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# Incorporating drought risk modelling as a planning tool for climate change adaptation measures in Saint Kitts and Nevis

Benchmarking of drought prediction models



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| Client representative | Ramiro Salinas  |
| Project manager       | Gina Tsarouchi  |
| Project director      | Nigel Walmsley  |

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|                                   |  |  |
|-----------------------------------|--|--|
| <b>Prepared</b><br>Gina Tsarouchi | <b>Approved</b><br>Azucena Rodriguez Yebra | <b>Authorised</b><br>Azucena Rodriguez Yebra |
|-----------------------------------|--|--|

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# 1 Background

## 1.1 Project summary

In an effort to address the impacts of climate change and climate variability in a sustainable way, access to critical information within the water sector is vital. Drought prediction models can identify areas most susceptible to water supply variability and shortages, and therefore facilitate early action to manage risks. In doing so, this will increase resilience in the water sector to improve use of water resources and therefore ensure food security and water usage including from the agricultural, domestic and tourism sectors in the two islands of St. Kitts and Nevis.

The overall objective of this project is to incorporate drought risks modelling as a planning tool for climate change adaptation measures in St. Kitts and Nevis. The main outputs include to:

- Map stakeholders and establish a stakeholder working group;
- Assess drought risk and water resources in St. Kitts and in Nevis;
- Benchmark, design and implement a drought prediction tool in St. Kitts and in Nevis;
- Train administrators and users of St. Kitts and Nevis to use the drought prediction tool.

The project outcomes respond directly to SDG 13 'Taking early action to combat climate change and its impacts' by providing a system that will support planning and decision-making for the sustainable management and conservation of water resources in St. Kitts and Nevis. The project will also contribute to SDG 1 (End poverty), SDG 2 (Food security) and SDG 6 (Availability and sustainable management of water) as the drought prediction tool will improve agricultural practices and use of water resources, improve food security and increase the income of rural communities.

## 1.2 About this report

This report identifies the latest tools and approaches used to monitor and forecast droughts, and discusses the technical details of these tools, their implementation in a real-world setting and how well they align with the interests of stakeholders from Saint Kitts and Nevis. A review of groundwater and surface water modelling tools, which will provide a component of the drought prediction model is also presented. Based on the results of the drought assessment (Activity 2.1), as well as the quantity and quality of climate and water data available in Saint Kitts and Nevis, the existing models are prioritised and the groundwater and surface water modelling tool that is more suitable to Saint Kitts and Nevis is selected.

The next sub-section of this report gives a high-level summary of the benchmarking of existing drought monitoring and forecasting systems. Section 2 gives an overview of existing drought monitoring and forecasting systems. Section 3 gives an overview of hydrological modelling tools that could be used in the Saint Kitts and Nevis drought forecasting system. Section 4 discusses the selection of the hydrological model for the drought forecasting system.

## 1.3 Summary of the proposed approach

### 1.3.1 Considerations and limitations of existing drought monitoring and forecasting systems

Following a review of 11 drought monitoring and forecasting systems from around the world, a series of criteria helped inform what should be included in a drought forecasting system that best serves the interests of stakeholders from Saint Kitts and Nevis.

Considerations taken on board include: what might be appropriate / achievable in a small island context; what is appropriate to Saint Kitts and Nevis given limitations in terms of data availability; sustainability and capacity to maintain / operate the tool; ability to forecast as opposed to just monitor the current state; spatial and temporal resolution of data; operational costs; indicators identified by stakeholders as essential (during Output 2); inclusion of groundwater modeling.

The 11 existing technologies are prioritised and assigned a score, which helped identify the components that would be more suitable to the Saint Kitts and Nevis drought forecasting tool.

Given the limitations of what is already available, we have decided to proceed with developing a separate tool, which brings together elements of all 11 systems reviewed as part of this benchmarking exercise.

The key limitations of existing systems, as described in Table 1.1, include:

- Only used for monitoring and not for forecasting of droughts;
- Not updated regularly / or not operational;
- Not providing good spatial resolution of relevant data for St Kitts and Nevis / Not covering at all the islands;
- Not providing information on the wide range of indicators that were identified by the stakeholder working group as essential for the success of the tool;
- Not taking into account water balance or groundwater conditions.

Table 1.1: High-level outputs of the review of existing drought monitoring and forecasting systems

| Name                      | Caribbean coverage<br>Yes = 1<br>No = 0 | Forecasting system<br>Yes = 1<br>No = 0 | Monitoring system<br>Yes = 1<br>No = 0 | Operational<br>Yes = 1<br>No = 0 | Typical indicators                                       | Includes water balance<br>Yes = 1<br>No = 0 | Includes groundwater<br>Yes = 1<br>No = 0 | Includes satellite data<br>Yes = 1<br>No = 0 | Ease to use<br>Yes = 1<br>No = 0 | Score (max=8) |
|---------------------------|---|---|--|----------------------------------|--|---|---|--|----------------------------------|---------------|
| 2.1 CDPMN                 | Yes                                     | No                                      | Yes                                    | Yes                              | SPI, SPEI, rainfall, temperature anomalies               | No  | No  | No   | Yes                              | 4             |
| 2.2 CARiDRO               | Yes                                     | No                                      | Yes                                    | No                               | SPI, SPEI  | No  | No  | No   | Yes                              | 3             |
| 2.3 LAC drought monitor   | Yes                                     | Yes                                     | Yes                                    | No                               | drought index based on soil moisture percentiles         | Yes   | No  | Yes  | Yes                              | 6             |
| 2.4 CariCOF               | Yes                                     | Yes                                     | Yes                                    | Yes                              | SPI  | No  | No  | No   | Yes                              | 5             |
| 2.5 NLDAS drought monitor | No                                      | No                                      | Yes                                    | Yes                              | Soil moisture anomaly / percentile                       | Yes   | No  | Yes  | Yes                              | 5             |
| 2.6 US drought monitor    | No                                      | No                                      | Yes                                    | Yes                              | SPI, Palmer, vegetation health, soil moisture indicators | No  | No  | Yes  | Yes                              | 4             |
| 2.7 Global SM monitor     | Yes                                     | No                                      | Yes                                    | Yes                              | Soil Moisture  | Yes   | No  | Yes  | No                               | 5             |

| Name                             | Caribbean coverage<br>Yes = 1<br>No = 0 | Forecasting system<br>Yes = 1<br>No = 0 | Monitoring system<br>Yes = 1<br>No = 0 | Operational<br>Yes = 1<br>No = 0 | Typical indicators  | Includes water balance<br>Yes = 1<br>No = 0 | Includes groundwater<br>Yes = 1<br>No = 0 | Includes satellite data<br>Yes = 1<br>No = 0 | Ease to use<br>Yes = 1<br>No = 0 | Score (max=8) |
|----------------------------------|---|---|--|----------------------------------|---|---|---|--|----------------------------------|---------------|
| 2.8 European drought observatory | No                                      | No                                      | Yes                                    | Yes                              | Several indicators such as: precipitation, soil moisture, river flow, vegetation water stress | Yes   | No  | Yes  | No                               | 4             |
| 2.9 UK drought portal            | No                                      | No                                      | Yes                                    | Yes                              | SPI   | No  | No  | Yes  | No                               | 3             |
| 2.10 East Africa bulletins       | No                                      | Yes                                     | Yes                                    | Yes                              | Several biophysical and socio-economic impact indicators                                      | No  | No  | Yes  | Yes                              | 5             |
| 2.11 African drought monitor     | No                                      | Yes                                     | Yes                                    | Yes                              | SPI, NDVI, soil moisture, runoff  | Yes   | No  | Yes  | Yes                              | 6             |
| 2.12 FEWS NET                    | No                                      | No                                      | Yes                                    | Yes                              | SPI, NDVI, food security indicators   | No  | No  | Yes  | No                               | 3             |

### 1.3.2 Components selected for the Saint Kitts and Nevis drought forecasting system

Drought risk management involves three pillars: drought early warning, drought vulnerability and risk assessment, and drought preparedness, mitigation, and response. For the Saint Kitts and Nevis drought forecasting system, we will be incorporating and integrating a broad array of environmental information sources including weather station observations, satellite imagery, land surface model simulations, and weather and climate model forecasts, and analyse this information in context-relevant ways that take into account exposure and vulnerability. This will ensure that the tool will be in alignment with the most comprehensive modern drought early warning systems (Figure 1.1).

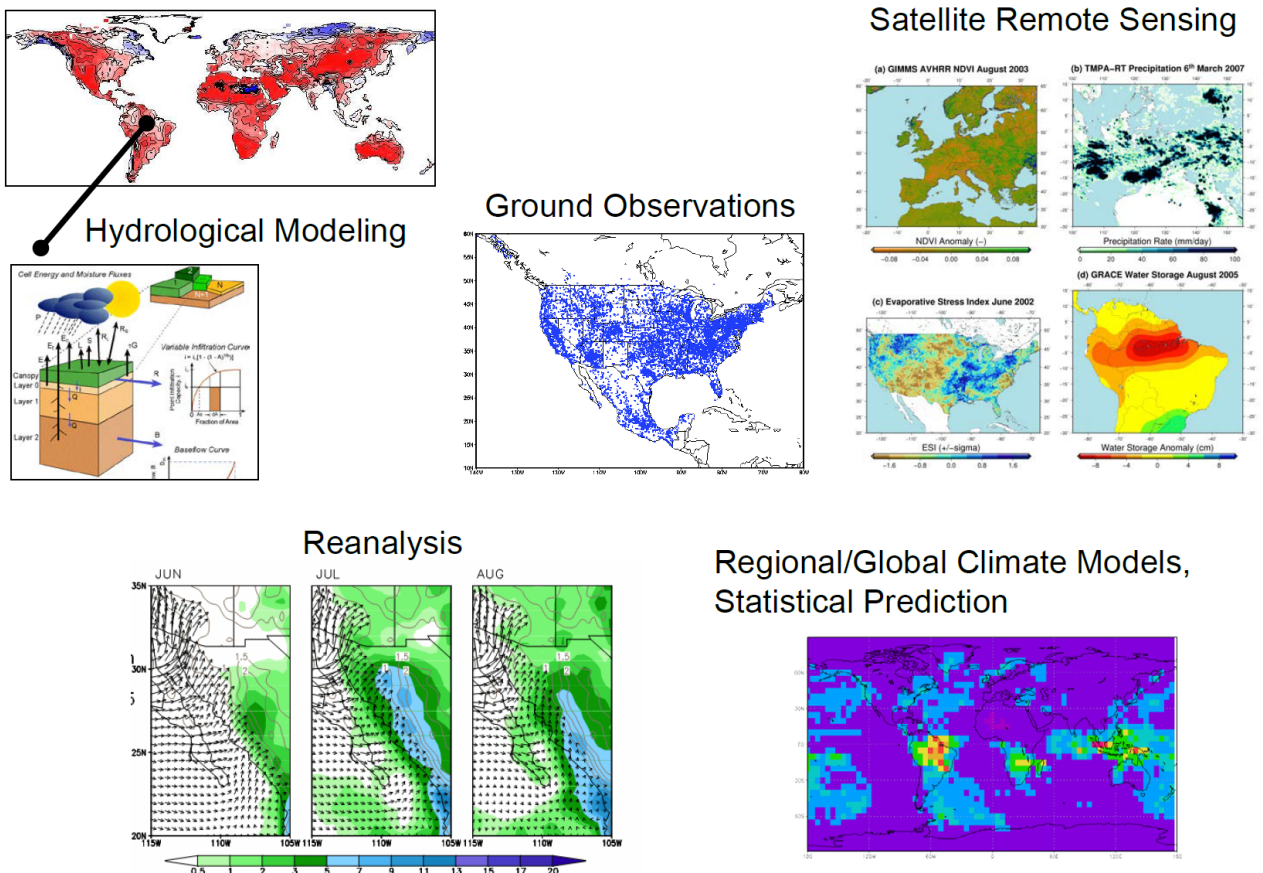


Figure 1.1: Technical components of modern drought monitoring and forecasting systems

## 2 Examples of drought monitoring and forecasting systems

### 2.1 Caribbean Drought and Precipitation Monitoring Network (CDPMN)

**Coverage:** Caribbean.

**Monitoring or Forecasting:** Monitoring.

**Operational:** Yes.

**Description:** The Caribbean Drought and Precipitation Monitoring Network (Figure 2.1) was launched in January 2009 under the Caribbean Water Initiative (CARIWIN).

