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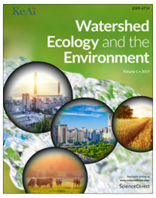

Recent progress in coupled surface–ground water models and their potential in watershed hydro-biogeochemical studies: A review

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ABSTRACT

Interactions between surface water (SW) and groundwater (GW) have been a focus of watershed hydrology research for a long time. A holistic perspective on integrated SW–GW modeling approach is necessary to understand the hydrological and biogeochemical processes of these two interconnected systems within the watershed. This paper reviewed the progress and coupling strategy of one important SW model (Soil and Water Assessment Tool, SWAT) and GW model (Modular Finite Difference Groundwater Flow, MODFLOW) since 1999. Three main stages of development of coupled SWAT–MODFLOW model are reflected by the high citation of publications by three pioneer studies, which are Sophocleous et al. (1999), Kim et al. (2008) and Bailey et al. (2016). Currently, the research scope of coupled SWAT–MODFLOW models is focused on hydrologic processes, solute transport and the effects of climate change and human activity on water resources. Major uncertainties of SWAT–MODFLOW from model structure, database and parameterization are discussed. In an era of big data, the coupled SWAT–MODFLOW model has great potential to improve understanding of hydro-biogeochemical processes and support sustainable water and ecological management in the watershed.

1. Introduction

The interaction between surface water (SW) and groundwater (GW) is an important process during water circulation in watersheds (Bailey et al., 2020; Deb et al., 2019; Markovic and Koch, 2015). This process is widespread in natural water bodies, including rivers, lakes, reservoirs, wetlands and estuaries (Deb et al., 2019; Kamali and Niksokhan, 2017; Ke, 2014; Pulido-Velazquez et al., 2015). However, SW and GW were traditionally regarded as two separated systems because they exist in different media with varying motion states (Bailey et al., 2016; Kim et al., 2008). SW and GW research has developed in respective fields for a long time, and the lack of interdisciplinary studies has limited the development of sustainable watershed management strategies and policies. In particular, various human activities and climate perturbations have greatly increased the burden on watershed ecology and water supplies (Izady et al., 2015; Kamali and Niksokhan, 2017; Surinaidu et al., 2016). Recent studies suggest that SW–GW interaction impacts water quantity and quality (Surinaidu et al., 2016), diffusion of pollutants (Ehtiat et al., 2018; Sith et al., 2019) and associated biogeochemical cycles (Liu et al., 2020a, 2020b). Therefore, a holistic perspective on integrated SW–GW modeling approach is essential to understand the hydrological and biogeochemical processes of these two interconnected systems to meet the requirement of watershed sustainability.

Numerical modeling is an effective tool for simulating SW–GW interactions (Menking et al., 2003, 2004; Ridwansyah et al., 2020; Sophocleous and Perkins, 2000). Hydrologic numerical models are usually divided into single model and coupled models (Park et al., 2019; Qi et al., 2019; Triana et al., 2019; Wei et al., 2019; Wei and Bailey, 2019). Aliyari et al. (2019) divide single hydrological models into two categories: (1) SW models that consider GW in a simple way, e.g. TOPMODEL (a topography based hydrological model, Beven and Kirkby, 1979), HL-RMS (hydrology laboratory research modeling system, Koren et al., 2004) and SWAT (soil and water assessment tool, Arnold et al., 1998); and (2) GW models that consider SW in a simple way, e.g. MicroFEM (microcomputer package for multiple-aquifer GW flow modeling, Diodato, 2000), ZOOMQ3D (object-oriented quasi 3-D regional GW model, Jackson, 2001) and MODFLOW (modular finite difference groundwater flow, McDonald and Harbaugh, 1988). However, these two categories of models usually take into account only a single SW or GW flow, ignoring the interactions between SW and GW. Triana et al. (2019) stated that modeling SW or GW in this way

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may not be sufficient to reflect accurately the nature of hydrological systems, and may lead to wrong conclusions. Thus, the development of coupled SW–GW models is of increasing concern in recent years.

Coupled models can be divided into completely- and loosely-coupled according to their coupling strategies (Guevara-Ochoa et al., 2020a). Examples of completely coupled models include CATHY (catchment hydrology model, Paniconi and Wood, 1993), ParFlow (parallel flow model, Kollet and Maxwell, 2006) and HGS (HydroGeoSphere, Therrien et al., 2010). Completely coupled models simulate SW and GW flow simultaneously (Aliyari et al., 2019); this adds complexity to modeling, and leads to over-parameterization (Cornelissen et al., 2016). Also, the lack of free source code and necessary modules (e.g. crop growth and rotation, reservoirs and so on) limit its application, especially at a regional scale (Guevara-Ochoa et al., 2020a). In contrast, loosely coupled models seem a better choice in practice (Liu et al., 2020a; Aliyari et al., 2019; Bailey et al., 2016; Wei et al., 2019; Wei and Bailey, 2019), e.g. GSFLOW (coupled GW and SW flow model, Markstrom et al., 2008), MODBRANCH (coupled MODFLOW and BRANCH model, Swain and Wexler, 1996) and SWAT–MODFLOW (Kim et al., 2008). The coupled SWAT and MODFLOW model have been widely used to simulate SW and GW interaction (Akbarpour and Niksokhan, 2018; Eshtawi et al., 2015, 2016; Surinaidu et al., 2016; Wei et al., 2019; Wei and Bailey, 2019), and have proved to have advantages in terms of simple operation, good visualization and low data requirements (Qi et al., 2019).

In this paper, we review SW–GW model development, applications and potential in watershed hydro-biogeochemical process studies. The main objectives were to: 1) retrace the evolution of SWAT–MODFLOW and coupling strategies; 2) identify the research scope of SWAT–MODFLOW; 3) discern major uncertainties in SWAT–MODFLOW applications; 4) explore future perspectives of SWAT–MODFLOW modeling and its potential to support sustainable water and ecology management.

2. Recent progress of SWAT–MODFLOW

A comprehensive literature search using keywords "SWAT" and "MODFLOW" in the Thomson Reuters Web of Science databases was carried out before September 30, 2020. After screening, a total of 64 peer-reviewed articles were selected for the review. Since 1999, the number of publications on SWAT–MODFLOW shows a significant increasing trend (Fig. 1a). In particular, articles published in 2019 and 2020 account for 42% of the total publications. The top four countries with the most published articles are USA (n = 18), Iran (n = 8), South Korea (n = 6), and China (Mainland and Taiwan) (n = 5) (Fig. 1b). Globally, the majority of publications on SWAT–MODFLOW are in Asia (n = 25), North America (n = 20) and Europe (n = 16) (Fig. 1d).

2.1. SWAT model

SWAT is a continuous-time, physically-based, semi-distributed model that operates on a daily time step (Arnold et al., 1998, 2012). The model is primarily used to evaluate the effects of land management practices on water resources and non-point-source pollution within basins. The movements of water, sediments, nutrients and pesticides are the main simulation objects for the model (Menking et al., 2004; Narula and Gosain, 2013). Main model components include climate, hydrology, soil temperature and properties, plant growth, nutrients, pesticides, land management, water routing, bacteria and pathogens (Kim et al., 2008). In the SWAT model framework, a watershed is usually divided into multiple sub-basins, each of which is further divided into a series of Hydrologic Response Units (HRUs) (Chung et al., 2010; Aliyari et al., 2019). HRUs are the simulation unit of SWAT, which are delineated according to similarity of soil types, land use, and slope characteristics (Arnold et al., 1998, 2012; Guzman et al., 2015).

