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Article

# Assessing Climate Change Impact on Water Resources under Water Demand Scenarios using SWAT-MODFLOW-WEAP

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**Abstract:** In this article, we present the use of the coupled land surface model and groundwater flow model SWAT-MODFLOW with the decision support tool WEAP (Water Evaluation and Planning software) to predict future surface water abstraction scenarios in a complex river basin, under conditions of climate change. The modeling framework is applied to the Dee River catchment in Wales, United Kingdom. Regarding hydrology, the coupled model improves overall water balance and low streamflow conditions, compared to a stand-alone SWAT model. The calibrated SWAT-MODFLOW is employed with high resolution climate model data from the UKCP18 project with future scenario of RCP85 from 2020 to 2040. Then, water supply results from SWAT-MODFLOW are fed into WEAP as input for the river reach in the downstream region of the river basin. This system is utilized to create various future scenarios of surface water abstraction of public water supply in the downstream region: maximum licensed withdraw, 50 % authorized abstractions, monthly time series with 1% increase of water use, and maximum water withdraw year based on historical records repeated every year with 1% increase of water use, to estimate the unmet demands and streamflow requirement. This modeling approach can be used in other river basins to manage scenarios of supply and demand.

**Keywords:** highly-regulated river basins; climate change; water demands; public water supply; SWAT-MODFLOW; WEAP; UKCP18

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## 1. Introduction

In the last few decades, there has been growing stress on surface and groundwater resources around the world e.g. [1, 2] due to climate change, population growth, and degradation of historical water sources. There is a need to balance available future water supply with future increasing demand, to provide reliable water supplies to various stakeholders and uses (domestic, agricultural, industrial, energy).

This can be performed using Integrated Water Resources Management (IWRM) at the catchment and watershed levels, which heavily depend on the use of computer model simulations that capture the underlying hydrological processes and surface water/groundwater allocations. Examples of simulation models include HydroGeoSphere - Integrated Hydrologic Models [3], Integrated Water Flow Model IWFM [4], MIKE-SHE [5], and Penn State Integrated Hydrological Modelling System PIHM [6].

Often-used hydrologic models for IWRM include: the Soil and Water Assessment Tool [SWAT; 7], a watershed modeling code that simulates principal hydrologic fluxes on a daily time step; MODFLOW [8], a groundwater modeling code that simulates groundwater head and associated flow rates in a heterogeneous aquifer system; and, to overcome the subsurface and surface process limitations in SWAT and MODFLOW, respectively, the coupled modeling code SWAT-MODFLOW [9], which has been used in numerous studies for water supply estimation and water management e.g. [10-13]. However, these models represent the physical world (i.e., model spatial discretization and process

simulation) differently and each is limited to its simulation domain, each having advantages and disadvantages when simulating biophysical processes and using computational resources [14].

A key part of IWRM is the estimation of future climate (precipitation, climate) and its impact on water supply and water demand. The impact of climate change on water resources needs to be quantified from regional to basin scales with the purpose of facilitating water resources planning and management to cope with future challenges. Global climate models (GCMs) are frequently utilized to simulate future climate dynamics and project future temperature and rates of precipitation for hydrologic assessment e.g. [15, 16]. Additionally, many studies show that future climate may be more extreme, not only in the sense of more storms and flooding, but also with more severe droughts and water scarcity problems [17- 19].

Typically, computer models are utilized to access reservoir operation, water allocation, flood risk assessment, drought conditions, groundwater development, water quality, irrigation operation and forecasting and control of high water. There are large numbers of software available to simulate problems water resources management, and it can be divided mainly into two groups: simulation models [20, 21] and allocation (optimization or decision-making system models).

Simulation models address certain limitations of allocation models by solving physically based flow equations to offer spatially distributed water resources outputs for several parameters (runoff, water table elevation, etc.) [21]. Allocation (optimization) models are frequently used in the applied problem of water resources management. These models optimize water allocation from various resources to meet a range of demands and what design and operating policy will best meet the identified objectives under a set of priorities and constraints [20]. Allocation models are used in several applications of water resources, such as development of a planning framework for short-term scenarios (land use change) and long-term scenarios (climate change) [22]; simulation crop evapotranspiration demand for agricultural land [23]; and modelling current and future water demands [24, 25]. The main advantage of allocation models is their lower demand for computing resources and data. However, these models have a lack of ability to simulating feedbacks to the physical system and have limited ability to simulate connections within complex, heterogeneous, conjunctively management water system.

In IWRM, ideally a combined simulation-allocation approach can be used, with the simulation model accounting for all major hydrological processes, fluxes, and state variables within a river basin or watershed system. For example, a fully integrated surface-groundwater model would be able to assess the spatially distributed hydrological variables such as river flow, groundwater table and soil moisture content. More significantly, it would also be able to simulate the surface and groundwater interaction in a heterogeneous and complex domain as well as land use change impact on these variables.

The accuracy of these kinds of models will be the central part of an IWRM system where water allocation models are driven by the outputs from the integrated surface-groundwater model to further simulate water management operations for defined operating policies and priorities under different scenarios of climate change. This integration framework is beneficial to grasp how the hydrological cycle is affected by management decisions, and vice versa.

The objective of this article is to evaluate the impacts of likely future water use for public water supply on the water resources in a heavily managed watershed system, under the stress of future climate change. This objective is achieved by linking the surface/subsurface hydrologic model SWAT-MODFLOW to the Water Evaluation and Planning (WEAP) software program to simulate hydrologic fluxes and different scenarios of water use for urban water supply, under future climate scenarios. The linked simulation/allocation modeling system is demonstrated for the highly managed Dee River watershed in Wales, United Kingdom, wherein surface water is abstracted for public water supply in the city of Chester, in the downstream area of the watershed. The SWAT-MODFLOW model is constructed and then tested against streamflow and groundwater head,

and then used with climate projections from the UKCP18 project (NCAR-CCSM4 model) for a future scenario of RCP85 from 2020 to 2040. The simulated streamflow of SWAT-MODFLOW model with UKCP18 model data is used as the input to the WEAP model to create different scenarios of water use for Chester. We consider four scenarios of water use rate: Maximum licensed water abstraction (constant value), 50 % of maximum licensed abstraction (constant value), time series of maximum water withdraw year based on historical records repeated every year with 1% increase of water use, and time series with 1% annual increase of water use. We expect that the methodology proposed herein can be utilized for other managed watersheds to aid with future water management.

## 2. Materials and Methods

### 2.1. Study Area

The Dee River flows from the mountains of the Snowdonia National Park in North of Wales in the United Kingdom. The length of main reach of the river is measured to be 113 km with a watershed area of 2,215 km<sup>2</sup> as illustrated in Figure 1. The river flows eastward to the border between England and Wales at the City of Chester before discharging into the Irish Sea at the Liverpool Bay. The average annual precipitation over the basin shows a clear west-east declining trend with 1,700 mm in the western part quickly reducing to 650 mm in the east where flat, lowland dominates as shown in Figure 2.

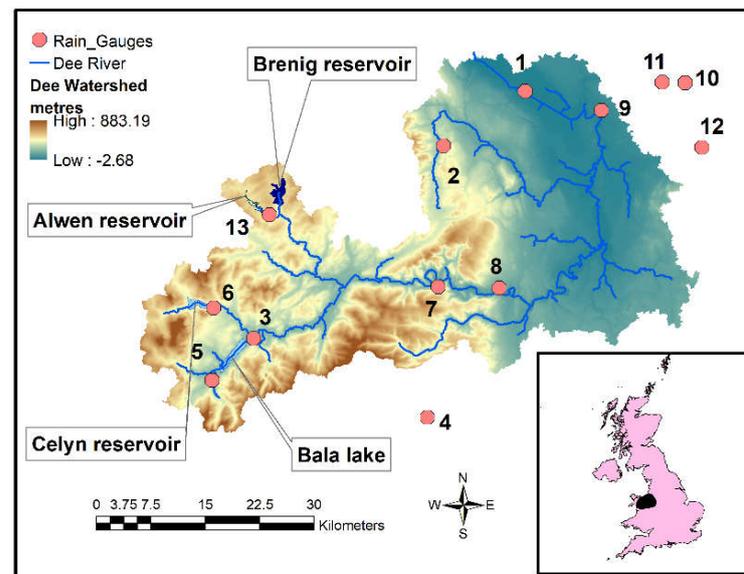
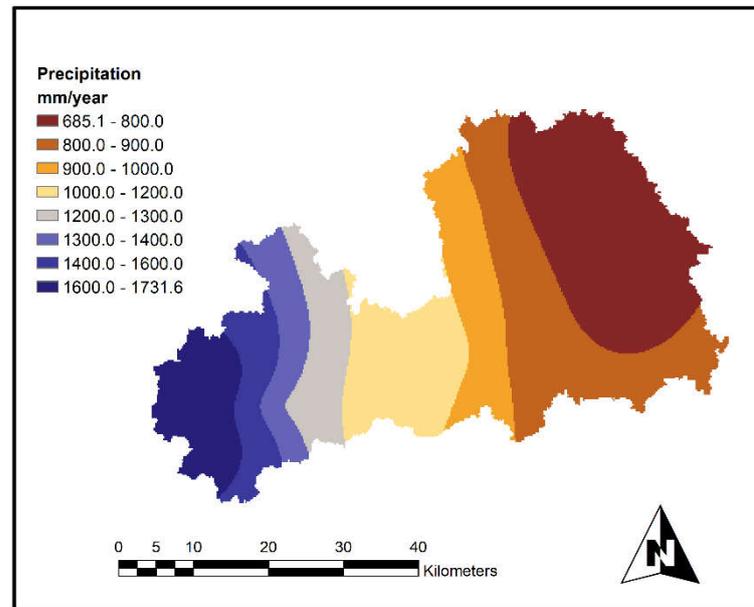