**Information provided:** Drought and the general precipitation status are monitored on two scales: (i) regional, encompassing the entire Caribbean basin and (ii) national using the Standardized Precipitation Index (SPI, Mckee 1993) and Deciles (Gibbs and Maher, 1967) as an indicator of normal or abnormal rainfall. In the future, other indices may provide information on normal or abnormal soil moisture (Palmer Drought Severity index, PDSI, developed by Palmer 1965; and Crop Moisture Index, CMI, developed by Palmer 1968) or status of vegetation (Normalized Difference Vegetation Index, NDVI).

**Comment:** In the future, as an addition to these final drought and precipitation status products, short term and seasonal precipitation forecasts will be used to provide a projection of future drought and excessive precipitation in the short and medium terms.

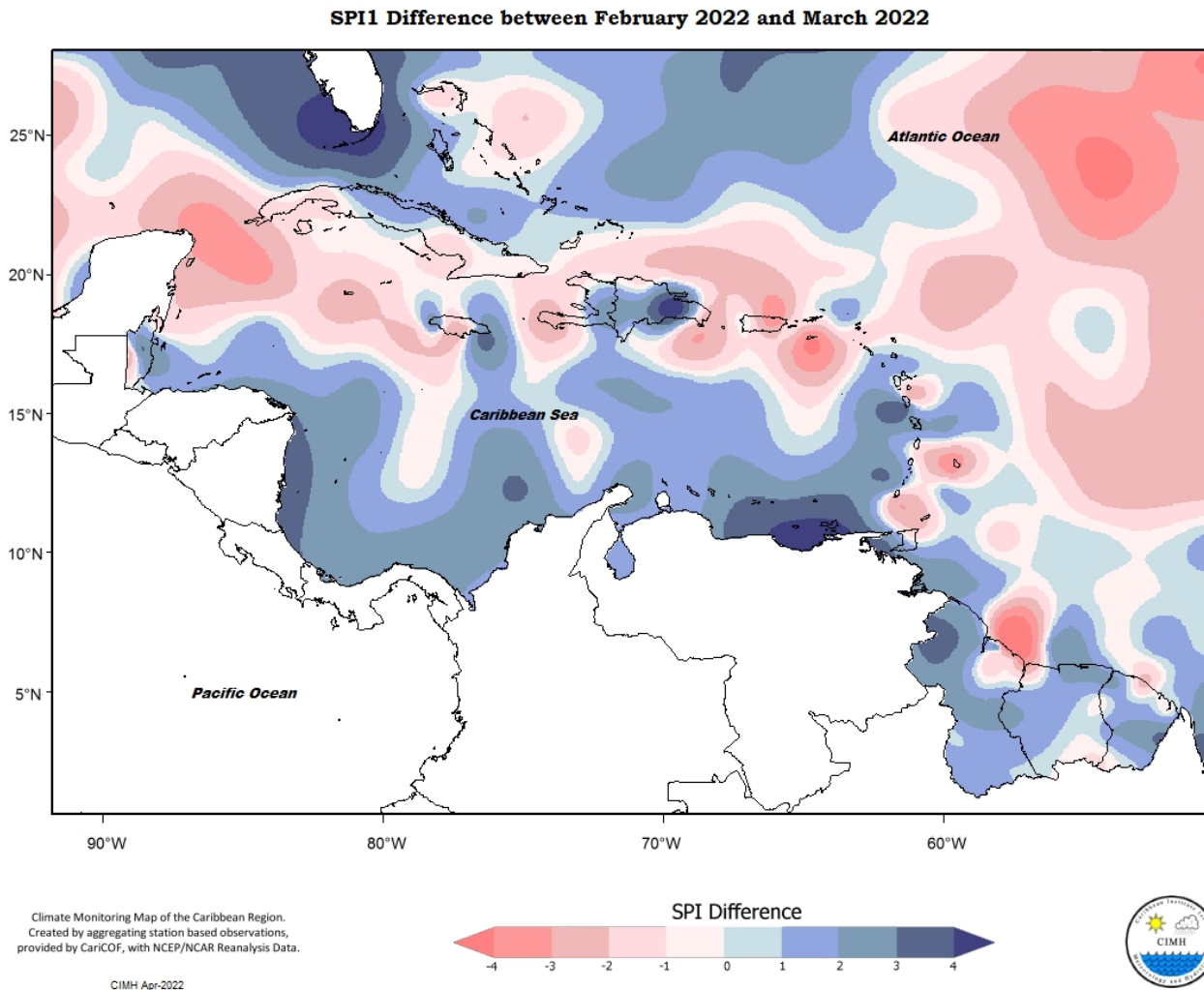


Figure 2.1: SPI 1 month, differences between February 2022 and March 2022 (from the CDPMN)

## 2.2 CARiDRO: Caribbean Assessment Regional DROught Tool

**Coverage:** Caribbean.

**Monitoring or Forecasting:** Monitoring.

**Operational:** No.

**Description:** The Caribbean Assessment Regional DROught Tool (CARiDRO, Figure 2.2) is an online web-based tool that can facilitate the assessment of drought events at regional and grid-point levels using modelled and observed datasets. It also provides a brief overview of the structure and characteristics of the application of this tool which is considered as the first step in the development of the CARIWIG cases studies related with drought.

**Information provided:** The CARiDRO has been designed to facilitate the development of assessment of drought events at regional and grid point levels by accessing and processing several datasets available from the Regional Climate Model and a number of observed gridded datasets. The tool is able to provide results based on two Drought Indexes; the Standardized Precipitation Index and the Standardized Precipitation-Evaporation Index. The former (SPI) is a well-known and popular drought index used in many regions to assess and to monitor drought events. The other one (SPEI) was designed mainly to evaluate the impact of climate change on drought and it is based on water balance instead of precipitation only. As both SPI and

SPEI indexes are calculated at various time scales (i.e. 1-month, 2-months, 6-months, 36-months, etc) they enable the identification of different drought types such as meteorological or hydrological drought.

**Comment:** The online version of the tool does not appear to be offering up to date SPI and SPEI information (latest date available is 2012).

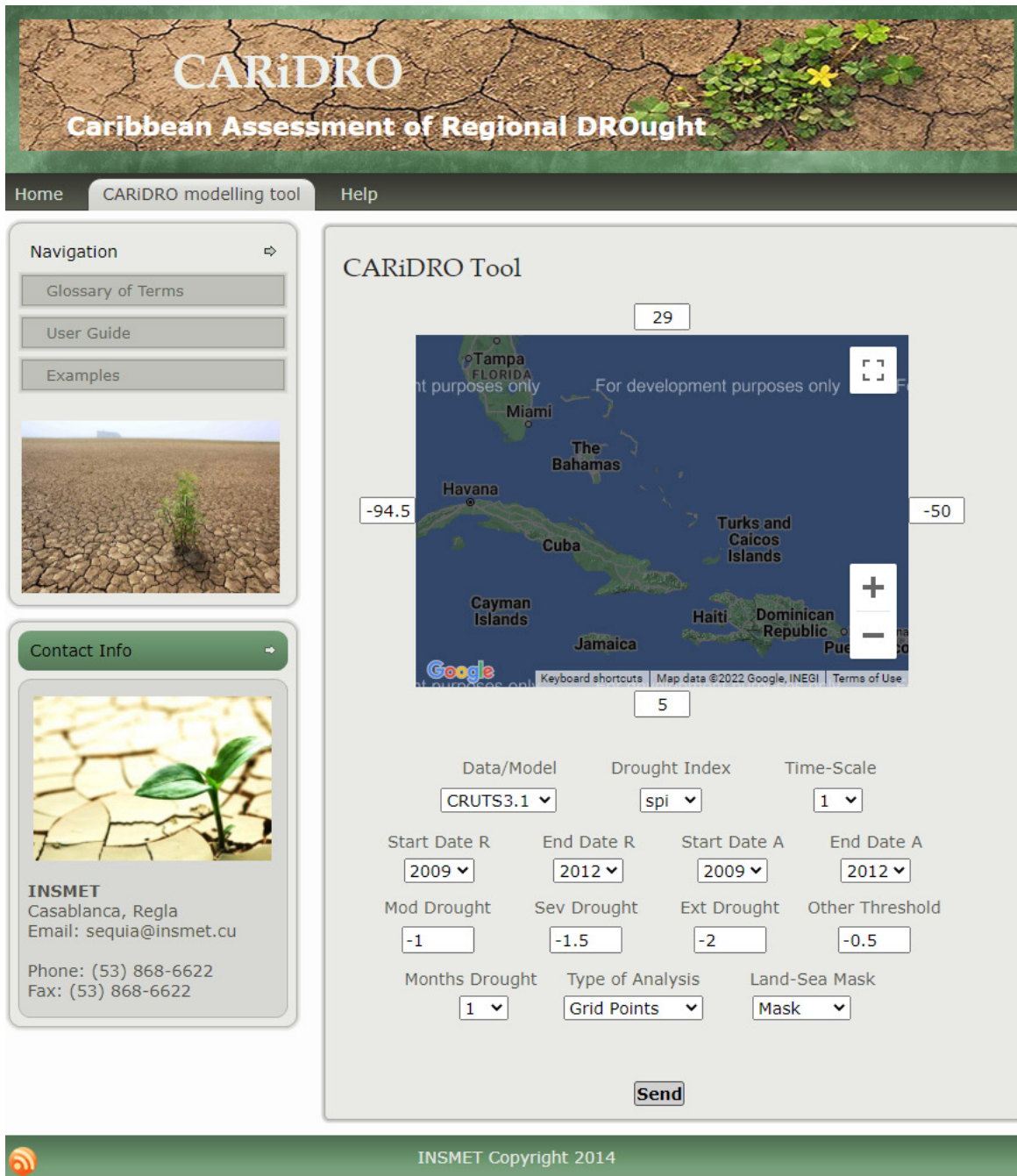


Figure 2.2: CARiDRO core form showing the options to run the tool

## 2.3 Latin American and Caribbean drought monitor

**Coverage:** Latin America and the Caribbean.

**Monitoring or Forecasting:** Both.

**Operational:** No.

**Description:** The Latin American and Caribbean drought monitor has also been developed since 2015, by the same team that developed the African Flood and Drought Monitor. Using available satellite remote sensing and in-situ information, a hydrologic modeling platform and accompanying web-based user interface has been developed by Princeton University in collaboration with ICIWaRM and UNESCO-IHP, for operational and research use in Latin America and the Caribbean.

**Information provided:** The system monitors in near real-time the terrestrial water cycle for the region based on remote sensing data and land surface hydrological modeling. The monitoring forms initial conditions for hydrological forecasts at short time scale, aimed at flood forecasting, and seasonal scale aimed at drought and crop yield forecasts. The flood forecasts are driven by precipitation and temperature forecasts from the Global Forecast System (GFS). The drought forecasts are driven by climate forecasts from the North American Multi-Model Ensemble (NMME).