SWAT is a lumped model (Arnold et al., 1998, 2012; Kim et al., 2008), and does not express in detail the spatial distribution of aquifer parameters (e.g. hydraulic conductivity, porosity, specific yield and specific storage) (Kim et al., 2008; Wei et al., 2019), despite having its own GW module. In addition, SWAT cannot simulate SW–GW interactions (i.e. runoff recharge and GW discharge) and GW level. Liu et al. (2020c) suggested that the two ways to make SWAT perform better in simulating GW are modifying the GW module code and coupling SWAT with a GW model. Some studies achieved a good result in simulating GW flow by changing SWAT module codes (Pfannerstill et al., 2013; Nguyen and Dietrich, 2018). However, the modified GW code only improves a part of aquifer system simulation (Liu et al., 2020c), and the professional skills required to carry out the modification limit the application of this approach. As a result, the latter coupling approach is usually preferred, and of all the GW models, MODFLOW has been developing more quickly and is widely used (Chung et al., 2015; Gao et al., 2019; Izady et al., 2015; Kim et al., 2017).

2.2. MODFLOW model

MODFLOW (McDonald and Harbaugh, 1988) is a modular three-dimensional finite difference GW flow model proposed by the U.S. Geological Survey. The model uses the finite difference method to simultaneously solve the differential equations of GW flow (Guzman et al., 2015). MODFLOW is a physically-based model because it combines Darcy's law and the mass balance for subsurface flow (Kim et al., 2008). The model is designed to simulate a variety of natural or artificially-induced hydrologic processes under steady and transient states for different types of aquifers (McDonald and Harbaugh, 1988; Kasahara and Wondzell, 2003; Ke, 2014). In MODFLOW, the GW flow processes are simulated using a series of boundary condition packages, e.g. Recharge, Well, Drain, Lake, Reservoir, and Streamflow Routing packages (Bailey et al., 2016; Aliyari et al., 2019). However, as mentioned earlier, this specialized GW model (MODFLOW) considers SW in a simplistic manner (Aliyari et al., 2019) and ignores the accuracy of SW recharge rates, this may cause a considerable uncertainty in the simulated GW flow (Kim et al., 2008). Therefore, the combination of MODFLOW and SWAT fully plays each of the two patterns, while overcoming the potential disadvantages when used alone (Taie-Semiromi and Koch, 2020).

2.3. SWAT–MODFLOW

The model linking SWAT and MODFLOW (i.e. SWAT–MODFLOW) was first proposed by Sophocleous et al. (1999), and has recently been further developed by Kim et al. (2008) and Bailey et al. (2016). In the last two decades, SWAT–MODFLOW has been continuously updated and widely applied to watersheds to simulate SW–GW interactions (Sophocleous and Perkins, 2000; Conan et al., 2003; Galbiati et al., 2006; Narula and Gosain, 2013; Guzman et al., 2015; Deb et al., 2019; Wei et al., 2019; Liu et al., 2020a, 2020b, 2020c; Sabzzadeh and Shourian, 2020). The hydrologic processes of SW and GW are main topic of these studies. For instance, Eshtawi et al. (2015) used SWAT–MODFLOW to analyse the interrelation between GW level and built-up area in the Gaza Strip, Palestine. Izady et al. (2015) simulated the flow of SW and GW and estimated GW recharge and water budget in the Neishaboor watershed (Iran) to support water-resources decision making. Overall, the development of the SWAT–MODFLOW model since 1999 can be divided into three main stages (Table 1).

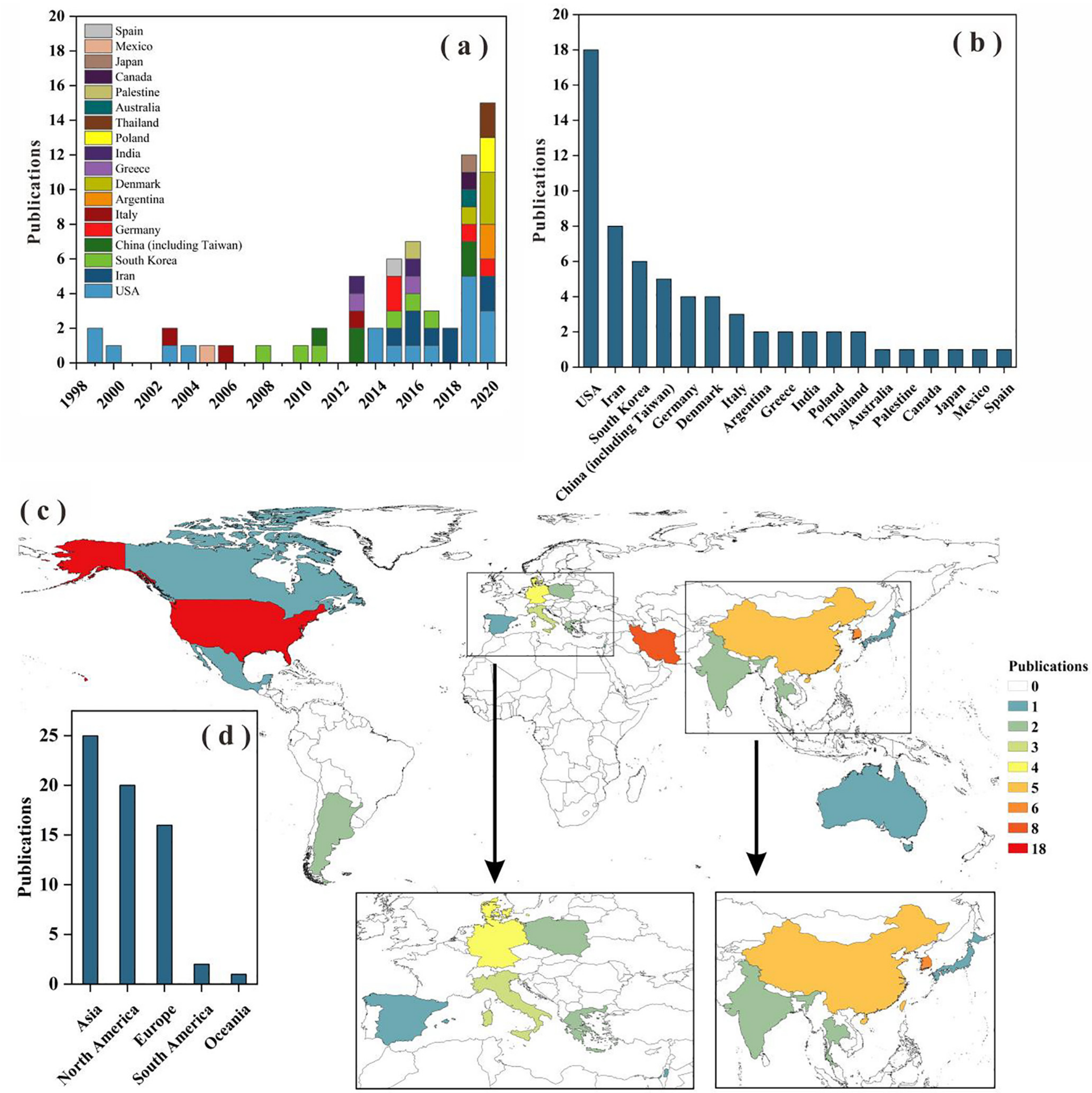

Fig. 1. (a) Publications associated with SWAT–MODFLOW studies for different countries by year (from 1999 to September 30, 2020); (b) Publication number by country; (c) Spatial distributions of publications of SWAT–MODFLOW studies around the world; (d) Sum of publication number by continent.