Figure 1. River Dee catchment location.



**Figure 2.** Average annual precipitation in the Dee River basin.

The temporal distribution of annual precipitation also demonstrates a definite seasonal pattern with wet winters (178-578) mm in (December, January and February) and ordinarily dry summers (165-278 mm) in (June, July and August). Therefore, the Dee River basin experiences both flooding and droughts in different seasons.

## 2.2. Collected Data

Three types of data are collected in this study (Table 1), namely: (1) static datasets, such as DEM, soil type data and land use that are assumed to be static over the study period; (2) the historical observations of river flow, precipitation, and temperature; and (3) the operational data of water abstraction and flow regulation data that represent management practice. The collected data used in this study are summarized in Table 1.

**Table 1.** Data Collected for the hydrological model.

Data	Resolution	Source
Digital Elevation Model (DEM)	25 m	ASTER Global Digital Elevation Model Version 2. NASA. <a href="https://doi.org/10.5067/aster/astgtm.002">https://doi.org/10.5067/aster/astgtm.002</a> Center for Ecology and Hydrology.
Land Use Map	25 m	<a href="https://doi.org/10.5285/a1f88807-4826-44bc-994d-a902da5119c2">https://doi.org/10.5285/a1f88807-4826-44bc-994d-a902da5119c2</a>
River Network	1:15,000 to 1:30,000	OS Open Rivers Ordnance Survey (GB), EDINA maps. <a href="https://www.ordnancesurvey.co.uk/business-and-government/products/os-open-rivers.html">https://www.ordnancesurvey.co.uk/business-and-government/products/os-open-rivers.html</a>
River Flow Data	Daily (1970-2003)	National River Flow Archive. Center for Ecology and Hydrology. <a href="https://nrfa.ceh.ac.uk/">https://nrfa.ceh.ac.uk/</a>
Precipitation and Air Temperature	Daily (1970-2003)	Met Office - MIDAS Land Surface Stations data. British Atmospheric Data Centre. <a href="https://www.ceda.ac.uk/">https://www.ceda.ac.uk/</a>
Surface-Groundwater withdraws	NA	Natural Resources Wales. Unpublished raw data
Groundwater depth map	50 m	British Geological Survey, BSG
Soil map	50 m	British Geological Survey, BSG
Soil map	3.5 km	Digital Soil Map of the World and Derived Soil Properties. FAO. DOI: <a href="https://doi.org/10.1111/j.1475-2743.1997.tb00550.x">https://doi.org/10.1111/j.1475-2743.1997.tb00550.x</a>
Aquifer designation	50 m	British Geological Survey, BSG
Groundwater level	Daily (1975-2014)	British Geological Survey, BSG
UKCP18 Model Projections for the UK	2.2 km resolution	British Atmospheric Data Centre (BADC) <a href="https://catalogue.ceda.ac.uk/uuid/ad2ac0ddd3f34210b0d6e19bfc335539">https://catalogue.ceda.ac.uk/uuid/ad2ac0ddd3f34210b0d6e19bfc335539</a>

Data screening has been conducted on the precipitation from rain gauges and the streamflow data from river gauge stations. The screening involves checking raw data, recognizing outliers, and dealing with missing data. The streamflow and precipitation data have been subjected to rigorous quality control by the Center for Ecology and Hydrology (CEH), the British Atmospheric Data Center (BADC), and the Met Office, respectively.

### 3. Methodology

#### 3.1. Simulation-Allocation Modelling using SWAT-MODFLOW-WEAP

In this study, we use a linked SWAT-MODFLOW-WEAP modeling system together with high-resolution climate model of UKCP18 under different future scenarios of surface water uses for public water supply (PWS) in the city of Chester, located in the downstream region of the Dee River Basin. The components of this system are presented in Figure 3 and described in the following sections.

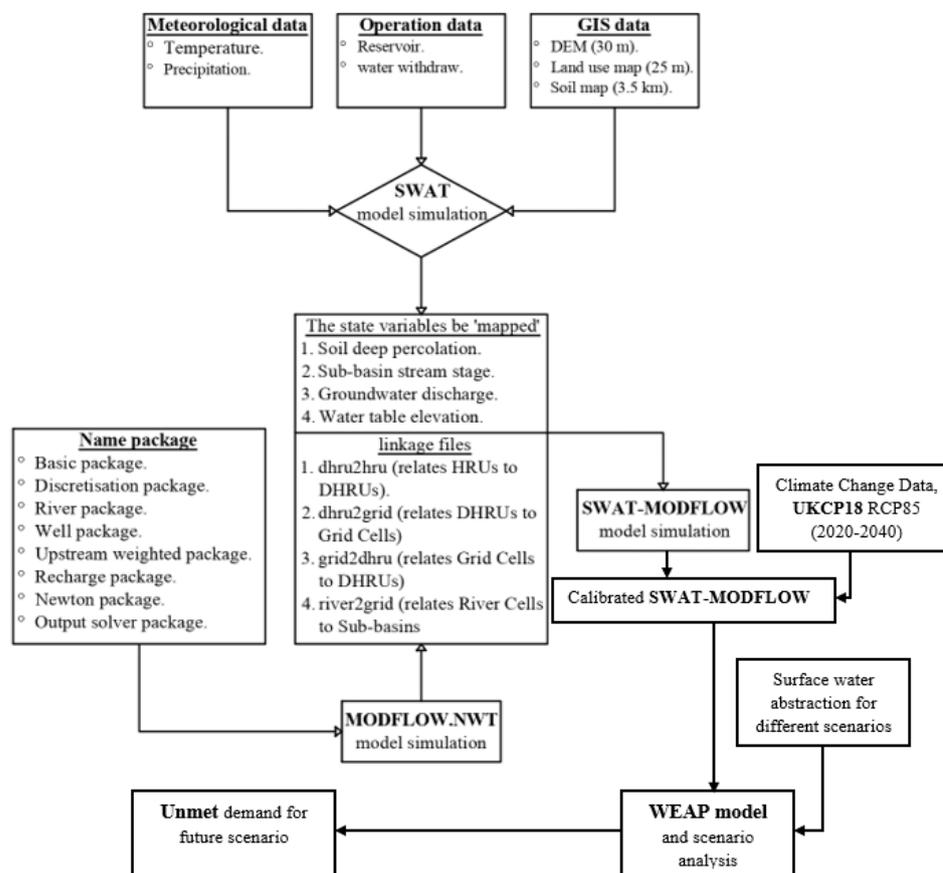
#### 3.2. Hydrological Modelling using SWAT-MODFLOW

##### 3.2.1. Overview of SWAT-MODFLOW Theory

In this study, we use the coupled surface/subsurface modeling code SWAT-MODFLOW to simulate hydrologic process in the Dee River watershed for both historical and future climate conditions.

