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Key Points:

- The catchment scale is of high relevance for simulating irrigation in the context of water resources planning and management
- Only few catchment models provide a full integration of hydrology and plant growth
- There is a growing number of catchment scale irrigation studies, many of which are related to climate change impact and adaptation

Supporting Information:

Supporting Information may be found in the online version of this article.

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Simulation of Irrigation Demand and Control in Catchments – A Review of Methods and Case Studies

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Abstract The world's water resources are continuously facing challenges in fulfilling the needs of increasing agricultural water demand with finite or diminishing resources. Therefore, it is important to quantify the amount of irrigation water required to attain sustainable yield at a local, regional, and global level, especially in arid and semi-arid regions. This is mostly quantified by using agro-hydrological or agricultural models. The advances in simulation models and several options incorporated in them allow catchment/site-specific application of irrigation water to depict the field management practices undertaken by farmers. The objective of the present study is to provide a review of the simulation of irrigation water demand at catchment scale by agro-hydrological and agricultural models. This study discusses the different types of models, their dimensions, and the hydrological and agricultural process models incorporated into them. Additionally, this review provides an overview of how irrigation can be scheduled, how water is applied, and from which sources irrigation water can be extracted by the considered models, taking horizontal hydrological connectivity into consideration. Adding to the model review, seven different fields of innovative case studies are covered. Many agricultural models have been applied in a regional context without simulating horizontal hydrological fluxes, but only a few hydrological catchment models provide full support of both irrigation and plant growth simulation, which are important for the simulation of future crop yield under different climatic and agricultural management scenarios.

1. Introduction

The continuously increasing world population will result in a considerable additional demand for food. It is expected that the global human population will exceed 9 billion by the end of 2050 (Assouline et al., 2015; Roberts, 2011; Tilman et al., 2011). Together with other factors like rising pollution, clean water scarcity is expected to increase drastically by 2050 (Boretti & Rosa, 2019). Further impact on water resources can be expected by the effects of climate change (Elliott et al., 2014). Therefore, the threat of shrinking water resources due to future change emphasizes the need for a smart and sustainable management of future land and water resources (Ali & Talukder, 2008; Rosa et al., 2020). Considering that most of the agriculture in the world is rainfed (Rost et al., 2008), an important strategy is to enhance the role of efficiently irrigated agriculture, thereby increasing crop yield per unit land (Rockström & Falkenmark, 2000; Scanlon et al., 2007; Siebert et al., 2005) and per unit water consumed under water scarce conditions (Fereres & Soriano, 2007).

Water consumption in irrigation is the most dominant water use in many parts of the world (Bruinsma, 2003), particularly in semi-arid and arid regions, and is expected to grow under global change (Fereres & Soriano, 2007; Rockström & Falkenmark, 2000; Scanlon et al., 2007; Siebert et al., 2005). It is expected that at the end of 2080 irrigation water requirements will increase over 50% in developing and 16% in developed regions (Fischer et al., 2007). Therefore, irrigation is a major field of interest in investigations related to food production, hydrology, water resources management, economy, and other fields on local level (farm management), regional level (resources management within catchments and irrigation command areas), national level (economics and services for the public) to continental and global level (global food safety and United Nation's sustainable development goals, SDGs).

In the light of growing concerns about water and food under global change, there have been numerous impact studies in the last years, where the quantitative simulation of future irrigation water requirement using different conceptual and process-based models plays a central role, either from a hydrological or an agricultural perspective, or from multiple perspectives (Fischer et al., 2007; Wisser et al., 2008; Wada et al., 2013).

Irrigation, as a human intervention to natural processes, places this field of research and practice not only in a very complex, but also in an interdisciplinary context. The simulation of irrigation is implemented into models of different sectors and fields of application. The concept of irrigation modeling using agro-hydrological models dates back to the 1980s (Bastiaanssen et al., 2007). We define here agro-hydrological models as such simulation models, which simulate water fluxes between soil, vegetation, and atmosphere but also include components for the implementation of agricultural management practices related to water. These models should be able to simulate plant water uptake, irrigation, crop growth, and crop yield at harvest. Other aspects of modeling include the spatial and temporal scale of analysis, the computational demand, data availability and data needs of the models, the underlying modeling equations, the level of testing and validation the model has undergone, and uncertainty analysis. Water resources planning and decision making are usually performed at regional (river catchment, irrigation command area) to national level. Therefore, it is important to simulate the irrigation water requirement and irrigation scheduling at that scale compared to the conventional field scale (Woznicki et al., 2015). However, data-driven uncertainties for irrigation water requirement simulations at large scale can be up to ±70% (Uniyal et al., 2019; Wisser et al., 2008). Model application at larger than field scale is mostly done in a planning context, but model applications in an operational context can be done for near-term prediction of irrigation water requirement based on the weather forecast. An early study was done with the hydrological model EPIC-PHASE for managing irrigation based on the soil water depletion (Cabelguenne et al., 1997).

This review aims to provide an overview about available modeling approaches for the design, control, and impact analysis of irrigation systems at catchment scale, that is, river catchments, irrigation command areas, national and sub-national administrative areas, where in all cases horizontal water fluxes and quantitative analyses of water resources availability and demand are involved. The review covers three-dimensional agro-hydrological catchment models as well as one-dimensional models if they have been applied at catchment scale. We focused on these aspects:

i. Model structure: implementation of hydrological and agricultural processes, in particular irrigation control;
ii. Availability of distributed hydrological and irrigation data;
iii. Calibration, validation, and uncertainty analysis in agro-hydrological modeling;
iv. Selected applications of catchment scale irrigation modeling; and
v. Emerging fields and challenges of catchment scale irrigation modeling.

After a categorization of the models we synthesize selected case studies, we conclude about the state of catchment scale irrigation modeling and give future implications.

2. Concept and Notion

Agro-hydrological models mainly differ with their overall concept (conceptual or mechanistic), the process representation (model structure including equations), and their dimensionality (typically 1-D or 3-D plus time). This review is not focused on a certain class of hydrological models but covers models, which can simulate irrigation water demand and irrigation control, where automatic irrigation control is dynamically done by the model based on certain criteria. This is due to the application for predictions, which is a major motivation for applying a model in water resources planning. Irrigation is the amount of water supplied to the agricultural field to supplement the water available from rainfall, soil moisture in the root zone, and the contribution of soil moisture from the shallow groundwater (Michael, 1978). It is applied to fill a gap between (a) the water demand of plants for growth and transpiration and (b) the plant available water in the root zone. As the review covers the catchment scale, the models usually incorporate equations for runoff generation and groundwater recharge. At that scale, the reviewed models do not simulate the conveyance of irrigation water and the functioning and control of field scale structures. For a review of surface irrigation models see Valipour et al. (2015). The coupling of agro-hydrological models with economic models is addressed by Expósito et al. (2020). This study does not cover the broad field of coupling hydrological and agricultural models, for which Kanda et al. (2018) and Siad et al. (2019) provided reviews. Nevertheless, our review includes several agricultural models, typically 1-D, which were applied in a catchment scale context with a focus on agricultural irrigation water demand.