In the first stage, Sophocleous et al. (1999) developed the first integration to link SWAT and MODFLOW, called SWATMOD. The model codes were written by C++ and applied to the Rattlesnake creek basin in south-central Kansas, USA. In the following years (before 2008), the model was constantly developed and applied to France (Conan et al., 2003), Italy (Galbiati et al., 2006) and other regions in the United States (Sophocleous and Perkins, 2000; Menking et al., 2003) to clarify a number of different scientific hypotheses.

In the next stage, Kim et al. (2008) developed a new version of integrated SWAT and MODFLOW, called SWAT–MODFLOW. This proposed an innovative hydrological response unit (HRU)-cell conversion interface, which could exchange daily flow data between HRUs (in SWAT) and cells (in MODFLOW), including recharge rate, river-aquifer interaction, evapotranspiration and pumping rate. SWAT–MODFLOW was applied to the Musimcheon Basin in South Korea, and showed a better result in simulating daily streamflow than SWAT alone. Subsequently, a series of new practice based on Kim et al. (2008) developed SWAT–MODFLOW. These included a multi-reservoir storage routing module (Chung et al., 2010), considering both climate change scenarios and solute transport in SWAT–MODFLOW (Narula and Gosain, 2013), MD–SWAT–MODFLOW (Ke 2014), SWAT–MODFLOW–USG (Eshtawi et al., 2015), SWATmf (Guzman et al., 2015), SWAT–SEAWAT (Chang et al., 2016) and SWAT–MODFLOW–MT3DMS (Eshtawi et al., 2016).

Table 1
Major research on the evolutionary process for SWAT–MODFLOW. The citation (up to September 30, 2020) and journal impact factor IF (2019) are from Thomson Reuters Web of Science (all databases).

Study	Content	Cited	Journal	Impact factor (2019)
Sophocleous et al. (1999)	• Developed the first integration to link SWAT and MODFLOW, called SWATMOD; • Model code was written in C++; • Applied model to the Rattlesnake creek basin in south-central Kansas, USA;	151	JOURNAL OF HYDROLOGY	4.500
Sophocleous and Perkins (2000)	• Applied integration model (Sophocleous et al., 1999) to three basins (Rattlesnake Creek subbasin, Lower Republican River basin and Wet Walnut Creek basin, USA) for clarification of different hypotheses; • Especially, modified model system to become a two-way coupling system to investigate irrigation effects on streamflow and groundwater levels in the Lower Republican River watershed in north central Kansas, USA;	153	JOURNAL OF HYDROLOGY	4.500
Conan et al. (2003)	• Considered solute transport (Zheng and Wang, 1999), and first coupled SWAT–MODFLOW and MT3DMS (modular 3-dimensional multi-species transport) to simulate nitrate fate in Coet-Dan watershed, Brittany, west of France;	80	JOURNAL OF ENVIRONMENTAL QUALITY	2.142
Menking et al. (2003)	• Studied the combined SWAT runoff results with previous estimates of GW flow, and employed the MODFLOW lake package LAK2 (Council, 1999) to assess the modern hydrological balance in Estancia Basin, New Mexico, USA;	20	HYDROLOGICAL SCIENCES JOURNAL-JOURNAL DES SCIENCES HYDROLOGIQUES	2.186
Galbiati et al. (2006)	• Integrated SWAT, MODFLOW, MT3DMS and QUAL2E (instream water quality model), called ISSm (Integrated Surface-Subsurface Model); • Applied model to the Bonello basin (Italy) to evaluate the ability of SW–GW interaction and nutrient transport within the catchment;	35	ECOLOGICAL MODELLING	2.497
Kim et al. (2008)	• A new version of integrated SWAT and MODFLOW, called SWAT–MODFLOW; • In SWAT–MODFLOW, an innovative hydrological response unit (HRU)-cell conversion interface was proposed, which can exchange daily flow data between HRUs (in SWAT) and cells (in MODFLOW), including river-aquifer interaction, evapotranspiration, recharge rate and pumping rate; • Applied model to the Musimcheon Basin in South Korea, and showed a better result in simulated daily runoff using SWAT–MODFLOW than SWAT alone;	162	JOURNAL OF HYDROLOGY	4.500
Chung et al. (2010)	• Further applied SWAT–MODFLOW based on Kim et al., (2008) to assess the distribution of GW recharge rate in Mihocheion watershed, South Korea; • To simulate the flow of the vadose zone, a multi-reservoir storage routing module was developed, which represent a more realistic delay in the travel of water through the vadose zone.	46	HYDROGEOLOGY JOURNAL	2.641
Narula and Gosain (2013)	• Considered climate change scenarios from the fourth assessment report, and coupled SWAT–MODFLOW and MT3DMS to evaluate temporal and spatial distribution of water availability, including GW recharge and quality (non-point NO_3-N loadings) in the Himalayan Upper Yamuna basin;	37	SCIENCE OF THE TOTAL ENVIRONMENT	6.551
Ke (2014)	• A new integrated model called MD–SWAT–MODFLOW, which takes into account the multi-aquifers condition (unconfined aquifers, confined aquifers, and in-between aquitard); • Applied model to address the multi-aquifers condition in Choushui River alluvial fan, Taiwan, China;	8	HYDROLOGICAL PROCESSES	3.256
Eshtawi et al. (2015)	• Used SWAT–MODFLOW–USG (Panday et al., 2013) to analyse the interrelation between GW level and built-up area in the Gaza Strip, Palestine; • MODFLOW–USG was a new version of MODFLOW that uses unstructured grids. It had a faster computing speed and the same level of simulation accuracy compared to previous versions (MODFLOW-2005);	5	ARABIAN JOURNAL OF GEOSCIENCES	1.327
Guzman et al. (2015)	• A modelling framework, called “SWATmf” was developed to analyse the anthropogenic impacts on the agroecosystems in the Fort Cobb reservoir, USA; • In SWATmf, a new MODFLOW–NWT solver (Niswonger et al., 2011) was used to solve the GW flow equation more precisely when cell drying occurs;	49	ENVIRONMENTAL MODELLING & SOFTWARE	4.807
Chang et al. (2016)	• First integrated SWAT with SEAWAT (a detailed saltwater-intrusion model) to explore the impacts of climate change and urban developments on a coastal GW system in Dauphin Island, Alabama, USA; • SEAWAT was developed by combining MODFLOW (Harbaugh et al. 2000) and MT3DMS (Zheng and Wang 1999) into a package that can calculate density-dependent flow coupled with GW flow and solute transport processes;	8	JOURNAL OF ENVIRONMENTAL ENGINEERING	1.264
Eshtawi et al. (2016)	• Coupled SWAT–MODFLOW–MT3DMS to quantify SW–GW and quantity–quality interactions under urban area expansion in the Gaza Strip, Palestine; • Investigated the potentials of non-conventional water resources scenarios, including desalination, stormwater harvesting and treated wastewater reuse;	10	WATER RESEARCH	9.130
Bailey et al. (2016)	• Developed SWAT–MODFLOW model using a new code (in Python); • Used HRU disaggregation (DHRU) techniques to represent HRU deep percolation spatially for linkage to MODFLOW grid cells; • Offered a graphical interface, and can identify locations of nutrient loading and enhanced understanding of spatial patterns of GW influence on SW flow; • Model can be used for free via open-source software;	56	HYDROLOGICAL PROCESSES	3.256
Bailey et al. (2017)	• Developed a graphical user interface for preparing coupled SWAT–MODFLOW simulations based on Bailey et al. (2016), called SWATMOD-Prep; • Applied SWATMOD-Prep to Little River experimental watershed, Georgia, USA;	11	JOURNAL OF THE AMERICAN WATER RESOURCES ASSOCIATION	2.472

Table 1 (*continued*)