The SWAT model [7] is a free, open-source hydrological model which has been used in thousands of applications in different regions of the world. It is a physically based continuous river basin scale, designed to simulate the rainfall-runoff process under various spatial and temporal scales. SWAT is semi-distributed model that uses hydrological response units (HRUs), based on the spatial distribution of topography, land use, and soil

characteristics within a watershed, to compute hydrologic fluxes at the land surface and within the subsurface (soil, aquifer). The computations in SWAT are conducted for each HRU and then scaled up to the sub-basin outlets according to the area of the HRU as a fraction of the sub-basin [9]. This results in the HRUs lacking spatial relations typically seen in a fully distributed model but yield a computationally efficient calculation scheme for rapid watershed simulation over long time periods [9].



**Figure 3.** Flowchart illustrating the coupled SWAT-MODFLOW-WEAP model with climate model of UKCP18 under different scenarios of water Demands for Dee River watershed.

The division of the watershed facilitates the model to simulate differences in evapotranspiration for different crops and soil. Runoff is computed separately for each HRU and routed to the subbasin channel to estimate the total runoff for the catchment. The simulation of the hydrology of a watershed can be divided into two main divisions [26]:

1. The land phase of the hydrological cycle, which controls the amount of water, sediment, nutrient and pesticide loadings to the main channel in each sub-basin; and
2. The routing phase, which can be defined as the movement of variables mentioned above through the stream networks of the watershed to the outlet.

Readers can refer to Neitsch et al. [26] for details.

MODFLOW [27] is a three-dimensional, physical-based, distributed finite difference groundwater flow model for the variably saturated sub-surface system. A recent addition to MODFLOW is the Newton-based solver algorithm that better satisfies the complex non-linear drying and re-wetting of grid cells in unconfined groundwater system [8], a problem with previous versions. Available processes to be simulated in MODFLOW include groundwater recharge, vadose zone percolation, evapotranspiration, pumping, discharge to sub-surface drains, river-aquifer interactions [9]. Most applications are limited to

investigating management and climate effects on groundwater and surface-groundwater interactions.

The SWAT model is principally limited in terms of dealing with groundwater flow because of its lumped nature. On the other hand, MODFLOW has difficulty in calculating the distributed groundwater recharge that is the primary input for the groundwater model, due to the lack of a land surface hydrology model. Therefore, spatiotemporal features in the catchment can be adequately represented [28] if the simplified features of each model are replaced with physically based features from the other model, i.e., recharge from SWAT HRUs is provided to MODFLOW cells, and groundwater discharge to streams from MODFLOW is provided to SWAT channels. More recently, progress has been made by Bailey et al. [29] to develop a series of tools that can conveniently couple SWAT with MODFLOW on a daily time step.

The basic process of linking SWAT and MODFLOW models is to pass HRU-calculated deep percolation (i.e., water that exits the bottom of the soil profile) as recharge to the grid cells of MODFLOW, and then pass MODFLOW-calculated groundwater-surface water fluxes to the stream channels of SWAT [9]. With this method, SWAT computes the volume of overland flow and soil lateral flow to streams, MODFLOW calculates the volume of groundwater discharge to streams, and then SWAT routes the water through channel networks of the watershed. Surface-groundwater interaction is simulated using the river package of MODFLOW, with Darcy's law applied to calculate the volumetric flow of water through the cross-sectional flow area between the aquifer and stream channel [9]:

$$Q_{leak} = k_{bed}(L_{str}P_{str})\left(\frac{h_{str} - h_{gw}}{z_{bed}}\right) \quad (1)$$

where:

$k_{bed}$  is riverbed hydraulic conductivity (L/T).

$L_{str}$  is the length of the stream (L).

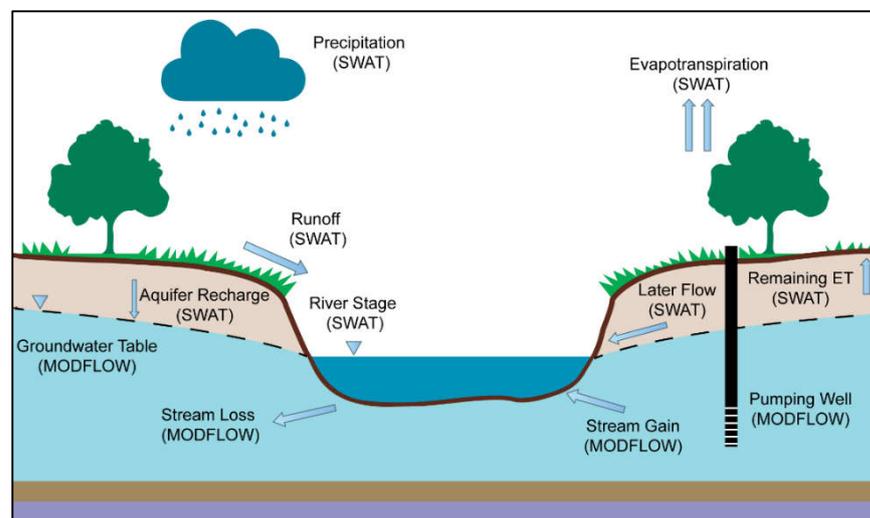
$P_{str}$  is the wetted perimeter of the stream (L).

$h_{str}$  is river stage (L).

$h_{gw}$  is the hydraulic head of groundwater (L).

$z_{bed}$  is the thickness of the riverbed (L), and

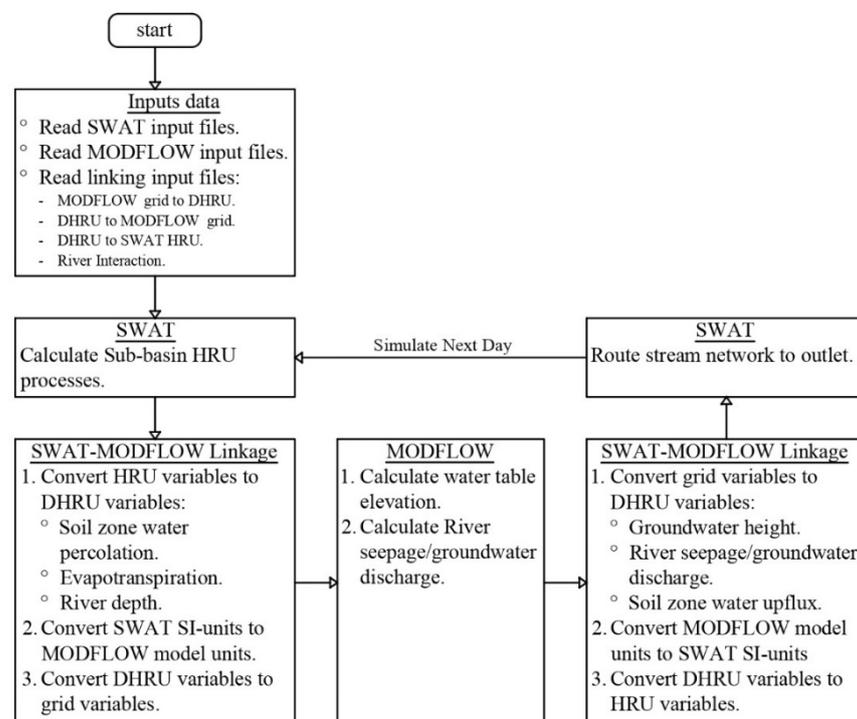
$Q_{leak}$  is negative if groundwater flows to the river (i.e., groundwater hydraulic head  $h_{gw}$  is above the river stage  $h_{str}$ ), and positive if river water seeps into the aquifer. Figure 4 shows the schematic representation water balance of SWAT-MODFLOW model, indicating the processes simulated, respectively, by SWAT and MODFLOW [9].



**Figure 4.** Schematic representation of conceptual water balance of coupling SWAT and MODFLOW [30].

Data are passed between the models using 'mapping' subroutines that relates HRUs to MODFLOW grid cells and MODFLOW river cells to SWAT stream channels [9]. The main elements of this mapping scheme are: HRUs; Disaggregated HRUs (DHRUs), which divide each original HRU into individual, contiguous areas within a sub-basin allow HRU calculations to be geo-located; MODFLOW grid cells; MODFLOW River cells; and SWAT stream channels [9]. The geographical connections between these objects are determined using GIS shape files, with connection data placed in text files for input into the SWAT-MODFLOW modeling code.