Drought is estimated primarily in terms of low soil moisture, which is given as a drought index based on soil moisture percentiles. The index is calculated by determining the percentile of the daily average of relative soil moisture at each grid cell with respect to its empirical cumulative probability distribution function provided by the historical simulations (1950 – 2008). The drought index (and all hydrological variables and meteorological forcings) is available for the entire record between 1950 and real-time.

**Comments:** The online version of the tool is no longer accessible.

## 2.4 CariCOF Drought Outlook

**Coverage:** Caribbean

**Monitoring or Forecasting:** Both

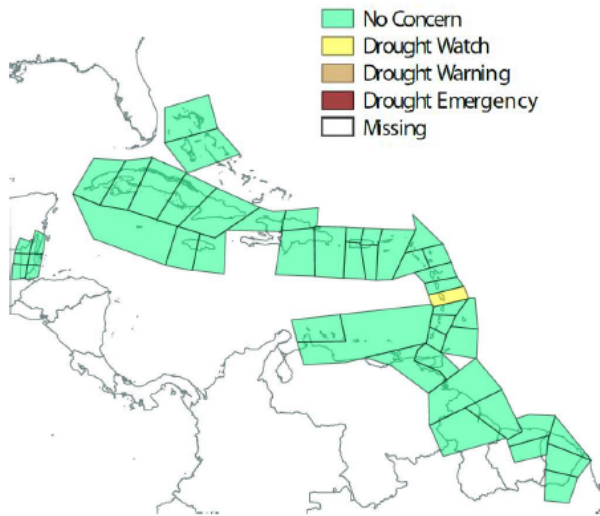
**Operational:** Yes

**Description:** The CariCOF Drought Outlook is an early warning tool that identifies the region's ongoing and emerging drought concerns. It also gives practical information on how to effectively handle those situations. <http://rcc.cimh.edu.bb/drought-outlook/>.

**Information provided:** The Outlook includes an overview of shorter- and longer-term concerns in map and textual formats. Also included is a definition of the relationship between drought alert levels and the action levels they trigger.

**Comments:** CariCOF outlooks speak to recent and expected climate trends across the Caribbean in general. For country-specific climate information, CariCOF advises to consult with the national meteorological service.

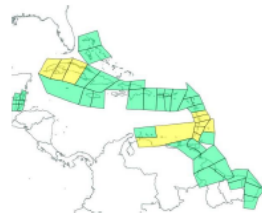
## What is the predicted short term drought concern by the end of August 2022?



### Current update (May 2022):

We are entering the first half of the wet season. Currently, no major shorter term drought concern is developing throughout the region.

- A **drought watch** should be considered for Martinique.



Previous update (April): short term drought alert levels at the end of July 2022

### Short term drought alert levels at the end of August 2022

(updated May 2022 – covering March to August 2022)

caricof@cimh.edu.bb

For climate information specific to your country, please consult with your national meteorological service. CariCOF outlooks speak to recent and expected climate trends across the Caribbean in general.



Figure 2.3: Information provided by CariCOF for August 2022

## 2.5 National Center for Environmental Predictions North American Land Data Assimilation System (NLDAS) drought monitor

**Coverage:** North America (Does it also include the Caribbean and Central America and Canada? Or really mostly US based?).

**Monitoring or Forecasting:** Monitoring.

**Operational:** Yes.

**Description:** The NLDAS modelling system<sup>1</sup> is one of the first operational multiple model-based drought monitoring systems. Each day, four models are run using the same atmospheric forcing data through the past day, to generate simulations of soil moisture and runoff (among other water and energy balance variables) for the past day.

**Information provided:** Current soil moisture and runoff data are used for monitoring drought by comparing them with a long-term (as far back as 1979) historical distribution of those variables for each grid cell. By comparing these data with the historical distributions, current values are converted into percentiles, which indicate the severity of the current drought conditions. Total soil moisture and top-one-meter soil moisture are used to provide estimates of current drought severity. Top-one-meter soil moisture is used for agricultural drought monitoring, and total soil moisture is used for hydrological drought monitoring (as it takes into account the moisture in the deeper layer). This contributes to baseflow and changes relatively slower than the top layers. Figure 2.4 depicts top-one-meter soil moisture percentile, as of 30 April 2022, over the continental US. The NLDAS system has been crucial in improving drought monitoring in the US.

<sup>1</sup> <https://ldas.gsfc.nasa.gov/nldas/drought-monitor>

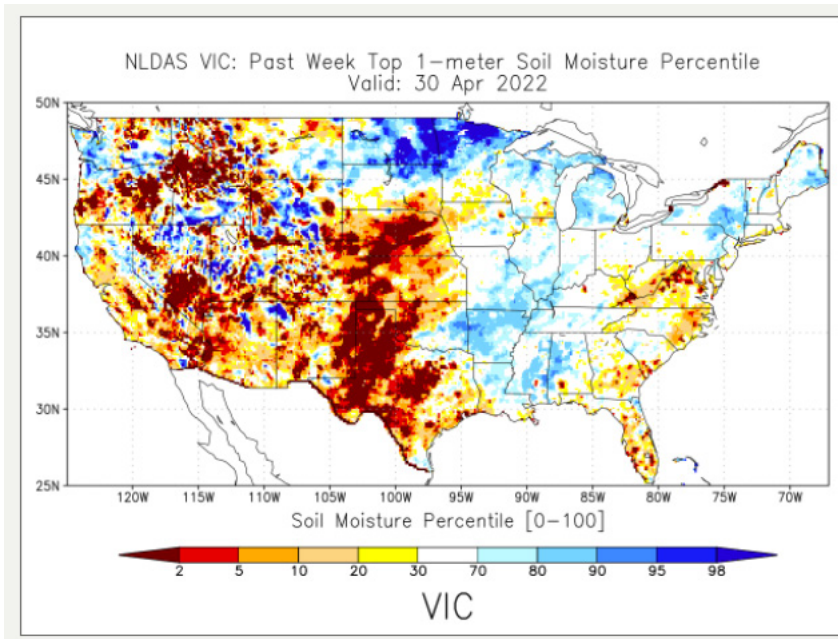


Figure 2.4: NLDAS top 1-meter soil moisture percentile (30 April 2022), based on the VIC model

## 2.6 US drought monitor

**Coverage:** USA.

**Monitoring or Forecasting:** Monitoring.

**Operational:** Yes.

**Description:** The Drought Monitor has been a team effort since its inception in 1999, produced jointly by the National Drought Mitigation Center (NDMC) at the University of Nebraska-Lincoln, the National Oceanic and Atmospheric Administration (NOAA), and the U.S. Department of Agriculture (USDA). The NDMC hosts the web site of the drought monitor and the associated data, and provides the map and data to NOAA, USDA and other agencies. It is freely available at [droughtmonitor.unl.edu](http://droughtmonitor.unl.edu) (Figure 2.5).

**Information provided:** The U.S. Drought Monitor is a map released every Thursday, showing parts of the U.S. that are in drought. The map uses five classifications: abnormally dry (D0), showing areas that may be going into or are coming out of drought, and four levels of drought: moderate (D1), severe (D2), extreme (D3) and exceptional (D4).

**Comments:** The USDA uses the drought monitor to trigger disaster declarations and eligibility for low-interest loans. The Farm Service Agency uses it to help determine eligibility for their Livestock Forage Program, and the Internal Revenue Service uses it for tax deferral on forced livestock sales due to drought. State, local, tribal and basin-level decision makers use it to trigger drought responses, ideally along with other more local indicators of drought.

## U.S. Drought Monitor

Current Map Maps Data Summary About Conditions & Outlooks En Español NADM

### Caribbean

Home > Caribbean

Map released: Thurs. May 5, 2022

Data valid: May 3, 2022 at 8 a.m. EDT

#### Intensity

|                          |
|--------------------------|
| None                     |
| D0 (Abnormally Dry)      |
| D1 (Moderate Drought)    |
| D2 (Severe Drought)      |
| D3 (Extreme Drought)     |
| D4 (Exceptional Drought) |
| No Data                  |



#### Authors

United States and Puerto Rico Author(s):  
David Simeral, Western Regional Climate Center

Pacific Islands and Virgin Islands Author(s):  
Curtis Riganti, National Drought Mitigation Center

Figure 2.5: Drought intensity map (Caribbean region), from the US drought monitor

## 2.7 Global soil moisture monitoring

**Coverage:** Global.

**Monitoring or Forecasting:** Monitoring.

**Operational:** Yes.

**Description:** One of the operational global soil monitoring systems is operated by the National Oceanic and Atmospheric Administration's (NOAA's) Climate Prediction Center (CPC). This system is based on the CPC's soil moisture model.

**Information provided:** This monitoring system provides the estimate of soil moisture percentile globally<sup>2</sup> at about 2-month lag time (Figure 2.6). Along with percentile of soil moisture it also provides anomaly and simulated value of soil moisture for the recent past and for all months in the last year.

<sup>2</sup> [https://www.cpc.ncep.noaa.gov/products/Soilmst\\_Monitoring/GLB/glb\\_s.shtml](https://www.cpc.ncep.noaa.gov/products/Soilmst_Monitoring/GLB/glb_s.shtml)

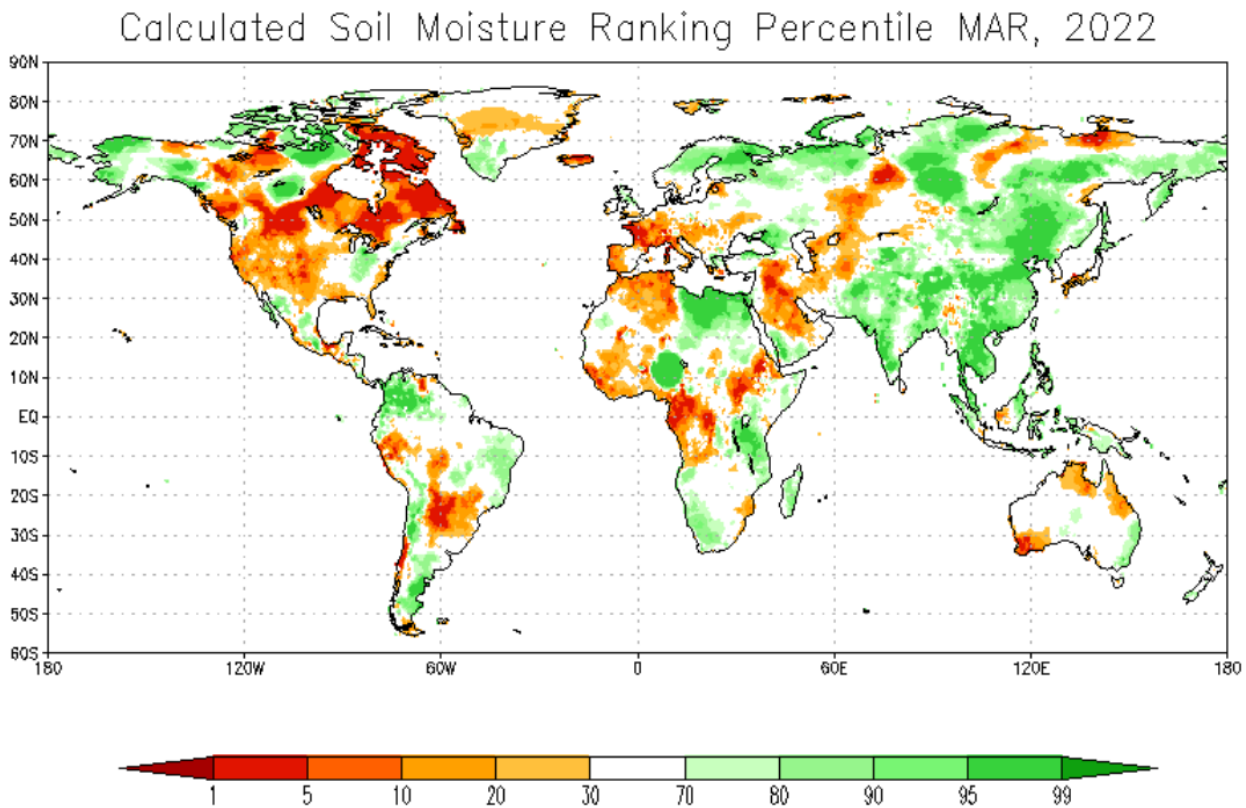


Figure 2.6: Global soil moisture percentile for March 2022

## 2.8 European Drought Observatory

**Coverage:** Europe.

**Monitoring or Forecasting:** Monitoring.

**Operational:** Yes.

**Description:** The European Drought Observatory (EDO<sup>3</sup>) is a service run by the European Commission's Joint Research Centre (Figure 2.7). Several indicators representing precipitation, soil moisture, river flow and vegetation water stress are used to generate drought information and warning.