The spatial extent of the model area, which we here also refer to as the scale of application, plays an important role depending on the motivation of the simulation study. This is different from the spatial resolution of the models. High computational resources nowadays allow to apply models on larger scale, which have been originally developed for smaller scales. Vice versa, there is a limitation due to the simplification of processes, but also global scale models are developing toward refinement of processes and higher spatial resolution. Specific models for very large basins, continents, or global studies offering irrigation capabilities are Variable Infiltration Capacity Model (VIC; Chen, Niu, et al., 2018; Liang et al., 1994), Global Irrigation Model (GIM; Döll, 2002), and LPJmL (Biemans et al., 2011). Telteu et al. (2021) provide a comparison of global water models including their capabilities of simulating irrigation. Field to catchment scale models like AquaCrop (Silvestro et al., 2017), HYPE (Arheimer et al., 2020), and SWAT (Abbaspour et al., 2015) have been applied for very large-scale studies. In this review study, the authors focus on studies conducted on a catchment scale, which is defined here from a functional point of view, covering an area of interest for the planning and management of water resources (Woznicki et al., 2015). Additional to natural river catchments described by water divides, there can be other spatial units of water resources management like irrigation command or project areas. Therefore, processes are simulated at three dimensions (3-D), which comprise the horizontal spatial extent of the investigation area plus at least the rooting depth of the plants as the vertical spatial extent. In many cases, groundwater is included, at least shallow aquifers. For this review, the authors have considered only those studies which investigate irrigation either by simulating with 3-D models on catchment scale, or by up-scaling 1-D model results to quantify irrigation on catchment scale. The latter can be done by identifying areas that are homogenous with respect to soil and hydrological properties (Wesseling & Feddes, 2006). The authors did not find relevant applications of data-based models, which are uncommon for simulating irrigation.

The Scopus database was used to search articles available until July 2020. A subselection of articles was made from more than 300 articles dealing with irrigation at catchment scale. References were organized with the Citavi literature management software. The authors chose articles, which introduced a new agro-hydrological model with irrigation capabilities, extended the irrigation routines of existing models, or applied the available models for an innovative case study dealing with irrigation. The innovation of a case study was defined by validating an established model, applying a modeling technique first time in the field of irrigation or by simulating a region of higher global relevance. Follow-up studies, repeated model applications, and case studies of mostly local interest have been excluded. Our review focuses on showing the current state of simulating irrigation on the catchment scale, but it is not intended to give a complete overview of all regional irrigation studies. For structuring the review, an interactive segregation of all selected articles was done by using the knowledge organizer within Citavi (Figure 1).

3. Representation of Catchment Scale Irrigation Processes and Management in Agro-Hydrological Models

In this study, a total of 13 agro-hydrological models were analyzed, which are suitable and well documented for simulating irrigation water requirement at catchment scale. The representation of natural processes and agricultural management within these models are presented in the following subsections. Detailed model properties are listed in Tables 1–3. Further models are referenced within the case studies presented in Section 4.

3.1. Representation of Natural Processes

Out of the considered models, APEX (Gassman et al., 2010; Williams et al., 1995), HYPE (Lindström et al., 2010), MIKE SHE (Abbott et al., 1986), SWAT and SWAT+ (Arnold et al., 1998; Bieger et al., 2017; Gassman et al., 2007), and WEAP (Raskin et al., 1992; Yates et al., 2005) are agro-hydrological models typically applied at catchment scale, whereas APSIM (Holzworth et al., 2014; Keating et al., 2003; McCown et al., 1996), CropWat (Smith, 1992), AquaCrop (Raes et al., 2009; Steduto et al., 2009), DAISY (Hansen et al., 1990, 2012; Styczen et al., 2010), DNDC (Gilhespy et al., 2014; Li et al., 1992; Zhang & Niu, 2016), DSSAT (Jones et al., 2003), and SWAP (Kroes et al., 2000, 2017) are agricultural crop models, which have often been applied at larger scales in the context of water resources management. WaSiM is mainly a hydrological model but has irrigation functionality (Hess, 2000; Jasper et al., 2002; Schulla, 1997). The mentioned

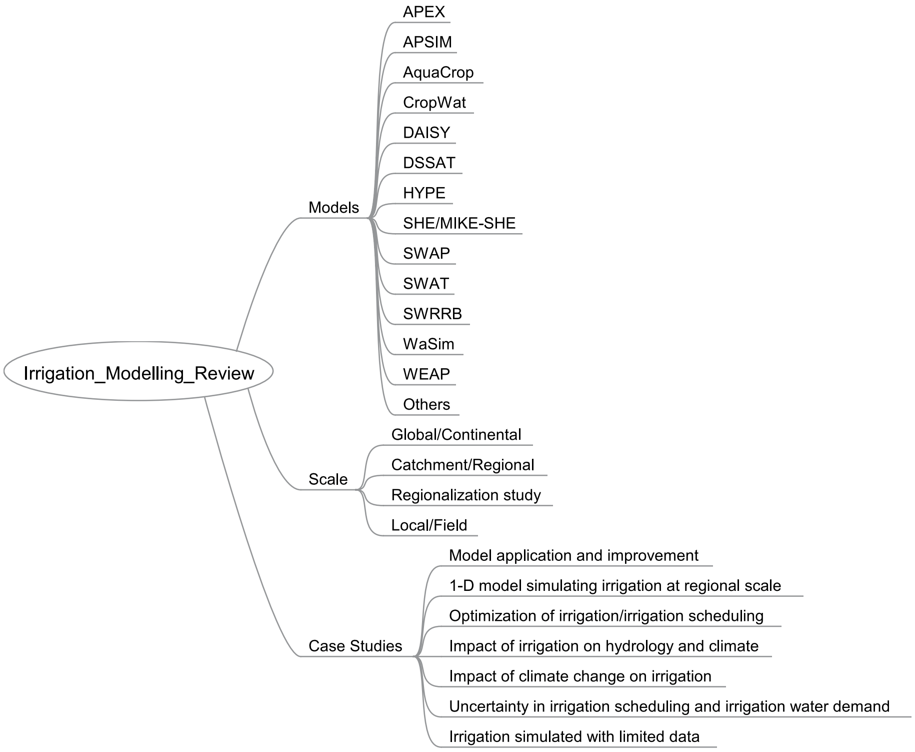

Figure 1. Mind map of review of irrigation modeling studies at catchment scale.

Table 1
List of Relevant Hydrological and Crop Growth Processes Used in the 13 Agro-Hydrological Models Considered in This Review (See Appendix A1 for More Details)

	Hydrological model type			Plant growth model type			
Model	Mechanistic	Conceptual	Dimension	Energy-driven	Biogeo-chemical	Water-driven	Others
APEX	–	y	3	y	–	–	–
APSIM	y	y	1+	y	–	–	y
AquaCrop	–	y	1	–	–	y	–
CropWat	–	y	1+	–	–	y	–
DAISY	y	–	2	–	y	–	–
DNDC	–	y	1–3	y	–	–	–
DSSAT	–	y	1	y	y	–	–
HYPE	–	y	3	–	–	y	–
MIKE SHE	y	–	3	–	–	–	–
SWAP/WOFOST	y	–	1	–	y	–	y
SWAT/SWAT+	–	y	3	y	–	–	–
WaSiM	y	y	3	–	–	–	–
WEAP	–	y	3	y	–	y	–

Note. 1+ dimension: simulates 1-D but supports multidimensional analysis, for example by combining locations within an irrigation scheme. CropWat: scheme values, APSIM: water transfer from sources in a catchment.

models with irrigation capacities can be conceptual or mechanistic in terms of representing the processes. Mechanistic models solve analytical equations for the underlying physical processes. Models, which use Richard's equation for describing the movement of water in the unsaturated soil, are classified here as "mechanistic" (Table 1). Table 1 summarizes the type of hydrological as well as plant growth model present in the different agro-hydrological models considered in this review. Mechanistic models include APSIM, DAISY, MIKE SHE, SWAP, and WaSiM. The authors classify models as "conceptual" models, when they use more simplified but still physically based equations, which may be partially derived from empirical knowledge. Conceptual models often use a bucket/cascade bucket approach for soil water movement, like in APEX, HYPE, SWAT, DSSAT, and WEAP. It can be seen from Table 1 that 10 models considered in this study are conceptual whereas 5 agro-hydrological models are mechanistic in nature. In addition, WaSiM and APSIM offer a choice between mechanistic and conceptual equations for soil moisture movement. Out of the agro-hydrological models selected for this review, six of the models are one-dimensional and the rest are two/three-dimensional models (Table 1).

