indicated, the scores have subjectivity, and the decision needs to be made in terms of the watershed modeler's goals, experience and resources available. The results of this work can serve to inform large-scale watershed model intercomparisons, such as those conducted by the Inter-Sectoral Impact Model Intercomparison Project (Warszawski et al., 2014).

CRediT authorship contribution statement

Arturo A. Keller: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing. **Kendra Garner:** Data curation, Formal analysis, Writing – original draft, Writing – review & editing. **Nalini Rao:** Conceptualization, Funding acquisition, Writing – review & editing. **Eladio Knipping:** Funding acquisition, Writing – review & editing. **Jeffrey Thomas:** Funding acquisition, Writing – review & editing.

Data availability

No data was used for the research described in the article.

Declaration of Competing Interest

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2022.161209.

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