**Information provided:**

- **Standardised Precipitation Index (SPI):** This indicator measures anomalies of accumulated precipitation during a given period, and is the most commonly used indicator for detecting and characterising meteorological droughts;
- **Standardised Snowpack Index (SSPI):** This indicator measures anomalies of daily soil moisture (water) content, and is used to measure the start and duration of agricultural drought conditions;
- **Soil Moisture Anomaly (SMA):** This indicator is used for determining the start and duration of agricultural drought conditions, which arise when soil moisture availability to plants drops to such a level that it adversely affects crop yield, and hence, agricultural production;
- **Anomaly of Vegetation Condition (FAPAR Anomaly):** This indicator measures anomalies of satellite-measured FAPAR (Fraction of Absorbed Photosynthetically Active Radiation), and is used to highlight areas of relative vegetation stress due to agricultural drought;

<sup>3</sup> <https://edo.jrc.ec.europa.eu/edov2/php/index.php?id=1000>

- **Low-Flow Index (LFI):** This indicator, which is derived from daily river discharge outputs produced by the JRC's in-house hydrological rainfall-runoff model (LISFLOOD), is used for near real-time monitoring of hydrological streamflow drought at European scale;
- **Heat and Cold Wave Index (HCWI):** This indicator is used to detect and characterise extreme temperature anomalies, such as heat waves (during the warm season) and cold waves (during the cold season), and is computed based on daily minimum and maximum temperatures; and
- **Combined Drought Indicator (CDI):** This indicator integrates information on anomalies of precipitation, soil moisture and satellite-measured vegetation condition, into a single index that is used to monitor both the onset of agricultural drought and its evolution in time and space.

**Comments:** Even though various indicators have been developed to represent the hydrological cycle, forecasting information is not translated into relevant information adapted to end-users (e.g. for planting / harvesting), and indicators to represent the groundwater component are lacking.

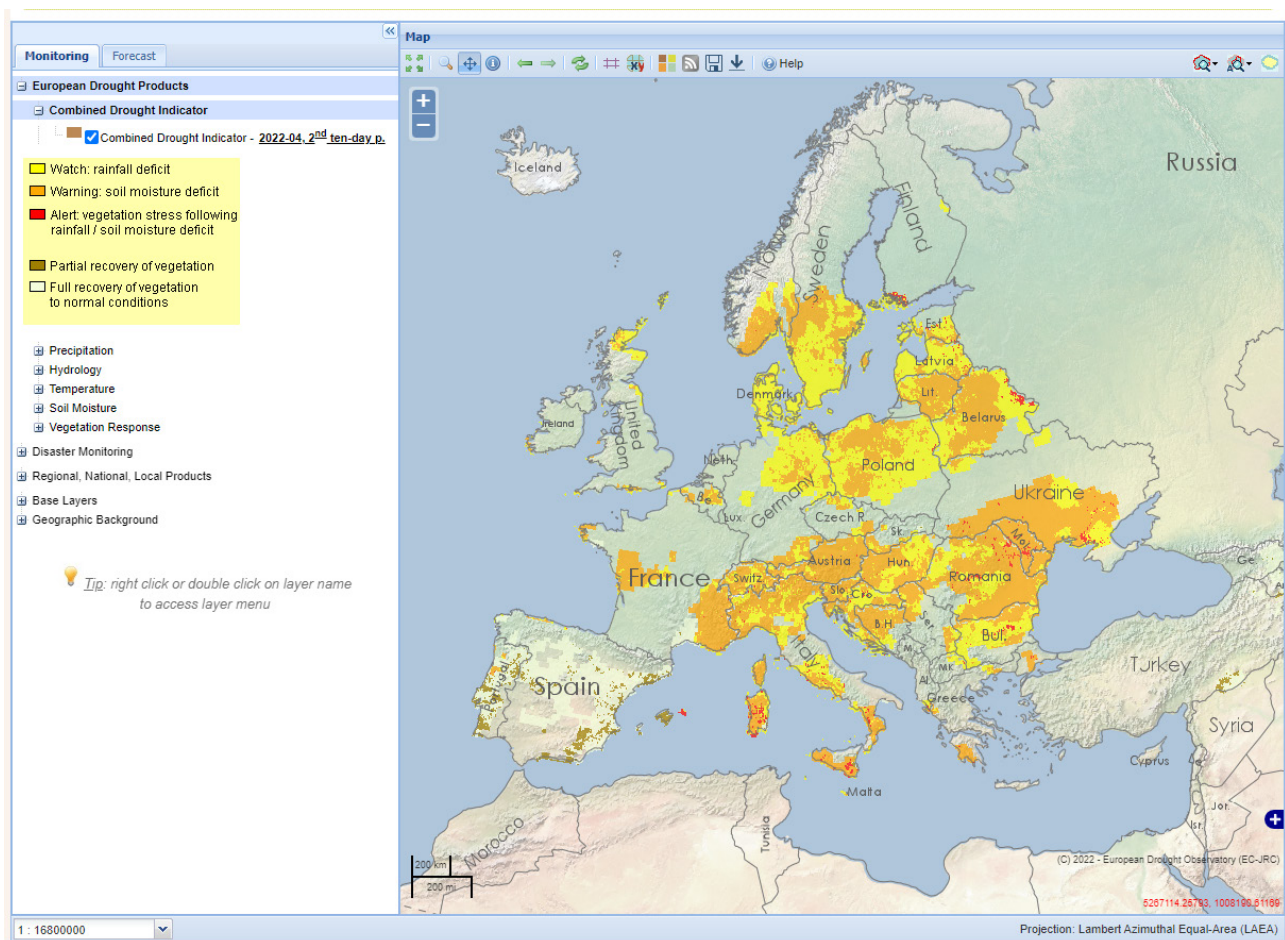


Figure 2.7: European drought observatory portal

## 2.9 UK Drought Portal

**Coverage:** UK.

**Monitoring or Forecasting:** Monitoring.

**Operational:** Yes.

**Description:** In the UK, the drought early warning system comes in the form of decentralized drought mitigation decisions. The national regulators and the Environment Agency, together, require all those who are (ground) water users to have a plan that aligns with general national guidelines. Operators then define their own triggers and drought mitigation action plans, including when relevant groundwater impacts.

**Information provided:** Currently, the UK drought portal<sup>4</sup> (Figure 2.8) assesses drought conditions based solely on precipitation datasets (SPI index) and is used as an awareness tool. Information on evaporation rates, or river flow and groundwater conditions are not provided. However, the UK Water Resources Portal<sup>5</sup> (Figure 2.9), which is an extension of the UK Drought Portal, provides an assessment on the hydrology and water situation in the country. It is an interactive tool that monitors the UK hydrological situation in (near) real-time at a range of spatial scales. The portal brings together rainfall, river flow, soil moisture and groundwater data in one place, and showcases the use of live river flow data from the Environment Agency and COSMOS-UK soil moisture data.

**Comments:** In addition, a National Drought Group has been formed to enhance effective collective action towards drought. This group is composed of governments departments, water companies, environmental groups, and other relevant stakeholders.