Most agro-hydrological models use a generic crop model for all types of crops, but crop coefficients vary amongst different crop types (e.g., EPIC). In few models (e.g., SWAP and DSSAT) users can choose a specific model depending upon the type of crop and data availability (Table 1). There is a large number of crop models available, for which worldwide intercomparisons have been performed in recent years (Rosenzweig et al., 2013). Crop growth models are here classified according to their method for biomass production (Nair et al., 2012). In energy-driven models, biomass is proportional to the radiation use efficiency (RUE). Another class of models incorporates a biogeochemical model, which can simulate the process of photosynthesis including carbon assimilation. Crop growth processes and phenological development in biogeochemical models are controlled by temperature, radiation, and carbon dioxide concentration. RUE models have advantages in their simplicity, while biogeochemical models allow a more process-based representation of plant growth. In water-driven models, biomass is directly proportional to the crop transpiration rate (Kanda et al., 2018; Todorovic et al., 2009). Most of the agro-hydrological models considered in this study are energy-driven (six models) or water-driven (four models) followed by biogeochemical (Table 1). Two models do not have a dynamic plant growth model but implement plant growth via time-dependent vegetation parameters like leaf area index (LAI) and maximum rooting depth (MIKE SHE and WaSiM). Such approach allows the simulation of plant water demand but not the simulation of crop yield. For climate change impact studies, these models may require external calculations of the respective plant parameters.

3.2. Representation of Irrigation Scheduling

Agro-hydrological models simulate irrigation water demand in terms of time (when?) and water amount (how much?) based on the hydrological and plant growth processes. They do not usually consider the technical real-time control of irrigation operations at farm level. In agro-hydrological models, the quantitative water demand of plants is combined with agricultural management aspects, like the frequency of irrigation operations or the implementation of water-saving strategies. As a result, the scheduling of irrigation operations is the core process of human-environment interaction, which can be found in agro-hydrological models of all types and scales as discussed in Table 1.

Irrigation scheduling techniques vary amongst different models. Table 2 summarizes the type of irrigation scheduling, how irrigation water is applied by a specific model, sources of irrigation, irrigation application techniques, and system losses defined in the different agro-hydrological models considered in this study. The triggering (starting) of irrigation operations and the amount (dose of water) to be irrigated are implemented by most of the models by two different methods: (a) user-defined (manual) scheduling given by a pre-defined scheme and (b) automatic scheduling based on current hydrological and/or plant conditions. The rationale of user-defined scheduling is the simulation of real practice, which is important for calibrating agro-hydrological models against the field data. The rationale of automatic scheduling is the rule-based simulation of irrigation when field data are not available, for example, when predicting future irrigation as a response to weather or climate. Both scheduling methods can use fixed or variable amounts of water. It can be seen from Table 2 that all the considered agro-hydrological models have options for manual irrigation scheduling and for triggering automatic irrigation based on soil moisture deficit. Most of the models also support automatic scheduling by plant water demand.

Table 2
Irrigation Modules Implemented in the 13 Agro-Hydrological Models Considered in This Review (See Appendix A1 for More Details)

	Irrigation scheduling					Irrigation water amount applied						
Model	Manual	Plant water demand	Soil moisture deficit	Dose restrictions	Frequency restrictions	Fixed and variable dose	Up to field capacity fc	Soil moist thres FAO-56	Partial fill of fc deficit	Target flooding level	River water	Ground-water
APEX	y	ET	y	y	–	y	y	–	y	–	–	–
APSIM	y	–	y	–	–	y	y	–	–	–	y	y
AquaCrop	y	–	y	–	–	y	y	–	y	–	–	–
CropWat	y	kc	y	y	–	y	y	–	y	–	–	–
DAISY	y	ET	y	y	–	y	y	–	y	–	–	–
DNDC	y	–	y	–	–	y	y	–	–	y	–	–
DSSAT	y	ET	y	y	y	y	y	–	y	–	–	–
HYPE	–	kc	y	–	–	y	y	y	–	–	y	y
MIKE SHE	y	y	y	–	–	–	y	y	y	y	y	y
SWAP/ WOFOST	y	ET	y	y	–	y	y	–	y	y	–	–
SWAT/ SWAT+	y	ET	y	y	–	y	y	–	y	y	y	y
WaSiM	y	ET	y	–	–	y	y	–	y	–	y	y
WEAP	y	kc	y	–	–	y	y	–	y	–	y	y

Note. Source partitioning: water can be mixed from different sources, Non-specific source: some models do not care about where the water is from, but they always have a source, if not explicitly mentioned we classify as non-specific.

*ET: evapotranspiration.

All models considered in this study have the capability to apply user-defined irrigation scheduling with a fixed dose on a specific date. Then, a given amount of irrigation water (as volume or depth per unit area) is applied by the model (Table 2). Based on the climatic water balance or empirical knowledge of farmers, seasonal irrigation schedules with variable doses can be developed. In case of variable dose and automatic scheduling, irrigation triggering as well as irrigation water amount are automatically applied by the model based on the soil/plant water demand. Some models allow to give a fixed dose always when the automatic scheduling triggers an irrigation operation. This can be justified by technical or management reasons to increase the efficiency of operation.

The main algorithms used for automatic scheduling of irrigation operations are based on a deficit of water supply, or on plant stress because plant water demand due to evapotranspiration needs to be compensated. Additionally, some models have an option of triggering based on precipitation deficit (water balance approach) and partial root drying (DAISY). A user must define the threshold for soil water deficit in mm (APEX, SWAP, SWAT, etc.) or as a fraction (APSIM, DAISY, MIKE SHE, etc.). In case of plant water demand triggering algorithm, some models start irrigation when a user-defined stress indicator falls less than the ratio of actual to potential evapotranspiration (SWAP, SWAT, etc.). However, other models trigger irrigation based on some of the following conditions: (1) predefined crop-specific threshold depending upon the level of water stress a specific crop can withstand (APSIM), (2) water use efficiency of crop and on crop stage (CropWat), (3) evapotranspiration between two consecutive irrigation events (HYDRUS), and (4) crop coefficients (HYPE and MIKE SHE). MIKE SHE provides an option to trigger the irrigation based on the ponding depth in case of submerged crops like rice. All models allow to fill soil water up to field capacity and most of the models allow partial filling, which is important for the implementation of deficit irrigation strategies. This is irrigation practice where water supply is reduced below maximum levels and mild stress is allowed with minimal effects on yield (FAO, 2002).

Apart from how irrigation is applied in the agricultural/hydrological models, it is also important to know the source of irrigation water, the conveyance and the application on the field, irrigation application tech-

Table 2
Continued

Sources of irrigation water withdrawal				Irrigation application techniques								System losses		
Reservoir/ lake/pond	Unspeci- fied	External	Inter-basin water transfer	Source partition- ing	Flood irrigation	Basin/ ponding	Furrow Furrow	Sprink- ler	Trickle/ drip	Sub surface	Unspeci- fied	Overall efficiency	Convey ance	Appli cation
–	y	–	–	–	–	y	y	y	y	–	–	–	–	–
y	y	–	y	y	–	–	–	–	–	y	y	y	–	–
–	y	–	–	–	y	y	y	y	y	–	–	y	–	–
–	y	–	–	–	–	–	–	–	–	–	y	y	–	–
–	y	–	–	–	y	–	y	y	y	y	–	–	–	–
–	y	–	–	–	y	–	–	y	y	–	–	–	y	y
–	y	–	–	–	y	y	y	y	y	–	y	y	–	–
y	y	y	y	y	–	–	–	–	–	–	y	y	y	y
y	–	y	–	y	y	y	–	y	y	–	–	–	–	–
–	y	–	–	–	–	y	–	–	–	–	y	y	–	–
y	y	y	y	y	y	–	–	–	–	–	y	y	y	y
–	–	–	–	–	–	–	–	–	–	–	y	–	–	–
y	–	–	–	y	y	y	y	y	y	–	–	y	–	–

niques (e.g., surface, drip, basin, or sub-surface irrigation) together with the losses occurring on each of the steps. Common irrigation water sources like rivers, reservoirs/ponds/lakes, or groundwater wells are implemented by all 3-D models. Sources from outside the model domain can be defined in HYPE, MIKE SHE, WEAP, and SWAT. Some models allow to combine different sources. However, in some field-scale models, the source of irrigation water is not defined (APEX, DAISY, SWAP, etc.), so extraction of water does not reduce water volume in another location.