The linking process is illustrated in Figure 5. Following the reading of linkage inputs, the simulation begins. The calculated deep percolation (i.e., recharge) for HRUs are first mapped to each individual DHRU, and then mapped to each MODFLOW grid cell according to the per cent of an area of the DHRU contained within the grid cell for use by the recharge package [9]. SWAT-calculated channel depth from each sub-basin is mapped to the group of River cells within the sub-basin for use by the river package [9]. MODFLOW then computes groundwater hydraulic head and groundwater-surface water interactions, with the latter volumetric flow rates passed to SWAT subbasin channels based on spatial connections. Groundwater discharge volumes, calculated on a cell-by-cell basis within MODFLOW, are summed and added to in-stream flow for each SWAT sub-basin. SWAT then completes the stream routing calculations for the day, with the daily loop continuing until the end of the simulation. For the possible scenario of a River cell intersecting more than one stream, the length of each stream within the cell is used to calculate the composite weighted value of channel depth for use by MODFLOW and to distribute the cell groundwater discharge volume to associated sub-basin main channels. Within this scheme, MODFLOW is called as a subroutine within the SWAT framework, providing a single compiled FORTRAN code [9].



**Figure 5.** Flowchart presenting the model code sequence of the coupled SWAT-MODFLOW model [9].

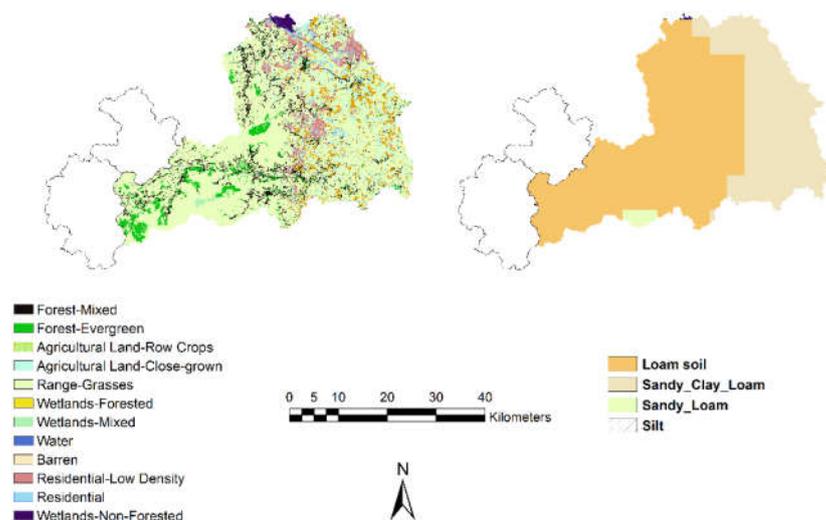
### 3.2.2. SWAT Model Construction and Initial Testing

In this study, the standard approach of the SWAT model setup is mostly followed. The Dee River watershed was subdivided into 57 sub-basins and 1,074 HRUs. The watershed parameterization and the model input are derived using the ArcSWAT interface

(SWAT 2012, revision 627). The underlying data sets required to develop the model input are topographical, land use, soil, and climatic data (Figure 6; see Table 1). The SWAT model is constructed for the study area based on daily time step with a 3-year warm-up period (1992-1994), a calibration period of 1995-2000, and a validation period of 2001-2003.

There are circa 30 Public Water Supply (PWS) licenses with substantial abstractions in the area. In 2009, the PWS abstracted a total of 197,042 million liters which accounted for approximately 93% of all the water abstracted in the Dee Catchment Abstraction Management Strategy (CAM) area. Of the water abstracted by PWS companies in 2009 only around 1% was taken from groundwater sources [32]. The locations of these PWS licenses are shown in Figure 7. Although the metric capacity data of the water abstraction points along with their positions are known, the real-time water abstraction data are not available.

To conserve water supplies and ensure efficiency of operation, the PWS companies provide a weekly abstraction forecast to Natural Resources Wales to assist in calculating the required releases from the reservoirs [32]. An inversion of this procedure is used to estimate the daily water withdrawal amount at the water abstraction points, as this amount is not available from the data collected. Abbas and Xuan [33] estimated the daily water uses of PWS based on the daily released data from 4 reservoirs in the upstream area of the Dee River watershed.



**Figure 6.** Land use and soil maps in the Dee River basin [31].

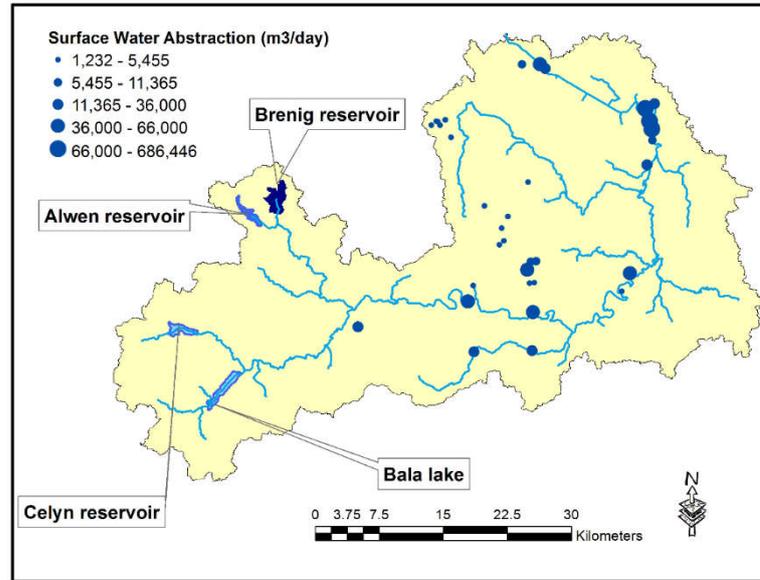


Figure 7. Significant Water Abstraction in the Dee River basin [31].

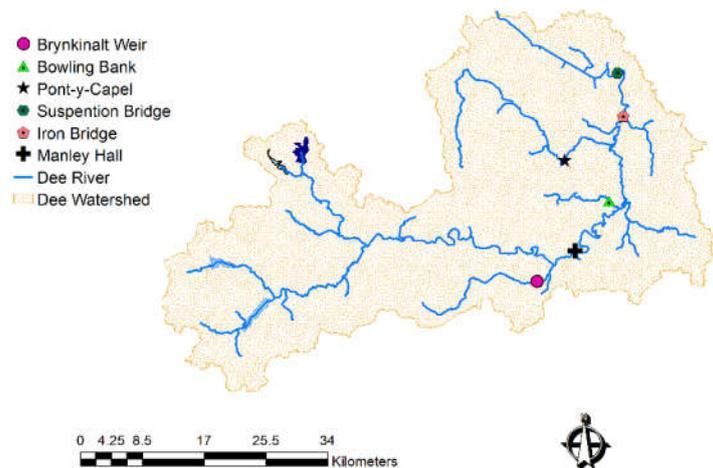
Before linking with MODFLOW, the model is calibrated and validated using the Sequential Uncertainty Fitting algorithm, SUFI2 [34, 35]. The goodness of fit is quantified using the Nash-Sutcliffe Efficiency Index NSE, Determination Coefficient  $R^2$ , and Percent of Bias PBIAS as defined by equations (2)-(4):

$$NSE = 1 - \frac{\sum_{t=1}^T (Q_{o,t} - Q_{s,t})^2}{\sum_{t=1}^T (Q_{o,t} - \bar{Q}_o)^2} \quad (2)$$

$$R^2 = \left[ \frac{\sum_{t=1}^T (Q_{o,t} - \bar{Q}_o)(Q_{s,t} - \bar{Q}_s)}{\sum_{t=1}^T [(Q_{o,t} - \bar{Q}_o)^2]^{0.5} \sum_{t=1}^T [(Q_{s,t} - \bar{Q}_s)^2]^{0.5}} \right]^2 \quad (3)$$

$$PBIAS = \left[ \frac{\sum_{t=1}^T (Q_{s,t} - Q_{o,t})}{\sum_{t=1}^T Q_{o,t}} \right] \times 100 \% \quad (4)$$

where  $Q_{o,t}$  is the observed flow at time  $t$  and  $Q_{s,t}$  is the simulated flow at time  $t$ . It was found that the natural process plays a secondary role and surface water abstractions have a considerable impact on the river flow regime [31]. Historical flow records at six river gauge stations (Figure 8) are used to measure the performance.



**Figure 8.** Locations of the main inlets and the river gauge stations in Dee River basin.

**Table 2.** The river gauge stations utilized in the calibration and validation of the hydrological model.

Station Name	Latitude	Longitude	General Description
Manley Hall	52.966	-2.972	A symmetrical compound Crump weir.
Chester Iron bridge	53.134	-2.873	Station utilizes Ultra-Sonic to derive flow.
Chester Suspension Bridge	53.187	-2.884	Ultra-Sonic flow gauge.
Alyn at Pont-y-Capel	53.079	-2.994	A symmetrical compound crump weir.
Clywedog at Bowling Bank	53.027	-2.903	Simple Crump profile weir.
Ceiriog at Brynkinalt Weir	52.928	-3.050	Compound broad-crested weir.