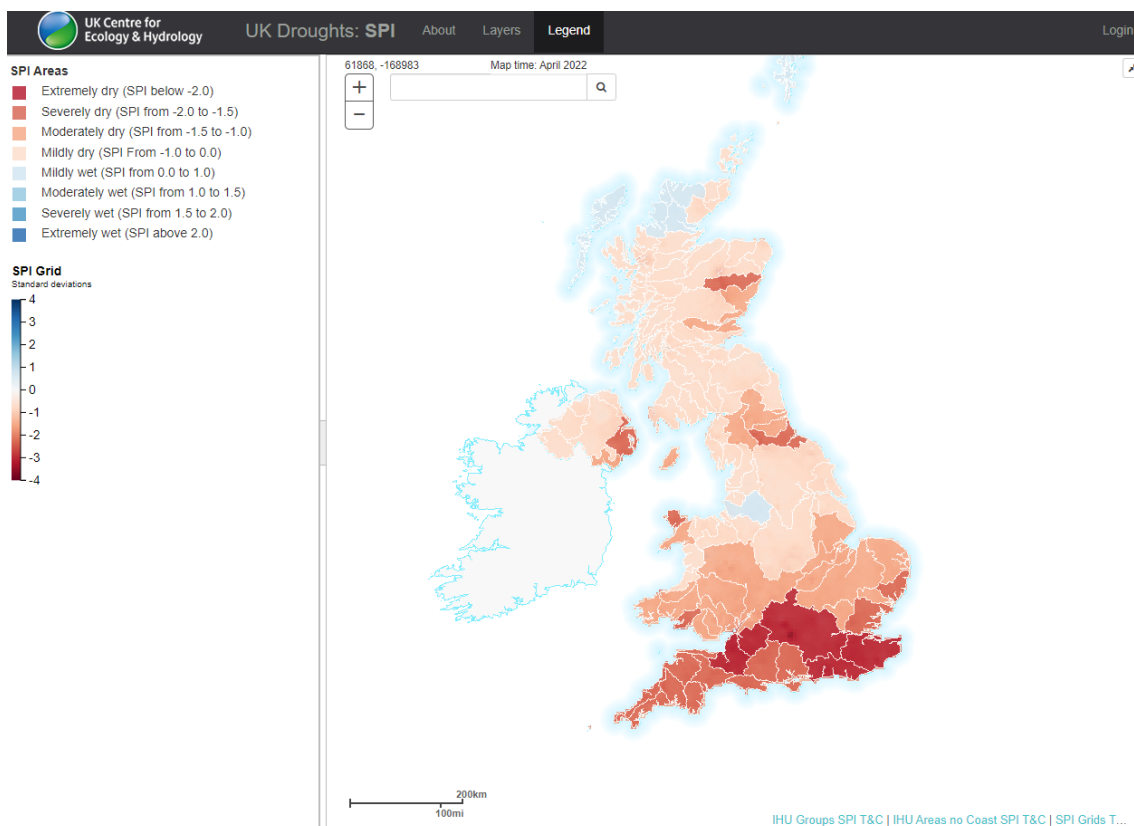


Figure 2.8: UK drought portal

<sup>4</sup> <https://eip.ceh.ac.uk/apps/droughts/>

<sup>5</sup> <https://eip.ceh.ac.uk/hydrology/water-resources/>

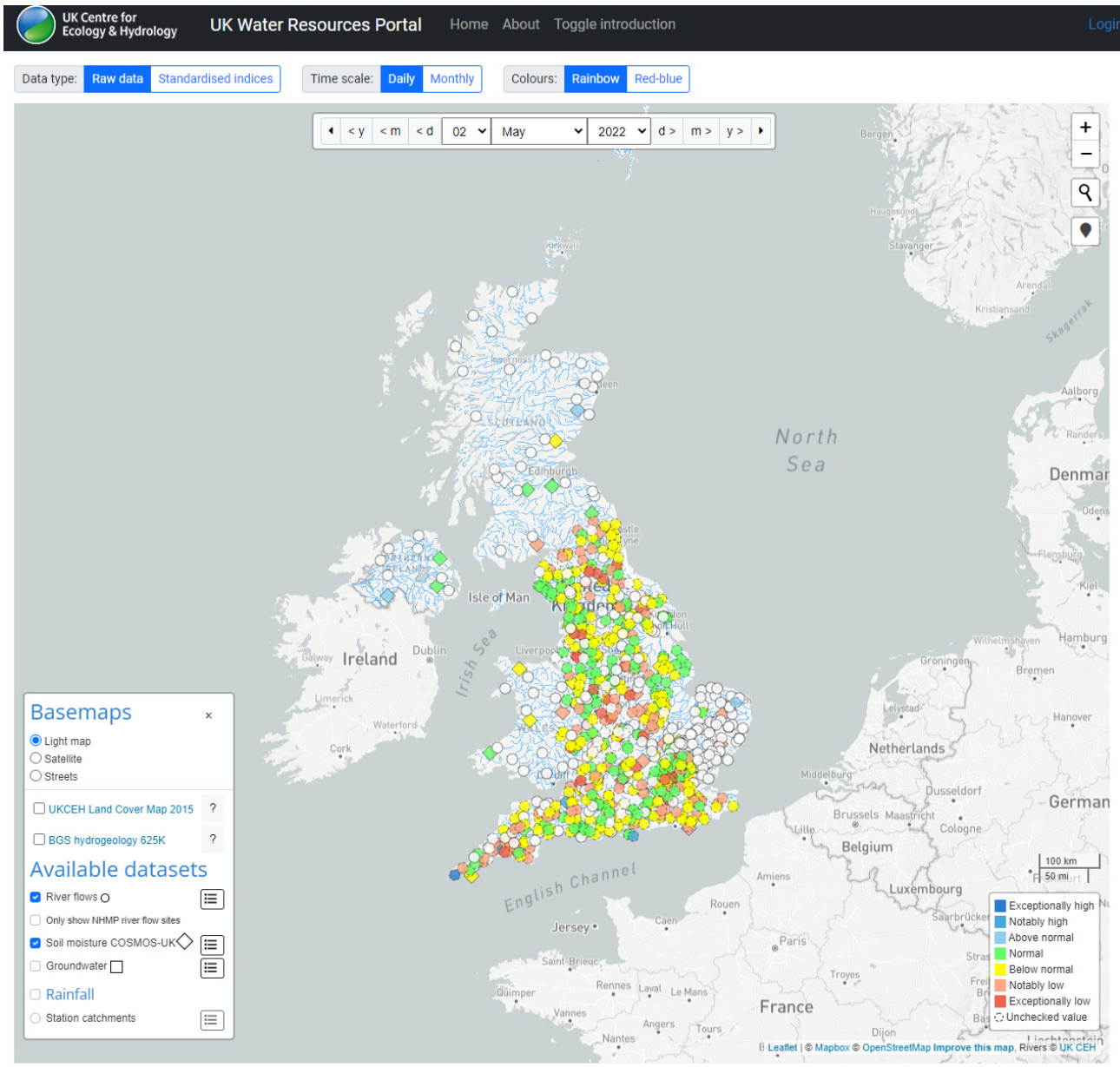


Figure 2.9: UK Water resources portal

## 2.10 Eastern Africa drought early warning bulletins


**Coverage:** Eastern Africa.

**Monitoring or Forecasting:** Both.

**Operational:** Yes.

**Description:** In Eastern Africa, droughts cause tremendous impacts on the agricultural sector, which has led to the development of user-centric seasonal forecasts through national hydrogeological and meteorological services, as a form of drought early warning system. However, this practice has been promoted as a tool to enhance food security and not necessarily water security. Indeed, water supply is assumed to be accessible by everyone although water demand in Africa is increasing. In Kenya, the seasonal forecast produced is mainly based on precipitation, temperature, and vegetation indices (Figure 2.10) at national scale and then downscaled at the county level with action plans being also decentralised at county levels.

**Information provided:** Based upon climate prediction, drought warnings are issued and provide agricultural advice such as type of crops to plant or locust information to enhance crop production. Post-season, there is also a drought early warning system based on the monitoring of soil moisture, vegetation, precipitation, and temperature. Based upon these results different warning levels from 'Normal', 'Alert', 'Alarm' to 'Emergency' are established.

| MARCH DROUGHT EW PHASE  |                        | Early Warning (EW) Phase Classification   |   |   |
|---|------------------------|---|---|---|
|  <p><b>Drought Status: NORMAL</b></p> <p>Shughuli za kawaida</p>   | <b>LIVELIHOOD ZONE</b> | <b>EW PHASE</b>   | <b>TRENDS</b>   |   |
|   | Marginal Mixed Farming | Normal  | stable  |   |
|   | Mixed Farming          | Normal  | stable  |   |
|   | <b>County</b>          | Normal  | stable  |   |
| <p><b>Drought Situation &amp; EW Phase Classification</b></p> <p><b>Biophysical Indicators</b></p> <ul style="list-style-type: none"> <li>Onset of the long rains was experienced in the fourth week of March as compare to the normal onset on the third week</li> <li>The rains received were good and evenly distributed.</li> <li>The vegetation greenness remains above normal for both livelihood zones. Forage condition remain fair to good</li> </ul> <p><b>Socio-Economic Indicators (Impact Indicators)</b></p> <p><b>Production Indicators</b></p> <ul style="list-style-type: none"> <li>Land preparation and planting currently in both livelihood zones.</li> <li>Livestock body conditions remain fair to good.</li> <li>Milk production remained stable due to stable body conditions.</li> </ul> <p><b>Access Indicators</b></p> <ul style="list-style-type: none"> <li>Milk consumption was stable attributed to stable production during the month.</li> <li>Terms of trade remained stable due to stable goat and maize prices during the month.</li> <li>Distances to water sources for both households and livestock remained increased occasioned by the dry condition which persisted during the three weeks of the month</li> </ul> <p><b>Utilization Indicators</b></p> <ul style="list-style-type: none"> <li>There were no cases of malnutrition reported in the sampled households.</li> <li>18% of the sampled households recorded borderline food consumption while 82% were in acceptable</li> <li>Coping strategy index decreased by 9% to 2.82.</li> </ul> |                        |   |   |   |
| <b>Biophysical Indicators</b>   |                        | <b>Value</b>  | <b>Normal ranges</b>  |   |
| Rainfall (% of normal)  |                        | 109   | 80-120  |   |
| VCI-3 month   |                        | 61.97   | 35-50   |   |
| VCI-1-month   |                        | 44.32   | 35-50   |   |
| Forage Condition  |                        | Fair to Poor  | Fair to Good  |   |
| <b>Production indicators</b>  |                        | <b>Value</b>  | <b>Normal ranges</b>  |   |
| Crop Condition  |                        | No crop   | No crop   |   |
| Livestock Body Condition  |                        | fair/good   | Fair  |   |
| Milk Production (in litres)   |                        | 0.5   | 1.2   |   |
| Livestock Migration Pattern   |                        | Nil   | Nil   |   |
| Livestock Deaths (from Drought)   |                        | Nil   | Nil   |   |
| <b>Access Indicators</b>  |                        | <b>Value</b>  | <b>Normal ranges</b>  |   |
| Terms of Trade (TeT)  |                        | 145   | 157   |   |
| Milk consumption (in litres)  |                        | 0.4   | 0.9   |   |
| Household Distance to Water Sources (in km)   |                        | 3.9   | 3.9   |   |
| Livestock Distance to Water Sources (in km)   |                        | 5   | 4.5   |   |
| <b>Utilization indicators</b>   |                        | <b>Value</b>  | <b>Normal ranges</b>  |   |
| % of Children at risk of malnutrition by MUAC   |                        | 0   | 0   |   |
| Coping Strategy Index (cCSI)  |                        | 2.82  | 2-4   |   |
| <ul style="list-style-type: none"> <li>Short rains harvests</li> <li>Short dry spell</li> <li>Reduced milk yields</li> <li>Increased HH Food Stocks</li> <li>Land preparation</li> </ul>  |                        | <ul style="list-style-type: none"> <li>Planting/Weeding</li> <li>Long rains</li> <li>High Calving Rate</li> <li>Milk Yields Increase</li> </ul> | <ul style="list-style-type: none"> <li>Long rains harvests</li> <li>A long dry spell</li> <li>Land preparation</li> <li>Increased HH Food Stocks</li> <li>Kidding (Sept)</li> </ul> | <ul style="list-style-type: none"> <li>Short rains</li> <li>Planting/weeding</li> </ul> |
| <b>Dry Season</b>   |                        | <b>Long Rains</b>   |   | <b>Short Rains Season</b>   |
| Jan   | Feb                    | Mar   | Apr   | May   |
| Jun   | Jul                    | Aug   | Sept  | Oct   |
| Nov   | Dec                    |   |   |   |

**Comments:** Recently, it has been recognized that the impacts of droughts extend beyond the agricultural sector to other sectors as well, leading to a focus on water access and the role of groundwater. In fact, the government of Kenya has launched an initiative to investigate groundwater availability to supply population during emergencies. But, due to a lack of funds and capacity the exploration of groundwater and monitoring of existing wells remains poor. In Ethiopia, such as in Kenya, the drought early system has been developed to answer to food security. Nevertheless, since the last drought in 2015, water access has been recognized as being also severely impacted. In response, the government of Ethiopia with the support of UNICEF also took an initiative in 2015 to integrate water resources in drought responses by assessing country-wide access to water. Groundwater represents a key water resource in the context of Eastern Africa; however lack of good data limits the possibility to identify groundwater impacts essential for effective drought action.

Figure 2.10: Example of Drought Early Warning Bulletin in Kenya

Source: <https://www.ndma.go.ke/index.php/resource-center/category/21-embu-mbeere>

## 2.11 African flood and drought monitor

**Coverage:** Africa.

**Monitoring or Forecasting:** Both.

**Operational:** Yes.

**Description:** The African Flood and Drought Monitor (AFDM, Figure 2.11) provides hydrological information and derived flood and drought indices in near real-time and forecasts, to provide useful information to various stakeholders to help in decision making on risk reduction. The forecasting capabilities include short-

term forecasts up to seven days in advance focused on flood risk, and seasonal drought forecasts up to six months in advance focused on drought and water resources.

**Information provided:** The AFDM had been running at a coarse 25 km resolution since it was first developed in 2008, using legacy climate datasets, and an out-of-date version of the hydrological model and web interface. Several improvements have been implemented in the AFDM over the past two years, including updating the core global data and hydrological models underlying the system, increasing the spatial resolution from 25 km to 5 km, and implementing various improvements to the underlying hydrological models, including the development of regionalized model parameters and use of a high-definition vector streamflow routing model, and to the forecast approaches.

The historic and real-time data are calculated using the Variable Infiltration Capacity (VIC) land surface hydrological model (Liang et al., 1994), which is run at a daily time step and ¼ degree spatial resolution for the whole of Africa. For the real-time monitor, the VIC model is forced by a mixture of observations and modelled/remotely sensed meteorology to produce updates of water cycle variables (e.g. soil moisture, runoff and evapotranspiration).