Here, the 3-D catchment models have a clear advantage over 1-D models when simulating a regional system. Irrigation water can be applied on the field by using different techniques like flood/sheet, drip, and sprinkler irrigation. In some models like HYDRUS, SWAP, and WEAP, users can specifically define an irrigation technique. However, in other models, users can give a value for irrigation efficiency (total or application and conveyance) to represent the losses occurring during an irrigation event in a catchment. The water finally applied is added with the losses to get the amount of water to be extracted from the source. Agricultural 1-D models often use total efficiency or losses only because the water lost will not be given back to the system, as it happens in 3-D models. There is no model, which incorporates the most common irrigation application techniques together with a differentiated accounting of the respective losses during conveyance and application. On a catchment scale, simplified calculations of systems efficiency or losses are more common.

It can be concluded from Table 2 that all 13 agro-hydrological models considered have an option of irrigation trigger using soil moisture deficit, and 12 support irrigation scheduling using manual-based irrigation routines, which is only missing in HYPE but important for implementing observed experiments or strategies based on local knowledge. Plant demand or plant stress-based scheduling is implemented in 10 of the models. The majority of the models supports unspecific irrigation sources, which allows flexibility but demonstrates the lack of irrigation process implementation at field scale in this class of models.

Table 3
Irrigation, Crop Management Operations, and Policies Implemented in the 13 Agro-Hydrological Models Considered in This Review (See Appendix A1 for More Details)

	Irrigation policy and management options							Other crop management							
Model	Crop priority	Water rights/ restrictions	Deficit irrigation	Scenario development	Salinity control	Environmental flow	Irrigation water reuse	Crop rotation	Tillage, ploughing	Planting, harvesting	Artificial drainage	Grazing	Fertilizer application	Pesticide application	Others
APEX	–	y	–	y	–	–	–	y	y	y	y	y	y	y	y
APSIM	y	y	–	y	y	–	–	y	y	y	–	y	y	y	y
AquaCrop	–	–	–	–	y	–	–	–	–	y	–	–	–	–	y
CropWat	–	–	y	y	–	–	–	–	–	y	–	–	–	–	–
DAISYY	–	–	y	–	y	–	–	y	y	y	y	–	y	y	y
DNDC	–	–	–	–	y	–	–	–	y	y	–	y	y	–	y
DSSAT	–	y	–	–	–	–	–	y	y	y	–	–	y	y	y
HYPE	–	–	–	–	–	–	–	y	y	y	y	–	y	–	–
MIKE SHE	y	y	–	–	–	–	–	y	–	y	y	–	–	–	–
SWAP/ WOFOST	–	–	–	–	y	–	–	y	y	y	y	–	y	–	y
SWAT/ SWAT+	–	–	–	–	–	y	–	y	y	y	y	–	y	y	y
WaSiM	–	y	–	–	–	–	–	–	–	–	y	–	–	–	y
WEAP	–	y	y	y	–	y	y	–	–	y	–	–	y	–	–

Note. Crop priority: if there is water scarcity, crops can be prioritized, Water restriction/rights: refers to limitation of annual amounts not single doses, Deficit irrigation as policy: it should be related with yield loss like done in CropWat: Irrigation is given if a certain loss threshold would be surpassed in case of continued water deficit, Scenario development: usually can be done outside of the model, but different preparations are available, Salinity control: here overirrigation to reduce soil salinity. Requires EC and salt transport. This does not necessarily mean that yield loss due to salt is calculated. Environmental flow: control of minimum stream flow of rivers in or downstream of the irrigation area. Usually only limits water extraction from rivers. Irrigation water reuse: allows to directly divert irrigation return flow from one unit to another unit to be used as irrigation water source.

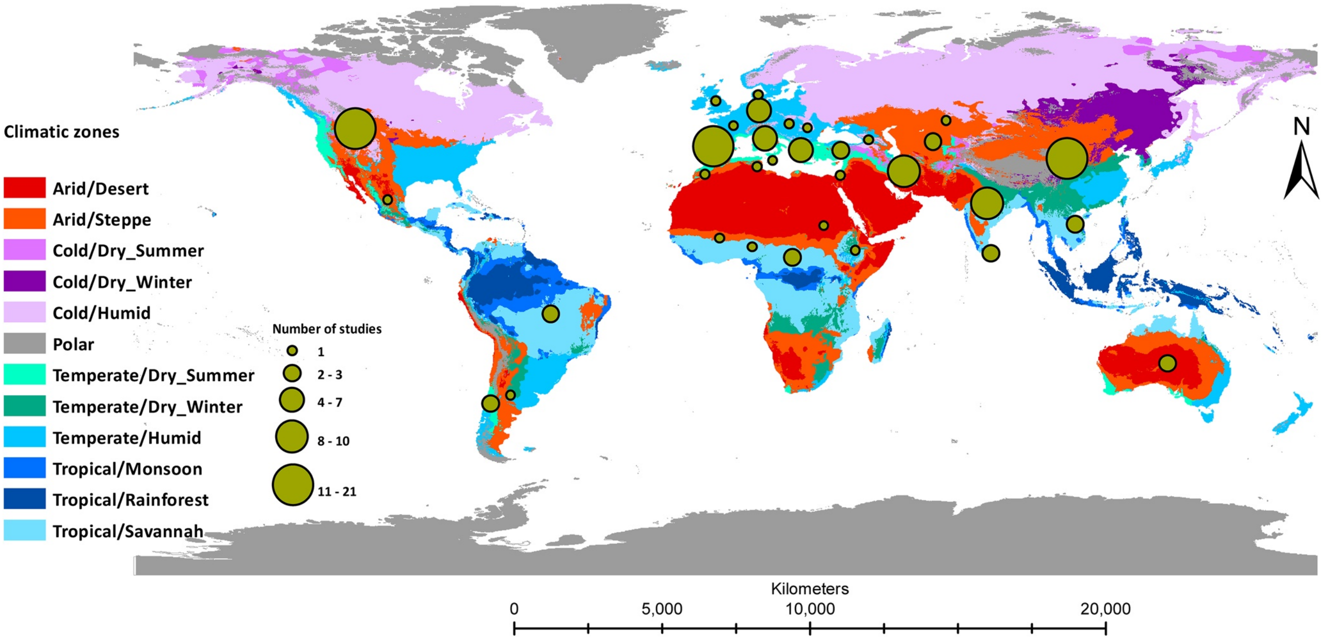

Figure 2. Global distribution of selected irrigation studies at catchment scale. *This figure comprised worldwide studies conducted on watershed-level/irrigation command area to simulate/quantify irrigation water demand according to the selection criteria as explained in Section 2.