### 3.2.3. MODFLOW Model Construction and Initial Testing

The MODFLOW model was constructed using a one-layer, unconfined aquifer, with 200 m grid cells, resulting in 241 rows and 317 columns (Figure 9). The topographical surface assigned as the top layer of the model was interpolated from the Digital Elevation Model (DEM).

The following MODFLOW packages are used:

1. Basic package (.bas).
2. Discretization package (.dis).
3. River package (.riv).
4. Well package (.wel).
5. Upstream weighted package (.upw).
6. Recharge package (.rch); and
7. Newton Solver package (.nwt).

As describe previously, recharge is provided by SWAT HRUs, and the cells in the River package (see Figure 9 for location) interact with SWAT subbasin channels to provide groundwater-stream exchange rates. A total number of 37 licensed wells are represented in this study with maximum water withdraw of 14-6800 m<sup>3</sup>/day (Figure 10). The pumping rates of these individual wells are simulated using the Well package.

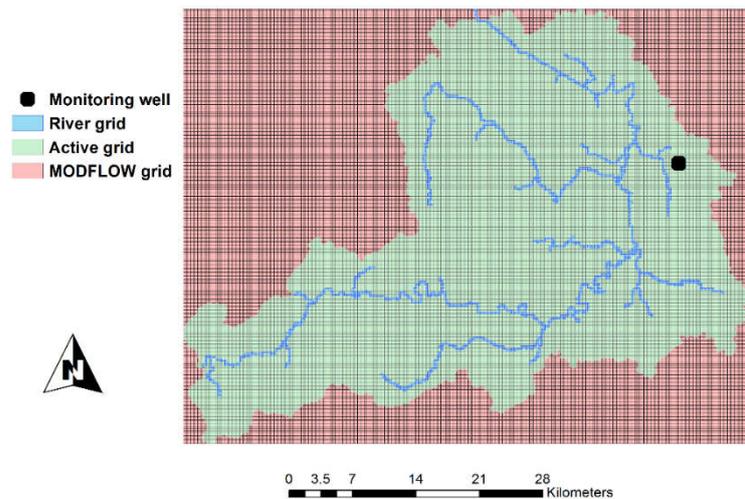


Figure 9. MODFLOW grid with the location of groundwater monitoring well in the Dee River basin.

The standalone MODFLOW is manually calibrated by adjusting:

1. The horizontal permeability coefficient from the upstream-weighted package (to control the recharge rate); and
2. The river conductance from the river package (to control the surface-groundwater interaction between the river channel and shallow aquifer).

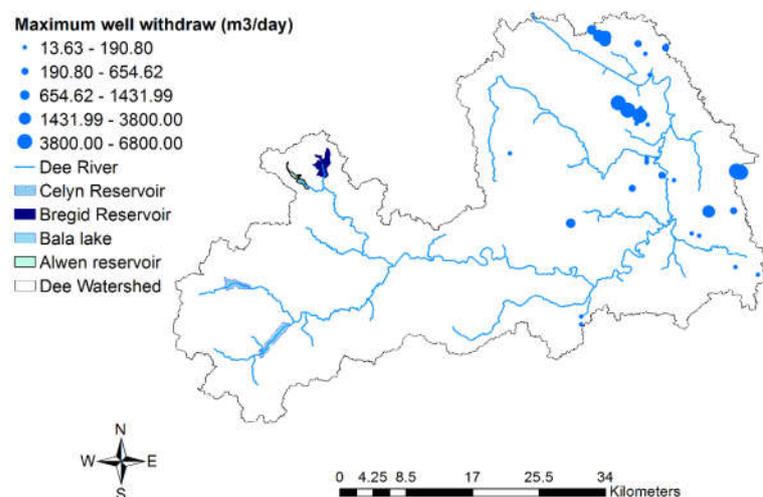


Figure 10. Location of the license withdraw wells used in MODFLOW model [31].

### 3.2.4. Linking SWAT and MODFLOW

The stand-alone SWAT and MODFLOW models are linked according to the theory and process described in Section 3.2.1. Model results are tested against (1) streamflow at the gage sites (Figure 8), (2) groundwater head at the monitoring well (Figure 9), and (3) baseflow. The latter is calculated using the recursive digital filter commonly used in signal analysis and processing [36] is used in this study. It was used by Nathan and McMahon [37] among others, providing a subjective and repeatable estimate of baseflow that is easily automated. Baseflow separation is conducted using the R statistical package 'EcoHydrology' [38] to separate baseflow from the daily streamflow records. Simulated baseflow is assessed using NSE and  $R^2$ .

### 3.3. Future Climate: UKCP18 Convection-Permitting Model Projections for the UK at 2.2km

In this study, high-resolution precipitation and temperature models from UKCP18 project is used with the calibrated SWAT-MODFLOW model with future scenario of RCP85 from 2020 to 2040 for the different scenarios of water uses. UKCP 18 is climate projection model that runs at convection-permitting scale for the UK for the historical period of (1981-2000) and future periods of (2021-2040, 2061-2080), produced by Met Office Hadley Center for UK Climate Projections. The data are available on a 2.2 km grid on a rotated pole at different temporal resolutions including hourly, daily, and monthly time step [39].

UKCP18 project offers a new set of climate tools and projections to obtain climate data. The main improvements in UKCP18 include the utilize of new observations of climate and weather including a more recent generation of global and regional climate models. The major improvement in the design of UKCP18 over the previous UK climate projections (e.g., UKCP09 model) is that it consists of updated probabilistic projections, giving estimates of different future climate outcomes. The regional and global model projections give users the capability to better investigate climate changes and variability, including the relationship between different climate metrics and retaining spatial coherence [39].

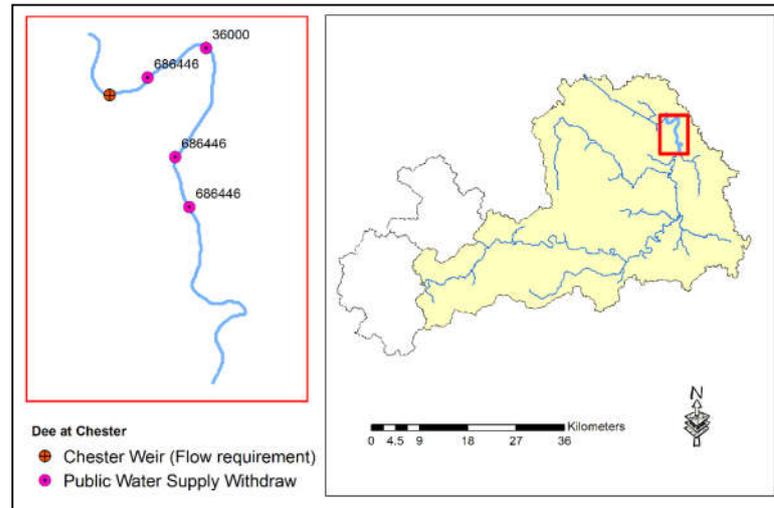
### 3.4. Water Evaluation And Planning (WEAP) model

The Water Evaluation and Planning software (WEAP) is an integrated water resource management software developed by the Stockholm Environment Institute SEI in the USA. It is designed to assess user-developed scenarios that accommodate changes in the socio-economic and biophysical conditions of catchments over time [40]. WEAP allows planner access to a more comprehensive view of the broad range of factors that should be considered in managing water resources for present and future use owing to its integrated approach to simulating both the natural (e.g., runoff, baseflow, evapotranspirative demands, etc.) and engineered structures (e.g., reservoirs) of water resources systems [41].

WEAP operates in many capacities including:

1. Water balance database: WEAP provides a system for maintaining water demand and supply information.
2. Scenario generation tool: WEAP simulates water demand, supply, runoff, storage, pollution generation, treatment and discharge and instream water quality; and
3. Policy analysis tool: WEAP evaluates a full range of water development and management options and takes account of multiple and competing uses of water systems.