**Comments:** The AFDM was developed by Princeton University with support from UNESCO IHP and ICIWaRM. Justin Sheffield of the University of Southampton, UK is currently the lead developer. The AFDM, along with country-level monitors for Namibia, Zimbabwe, Mozambique, and Cameroon can be accessed at <http://stream.princeton.edu/>.

AFDM data and information have been used for:

- Drought Resilience: Controlling for drought variables with the AFDM helped USAID establish that a) the overall shock exposure in Niger vs. Burkina Faso during their RISE study was due to insect invasions and food price increases, not climate; and b) their market-based interventions in the PRIME program in Ethiopia were effective;
- Health and Epidemiology: a) Temperature drives both tsetse fly relative abundance and trypanosome prevalence in Tanzania; b) Risk of cholera transmission in Cameroon varies with average daily maximum temperature and with the precipitation levels over the preceding two weeks;
- Impact of Irrigation Dams: Use of AFDM drought indices helped show that in northern Nigeria households downstream of the dams were less affected by drought and enjoyed more stable growth rates and food consumption than those upstream or in similar but undammed basins;
- Human migration: Rainfall shortages and excess temperature, with soil moisture as an additional important factor, are strong drivers of out-migration from South Africa, especially for black and low-income migrants.

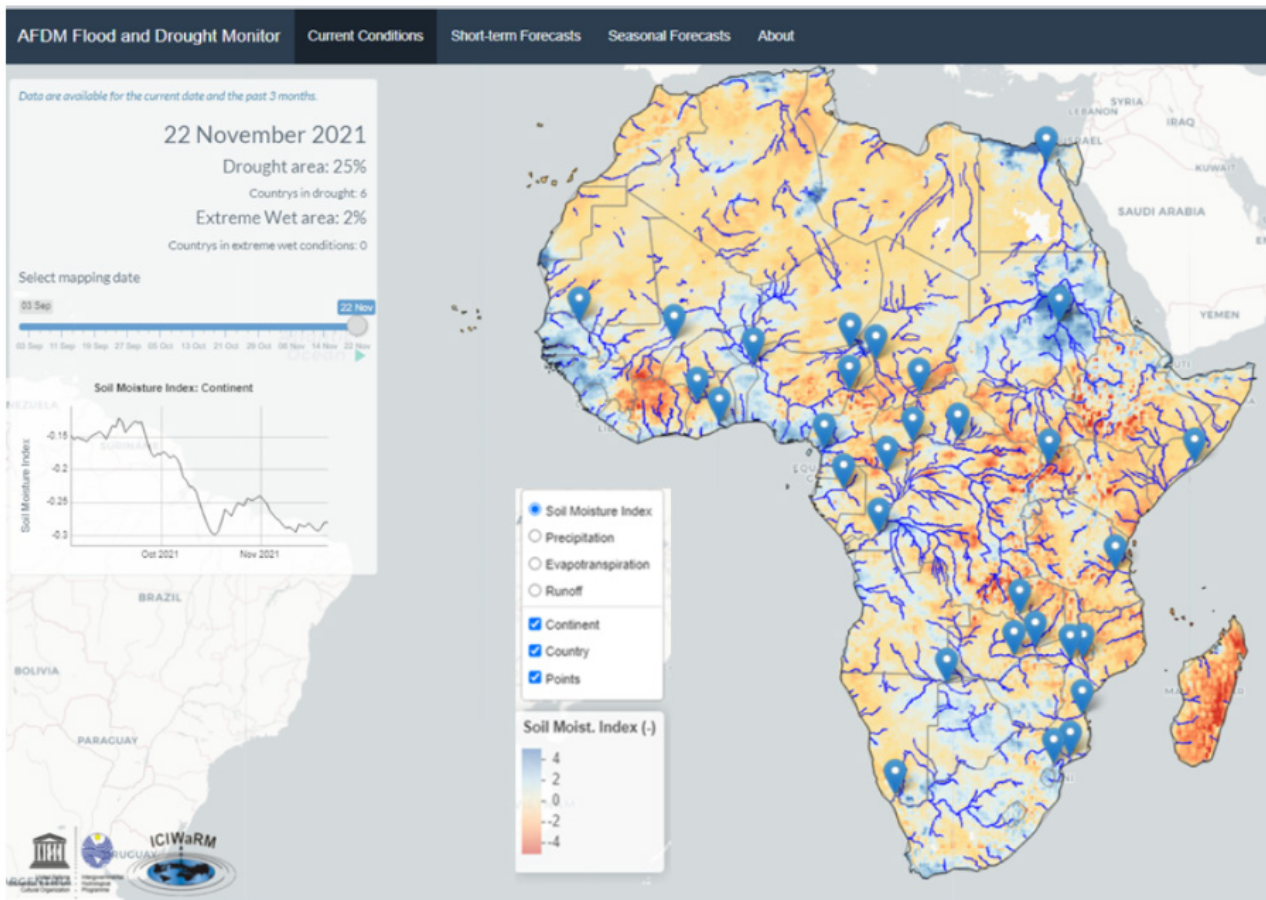


Figure 2.11: African Flood and Drought Monitor Nov 2021 showing soil moisture index

## 2.12 Famine Early Warning Systems Network land data assimilation system

**Coverage:** Global.

**Monitoring or Forecasting:** Monitoring.

**Operational:** Yes.

**Description:** The Famine Early Warning Systems Network (FEWS NET, Figure 2.12) Land Data Assimilation System (FLDAS) is another quasi-global (50S-50N) drought monitoring system. Recently extended to a global domain, FLDAS supports the FEWS NET Food Security Outlook process.

**Information provided:** A custom instance of the NASA Land Information System (LIS) has been modified to work with the models and data commonly used by FEWS NET. The LIS contains the Noah (Ek et al., 2003) and VIC (Liang, et al., 1994) models. Comparisons of FLDAS outputs with independent verification data (satellite vegetations and soil moisture, observed streamflow) indicate good performance and FLDAS outputs can be related to agricultural models to provide ag-impact models.

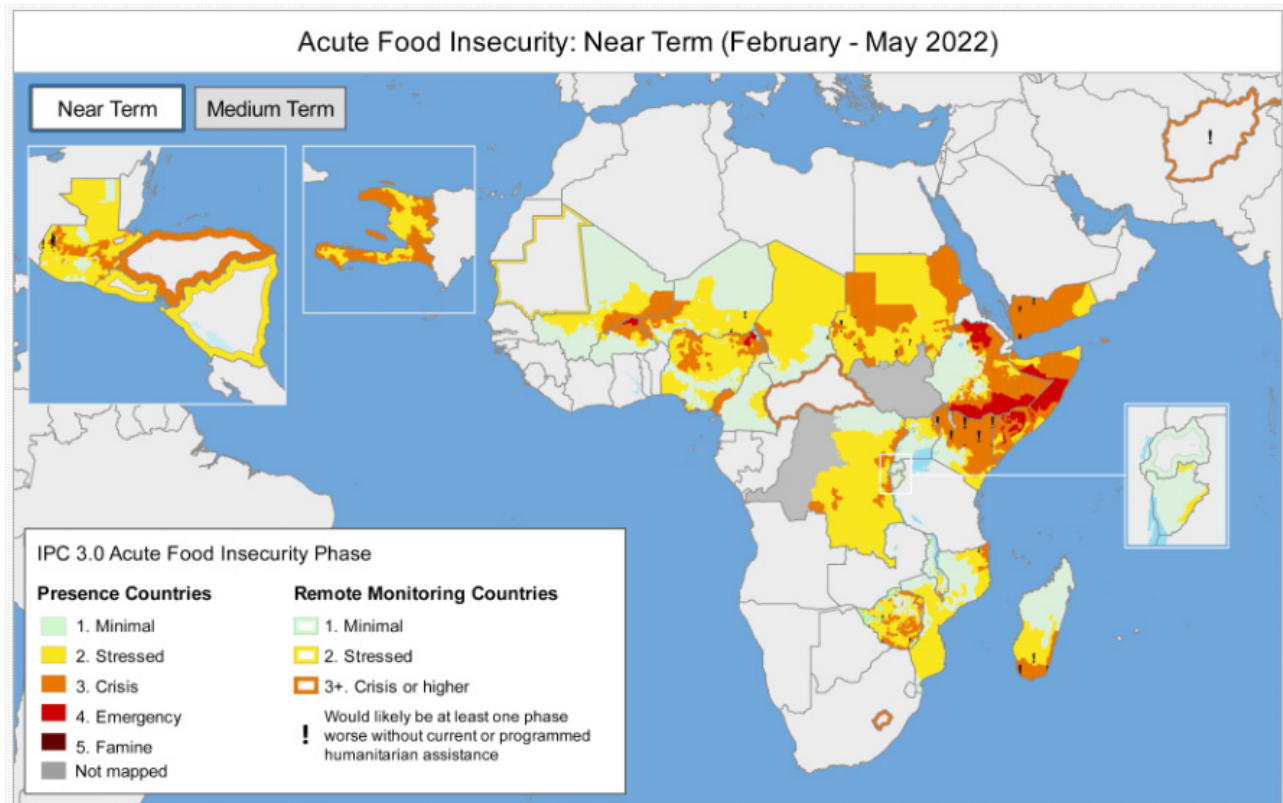


Figure 2.12: Near term acute food insecurity map, based on FEWS NET

## 3 Groundwater-surface water modelling approaches

### 3.1 High-level overview modelling approaches

Research indicates that large-scale hydrological models need better representation of groundwater processes to improve hydrological and climate simulations at both regional and global scales (Taylor et al., 2012; Wada et al., 2017). Integrated water resources management (IWRM) is needed for an improved understanding of the interactions between the human and natural systems. In recent years, different models and approaches have been developed, to better represent this interaction<sup>6</sup>. Mathematical models, including numerical and analytical models, have been widely used to investigate groundwater flow systems.

### 3.2 System requirements for St Kitts and Nevis

Discussions on the desired outcome of the drought prediction tool (including variables, indicators and other outputs), have taken place with the client and stakeholders. These included Agriculture, Water Services, Meteorological Office and Disaster Management sectors from both Saint Kitts and Nevis. These discussions provided us with an initial list of desired variables of interest, that have been summarised in Table 3.1. It is notable that during discussions with stakeholders at the beginning of the project, the need for actionable information was expressed and a desire to have additional information, including groundwater levels, apart from just SPI / SPEI (which is what is already available in some of the tools described in Section 3).

<sup>6</sup> Bizhanimanzar, M., Leconte, R., & Nuth, M. (2020). Catchment-scale integrated surface water-groundwater hydrologic modelling using conceptual and physically based models: A model comparison study. *Water (Switzerland)*, 12(2), 1–26. <https://doi.org/10.3390/w12020363>

Table 3.1: Variables of interest

| Variable                    | Source   | Spatial resolution | Ease of implementation | Output provided                         |
|-----------------------------|--|--------------------|------------------------|---|
| <b>Precipitation</b>        | ECMWF seasonal weather forecasts                                       | 36 km              | Moderate               | Historical<br>Current State<br>Forecast |
| <b>Temperature</b>          | ECMWF seasonal weather forecasts                                       | 36 km              | Moderate               |   |
| <b>Soil moisture</b>        | Hydrological model outputs   | Island-level       | Moderate               |   |
| <b>Surface runoff</b>       | Hydrological model outputs   | Island-level       | Moderate               |   |
| <b>Groundwater recharge</b> | Hydrological model outputs   | Island-level       | Moderate               |   |
| <b>Groundwater yield</b>    | Hydrological model outputs   | Borehole specific  | Hard                   |   |
| <b>Groundwater levels</b>   | Hydrological model outputs or linked to existing observation data sets | Island-level       | Moderate               |   |
| <b>Evaporation</b>          | Hydrological model outputs   | Island-level       | Moderate               |   |

|   |          |
|---|----------|
|  | Moderate |
|  | Hard     |

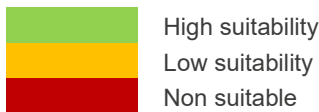
### 3.3 Models considered for this benchmarking exercise

For this benchmarking exercise and to make an informed decision on the modelling approach that will feed the drought prediction tool, a series of modelling tools are compared (Table 3.2). For each modelling tool in the table below, a description is given later in this section, highlighting their applicability, limitations and whether they can provide the prediction tool with the desired outputs as shown in Table 3.1 above.