3.3. Management Options

To use agro-hydrological models for water resources management, it is necessary that a user can implement certain rules that represent real-world water extraction and transfer rules on a catchment scale. These rules can be in terms of hydrology-related irrigation policy implementations like a specific amount of water that can be released from a reservoir or a specific level of groundwater depletion being allowed in a catchment. It is also important to consider environmental flow and the functioning of water-depending ecosystems to design holistic and sustainable water resource management plans. Table 3 provides an overview about irrigation and other crop management operations and policies implemented in terms of water rights and water use restrictions, yield optimized deficit irrigation control, salinity control, environmental flow, irrigation water reuse, crop rotations, artificial drainage, fertilizer application, grazing, etc., implemented in the considered agro-hydrological models. HYPE, DSSAT, MIKE SHE, and SWAT models have simple functions that limit the amount of water abstraction for irrigation as defined by the user (Table 3). Agricultural management includes crop planting, tillage, harvesting, and drainage, which is supported by most of the models. Only a few models like APEX and WEAP provide economic calculations, which are helpful in designing and optimizing policies and management decisions. APSIM and MIKE SHE can prioritize drought-sensitive crop types if the irrigation supply is less than the irrigation demand. Whereas most models allow a partial fill-up of field capacity, only a few models have incorporated deficit irrigation strategies, which allow a compromise between saving irrigation water and the reduction of crop yield. Here, CropWat is most developed but also DAISY and WEAP have incorporated similar functionality. In general, six models have an option to implement water rights and water use restrictions and five models have an option to implement salinity control mechanism into them but only WEAP allows the reuse of irrigation water. More details can be found in Appendix A1.

4. Irrigation Modeling Case Studies

A total of 115 relevant studies conducted at catchment scale for simulating irrigation using agro-hydrological models have been selected out of more than 300 studies according to the criteria listed in Section 2. The map in Figure 2 shows the number of selected irrigation studies at catchment scale performed in different countries along with the modified Köppen's climate zones. It can be seen from the figure that most of the studies are concentrated in Asia (China, India, and Iran), Europe (Germany, Spain, and Italy), and the

United States. As irrigation is highly important for crop growth in arid climatic zones (shown by red and orange color) therefore there is a need to conduct more irrigation studies in these areas as well. The following Sections 4.1–4.7 will focus on catchment studies dealing with model application of different models in irrigation simulation, evaluation of irrigation scheduling, impact of climate change of irrigation, effect of irrigation on different conservational strategies, and so on.

Table S1 provides a summary of main available attributes of the selected case studies in terms of catchment characteristics, models used for quantifying ET, soil moisture and crop growth, irrigation trigger, source, type and water allocation, and information about the calibration process undertaken by the authors of the selected studies. It can be seen from this table that a range of agro-hydrological models is used for quantifying irrigation water demand at catchment scale out of which SWAT was favored by many researchers in the considered studies. The highest number of selected studies were in China and United States (USA). Many climatic zones from humid to arid are covered, where the majority of studies lie within temperate/dry to arid regions in the Northern hemisphere, which can be explained with deficits in the climatic water balance plus the availability of resources for installing irrigation systems. In Afrika, there was a comparably low number of studies, which can be explained by the dominance of rainfed agriculture among other reasons. The catchment area is rather small for some detailed studies but covers up to 71,000 km^2. Most of the studies have used Penman-Monteith for ET calculation and bucket model for soil moisture movement followed by soil water deficit as an irrigation trigger mechanism with irrigation sources ranging from canals, reservoirs to outside sources. The calibration method was sometimes not documented. Manual calibration is very common but some studies used automatic tools. Furthermore, Table S1 provides information about which objective function (e.g., NSE, PBIAS, etc.) was used in a specific study for calibrating which hydrological variable (e.g., streamflow, crop yield, irrigation amounts, etc.). Also, it provides information about the use of observed irrigation data as well as the use of reanalysis and other remote sensing products (ET, leaf area index, etc.).

4.1. Catchment Model Improvement

This section presents case studies about the improvement and validation of existing irrigation modules/sub-routines in the widely used (agro-)hydrological models WaSiM, WEAP, and SWAT as introduced in Section 3. Uribe-C et al. (2009) extended WaSiM by the incorporation of a crop coefficient (K_c) method, which can be operated with less variables. This version of WaSiM allows its application in data scarce regions. Within a case study in Chile, the authors achieved good results on larger scale, whereas the model showed more uncertainties in small agricultural basins. WEAP has a more simplified model for computation of irrigation water demand. Agarwal et al. (2019) applied WEAP with the so-called MABIA extension in India. MABIA adds a dual crop coefficient approach like CropWat for calculating plant water demand on a daily basis compared to the typical application of WEAP with monthly time steps. Most of the model improvement studies were found to deal with the widely used agro-hydrological model SWAT. Santhi et al. (2005), Kannan et al. (2011), and Xie and Cui (2011) improved the capabilities of SWAT for regional planning of irrigated agriculture by incorporating a canal irrigation module and new processes for paddy, an improved multi-source irrigation SWAT module was also proposed by Wu, Cui, Xie et al. (2019). Galelli et al. (2010) built a metamodel to represent the dynamic irrigation water demand to design the reservoir water release routines in Italy. The modified SWAT was validated at an intensive agricultural catchment located in Texas and Zhanghe Irrigation District, China, respectively. Lecina et al. (2011) developed a combined approach to evaluate irrigated areas based on irrigation performance analysis and preliminary water accounting. This approach was tested on a surface irrigated area (1,213 ha) of Bear River Irrigation Project located in Utah, USA. The results revealed that there is a decrease in water depletion in the study area due to better irrigation performance. Dechmi and Skhiri (2013) modified and verified the modified SWAT (SWAT-IRRG) model for an agricultural catchment under intensive irrigation to incorporate the irrigation return flow into the water balance calculations. Wei et al. (2018) developed a new methodology to apply SWAT in highly managed irrigated agricultural catchments. This includes the designation of every cultivated field as a hydrologic response unit (HRU) and including recorded crop rotations, scheduling irrigation based on water rights, and seepage simulation from earthen irrigation canals. Chen, Marek, et al. (2018) and Uniyal and Dietrich (2019) modified the auto-irrigation subroutine of SWAT and validated their modified model corresponding to observed irrigation data located at Texas, US and Hamerstorf, Germany, respectively.

Results revealed that there has been a tremendous improvement in the simulation of seasonal irrigation water amounts simulated by the modified model in both cases. Chen et al. (2020) further improved the SWAT irrigation module of Chen, Marek, et al. (2018) by stopping the irrigation application once the crop is harvested. This has reduced the overestimation of SWAT simulated irrigation amounts compared to the observed irrigation amounts for Palo Duro watershed in the United States. Liu et al. (2020) used SWAT and SWAT-MODFLOW to quantify the streamflow response corresponding to groundwater abstractions for either irrigation or drinking water at catchment scale. The results indicated that groundwater abstractions for drinking water reduced streamflow, whereas groundwater abstractions for irrigation produced a slight increase in streamflow due to return flow on site.

4.2. Application of One-Dimensional Models for Simulating Irrigation in Catchments

Many water management decisions are made on a regional level and decision-makers cannot simply use 1-D models for this purpose. In this case, upscaling of 1-D hydrological models is performed for simulating irrigation water demand within catchment areas. Droogers and Bastiaanssen (2002) combined satellite data (Landsat Thematic Mapper) with the SWAP model for translating the spatially distributed data into the hydrological model with stochastic input data. Later, the annual water balance component is simulated during the irrigation season 1998 for western Turkey to conduct irrigation performance analyses. It was seen from the results that the probabilistic simulations are in the expected range of water balance components. Ines et al. (2006) conducted a stochastic data assimilation, where model inputs for regional modeling were estimated by minimizing the residuals between the distributions of SWAP simulated ET and by surface energy balance algorithm for land (SEBAL) using two Landsat images in Haryana, India. Later, water management optimization was performed under numerous water availability conditions. It can be seen from the results that adjusting sowing dates and its distribution in the irrigated area could enhance the regional crop yield. Diaz et al. (2007) used CropWat to simulate the impact of climate change on ET and irrigation water requirement for 14 irrigation districts located in the Guadalquivir River basin, Spain. After that, extrapolation was used to show the impact of climate change on irrigation water requirement at catchment level. Minacapilli et al. (2008) used the one-dimensional agro-hydrological model SIMODIS (SImulation and Management of On-Demand Irrigation Systems) at various locations and remotely sensed data to assess irrigation water demand in Sicily's district, Italy. The results reveal that the spatial variability of crop conditions was more significant than the soil's spatial variability. Shen et al. (2013) analyzed the spatio-temporal variations of irrigation water demand as well as crop water requirement by combining the modified Penman-Monteith equation and GIS for five main crops (wheat, corn, cotton, oilseed, and sugar beet) during 1989–2010 in China. The Thiessen polygon method was used to calculate the spatial representation of crop water requirement. The results showed a 41.2% increase in total irrigation water requirement in 2010 compared to 1989. Furthermore, SWAP-EPIC is coupled with GIS for performing distributed agro-hydrological modeling in the Heihe River basin at field and catchment scales. The simulated results showed a high spatial variability of irrigation applied (242–898 mm) and an improvement in water conveyance and irrigation scheduling could reduce the deep percolation by 30% which could save up to 15% of irrigation water without negative effects on crop yields (Jiang et al., 2015).