WEAP has been used for climate scenario analysis of water supply and demands in different regions of the world e.g. [42, 43]. The model optimizes water use in the basin using a linear optimization algorithm to allocate water to the various demand sites, as per the demand priorities that range from 1 to 99, with 1 being the highest priority. For more information on the WEAP model, readers are directed to [40, 44]. In the present study, the simulated streamflow for future scenarios of the SWAT-MODFLOW model are used as the input to the head of the river reach in the downstream region for the WEAP model (Figure 11)



**Figure 11.** Study region of coupled SWAT-MODFLOW-WEAP model (surface water abstraction in  $\text{m}^3/\text{day}$ ).

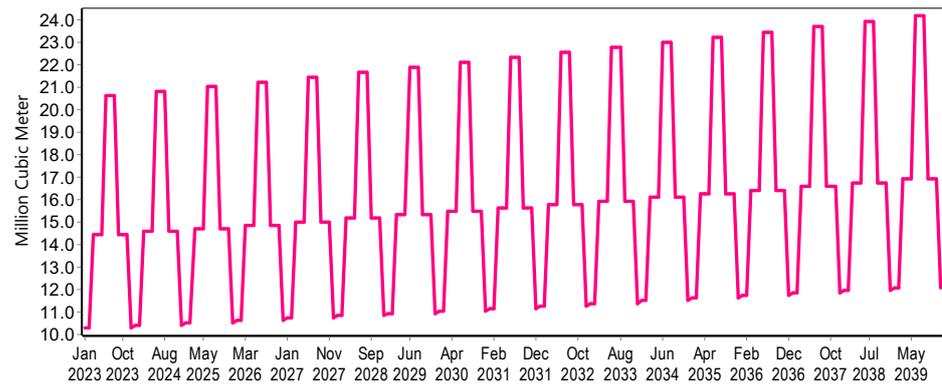
In the coupled SWAT-MODFLOW-WEAP modeling system, the Chester weir gauge station (that is located in the downstream of Dee River Basin) is utilized as a checkpoint for minimum streamflow requirement for ecological purposes with minimum river flow of  $4.2 \text{ m}^3/\text{s}$  [32] and the evaluation of the unmet flow requirements.

The Dee River basin is an example of the complex river flow system and highly regulated through a management scheme that provides water for both industrial and public water supply (PWS) in summers and prevents flooding between Bala Lake and city of Chester in winters [33]. There are massive PWS in the downstream area of the river basin (Chester city) as revealed in Figure 11 which are considered for the evaluation of the impact of water demand on the availability of water resources under scenarios of climate change. These demands are:

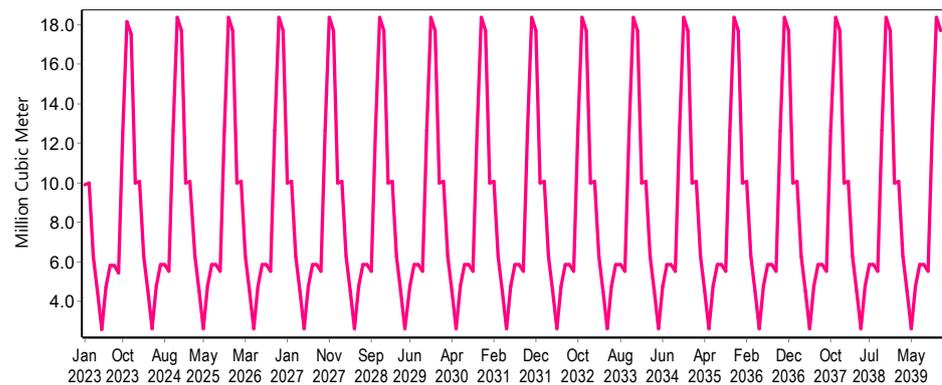
1.  $\text{PWS}_1$  that consumes a maximum of ( $686,446 \text{ m}^3/\text{day}$ ).
2.  $\text{PWS}_2$  that consumes a maximum of ( $686,446 \text{ m}^3/\text{day}$ ).
3.  $\text{PWS}_3$  that consumes a maximum of ( $36,000 \text{ m}^3/\text{day}$ ); and
4.  $\text{PWS}_4$  that consumes a maximum of ( $686,446 \text{ m}^3/\text{day}$ ).

It is reported that the daily water uses in the UK has gradually increased by 1% per year since 1930, and the average person now consumes 150 liters a day [47]. The calibrated simulated discharge from the SWAT-MODFLOW model with climate model data of UKCP18 is aggregated into monthly time series and used as input for the WEAP model. In the coupled SWAT-MODFLOW-WEAP system, four scenarios of surface water abstraction to check the unmet demands and streamflow requirements as follow:

1. Scenario I: 100 % of the maximum licensed of surface water abstraction (RCP85 scenario, 2020-2040).
2. Scenario II: 50 % of the maximum licensed of surface water abstraction (RCP85 scenario, 2020-2040).
3. Scenario III: Monthly time series that is percent of maximum licensed of surface water abstraction with 1 % of increase in water use rate (100 % of maximum licensed abstractions for summer months (June, July and August), 50 % of maximum licensed abstractions for winter months (December, January and February), and 70 % for the rest of months) for (RCP85 scenario, 2020-2040) as it can be seen in Figure 12a for  $\text{PWS}_1$ ; and
4. Scenario IV: Monthly time series: the maximum year of water withdraw is calculated based on historical data of surface water abstraction for the period of 1970-2004 that is estimated by Abbas and Xuan [33] for (RCP85 scenario, 2020-2040) as it can be seen in Figure 12b for  $\text{PWS}_1$ .



a. Scenario III



b. Scenario IV

**Figure 12.** Public water supply abstractions at PWS<sub>1</sub> for scenarios III and IV (Million cubic meter per month).

## 4. Results and Discussion

### 4.1. Hydrologic Fluxes and States using SWAT-MODFLOW

Table 3 shows the performance statistics of the model regarding streamflow for the calibration period, e.g., a standalone calibrated SWAT model and the coupled SWAT-MODFLOW model. Several indices are used including Nash-Sutcliffe Coefficient (NSE),  $R^2$ , and percentage of bias (PBIAS) to measure the deviation of simulations from the observations at the chosen gauge stations. A small decrease of  $R^2$  and NSE and can be observed across all gauge stations except two stations where groundwater is dominant. Regarding PBIAS, the coupled model performs better or similar except that of the gauge Brynkinalt Weir.

Meanwhile, for the validation period (Table 4), the overall water balances (PBIAS) are improved for the coupled SWAT-MODFLOW are improved at three sites. The overall trends ( $R^2$ ) are also enhanced as it is demonstrated in Table 4.

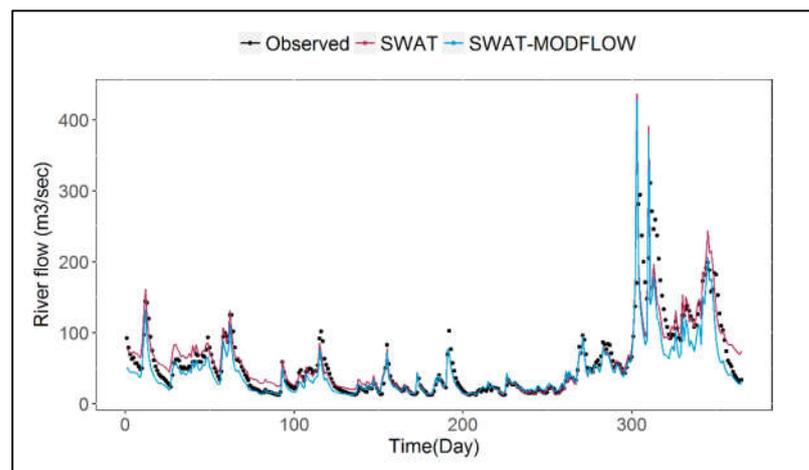
**Table 3.** Performance statistics of the standalone SWAT model and the coupled SWAT-MODFLOW model for the calibration period of 1995-2000, for streamflow.

Station Name	SWAT			SWAT-MODFLOW		
	NSE	$R^2$	PBIAS	NSE	$R^2$	PBIAS
Manley Hall	0.92	0.94	-3.20	0.88	0.98	+16.30
Chester Iron bridge	0.80	0.80	-6.30	0.76	0.81	+9.10
Chester Suspension Bridge	0.72	0.75	-18.90	0.84	0.87	+5.80
Pont-y-Capel	0.67	0.76	-21.00	0.68	0.68	-1.80
Bowling Bank	0.48	0.52	-19.20	0.47	0.47	-0.50
Brynkinalt Weir	0.68	0.72	+8.70	0.57	0.66	+24.30

**Table 4.** Performance statistics of the standalone SWAT model and the coupled SWAT-MODFLOW model for the validation period of 2001-2003, for streamflow.