Table 3.2: Groundwater-surface water modelling approaches

| Model          | Model description                  | Suitability for use by client with no in-house expertise | Suitability for use by client if in-house expertise | Previously used in prediction/forecasting tools |
|----------------|------------------------------------|--|---|---|
| VIC            | Semi-distributed hydrologic model  | Hard   | Moderate  | Yes   |
| MODFLOW        | Distributed groundwater model      | Hard   | Moderate  | Yes   |
| Aquimod        | Lumped-catchment groundwater model | Moderate   | Good  | Yes   |
| GISGroundwater | Add-in to ArcGIS                   | Moderate   | Good  | No  |
| ZOOMQ3D        | Numerical finite-difference model  | Hard   | Moderate  | No  |

| Model                         | Model description                                     | Suitability for use by client with no in-house expertise | Suitability for use by client if in-house expertise | Previously used in prediction/forecasting tools |
|-------------------------------|---|--|---|---|
| BGSGW                         | Semi-distributed groundwater flow model               | Non suitable   | Low suitability                                     | No  |
| Statistical Groundwater Model | Multiple linear regression approach                   | Low suitability  | High suitability                                    | Yes   |
| Kestrel-IHM                   | Models aquifer "blocks". No interaction between them. | Non suitable   | Low suitability                                     | Yes   |



## 3.4 Description of models considered during the benchmarking

### 3.4.1 VIC

**Type of model:** Semi-distributed hydrologic model.

**Description:** The Variable Infiltration Capacity (VIC) model is a macroscale hydrologic model used to solve full water and energy balances, developed in its initial version by Liang et al., (1994). Hydrological processes are simulated by the models which provides a useful tool for different applications, such as streamflow simulation and forecasting, water and energy balance calculations, reservoir water management, and climate change studies. VIC also models land-surface interactions and flow routing. The model simulates land-atmospheric fluxes, and water and energy balances on the land for each grid independently, and then routes estimated surface flows and base flows to produce streamflows from the network of grids (Figure 3.1). Many studies of river basins around the world had applied VIC (Wang et al., 2017<sup>7</sup>; Bennet et al., 2017<sup>8</sup>) as it is an open-source modelling tool and not memory-intensive allowing to perform studies at a continental scale.

<sup>7</sup> Wang, G., Zhang, J., Xu, Y., Bao, Z., & Yang, X. (2017). Estimation of future water resources of Xiangjiang River Basin with VIC model under multiple climate scenarios. *Water Science and Engineering*, 10(2), 87–96. <https://doi.org/https://doi.org/10.1016/j.wse.2017.06.003>.

<sup>8</sup> Bennett, K. E., Urrego Blanco, J. R., Jonko, A., Bohn, T. J., Atchley, A. L., Urban, N. M., & Middleton, R. S. (2018). Global Sensitivity of Simulated Water Balance Indicators Under Future Climate Change in the Colorado Basin. *Water Resources Research*, 54(1), 132–149. <https://doi.org/10.1002/2017WR020471>.

## Variable Infiltration Capacity (VIC) Macroscale Hydrologic Model

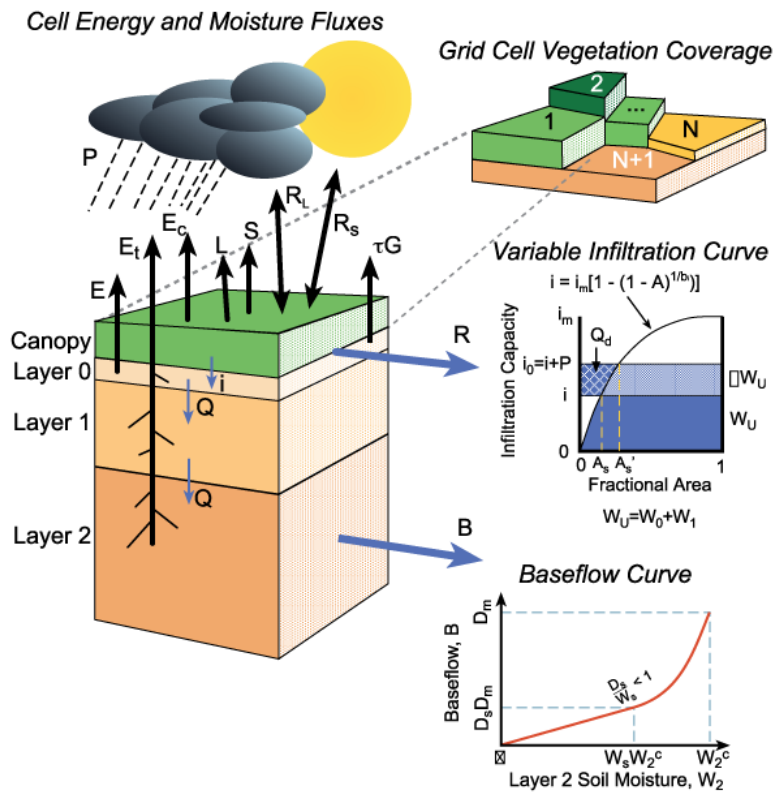


Figure 3.1: VIC land cover tiles and soil column, with major water and energy fluxes

**Application:** Several examples exist in the literature using the standard version of VIC as a hydrological model (e.g, ShengLian et al., 2018<sup>9</sup>; Hamman et al., 2018<sup>10</sup>; Niraula et al., 2016<sup>11</sup>). This version does not simulate groundwater flow, but this has been addressed by a series of studies (Niu et al., 2007<sup>12</sup>; Rosenberg et al., 2013<sup>13</sup>; Kang et al., 2019<sup>14</sup>) and more recently by Scheidegger et al. (2021)<sup>15</sup> by integrating a 2D groundwater model into the VIC code (Figure 3.2), implementing soil moisture-groundwater table interaction according to Niu et al. (2007)<sup>12</sup>, and enabling direct river-aquifer interaction.

**Advantages and Limitations:** HR Wallingford has in-house expertise in using VIC and the standard version has already been used as the driving model for a water availability web-tool as part of a dengue fever

<sup>9</sup> Shenglian, G., Jing, G., Jun, Z., & Hua, C. (2009). VIC distributed hydrological model to predict climate change impact in the Hanjiang basin. *Science in China, Series E: Technological Sciences*, 52(11), 3234–3239. <https://doi.org/10.1007/s11431-009-0355-2>.

<sup>10</sup> Hamman, J. J., Nijssen, B., Bohn, T. J., Gergel, D. R., & Mao, Y. (2018). The Variable Infiltration Capacity model version 5 (VIC-5): infrastructure improvements for new applications and reproducibility. *Geoscientific Model Development*, 11(8), 3481–3496. <https://doi.org/10.5194/gmd-11-3481-2018>.

<sup>11</sup> Niraula, R., Meixner, T., Ajami, H., Rodell, M., Gochis, D., & Castro, C. L. (2017). Comparing potential recharge estimates from three Land Surface Models across the western US. *Journal of Hydrology*, 545, 410–423. <https://doi.org/https://doi.org/10.1016/j.jhydrol.2016.12.028>.

<sup>12</sup> Niu, G.Y.; Yang, Z.L.; Dickinson, R.E.; Gulden, L.E.; Su, H. Development of a simple groundwater model for use in climate models and evaluation with Gravity Recovery and Climate Experiment data. *J. Geophys. Res. Atmos.* 2007, 112, D07103.

<sup>13</sup> Rosenberg, E.A.; Clark, E.A.; Steinemann, A.C.; Lettenmaier, D.P. On the contribution of groundwater storage to interannual streamflow anomalies in the Colorado River basin. *Hydrol. Earth Syst. Sci.* 2013, 17, 1475–1491.

<sup>14</sup> Kang, H.; Sridhar, V. Drought assessment with a surface-groundwater coupled model in the Chesapeake Bay watershed. *Environ. Model. Softw.* 2019, 119, 379–389.

<sup>15</sup> Scheidegger, J. M., Jackson, C. R., Muddu, S., Tomer, S. K., & Filgueira, R. (2021). Integration of 2D Lateral Groundwater Flow into the Variable Infiltration Capacity (VIC) Model and Effects on Simulated Fluxes for Different Grid Resolutions and Aquifer Diffusivities. *Water*, 13(5). <https://doi.org/10.3390/w13050663>.

forecasting system. Although it can be input intensive, it has been designed to operate with input from freely available Earth Observation datasets and reanalysis meteorological forcing products, which offer global coverage, making it particularly suitable for applications in data scarce regions, like the Caribbean.

VIC is one of the most widely used hydrological models. It was originally developed as a land surface model, but it has mostly been used as a stand-alone hydrological model (Abdulla et al., 1996<sup>16</sup>; Nijssen et al., 1997<sup>17</sup>) using an offline routing module (Lohmann et al., 1996, 1998a, b<sup>18</sup>). Whilst land surface models focus on the vertical exchange of water and energy between the land surface and the atmosphere, hydrological models focus on the lateral movement and availability of water. By combining these two approaches, VIC simulations are strongly process based; this provides a good basis for climate-impact modelling. VIC has been used extensively in studies such as coupled regional climate model simulations (Zhu et al., 2009<sup>19</sup>; Hamman et al., 2016<sup>20</sup>), combined river streamflow and water temperature simulations (van Vliet et al., 2016<sup>21</sup>), hydrological sensitivity to climate change research (Hamlet and Lettenmaier, 1999<sup>22</sup>; Nijssen et al., 2001a<sup>23</sup>; Chegwiddden et al., 2019<sup>24</sup>), streamflow simulations (Nijssen et al., 2001b<sup>25</sup>), flow regulation and redistribution research (Voisin et al., 2018<sup>26</sup>; Zhou et al., 2018<sup>27</sup>), and most importantly real-time drought forecasting (Wood and Lettenmaier, 2006<sup>28</sup>; Mo, 2008<sup>29</sup>, Sheffield et al., 2014<sup>30</sup>).

<sup>16</sup> Abdulla, F. A., Lettenmaier, D. P., Wood, E. F., and Smith, J. A.: Application of a macroscale hydrologic model to estimate the water balance of the Arkansas Red River basin, *J. Geophys. Res.-Atmos.*, 101, 7449–7459, <https://doi.org/10.1029/95jd02416>, 1996.

<sup>17</sup> Nijssen, B., Lettenmaier, D. P., Liang, X., Wetzel, S. W., and Wood, E. F.: Streamflow simulation for continental-scale river basins, *Water Resour. Res.*, 33, 711–724, <https://doi.org/10.1029/96wr03517>, 1997.

<sup>18</sup> Lohmann, D., Nolte-Holube, R., and Raschke, E.: A large-scale horizontal routing model to be coupled to land surface parametrization schemes, *Tellus A*, 48, 708–721, <https://doi.org/10.1034/j.1600-0870.1996.t01-3-00009.x>, 1996.

Lohmann, D., Raschke, E., Nijssen, B., and Lettenmaier, D. P.: Regional scale hydrology: II. Application of the VIC-2L model to the Weser River, Germany, *Hydrolog. Sci. J.*, 43, 143–158, <https://doi.org/10.1080/02626669809492108>, 1998a.