4.3. Optimization of Irrigation/Irrigation Scheduling

The motivation for simulating irrigation is often the need for saving costs, or for reducing irrigation water consumption. As models can predict variables but not optimize parameters or policies, agro-hydrological models have been incorporated into optimization frameworks to solve practical problems in irrigation planning and management. Shangguan et al. (2002) used dynamic programming for optimal irrigation scheduling and water resource allocation (among various crops and sub-regions) for a semi-arid Loess Plateau, China. The results revealed that the developed approach is efficient in improving irrigation efficiency, implementation of water-saving strategies, and solving water shortage issues at catchment level. Fortes et al. (2005) used the ISAREG model, which is integrated with a GIS to simulate the irrigation scheduling over a large area/irrigation project. The impact of different irrigation scenarios in water saving is tested in the Syr Darya basin, Uzbekistan. The results revealed that 15–20 day time intervals should be maintained between consecutive irrigation events for effective water saving. Mishra et al. (2005) developed and applied an integrated optimization-simulation model. A nonlinear, constrained multivariable optimization routine is developed and coupled with MIKE SHE. Results showed an improved delivery schedule that reduced the overall deficit by minimizing the mismatch between demand and supply. Ahrends et al. (2008) coupled WaSiM with an economical model (GAMS-ECIM) for optimizing irrigation in an agricultural catchment in West Africa. The results showed that the combined approach can maximize irrigation profits under limited available water resources. Noory et al. (2012) maximized the net benefit for all cultivated crops within irrigated areas in a reservoir-irrigation system in Iran using a linear and a mixed-integer linear (MIL) model. The results showed that the discrete nature of cropping area variables in the MIL model had a significant effect on assigned areas and reservoir operation policies. Kourgialas and Karatzas (2015) developed an efficient cost-effective irrigation scheduling for citrus orchards using MIKE SHE in Crete, Greece. Results suggested that a proper irrigation plan can be designed at every site of the model domain, which could reduce water consumption by up to 38% with respect to the common irrigation practices and will ensure the citrus water productivity. Furthermore, they have also developed a decision support system to develop optimal irrigation schedules for citrus fruit crops by monitoring soil moisture and unsaturated soil pressure in Crete using MIKE SHE. The results showed that the designed optimal irrigation management plan is effective in water saving under different climate change scenarios (Kourgialas et al., 2019). Maier and Dietrich (2016) used SWAT for Pareto-type trade-off analyses between irrigation water saving scenarios and yield reduction. The model showed more sensitivity toward changes in the irrigation control than toward yield. Similar results were obtained by Uniyal et al. (2019) for four catchments in different climate zones (Chile, Germany, India, and Vietnam). Udias et al. (2018) used a decision support tool to combine SWAT, an economic model, and genetic algorithm multi-objective optimization to simulate crop productivity under current and alternate scenarios. Additionally, the authors tried to locate optimal irrigation strategies by considering crop water requirements, impact of irrigation changes on crop productivity, optimal spatial allocation of management strategies, and so on. The results revealed the optimal allocation of water could allow water savings of 52% with marginal reduction in farmer's income (7%). Fu et al. (2019) used SWAT to simulate 16 irrigation schedules for corn and soybean in the Songhua river basin, China. Analytic Hierarchy Process (AHP) and Gray Interconnect Degree Analysis (GIDA) were used to define the optimal irrigation schedules for the key growth stages from the simulated results. The results revealed that the irrigation should be applied six times during the key growth stages. Githui et al. (2016) used SWAT to test the impact of two different irrigation inputs based on irrigation amount (fixed and variable irrigation amounts), flows, and ET in Australia. Results revealed that using variable irrigation inputs produced better results compared to fixed inputs.

4.4. Impact of Irrigation on Hydrology and Climate

Irrigation is a human intervention, which may disturb the water cycle and may have influence on the local climate due to increased evapotranspiration and cooling effects. One of the first models simulating the hydrological impact of irrigation systems on a larger scale is SLURP (Kite & Droogers, 1999). Irrigation highly impacts the groundwater recharge in agricultural catchments. A study performed by Githui et al. (2012) revealed that irrigation increases the groundwater recharge on an irrigated perennial pasture located in Australia. Pandey et al. (2013) developed a conceptual model to calculate soil moisture availability and crop yield in irrigated and rainfed systems and estimate the supplemental irrigation requirement of a crop. Additionally, the authors calculated and estimated changes in potential benefits from improved grain production and water availability. The impacts of the size of an on-farm reservoir on the benefits of the irrigated system were also evaluated. The developed system could increase the crop yield of rainfed agriculture considerably (30%–40%). The total value gains for the irrigated system were 31%–74% greater than the rainfed system. Huang et al. (2015) simulated the impact of different irrigation schemes on streamflow in the Aksu River Basin, China. An irrigation module and a river transmission losses module were developed for the SWIM model (a model derived from SWAT) and then the downstream discharge simulated by the modified SWIM was compared with the discharge simulated by WEAP. An increase in irrigation efficiency was found to be the most effective measure for reducing irrigation water consumption. McInerney et al. (2018) evaluated the impact of irrigation schedules on streamflow, evapotranspiration, and potential recharge with SWAT in the Murray Darling Basin, Australia. Four different irrigation schedule models were evaluated which differ in their representations of spatio-temporal variability of irrigation. A new spatially variable event-based random irrigation ordering model (SV-EB-RO) based irrigated HRUs matched better with the catchment's observed irrigation than an existing spatially variable event-based model (SV-EB-RT) random timing model. Wu, Cui, Wang, et al. (2019) investigated the fate of return flows and irrigation water reuses to watershed scale using SWAT for paddy rice irrigated agricultural watershed in China. The results revealed that the irrigation water reuse rates increase with increasing the size of watershed and it is high during dry years.