Study	Content	Cited	Journal	Impact factor (2019)
Aliyari et al. (2019)	- Proposed an updated code of SWAT–MODFLOW that allows application to large agro-urban river basins in semi-arid regions; - Code changes include linkage between MODFLOW pumping cells and SWAT HRUs for GW irrigation, joint GW and SW irrigation routines, and the use of MODFLOW–PSB to handle the large array of GW sources/sinks that exist in a highly managed river basin; - Applied model to South Platte River Basin, Colorado, USA;	11	ENVIRONMENTAL MODELLING & SOFTWARE	4.807
Deb et al. (2019)	- Coupled SWAT grid (a fully-distributed SW model) and MODFLOW to test model under different climatic conditions (Average, Dry and Wet periods) in two heterogeneous, semi-arid catchments in southeast Australia;	16	JOURNAL OF HYDROLOGY	4.500
Park et al. (2019)	- A QGIS-based graphical user interface for application and evaluation of SWAT–MODFLOW models based on Bailey et al. (2017), called QSWATMOD (written in Python); - QSWATMOD can create linkage files between SWAT and MODFLOW models, runs a simulation, and displays results within the open source Quantum Geographic Information System (QGIS) environment; - Applied QSWATMOD to Middle Bosque River Watershed in central Texas, USA;	7	ENVIRONMENTAL MODELLING & SOFTWARE	4.807
Sith et al. (2019)	- First quantified the impacts of multiple agricultural mitigation measures on long-term water quality for sediment, nitrate, and phosphate using high frequency data (hourly); - Applied model to Todoroki watershed, Okinawa Island, Japan;	10	AGRICULTURAL WATER MANAGEMENT	4.021
Triana et al. (2019)	- Proposed that to properly represent the hydrologic system, calibration tasks focused on modifying model parameters should account for equifinality, model inadequacy, and constraint inadequacy; - Used SWATmf (Guzman et al., 2015) to simulate the hydrologic processes in the Fort Cobb Reservoir Experimental Watershed in central western Oklahoma, USA;	3	JOURNAL OF HYDROLOGY	4.500
Wei et al. (2019)	- Coupled SWAT–MODFLOW (Bailey et al., 2016) and RT3D (solute reactive transport model) to identify the loads of NO_3-N in space during the interaction process of surface and grounder water; - Applied model to the Sprague River Watershed in Oregon, USA;	12	ENVIRONMENTAL MODELLING & SOFTWARE	4.807
Bailey et al. (2020)	- Used a version of SWAT plus link to MODFLOW to simulate GW flow and SW–GW interactions within a watershed; - Applied modeling code to Middle Bosque River Watershed (Texas, USA) to demonstrate accuracy and differences with SWAT plus.	0	ENVIRONMENTAL MODELLING & SOFTWARE	4.807
Dybowski et al. (2020)	- Coupled SWAT–MODFLOW and EcoPuckBay model (ecohydrodynamic predictive model) to assess the state of the Puck Bay coastal environment and its ecosystem;	0	WATER	2.544
Liu et al. (2020a)	- Coupled SWAT–MODFLOW and flow-biota empirical models to quantify the impacts of streamflow alterations induced by climate change on stream biota beyond specific species in Denmark;	0	SCIENCE OF THE TOTAL ENVIRONMENT	6.551
Sabzzadeh and Shourian (2020)	- Coupled SWAT–MODFLOW and PSO (Particle Swarm Optimization algorithm) to solve the optimization problem between crops areas and water depletion by wells for Asemanabad plain in west of Iran;	0	JOURNAL OF CLEANER PRODUCTION	7.246
Taie-Semiromi and Koch (2020)	- Coupled SWAT–MODFLOW–NWT to explore the potential impacts of climate change and GW abstraction on gaining and losing SW; - GW overutilization is the compelling reason for the future water scarcity in the Gharehsoo River Basin (northwestern Iran), rather than climate change alone;	0	WATER RESOURCES RESEARCH	4.309
Liu et al. (2020c)	- An approach based on PEST (parameter estimation by sequential test) was developed to calibrate both SWAT and MODFLOW parameters simultaneously; - Applied model to Uggerby River catchment (Denmark) to quantify the streamflow response to groundwater abstractions due to irrigation or drinking water.	0	ENVIRONMENTAL SCIENCES EUROPE	5.394

Finally, Bailey et al. (2016) developed a SWAT–MODFLOW model using new code (in Python). In the new version, a HRU disaggregation (DHRU) technique was proposed, which can represent HRU deep percolation spatially for linkage to MODFLOW grid cells. Meanwhile, the model offered a graphical user interface (GUI), could identify locations of nutrient loading, and enhanced understanding of spatial patterns of GW influence on SW flow. In the following year, Bailey et al. (2017) developed a GUI for preparing coupled SWAT–MODFLOW simulations called SWATMOD-Prep. However, SWATMOD-Prep has some disadvantages, including the inability to provide geographical context with maps, not allowing linkage between SWAT and an existing MODFLOW model, and not displaying results or comparing model results. Park et al. (2019) developed a QGIS-based GUI based on Bailey et al. (2016, 2017)), called QSWATMOD which facilitated model preparation and model results viewing for the broad SWAT–MODFLOW users. The SWAT–MODFLOW and QSWATMOD executables are available at: http://swat.tamu.edu/software/swat-modflow/. After a two-year development period (a total of 5 articles in 2017–2018, Fig. 1a), the application of SWAT–MODFLOW (Bailey et al., 2016) ushered in a period of rapid development (2019–2020). The following research mainly focused on the improvement of model code (Aliyari et al., 2019), linking a new version of SWAT to MODFLOW (SWAT grid-MODFLOW, Deb et al., 2019; SWAT plus-MODFLOW, Bailey et al., 2020), use of high frequency (hourly) data in SWAT–MODFLOW (Sith et al., 2019), and coupled SWAT–MODFLOW and other models or methods (Triana et al., 2019; Wei et al., 2019; Dybowski et al., 2020; Liu et al., 2020a, 2020b; Sabzzadeh and Shourian, 2020).

The three main stages are also reflected by the high citation of publications by three pioneer studies: Sophocleous et al. (1999), Kim et al. (2008) and Bailey et al. (2016) were cited 151, 162 and 56 times, respectively (Table 1). In Table 1 (n = 27), SWAT–MODFLOW studies were mainly published in high impact international journals, e.g., *ENVIRONMENTAL MODELLING & SOFTWARE* (n = 5, IF_{2019} = 4.807), *JOURNAL OF HYDROLOGY* (n = 5, IF_{2019} = 4.500), *SCIENCE OF THE TOTAL ENVIRONMENT* (n = 2, IF_{2019} = 6.551) and *HYDROLOGICAL PROCESSES* (n = 2, IF_{2019} = 3.256). Some studies have also been published in *WATER RESEARCH* (Eshtawi et al., 2016) and *WATER RESOURCES RESEARCH* (Taie-Semiromi and Koch, 2020). These journals have a high degree of recognition, indicating that the SWAT–MODFLOW model was of considerable interest in the scientific community.

2.4. Coupling strategy

Initially, Sophocleous et al. (1999) developed a subroutine to transfer information between SWAT and MODFLOW as a way of coupling SW and GW. Kim et al. (2008) proposed a conversion interface of HRUs-cells to exchange data between SWAT and MODFLOW, which improved the efficiency and accuracy of coupling. Recently, a new DHRU technique based on Kim et al. (2008) was proposed by Bailey et al. (2016), and has a wide application due to its advantages of good GUI, hot-spots identification and free code. According to Bailey et al. (2016), three main steps for coupling SWAT–MODFLOW are (1) disaggregating SWAT HRUs and attaching geographical location information for each HRU; (2) linking disaggregated HRUs (DHRUs) to MODFLOW grid cells in space, which ensures SWAT transfers its deep percolation into MODFLOW cells as recharge for each time step of the simulation; (3) linking MODFLOW river cells to the channel of SWAT sub-basins, which enables MODFLOW calculated GW/SW exchange rates can be transferred to the correct sub-basin channel. The flow chart of the SWAT–MODFLOW model is shown in Fig. 2.