Station Name	SWAT			SWAT-MODFLOW		
	NSE	R <sup>2</sup>	PBIAS	NSE	R <sup>2</sup>	PBIAS
Manley Hall	0.94	0.98	-5.80	0.90	0.98	+14.50
Chester Iron bridge	0.82	0.82	-6.20	0.76	0.79	+11.40
Chester Suspension Bridge	0.78	0.80	-10.20	0.83	0.91	+16.10
Pont-y-Capel	0.80	0.82	-14.70	0.77	0.78	+8.80
Bowling Bank	0.66	0.71	-25.10	0.67	0.67	-3.00
Brynkinalt Weir	0.66	0.70	+10.90	0.57	0.64	+27.00

The simulations from the standalone SWAT model and the coupled model are compared with the observed flow data at the river gauges. Figure 13 shows such comparison for a selected station (Chester Ironbridge) over the water year 1999. A remarkable feature revealed by Figure 13 is that the coupled model outperforms the standalone SWAT model for the low flow conditions, particularly for the recession curves after of each peak. While both models simulate peak flow well, the standalone SWAT model does better for the 2nd peak. It is plausible that the MODFLOW component has well compensated the deficiency of SWAT in low flow representation (such as baseflow) in terms of taking more water as the recharge and lagging it to the streams via groundwater gradients. This is, in fact, an influential aspect of the coupled model, as it is more stressful in the flow period for water supply and the coupled model might be preferred in this occasion for better simulations.



**Figure 13.** The comparison of simulated river flow from the standalone SWAT model and the coupled SWAT-MODFLOW at Ironbridge for the water year of 1999 [30,31].

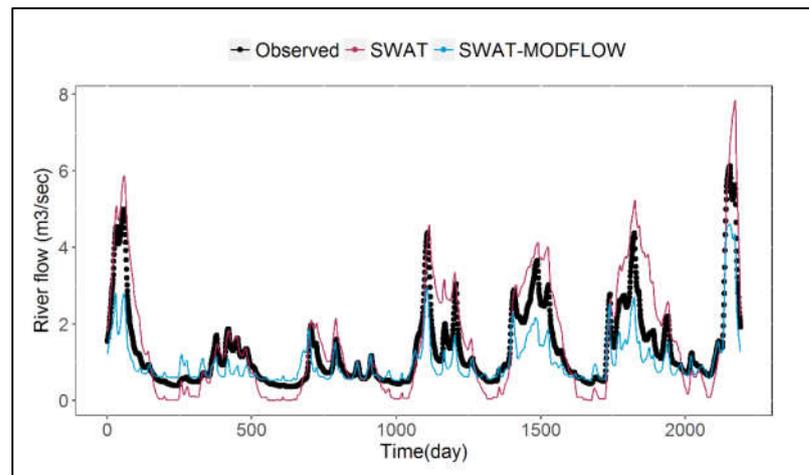
A baseflow separation of SWAT and coupled SWAT-MODFLOW are created and presented. The NSE and R<sup>2</sup> are employed to evaluate the baseflow simulation against observed one. Tables 5 and 6 show that SWAT-MODFLOW simulation has a better baseflow simulation than the standalone SWAT model. Figure 14 reveals the baseflow from SWAT, SWAT-MODFLOW and the observed one at Pont-y-Capel station for the period of 1995-2000. Noticeably, SWAT-MODFLOW improves the origin of SWAT simulation regarding baseflow.

**Table 5.** The simulated baseflow results of the standalone SWAT model and the coupled SWAT-MODFLOW model for the calibration period of 1995-2000.

Station Name	SWAT		SWAT-MODFLOW	
	NSE	R <sup>2</sup>	NSE	R <sup>2</sup>
Manley Hall	0.55	0.79	0.79	0.94
Chester Iron bridge	0.31	0.69	0.76	0.91
Chester Suspension Bridge	-0.10	0.63	0.90	0.98
Pont-y-Capel	0.27	0.89	0.58	0.74
Bowling Bank	-0.26	0.91	0.76	0.80
Brynkinalt Weir	0.80	0.88	0.04	0.75

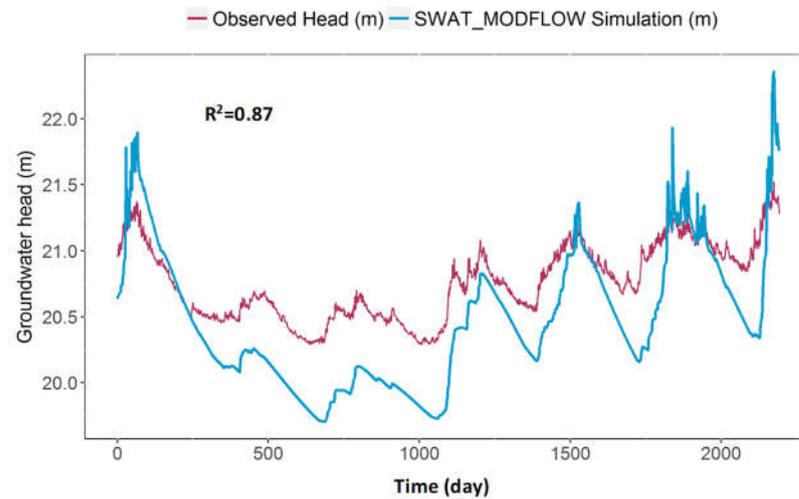
**Table 6.** The simulated baseflow results of the standalone SWAT model and the coupled SWAT-MODFLOW model for the validation period of 2001-2003.

Station Name	SWAT		SWAT-MODFLOW	
	NSE	R <sup>2</sup>	NSE	R <sup>2</sup>
Manley Hall	0.76	0.90	0.88	0.96
Chester Iron bridge	0.70	0.86	0.83	0.98
Chester Suspension Bridge	0.56	0.79	0.98	0.91
Pont-y-Capel	0.57	0.87	0.67	0.85
Bowling Bank	-0.42	0.86	0.77	0.85
Brynkinalt Weir	0.82	0.89	0.27	0.87



**Figure 14.** The comparison of simulated baseflow from the standalone SWAT model and the coupled SWAT-MODFLOW at Pont-y-Capel for the period of 1995-2000 [30,31].

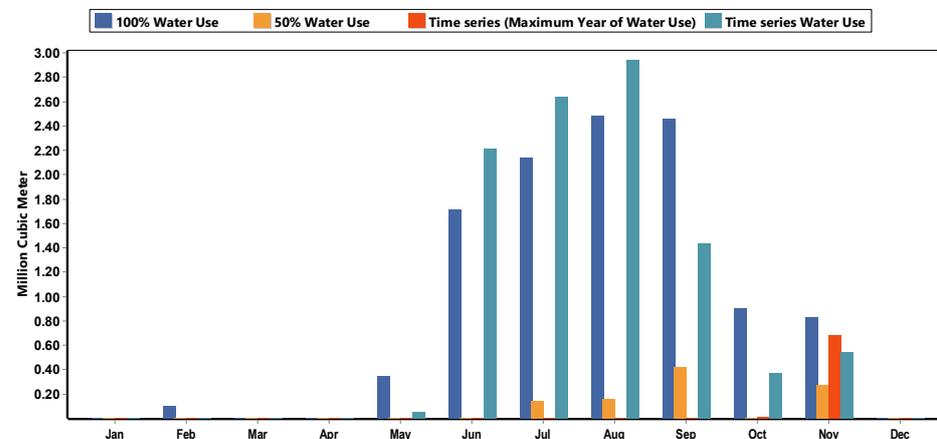
Figure 15 shows the comparison of daily simulated groundwater level against observed one at the monitoring well in the east of Dee watershed which shows that coupled SWAT-MODFLOW performs well with R<sup>2</sup> of 0.87 for the calibration period of 1995-2000 and 0.88 for the validation period of 2001-2003. The model is able to track the temporal patterns of groundwater head fluctuation, within 0.5 m of the true values.