4.5. Impact of Climate Change on Irrigation

Irrigation water demand is a consequence of plant evapotranspiration, which is a function of climate variables. Thus, climate variability and climate change have an impact on irrigation. There is a major interest in simulating the impact of climate change on irrigation as this will define the boundary conditions for future food production in many areas of the globe. Therefore, to prepare us for climate change it is necessary to find out our future needs and accordingly implement new and innovative water management measures to secure the uncertain future (Brookfield & Gnau, 2016). Diaz et al. (2007) showed that regional climate is directly impacting the irrigation need and there has been an increase in irrigation water requirement between 15% and 20% by 2050s which depends majorly on the location, cropping pattern, and so on. Kahil et al. (2015) evaluated the economic and environmental effects of two incentive-based water management policies for addressing the impact of climate change on irrigated agriculture, water markets, and respective irrigation subsidies. Herrmann et al. (2016) used mGROWA to quantify the ratio of irrigation need and groundwater recharge in Hamburg, Germany for the current and future climate. This was conducted to show the overexploitation of groundwater vulnerable areas for fulfilling the irrigation needs. Results of ensemble simulations do not indicate a concrete information about the change of groundwater recharge in future. Zou et al. (2018) used an improved SWAT model and two logarithmic mean division index decompositions (additive and multiplicative) to quantify the variation in different driving factors (planting scale, planting pattern, climate change, and water saving) on irrigation water demand (spring wheat and corn, cotton, oil-bearing crops, vegetables, barley, and potato, etc.) for the Heihe River Basin, China. The results for additive decomposition suggested an increase in irrigation demand due to planting scale, planting pattern, and climate change whereas the use of water-saving technologies tends to reduce the irrigation water demand. However, for multiplicative decomposition, the response of the rest of the drivers is same as in the additive decomposition. But, in case of climate change, the irrigation demand is increasing at the beginning of the future period and then it is decreasing. Other studies focused on adaptation measures to overcome the negative impact of climate change on irrigation. Bazzani (2005) used the “Decision Support for IRRigated Agriculture (DSIRR)” tool to evaluate the impact of farmers' decisions on changes in irrigation pricing policy on Po basin, Italy. The results indicated that the acceptance of the water pricing policies varies with the region as well as with the crop. Droogers and Aerts (2005) linked the WSBM (water and salinity basin model) model with SWAP to simulate the impact of certain adaptation strategies to climate change on crop yield and crop water consumption for the Walawe Basin, Sri Lanka. It was seen from the results that change in the cropped area and irrigation amount applied were the most relevant adaptation strategies against climate change. Barros et al. (2011) evaluated the changes in irrigation performance indices due to the structural and management improvement in La Violada irrigation district, Spain. The results revealed that structural and management improvements in the irrigation systems have led to decreased seepage (lower relative water deficit) and lower drainage fractions with an increase in irrigation scheduling flexibility. For devising the adaptation and mitigation measures it is also important to simulate the human impact on irrigation water demand using the available hydrological models. There are certain studies like Sang et al. (2010), in which the authors modified the SWAT model to represent the regional human water use in a high human activity catchment located in Tianjin city, China. The authors have incorporated multiple water sources for irrigation in the modified SWAT. The results revealed that this model has a potential to be applied to examine the sensitivity of water yield response to irrigation system and industry structure change on a long-term basis.

4.6. Uncertainty in Irrigation Scheduling and Irrigation Water Demand

Like in all model applications, there is uncertainty from various sources (mostly data, model structure, and parameters) in irrigation modeling, which needs to be investigated and communicated in case of decision support. Huang et al. (2012) developed a two-stage interval-quadratic model (comprising of stochastic and interval-quadratic programming, and hydrological model) to yield water allocation solutions under uncertain spatio-temporal data environment in Tarin River Basin, China. Here uncertain parameters (e.g., water availability) were expressed as probability distributions. Results showed that the forecasted available irrigation water can help in generating the necessary policies for water resources management at catchment level. Wallach et al. (2012) questioned how a combined crop and decision model can be used to predict the model uncertainty. They compared different irrigation strategies for corn. The uncertainty in the model parameters and model residual error was considered as the sources of uncertainty and it was quantified by using a Bayesian approach. Results revealed that it is very important to specify the criteria involving predicted yield to evaluate an irrigation strategy. Leng et al. (2013) evaluated the simulated irrigation water use by the Community Land Model version 4 (CLM4) using two different irrigation area maps against observations from agriculture census. Results revealed large uncertainty in the irrigation area data from two sources, which produced unrealistically large temporal variations of irrigation water demand. Woznicki et al. (2015) used SWAT to assess the impact of climate change on corn and soybean irrigation demand in the Kalamazoo River Watershed, United States. Bias-corrected statistically downscaled climate change data from 10 global climate models and 4 emissions scenarios were used in SWAT to develop projections of irrigation demand and yields for 2020–2039 and 2060–2079. It was seen from the results that the overall uncertainties in the irrigation simulation vary from 18% to 30%. Uncertainty in irrigation demand was found to increase moving from 2020–2039 to 2060–2079 for corn and soybean. Jiang et al. (2016) optimized the regional irrigation water use and cropping pattern by using SWAP/EPIC model in combination with the optimization model in Yingke Irrigation District, China. Results showed that a variation in risk range can be obtained by considering the impacts of climate uncertainties.

4.7. Irrigation Simulation With Limited Data

Procuring observed data is a huge concern in developing and under-developed nations. To develop hydrological models at catchment scale data plays a major role. However, there have been several studies, in which researchers are using freely available global datasets for simulating irrigation water demand. Some studies dealing with this topic are as follows: Peña-Arancibia et al. (2016) used random forest to develop the irrigation areas and actual ET maps at catchment level using a monthly based hydrological model for Murray-Darling Basin, Australia. The results revealed that remote sensing irrigated areas and actual evapotranspiration can be used to understand the irrigation dynamics and to constrain the irrigation models in data scarce regions. Corbari et al. (2019) developed a system for operative irrigation water management for Southern Italy by coupling remotely sensed Landsat data with a distributed hydrological water-energy balance model (FEST-EWB) and meteorological forecasts. The results show it is possible to get reliable SM forecasts for up to 3 days, and this helped farmers to properly decide irrigation scheduling. Uniyal et al. (2019) used freely available reanalysis climate data (ERA-interim and NCEP) to simulate the irrigation water demand for four different catchments under different agro-climatic conditions. This was performed to check the applicability of reanalysis data under data scarce conditions. Results revealed that observed weather data are of essential value for bias-correcting the reanalysis climate data set because the bias would result in wrong irrigation water amounts. Jalilvand et al. (2019) assessed the capability of different soil moisture products for detection of irrigation and selection of the best product in Urmia Basin, Iran. The results showed that the SM2RAIN algorithm (Brocca et al., 2015) when applied to AMSR2-JAXA soil moisture product during 2012–2015 was able to capture the temporal patterns in irrigation, but also overestimate the irrigation amounts compared to observed data. Moreover, these studies highlight the importance of spatio-temporal variability of inputs in distributed hydrological models and the necessity to use multivariate calibration to test and refine the hydrological models.

5. Discussion

5.1. Model Selection

The three key technical aspects of irrigation in a modeling framework are the irrigation trigger (when to irrigate), amount (how much to irrigate), and the application technique (e.g., rain, spray, drip, and flood). Therefore, it is important to select an efficient and suitable model, which can represent the irrigation application processes at catchment level. Even if it were seen from the literature that the deviation of model simulated irrigation amount can be much larger than the deviation in yield (Maier & Dietrich, 2016; Uniyal et al., 2019), it might be important to utilize a dynamic plant growth model in the context of agricultural water management, which would exclude some mostly hydrological models. Among the models of this review, SWAT/SWAT+, HYPE, and WEAP provide the most integrated solutions for simulating hydrology and irrigated crop production at catchment scale, even if these models are simplifying single aspects compared to more capable specific model structures. The efficient representation of practical management operations (planting, harvesting, fertilization, pesticide application, etc.) and irrigation policy and management options also plays a major role in selecting a model. This is of particular importance if model results are finally disseminated to the users as a quantitative tool in irrigation planning.

This review pointed out that there is no perfect model, which incorporates all possible functionalities. Users need to select an appropriate model based on their criteria. Both major strategies, applying a 3-D agro-hydrological catchment model or upscaling 1-D field models, can be successful. Moreover, it is worth to check the updated version of the selected model as due to the increased popularity of open-source models, they are being modified/updated continuously. One such example is the latest version of SWAT called SWAT+ (Bieger et al., 2017), which adds generic agricultural management and decision rules into the agro-hydrological model (Arnold et al., 2018).