Table 2 shows the SWAT–MODFLOW evaluation results of previous studies (Petpongpan et al., 2020; Guevara-Ochoa et al., 2020b; Taie-Semiromi and Koch, 2019; Molina-Navarro et al., 2019; Gao et al., 2019; Wei and Bailey, 2019). A good model performance evaluation may be based on NSE (Nash-Sutcliffe efficiency) and R^2 (coefficient of determination) close to 1, and a RMSE (root mean square error) and PBIAS (the percent bias) close to 0. The coupled SWAT-MODFLOW models usually get a lower value for RMSE/PBIAS and about 0.5 (acceptable level) for NSE/R^2 in simulating streamflow and GW level. Some studies have an NSE/R^2 value of more than 0.75 (very good level). In addition, previous studies have shown a good performance in simulating streamflow using the coupled SWAT–MODFLOW rather than the SWAT alone (Kim et al., 2008; Guzman et al., 2015; Bailey et al., 2016).

3. Research scope of SWAT–MODFLOW

3.1. Hydrologic process

Existing studies on hydrological processes by SWAT–MODFLOW can be grouped into non-situational simulation and situational simulation (Table 3). In non-situational scenario, previous studies were mainly concerned with streamflow simulation, GW discharge, SW–GW interaction and regional water balance (Guevara-Ochoa et al., 2020a; Bailey et al., 2020, 2016; Taie-Semiromi and Koch, 2019; Gao et al., 2019; Aliyari et al., 2019; Kim et al., 2017; Dowlatabadi and Zomorodian, 2016; Guzman et al., 2015; Eshtawi et al., 2015; Lin et al., 2013; Luo and Sophocleous, 2011; Ke, 2014; Chung et al., 2010). For instance, Guevara-Ochoa et al. (2020a) indicated that an annual average of 34 mm GW discharge to stream and 1.4 mm stream recharge to aquifer were determined by SWAT–MODFLOW in the upper creek basin of Del Azul, Argentina; furthermore, the results of annual water balances showed that recharge (80 mm) accounted for 10.2%, surface runoff (37 mm) for 4.8%, and total rainfall (776 mm) and evapotranspiration (659 mm) for 85%. Bailey et al. (2016) indicated that GW discharge has a high spatial variability in Sprague River Watershed (USA), with an average annual GW discharge of 20.5 $m^3 s^{-1}$. Luo and Sophocleous (2011) pointed out that the amount of annual recharge to shallow GW is 29 × 10^8 m^3 in Hetao irrigation district (China), while shallow GW evaporation is 23 × 10^8 m^3. However, the quantified analysis of SW–GW interactions still requires consideration of multiple scenarios to support policy formulation.

In situational scenarios, the impacts of GW pumping and irrigation on the environment have been considered by several SWAT–MODFLOW users (Wei and Bailey, 2019; Surinaidu et al., 2016; Izady et al., 2015; Chung et al., 2011, 2015). Liu et al. (2020b) assessed the effects of current state, no drinking water wells and extreme abstraction scenarios on GW discharge and stream biota by SWAT–MODFLOW in the Uggerby River catchment, Denmark. The results showed that extreme abstract scenarios have significant effects on small streams, especially on fish and macrophyte indices. This research has improved the understanding of watershed water ecology by SWAT–MODFLOW and scenario simulation. Considering the characteristics of aquifers (high transmissivity and percolation rates) in the Ganges river basin, Surinaidu et al. (2016) combined SWAT–MODFLOW with climate scenarios and proposed more pre-monsoon pumping of GW from aquifers for irrigation and other uses. This allows GW to be recharged during the monsoon, thus creating additional subsurface storage to alleviate the water shortage. Chung et al. (2015) analyzed the changes of hydrological composition caused by various GW pumping scenarios in Mihocheon basins, South Korea. The results indicated an optimal total of 104 mm GW abstraction would only reduce 16 mm GW storage, providing a powerful reference for local policymakers. Several other studies have also demonstrated that SWAT–MODFLOW has a good performance in evaluating the impact of irrigation and GW extraction on SW (Liu et al., 2020b; Wei and Bailey, 2019; Izady et al., 2015; Chung et al., 2011). Overall, these quantitative analyses of SW–GW interaction improved understanding of complicated hydrologic processes. In addition, the integrated model is a powerful tool for sustainable water resource planning and management in areas with high aquifer pressure.

3.2. Solute transport

Anthropogenic development has caused the application of large amounts of fertilizers and pesticides to the environment, thus increasing the concentration of pollutants in the watershed (Ehtiat et al., 2018; Eshtawi et al., 2016; Narula and Gosain, 2013; Sith et al., 2019). In recent decades, the interaction of SW–GW was more frequent in the basin due to urbanization and climate change (Akbarpour and Niksokhan, 2018; Chang et al., 2016; Eshtawi et al., 2015). These high-intensity human activities, as well as extreme weather events, increase pollutants exported from the agricultural watershed (Eshtawi et al., 2016; Narula and Gosain, 2013; Wei et al., 2019), especially in subtropical areas with frequent typhoons and storm events (Sith et al., 2019). With the development of solute transport modules, e.g. RT3D (Reactive Transport in Three Dimensions, Clement, 1997) and MT3DMS (modular 3-dimensional multi-species transport, Zheng and Wang, 1999), and a recently developed SWAT–MODFLOW model (Bailey et al., 2016), the combination of both models improves assessment capability in the watershed aquatic environment. A spatial interaction map of SW–GW can also be obtained, helping to identify and control pollutant discharge from sources in the watershed (Wei et al., 2019).

Until the present, nitrate nitrogen (NO_3-N) has been the most popular simulation subject (e.g. Szymkiewicz et al., 2020; Wei et al., 2019; Eshtawi et al., 2016; Narula and Gosain, 2013; Conan et al., 2003). At the initial stage of model coupling, Conan et al. (2003) first simulated NO_3-N and assessed the impacts of intensive