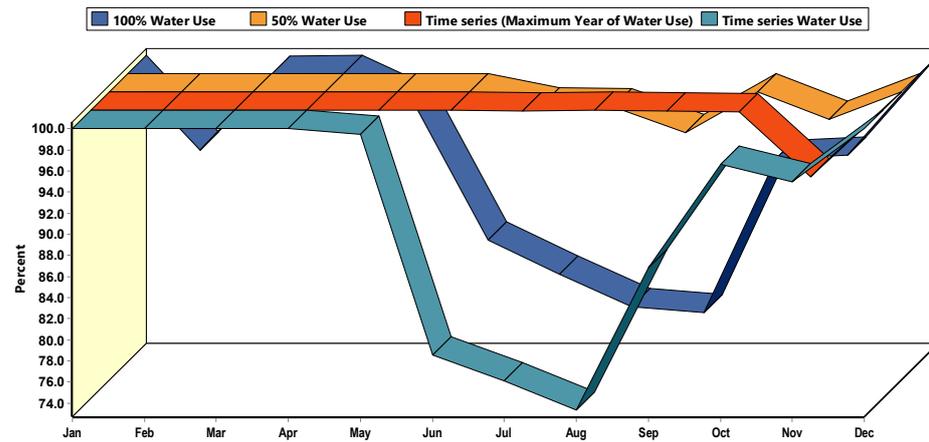
**Figure 15.** The comparison of simulated groundwater level from the coupled SWAT-MODFLOW at the monitoring well for the period of 1995-2000.

#### 4.2. Decision Support Analysis

The coupled SWAT-MODFLOW-WEAP model (Allocation-Simulation model) is built for the future scenario to evaluate the likely unmet demands at the public water supply locations. Firstly, the unmet flow requirement and per cent of coverage at Chester weir station ( $4.2 \text{ m}^3/\text{s}$ ). Clearly, in RCP85 scenarios, there is unmet flow demand from June until November with the maximum monthly average unmet flow of 2.95 million cubic meter (74 % of flow needed) in August as illustrated in Figures 16 and 17.

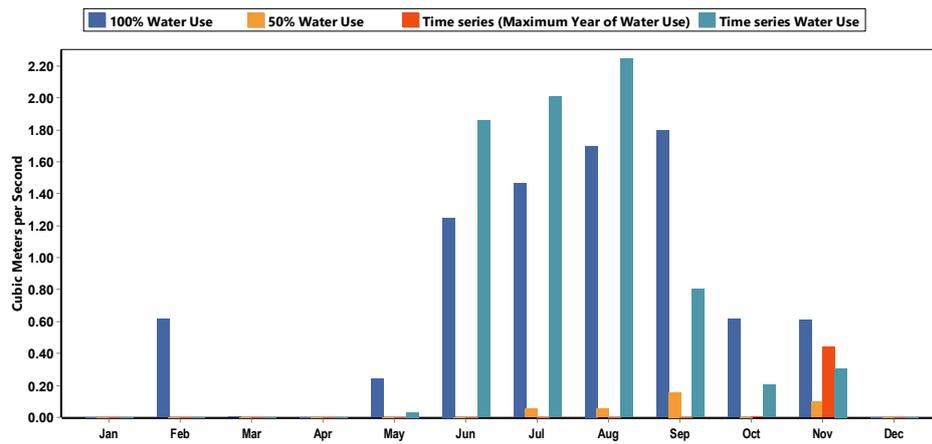
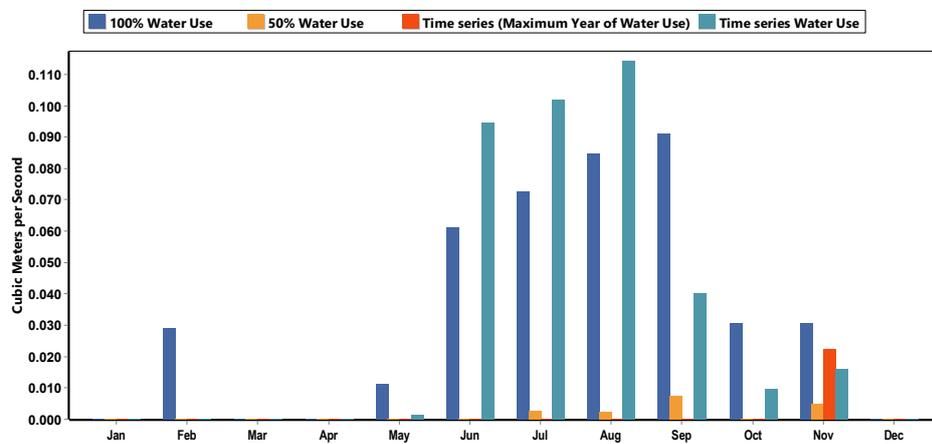


**Figure 16.** The average monthly unmet streamflow requirement (million cubic meter) in Chester weir for RCP85 future scenarios for the period of 2021-2039.



**Figure 17.** The average monthly flow requirement coverage (% of flow requirement) in Chester weir for the period of 2021-2039.

The average monthly unmet demand for all scenarios is revealed in Fig. 18. It can be clearly seen that in the summer a significant unmet demand reaches more than  $2.2 \text{ m}^3/\text{s}$  for the PWS<sub>1</sub>, PWS<sub>2</sub> and PWS<sub>4</sub> as in Figure 18a for all the future scenarios. On the other hand, PWS<sub>3</sub> has also had unmet demand with a maximum projected value of  $0.11 \text{ m}^3/\text{s}$  as in Figure 18b. Under two of the future demand scenarios, there is intensified occurrence of inadequate streamflow to satisfy PWS demand especially, in summer season. The major result is that declines in forecasted streamflow during the summer and autumn months result in continued shortages of water, even in the reduced demand scenario. However, during the spring months, streamflow is adequate. This indicates that there is no compensation for decreased streamflow and the increased demand observed in summer and autumn, leading to a growth volume of unmet demand under most scenarios. These findings are in agreement with reports from [46,47] itemizing the required stages for resilience in water supply in Wales and, affirming more action is needed to adequately meet public water demand in the coming decades. The observed imbalances could pose an issue to water supply, particularly during extended droughts, as increase flow in winter and spring will be ineffective at addressing summer and autumn water shortages, if reservoirs are already full.

a. PWS<sub>1</sub>, PWS<sub>2</sub>, and PWS<sub>4</sub>b. PWS<sub>3</sub>

**Figure 18.** The average monthly unmet demand ( $\text{m}^3/\text{s}$ ) for public water supply PWS future scenarios for the period of 2023-2039.

## 5. Summary and Conclusions

In this article, we present a coupled SWAT-MODFLOW-WEAP system to estimate the impact of future climate conditions on water supply and demand in a complex watershed system, the Dee River watershed in Wales, United Kingdom. The SWAT model is created and coupled with groundwater flow model MODFLOW to simulate streamflow and baseflow for the Dee River basin, with the latter a key component of minimum flows and overall water resource management in the region.

The coupled SWAT-MODFLOW-WEAP model is constructed, calibrated, and tested against historical streamflow, baseflow, and groundwater head and then used with climate change data of the UKCP18 project to evaluate unmet demand of water for public water supply in the downstream region (city of Chester) as well as check unmet streamflow requirement in Chester weir. The high-resolution future climate data of UKCP18 model (precipitation, maximum and minimum air temperature), for future scenario of RCP85 are used as input in calibrated SWAT-MODFLOW model to simulate the catchment hydrology for the period of 2021-2039 with 2 years' warm-up period. The simulated discharge from the SWAT-MODFLOW model was used as input to the modelled reach in the WEAP model on a monthly time step.

Four scenarios of water use rate of 4 selected location of public water supplies in the downstream of the Dee River basin with a considerable amount of water abstraction utilized to evaluate the likely unmet demands. The results agreed that there is expected unmet demand at large quantities, especially in the summer season (June, July and August). Actions and measurements for mitigating the effects of unmet water demands and uncertainties as to how the climate will change and how it will affect water resources are the challenges that planners and designers will have to cope. How water resources management will have to adapt to climate changes is the pressing question to be answered. The possible mitigations for the unmet water demands are:

- 1) Augmenting streamflow from a deep well source.
- 2) Using reclaimed water.
- 3) Storing and recovering surface or groundwater.
- 4) Transferring water into basins; and
- 5) Adjust reservoirs regulation rules.

Overall, the study shows a promising direction for using coupled surface-groundwater models and allocation models (WEAP) in IWRM. We expect that this same system can be used in other regions of the worldwide to estimate future water supply and aid in water management decisions.

## 6. Patents

This section is not mandatory but may be added if there are patents resulting from the work reported in this manuscript.

**Author Contributions:** Conceptualization, R.B and Y.X., methodology R.T.B, Y.X. and S.A.A., formal analysis S.A.A., R.T.B. and Y.X., writing—original draft preparation S.A.A., writing—review and editing, R.T.B. All authors have read and agreed to the published version of the manuscript.

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