5.2. Importance of Model Calibration Using Soil Moisture, ET, and Crop Yield

Calibration is an essential step in hydrological modeling. As every hydrological model has uncertainty due to data, model processes, and model parameters, therefore model simulated results are first calibrated to obtain a satisfactory model. Due to the complexity of the agricultural catchments and unavailability of the observed irrigation data at regional level it is always recommended to perform multivariable calibration. It is not always guaranteed that a good model for streamflow simulation will also provide satisfactory simulation of irrigation water demand or crop yield (Chen, Marek, et al., 2018; Uniyal et al., 2019). Therefore, it is always recommended to calibrate the developed hydrological models using more than one variable. It was seen from the analysis of the studies selected for the review that most of the studies are only calibrated using streamflow. However, in some studies models have also been calibrated using ET, soil moisture, and crop yield apart from streamflow. Additionally, some studies have also used crop growth parameters like leaf area index, crop height, and sensible heat. Out of the total number of studies, there were only five studies that had used irrigation data for calibrating/comparing the simulated irrigation amounts by the respective hydrological models (Barros et al., 2011; Chen, Marek, et al., 2018; Fu et al., 2019; Githui et al., 2016; Uniyal & Dietrich, 2019). Furthermore, Leng et al. (2013) suggested that the simulated irrigation amounts can be improved by calibrating model parameter values and accurate representation of the spatial distribution and intensity of irrigated areas.

5.3. Scarcity of Real Irrigation Data

Data scarcity is a major concern in developing as well as in the underdeveloped nations and observed irrigation data at regional level is rarely available in any part of the world. Therefore, to overcome this data scarcity an indirect estimation of irrigation in form of ET is often used in case of hydrological models. The hydrological models are also developed using remotely sensed soil moisture and ET data as well as using freely global weather data (Corbari et al., 2019; Githui et al., 2016; Peña-Arancibia et al., 2016). From the 56 research articles considered for this review, only 8 studies compared simulated irrigation amounts with observed irrigation amounts at catchment level. There can be two main reasons: first, irrigation amounts are often observed at an experimental plot scale but not the catchment scale. Second, there is no regular monitoring and public reporting of actual irrigation amounts used by farmers. Published data are often aggregated to larger administrative areas. A better quality, quantity, and availability of irrigation measurements at catchment scale could contribute to improved irrigation simulation by hydrological models, which can further compliment management decisions.

5.4. Climate Change Adaptation

Adaptation measures refer to increased water storage (reservoirs, soil water, and groundwater), but also to increased economic benefits (savings/loans/crop yield). There have been a lot of studies, which provide possible solutions like using deficit irrigation, use of treated waste water for irrigation, changing the type of crop, changing the planting and harvesting dates of crops, reducing the irrigation conveyance loss, using water-saving irrigation systems, and so on, to adapt the existing systems toward future climate change. Additionally, modeling studies should involve different stakeholders to come up with socially acceptable sustainable solutions against climate change. Most studies deal with the negative effects of climate change on agro-hydrology. There are less studies dealing with positive effects and feedbacks.

6. Conclusions

There is a range of agricultural and agro-hydrological simulation models, which can simulate irrigation water demand and irrigation operations at catchment scale, but the selection of an appropriate model is critical. It was seen from the literature that models show different strengths in relevant aspects of irrigation scheduling and crop production, based on the different hydrological and plant growth models as well as on the different implementation of agricultural water management. Few models integrate both catchment hydrology and irrigated crop production with detailed management operations. It is evident that coupling hydrological models with suitable crop models can help in the optimization of irrigation management practices (Kanda et al., 2018; Malik et al., 2020). However, some models are lacking support for relevant crops like rice and most models do not address agroforestry. Promoting water-saving agriculture will not only increase water productivity but also enhance the economic returns of the farmers. Models can help to find a compromise solution between water saving and yield reductions at catchment level (Maier & Dietrich, 2016). However, deficit irrigation as an important strategy proposed by FAO is not yet standard in all models. Other water-saving strategies like water reuse or new technological solutions in water-saving irrigation are rarely implemented.

Further integration of irrigation models with biogeochemical models (like DayCent, DNDC) to simulate the “whole” agricultural water and matter cycle including greenhouse gas emissions can be the next step forward in the direction of enhancing the capabilities of agro-hydrological models. This could improve the simulation of integrated and sustainable agricultural production and integrated climate adaptation strategies, looking at both mitigation and adaptation of the agricultural sector at the catchment scale.

Unfortunately, there were not many studies about parameter, model, and data uncertainty in irrigation simulation. These are seemingly not as often investigated as uncertainty associated with streamflow. Future studies should address these uncertainties to obtain a more robust estimation of future irrigation water demand. The availability of remote sensing data of soil moisture and plant cover, which could be assimilated into agro-hydrological models, allows to perform daily real-time irrigation forecasting at catchment scale, which could help the irrigator to answer the basic questions in irrigation scheduling: “how much” and “when” to irrigate. However, the efficiency of this schedule/forecast is majorly dependent on the accuracy of forecasted weather data. Using ensemble weather predictions from short-term to subseasonal lead times can improve the consideration of climate uncertainty in operational agricultural water management.

For checking the applicability of climate-resilient policies/scenarios, it is essential to incorporate farmers' responses or farmers' attitudes toward adaptation measures which could be incorporated by conducting farmer survey (Bird et al., 2016). Additionally, hydrological models could be combined with the reliable cost estimates and the developed cost metrics can be used to identify and prioritize the suitable irrigation water management decisions at catchment scale (Panagopoulos et al., 2014).

We tried to investigate all possible literature sources about catchment scale irrigation modeling, but it seems to be impractical to include all publications in one review study. Therefore, this review study focused on often cited models and only selected case studies, which provided progress in the development and application of models of irrigated agriculture at catchment scale. Most of the topics can deserve an exhaustive individual review. Moreover, it is also possible that some aspects have either been overlooked or only briefly referred to due to the vast spectrum of the considered topic.

Appendix A

Model	Main model reference	Model webpage	Software documentation
APEX	Williams et al. (1995)	https://blackland.tamu.edu/models/apex/	http://agrilife.org/brc/files/2012/10/the-apex-theoretical-documentation.pdf
APSIM	McCown et al. (1996)	https://www.apsim.info/	https://www.apsim.info/documentation/
AquaCrop	Steduto et al. (2009), Raes et al. (2009)	http://www.fao.org/aquacrop	http://www.fao.org/aquacrop/resources/referencemanuals/en/
CropWat	Smith (1992)	http://www.fao.org/land-water/databases-and-software/cropwat/en/	Not available
DAISY	Hansen et al. (1990)	https://daisy.ku.dk/	Not available
DNDC	Li et al. (1992)	https://www.dndc.sr.unh.edu//	https://www.dndc.sr.unh.edu//model/GuideDNDC95.pdf
DSSAT	Jones et al. (2003)	https://dssat.net/	https://dssat.net/wp-content/uploads/2020/03/The-DSSAT-Crop-Modeling-Ecosystem.pdf
HYPE	Lindström et al. (2010)	https://www.smhi.se/en/research/research-departments/hydrology/hype-our-hydrological-model-1.7994	http://www.smhi.net/hype/wiki/doku.php?id=start
MIKE SHE	Abbott et al. (1986)	https://www.mikepoweredbydhi.com/products/mike-she	https://manuals.mikepoweredbydhi.help/2017/MIKE_SHE.htm
SWAP/WOFOST	Kroes et al. (2000)	https://www.swap.alterra.nl/	http://library.wur.nl/WebQuery/wurpubs/fulltext/416321
SWAT/SWAT+	Arnold et al. (1998)	https://swat.tamu.edu/	https://swat.tamu.edu/docs/
WaSiM	Schulla (1997)	http://www.wasim.ch/en/index.html	http://www.wasim.ch/en/products/wasim_description.htm
WEAP	Raskin et al. (1992)	https://www.weap21.org/	https://www.weap21.org/index.asp?action=208

Data Availability Statement

The paper does not rely on any real-world data. Data were not used nor created for this paper.

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