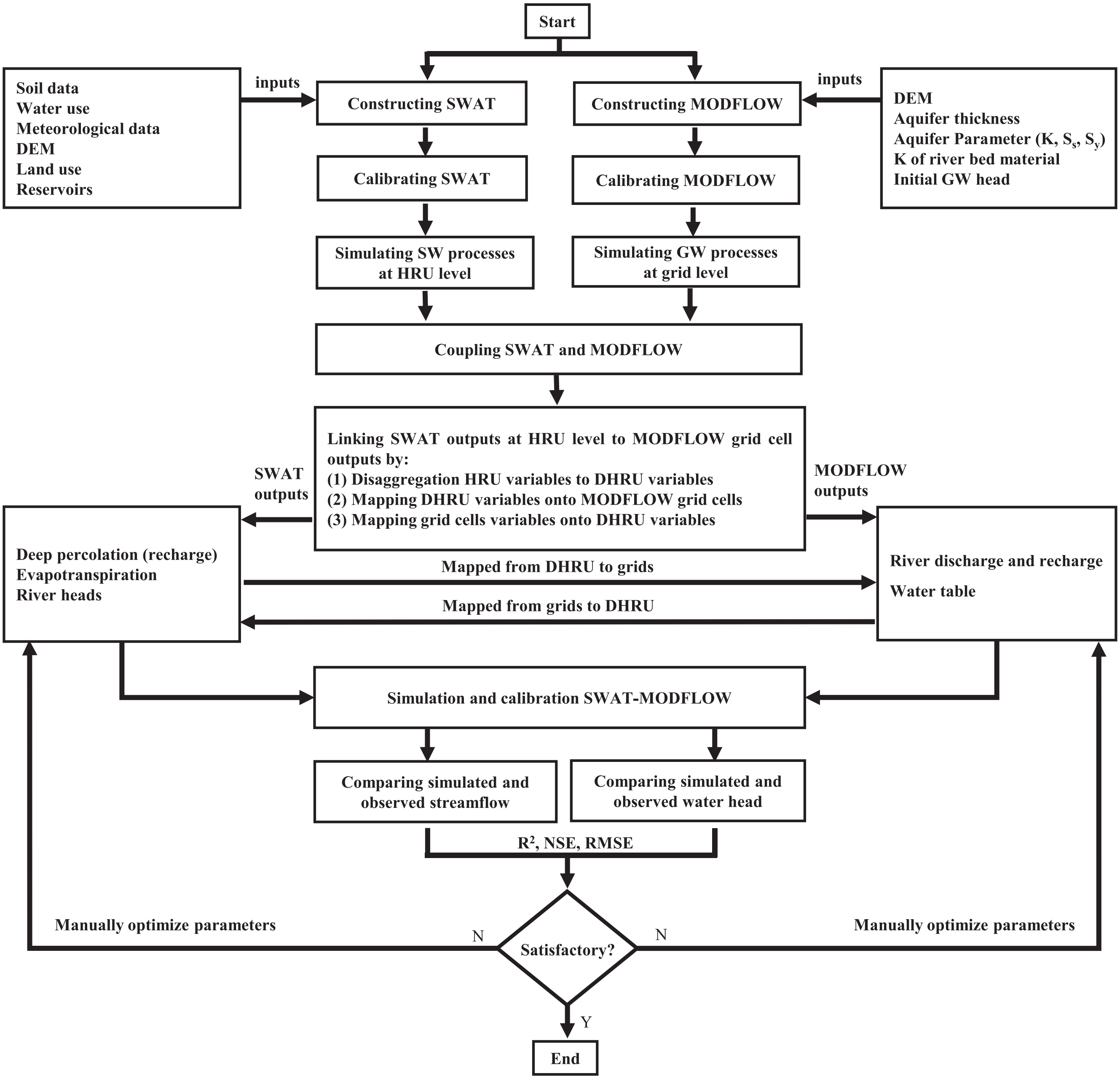

Fig. 2. Workflow of the SWAT–MODFLOW model based on the DHRU technique. Adapted from Taie-Semiromi and Koch (2020) and Bailey et al. (2016). SW, surface water; GW, groundwater; DEM, digital elevation model; K, hydraulic conductivity; S_s, specific storage; S_y, specific yield; HRU, hydrologic response unit; DHRU, disaggregated HRU; R^2, coefficient of determination; NSE, Nash-Sutcliffe efficiency; RMSE, root mean square error; Y, yes; N, no.

pig-farms on the water environment using SWAT–MODFLOW–MT3DMS in the Coet-Dan watershed, France. Narula and Gosain (2013) further evaluated the SW–GW hydrologic processes and the fate of NO_3-N under climate change in the Himalayan Upper Yamuna basin. However, the spatial positioning of pollutants loading was unexplored until Wei et al. (2019) identified the loading of NO_3-N in space during the process of SW–GW interaction in the Sprague River Watershed (USA) by coupled SWAT–MODFLOW (Bailey et al., 2016) and RT3D (Clement, 1997). SWAT–MODFLOW–RT3D executables are available from: http://swat.tamu.edu/software/swat-modflow/.

Besides NO_3-N, other constituents have also been addressed, including nitrite (NO_2-N), ammonia (NH_4-N), phosphate (PO_4-P), chloridion (Cl^-) and total dissolved solids (TDS). Galbiati et al. (2006) developed an ISSm model to predict the influence of anthropogenic activities on water quality (NO_3-N, NO_2-N and NH_4-N) of both SW and GW in the Bonello watershed, Italy. The ISSm model was composed of SWAT, MODFLOW–MT3DMS and Qual2E (in-stream water quality model). Sith et al. (2019) combined high-resolution data, SWAT–MODFLOW and best management practices (BMPs) to assess the reduction of non-point source pollution (TDS, NO_3-N, PO_4-P) in the Todoroki river watershed in Ishigaki island, Japan. Cl^- and TDS were considered by Ehtiat et al. (2018), Eshtawi et al. (2016) and Kamali and Niksokhan (2017). Dybowski et al. (2020) coupled the EcoPuckBay model (ecohydrodynamic predictive model-the ecosystem part) with SWAT–MODFLOW to provide a decision-making service tool which is capable of forecasting seven biochemical indexes (NO_3-N, NH_4-N, PO_4-P, silicate, chlorophyll-a, dissolved oxygen, and active ingredient of pesticide). These studies integrating SWAT–MODFLOW and solute

Table 2
Performance for the coupled SWAT–MODFLOW model.

Study	Location	Simulation period		Streamflow					Ground water level				
	(watershed, area)			n of station	R^2 (m^3 s^{-1})	NSE (m^3 s^{-1})	RMSE (m^3 s^{-1})	PBIAS (%)	n of well	R^2 (m)	NSE (m)	RMSE (m)	PBIAS (%)
Petpongpan et al. (2020)	Thailand	2007–2016	Calibration	10	0.78–0.89	0.78–0.86	42.74–191.04	−10.08–10.35	14	0.77	0.71	2.21	−10.6
	(Yom and Nan river basin, 58,783 km^2)		Validation	10	0.65–0.86	0.64–0.83	42.25–100.38	−35.60–14.29	14	0.83	0.76	2.35	12.36
Taie-Semiromi and Koch (2019)	Iran	1978–2012	Calibration	5	0.49–0.67	0.04–0.64	–	–	68	0.98	0.98	–	–
	(Gharehsoo River basin, 4,193 km^2)		Validation	2	0.33–0.60	0.07–0.57	–	–	68	0.95	0.98	–	–
Molina-Navarro et al. (2019)	Denmark	2000–2010	Calibration	1	0.71	0.69	0.30–0.75	7.00	–	–	–	–	–
	(Odderbæk catchment, 11 km^2)		Validation	1	0.68	0.65	0.30–0.66	7.60	–	–	–	–	–
Gao et al. (2019)	USA	2000–2016	Calibration	3	0.68–0.73	0.64–0.69	20.66–26.71	−21.00–24.00	46	0.95	0.99	0.51	–
	(Big Sunflower River watershed, 10,488 km^2)		Validation	3	0.66–0.77	0.68–0.74	18.82–20.54	−12.00–21.00	46	0.88	0.93	0.59	–
Guevara-Ochoa et al. (2020b)	Argentina	2003–2015	Whole period	3	0.46–0.60	0.35–0.60	–	–	9	–	–	0.75–2.17	–
	(Upper creek basin of Del Azul, 1,024 km^2)												
Wei and Bailey (2019)	USA	1999–2016	Whole period	5	0.12–0.91	0.44–0.94	–	–	89	–	–	2.32	–
	(Lower Arkansas River valley, 732 km^2)												

Note: n, number; R^2, coefficient of determination; NSE, Nash–Sutcliffe efficiency; RMSE, root mean square error; PBIAS, percentage bias.

transport model are helpful to identify hot-spots of nitrogen pollution across the stream network and GW aquifer, providing a scientific basis for managing non-point source pollution in the watershed (Wei et al., 2019; Kamali and Niksokhan, 2017; Ehtiat et al., 2016).

3.3. Effects of climate change and human activity

Climate change is one of the most important global challenges for humanity (Petpongpan et al., 2020). Climate change overall increases temperature and evapotranspiration, and intensifies seasonal patterns of precipitation in the Mediterranean region (Chaouche et al., 2010; Molina-Navarro et al., 2019). China Meteorological Administration Climate Change Centre (2020) reported that annual mean temperature in China rose by 0.24℃ every 10 years from 1951 to 2019, with a higher temperature rise rate than the global average for the same period. Meanwhile, the occurrence of rain storms (i.e. daily precipitation more than 50 mm) increased by 3.8% per decade on average from 1961 to 2019. As reported by the Intergovernmental Panel on Climate Change (IPCC), the climate change causes more frequent floods and droughts and the situation could get worse in the future, especially in mid-latitude and subtropical regions (IPCC, 2013). Undoubtedly, climate change substantially affects watershed hydrological processes (Akbarpour and Niksokhan, 2018; Guevara-Ochoa et al., 2020a). Numerous studies have focused on the influence of climate change on surface hydrological processes (Ficklin et al., 2009; Du et al., 2019), but few studies have addressed subsurface hydrological processes and the GW–SW interaction (Pulido-Velazquez et al., 2015; Taie-Semiromi and Koch, 2020). Currently, in existing research, two modelling works have been carried out addressing the effects of climate change (sometimes combined with human activities) on hydrology based on the coupled SWAT–MODFLOW model.

(1) *Effects of climate change on hydrological processes.* Qi et al. (2019) suggested that the annual streamflow and GW recharge varied by a factor of 17 and 19 times respectively between wet and dry years under RCP 8.5 scenario in the Naoli River basin of China. Petpongpan et al. (2020) suggested that the summation of SW (water yield) and GW recharge (water percolation) decreased by 443.98 (RCP 2.6) and 316.77 (RCP 8.5) million m^3 yr^{-1} in the Yom river basin, Thailand. Similar decreases were found in Kathmandu Valley, Nepal, in which the GW recharge decreased by a range of 3.3–50.7 mm yr^{-1} (RCP 4.5) and 19–102.1 mm yr^{-1} (RCP 8.5) (Shrestha et al., 2020). However, the opposite result was found in Buenos Aires, Argentina, in which the annual average GW discharge to SW increased by 5–24% (Guevara-Ochoa et al., 2020a). In addition, the effects of climate change on hydrological regime and stream biota in a GW-dominated catchment was assessed using SWAT–MODFLOW with flow-biota empirical models by Liu et al. (2020a). These studies highlight the direct influence of climate change on both SW quantity and GW discharge.

(2) *Combined effects of climate change and human activities.* Triana et al. (2020) suggested that climate changes would decrease GW level by 99–120% by the end of the 21st century if land use was maintained at current levels, but could recover within 7–10 years under mitigation scenarios (i.e. decrease irrigation depth by 50% and transfer 50% of agricultural land area to rangelands with no irrigation). Chunn et al. (2019) pointed out that over-exploitation of GW contributes more in the reduction of river flows and GW level than climate change, and this statement is also supported by Pisinaras (2016) and Taie-Semiromi and Koch (2020).

Table 3
Summary of hydrologic processes addressed in the SWAT–MODFLOW studies.

Study	Location	Catchment size (km^2)	Climatic zone	Annual precipitation (mm)	Elevation (m)	Number of subbasin	HRUs	Layer	Cell-size (m)	Simulation period	Processes analyzed	Scenario
Guevara-Ochoa et al. (2020a)	Upper creek basin of Del Azul, Argentina	1,024	Subtropical	–	129–367	3	1,161	1	180 × 180	2003–2015	Stream discharge; GW level; SW–GW interactions; water balance;	–
Bailey et al. (2020)	Middle Bosque River watershed, USA	470	Subtropical	800	161–367	69	1,693	5	150 × 150	1980–2012	Water balance; SW–GW interactions; build and apply SWAT plus and MODFLOW frameworks;	–
Taie-Semiromi and Koch (2019)	Gharehsoo River basin, Iran	4,193	Subtropical	300	1,259–1,811	124	1,778	1	200 × 200	1978–2012	SW–GW interactions;	–
Gao et al. (2019)	Big Sunflower River watershed, USA	10,488	Subtropical	1,371	Relatively flat	23	–	–	1,000 × 1,000	2000–2016	Temporal and spatial variability of stream and pond resources; water resources assessment;	–
Aliyari et al. (2019)	South Platte River basin, USA	72,000	Subtropical	250–1,000	850–4,300	194	1,994	1	305 × 305	1997–2012	Water balance; impact of irrigation; model enhancement;	–
Dowlatabadi and Zomorodian (2016)	Firoozabad watershed, Iran	723	Subtropical	403	1,300–2,891	79	–	1	300 × 300	–	Assess MODFLOW performance by using SWAT recharge;	–
Bailey et al. (2016)	Sprague River watershed, USA	4,100	Temperate	340–950	1,270–2,600	142	1,940	3	762 × 762	1970–2003	GW level and GW discharge; SW–GW interactions;	–
Guzman et al. (2015)	Fort Cobb Reservoir experimental watershed, USA	780	Subtropical	–	380–560	79	1,001	2	300 × 300	2010–2012	Hydrologic processes; model enhancement;	–
Eshtawi et al. (2015)	Gaza Strip, Palestine	365	Subtropical	320	–	3	–	4	1 × 1 (Voronoi grid)	2004–2030	GW level trend and urban expansion;	–
Lin et al. (2013)	Choushui River alluvial fan, Taiwan, China	2,500	Subtropical	1,537	0–100	64	603	5	1,000 × 1,000	1999–2002	Estimating pumping rates; identifying potential recharge zones;	–
Luo and Sophocleous (2011)	Hetao Irrigation District, China	14,917	Temperate	150–200	–	11	33	1	1,970 × 1,970	1980–2000	Stream recharge; GW water table and evaporation; water balance; model enhancement;	–
Ke (2014)	Choushui River alluvial fan, Taiwan, China	2,399	Subtropical	–	–	86	1,800	5	500 × 500	2007–2009	Hydrologic processes; pumping/recharge estimation; model enhancement;	–
Chung et al. (2010)	Mihocheon watershed, South Korea	1,868	Subtropical	–	0–600	19	–	3	300 × 300	2000–2005	Water balance; distributed GW recharge;	–
Liu et al. (2020b)	Uggerby River catchment, Denmark	357	Temperate	933	0–108	19	2,620	5	100 × 100	2002–2015	Impacts of GW abstractions on environment; scenario simulation;	Baseline; no drinking water wells; extreme abstraction;
Wei and Bailey (2019)	Lower Arkansas River valley, USA	732	Subtropical	273	–	72	5,270	–	250 × 250	1999–2016	Water balance; SW–GW Interactions; scenario simulation;	Baseline scenario; reduced irrigation scenario;

(*continued on next page*)

Table 3 (*continued*)

Study	Location	Catchment size (km^2)	Climatic zone	Annual precipitation (mm)	Elevation (m)	Number of subbasin	HRUs	Layer	Cell-size (m)	Simulation period	Processes analyzed	Scenario
Surinaidu et al. (2016)	Ramganga sub-basin, India	18,668	Subtropical	923	1,000–2,688	27	–	2	500 × 500	1999–2010	Water balance; scenario simulation;	Increase GW pumping; increase GW pumping under climate change;
Izady et al. (2015)	Neishaboor watershed, Iran	9,158	Subtropical	265	1,050–3,300	248	–	1	500 × 500	2000–2012	Hydrologic processes; water balance; scenario simulation;	Baseline; reduce GW extraction;
Chung et al. (2015)	Mihocheonbasin, South Korea	1,602	Subtropical	–	25–585	34	–	3	300 × 300	2004–2010	Scenario simulation;	0,0.5, 1, 1.4,1.7 and 2 times at current pumping rate;
Chung et al. (2011)	Pyoseon watershed, South Korea	207	Subtropical	2,174	0–1,320	13	–	2	100 × 100	August–November 2006	Hydrologic processes; scenario simulation;	GW pumping increased by 10- and 20- fold.

Note: SW, surface water; GW, groundwater.

Akbarpour and Niksokhan (2018) further stated that urbanization and future population growth increase pumping rate yield, resulting in adverse impacts on unconfined aquifers. Based on the coupled SWAT–MODFLOW with MT3DMS, Pulido-Velazquez et al. (2015) assessed the fate and transport of nitrate under different climate scenarios and found GW recharge decreases and nitrate content increases. Chang et al. (2016) used SWAT–MODFLOW–SEAWAT (multi-species solute and heat transport) to explore the effects of lateral saltwater intrusion on both GW and freshwater quality. These studies emphasized anthropogenic disturbances on GW due to land use change, water withdrawal and urbanization alongside climate change.

4. Uncertainty in SWAT–MODFLOW

SWAT–MODFLOW has distinct advantages in simulating SW–GW interaction, e.g. high precision evaluation for streamflow (Luo and Sophocleous, 2011; Guzman et al., 2015; Bailey et al., 2016), but uncertainty is a normal, inherent defect for numerical models (Yuan et al., 2020). The three major sources of uncertainty in SWAT–MODFLOW are outlined below.

(1) *Uncertainty from model structure.* SWAT (e.g. SWAT grid, SWAT plus) and MODFLOW (e.g. MODFLOW–USG, MODFLOW–NWT) are constantly updated, and different versions of coupling SWAT and MODFLOW are being tested, but some codes/modules are still missing. Guevara-Ochoa et al. (2020a) pointed out that there was no module to link changes between GW levels and soil saturation, resulting in SWAT delivering a higher recharge to MODFLOW rather than creating surface runoff during wet periods. Newly developed codes are still few in number. Aliyari et al. (2019) developed an integrated hydrologic modeling code to link SW–GW (canal diversion-pumping) for large-scale mixed agro-urban river basins in South Platte River Basin, Colorado, USA, but these codes need more validation.

(2) *Uncertainty from database.* The difficulty in obtaining hydrogeological data results in considerable uncertainty in geological stratification. In addition, the number and distribution of monitoring wells, as well as the frequency of GW observed head, may affect the initial conditions and calculation procedures for the model. Moreover, the uncertainty of input data may also come from the heterogeneity of rainfall, size of streamflow, Digital Elevation Model (DEM) resolution, soil, land use/land cover, and so on.

(3) *Uncertainty from parameterization.* Calibration of the model usually obtains the best performance by configuring model parameters. However, different combinations of parameters may produce similar results (i.e. parameter non-uniqueness). A few efforts have been made to reduce uncertainty. For example, Liu et al. (2020b) calibrated SWAT and MODFLOW simultaneously using a PEST (parameter estimation by sequential testing) approach for the Uggerby River catchment in northern Denmark, while Zambrano-Bigiarini and Rojas (2013) calibrated SWAT–MODFLOW by Particle Swarm Optimisation (PSO) algorithm in the Ega River Basin, Spain. More work is necessary to reduce uncertainties through appropriate parameterization (Akbarpour and Niksokhan, 2018).

5. Perspectives on SWAT–MODFLOW in an era of big data

The coupled SWAT–MODFLOW model has been developed well in the past two decades. However, future work is needed to expand its potential application to the study of watershed hydro-biogeochemistry at various temporal and spatial scales.

(1) *Adapting the coupled SW–GW model to operate at multiple time scales*. Current SWAT–MODFLOW simulation are mostly performed at mid- or long-term scales (e.g. monthly, yearly or decadal assessment) (Table 3). Little research has targeted the short-term response of SW–GW interactions to extreme events, largely due to the lack of high temporal resolution monitoring data to calibrate and validate the model. Under global climate change, extreme weather events such as storms and accompanied flooding likely become more frequent and intensive (Shrestha et al., 2020; Akbarpour and Niksokhan, 2018). These events dramatically alter watershed hydrography and cause a short-term pulse of nutrient export (Chen et al., 2018a, 2018b). Although hourly data was integrated in modeling by Sith et al. (2019), it mainly focused on rainfall, streamflow, sediment and GW head. Therefore, the SWAT–MODFLOW should be adapted to short time scales with high-frequency data (e.g. minutely, hourly or daily) to describe detailed hydrological responses under extreme climate conditions.

(2) *Reduce model uncertainties by refining model structure and local parameterization*. Specific codes or modules should be developed and integrated into the current modeling framework to reflect the complicated interactions between surface and subsurface processes, particularly in the case of human disturbances in the watershed (e.g. artificial irrigation for a variety of crops, crop growth and rotation, impoundment or reservoirs, and cross-basin water diversion) (Wei et al., 2019; Pulido-Velazquez et al., 2015; Triana et al., 2020; Liu et al., 2020b; Guevara-Ochoa et al., 2020a). Furthermore, local parameterization is necessary to achieve good model performance in a specific watershed with heterogenetic characteristics (meteorology, geology, soil, land use, etc.) (Bailey et al., 2016; Wei et al., 2019; Aliyari et al., 2019).

(3) *Expanding model objects and potential in studies of hydro-biogeochemical process.* Numerous studies yielded good results through the use of coupled SWAT–MODFLOW, demonstrating the advantages and potential for future research (Narula and Gosain, 2013; Guzman et al., 2015; Deb et al., 2019; Sabzzadeh and Shourian, 2020). However, modeling of solute transport in the SW–GW interaction has mainly focused on NO_3-N (Wei et al., 2019; Conan et al., 2003). Future research should emphasize on hydrology-driven biogeochemical processes including the transport and cycling of other major constituents (nitrogen and phosphorus species, metals, pesticides, etc.) in the aquifer system, and their interaction between SW and GW. In addition, previous studies mainly focused on the physical process of unsaturated flow (Al–Jaf et al., 2020; Liu et al., 2020d), but the effect of unsaturated flow on hydro-biogeochemical process is still unclear, which could be incorporated into SWAT–MODFLOW in the future work.

(4) *Facilitating transfer of model outputs into the decision-making process.* With the rapid development of environmental sensors and auto-monitoring techniques, acquisition of high-frequency measurement will become more convenient. In an era of big data, the use of Internet of Things (IoT) and cloud computing techniques will make the SWAT–MODFLOW model more intelligent (Jiang et al., 2011). Big data assimilation can be expected to improve the predictability of SWAT–MODFLOW and support more detailed studies of hydrological dynamics. This will allow the attainment of a systematic understanding of water and solute transport across surface runoff, interflow and GW and downstream river (Guevara-Ochoa et al., 2020a; Bailey et al., 2020; Gao et al., 2019; Aliyari et al., 2019; Szymkiewicz et al., 2020; Narula and Gosain, 2013). To meet the requirement of sustainable water management and ecological restoration, SWAT–MODFLOW should be linked with other biogeochemical models, and combined into an integrated watershed management information system to assist decision-making by non-professional users (Pisinaras et al., 2013; Ni et al., 2020; Sabzzadeh and Shourian, 2020; Norouzi-Khatiri et al., 2020).

6. Conclusions

In this paper, we reviewed the main progress on coupling strategy between SWAT and MODFLOW, determined the research hotspots, discerned major uncertainties and discussed the potential future work regarding SWAT–MODFLOW. In summary, the coupled surface and ground water models have proven their great potential in hydro-biogeochemical studies and support the management of watershed ecology and environment.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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