Lohmann, D., Raschke, E., Nijssen, B., and Lettenmaier, D. P.: Regional scale hydrology: I. Formulation of the VIC-2L model coupled to a routing model, *Hydrolog. Sci. J.*, 43, 131–141, <https://doi.org/10.1080/02626669809492107>, 1998b.

<sup>19</sup> Zhu, C. M., Leung, L. R., Gochis, D., Qian, Y., and Lettenmaier, D. P.: Evaluating the Influence of Antecedent Soil Moisture on Variability of the North American Monsoon Precipitation in the Coupled MM5/VIC Modeling System, *J. Adv. Model. Earth. Sy.*, 1, 13, <https://doi.org/10.3894/James.2009.1.13>, 2009.

<sup>20</sup> Hamman, J., Nijssen, B., Brunke, M., Cassano, J., Craig, A., DuVivier, A., Hughes, M., Lettenmaier, D. P., Maslowski, W., Osinski, R., Roberts, A., and Zeng, X. B.: Land Surface Climate in the Regional Arctic System Model, *J. Climate*, 29, 6543–6562, <https://doi.org/10.1175/Jcli-D-15-0415.1>, 2016.

<sup>21</sup> van Vliet, M. T. H., Wiberg, D., Leduc, S., and Riahi, K.: Power-generation system vulnerability and adaptation to changes in climate and water resources, *Nat. Clim. Change*, 6, 375–380, <https://doi.org/10.1038/Nclimate2903>, 2016.

<sup>22</sup> Hamlet, A. F. and Lettenmaier, D. P.: Effects of climate change on hydrology and water resources in the Columbia River basin, *J. Am. Water Resour. As.*, 35, 1597–1623, <https://doi.org/10.1111/j.1752-1688.1999.tb04240.x>, 1999.

<sup>23</sup> Nijssen, B., O'Donnell, G. M., Hamlet, A. F., and Lettenmaier, D. P.: Hydrologic sensitivity of global rivers to climate change, *Climatic Change*, 50, 143–175, <https://doi.org/10.1023/A:1010616428763>, 2001a.

<sup>24</sup> Chegwiddden, O. S., Nijssen, B., Rupp, D. E., Arnold, J. R., Clark, M. P., Hamman, J. J., Kao, S. C., & Mao, Y. (2019). How Do Modeling Decisions Affect the Spread Among Hydrologic Climate Change Projections? Exploring a Large Ensemble of Simulations Across a Diversity of Hydroclimates Earth's Future. *Earth's Future*, 623–637. <https://doi.org/10.1029/2018EF001047>.

<sup>25</sup> Nijssen, B., O'Donnell, G. M., Lettenmaier, D. P., Lohmann, D., and Wood, E. F.: Predicting the discharge of global rivers, *J. Climate*, 14, 3307–3323, [https://doi.org/10.1175/1520-0442\(2001\)014<3307:Ptdogr>2.0.Co;2](https://doi.org/10.1175/1520-0442(2001)014<3307:Ptdogr>2.0.Co;2), 2001b.

<sup>26</sup> Voisin, N., Kintner-Meyer, M., Wu, D., Skaggs, R., Fu, T., Zhou, T., Nguyen, T., and Kraucunas, I.: Opportunities for Joint Water–Energy Management Sensitivity of the 2010 Western US Electricity Grid Operations to Climate Oscillations, *B. Am. Meteorol. Soc.*, 99, 299–312, <https://doi.org/10.1175/Bams-D-16-0253.1>, 2018.

<sup>27</sup> Zhou, T., Voisin, N., Leng, G. Y., Huang, M. Y., and Kraucunas, I.: Sensitivity of Regulated Flow Regimes to Climate Change in the Western United States, *J. Hydrometeorol.*, 19, 499–515, <https://doi.org/10.1175/Jhm-D-17-0095.1>, 2018.

<sup>28</sup> Wood, A. W. and Lettenmaier, D. P.: A test bed for new seasonal hydrologic forecasting approaches in the western United States, *B. Am. Meteorol. Soc.*, 87, 1699–1712, <https://doi.org/10.1175/Bams-87-12-1699>, 2006.

<sup>29</sup> Mo, K. C.: Model-Based Drought Indices over the United States, *J. Hydrometeorol.*, 9, 1212–1230, <https://doi.org/10.1175/2008jhm1002.1>, 2008.

<sup>30</sup> Sheffield, J., Wood, E. F., Chaney, N., Guan, K., Sadri, S., Yuan, X., Olang, L., Amani, A., Ali, A., Demuth, S., & Ogallo, L. (2014). A Drought Monitoring and Forecasting System for Sub-Saharan African Water Resources and Food Security, *Bulletin of the American Meteorological Society*, 95(6), 861–882. Retrieved Jun 14, 2022, from <https://journals.ametsoc.org/view/journals/bams/95/6/bams-d-12-00124.1.xml>.

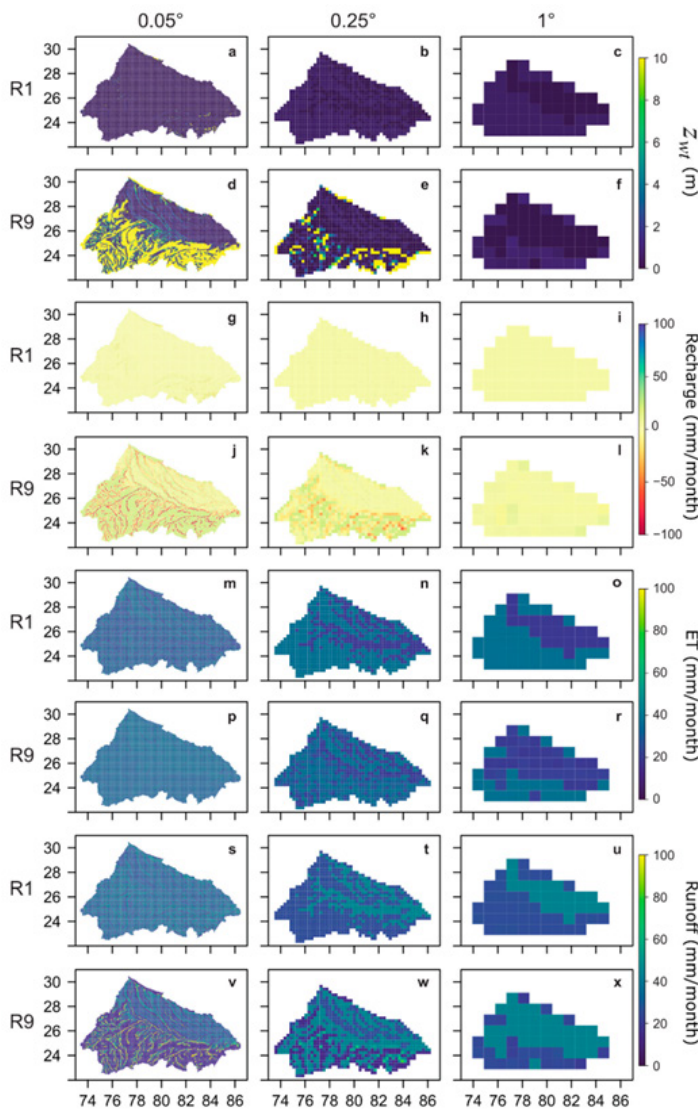


Figure 3.2: Examples of different outputs for the VIC-AMBHAS extension (Scheidegger et al., 2021)<sup>15</sup>

### 3.4.2 MODFLOW

**Type of model:** Distributed groundwater model.

**Description:** MODFLOW is the USGS's modular hydrologic model. MODFLOW is considered an international standard for simulating and predicting groundwater conditions and groundwater / surface-water interactions. MODFLOW 6 is presently the core MODFLOW version distributed by the USGS. Originally developed and released solely as a groundwater-flow simulation code when first published in 1984, MODFLOW's modular structure has provided a robust framework for integration of additional simulation capabilities that build on and enhance its original scope. The family of MODFLOW-related programs now includes capabilities to simulate coupled groundwater / surface-water systems, solute transport, variable-density flow (including saltwater), aquifer-system compaction and land subsidence, parameter estimation, and groundwater management (Langevin et al., 2017<sup>31</sup>). Finite-difference, finite-element, finite-volume and boundary element methods are numerical approaches used to solve partial differential

<sup>31</sup> Langevin, C. D., Hughes, J. D., Banta, E. R., Niswonger, R. G., Panday, S., & Provost, A. M. (2017). Documentation for the MODFLOW 6 Groundwater Flow Model: U.S. Geological Survey Techniques and Methods. In U.S. Geological Survey Techniques and Methods, book 6, chap. A55, 197 p. <https://doi.org/https://doi.org/10.3133/tm6A55>.

equations that describe flow porous media (Shaw et al., 2010<sup>32</sup>). MODFLOW is based on a set of governing equations which are the basis of most mathematical models of groundwater systems. These set of equations are based on Darcy's Law, which describes flow through porous media.

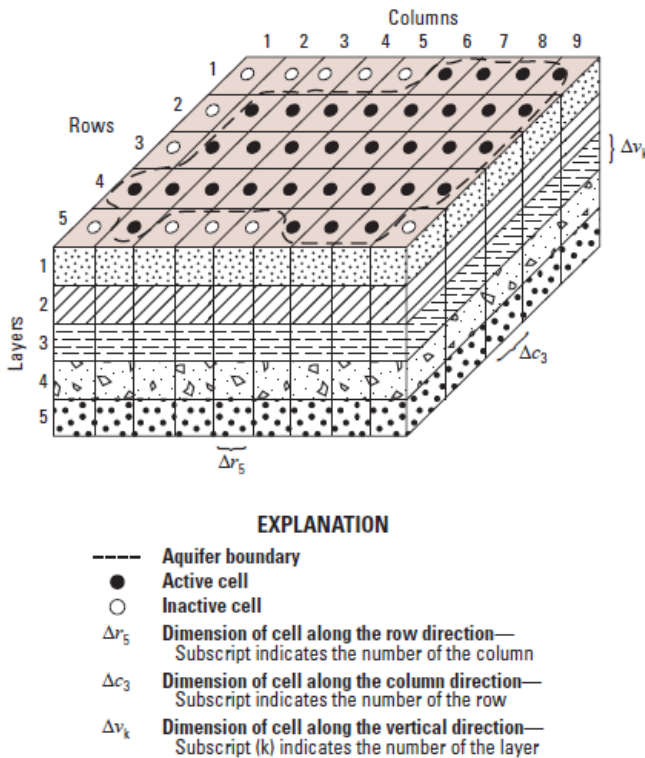


Figure 3.3: Regular MODFLOW grid showing a hypothetical aquifer system (Langevin et al., 2017)

**Application:** MODFLOW have been widely applied worldwide (e.g., Daoud et al., 2021<sup>33</sup>; Serrano-Hidalgo et al., 2021<sup>34</sup>; Aghlmand&Abbasi, 2019<sup>35</sup>; Ostad-Ali-Askari et al., 2019<sup>36</sup>; Almuhaylan et al., 2020<sup>37</sup>; Wei&Bailey, 2019<sup>38</sup>), as well as regionally. For example, regional groundwater models of UK aquifers have predominantly been developed by the Environment Agency (Shepley et al., 2012<sup>39</sup>; Whiteman et al., 2012<sup>40</sup>)

<sup>32</sup> Shaw, E. M., Beven, K. J., Chappell, N. A., & Lamb, R. (2010). Hydrology in Practice (4th Editio). CRC Press.

<sup>3333</sup> Daoud, M. G., Lubczynski, M. W., Vekerdy, Z., & Francés, A. P. (2022). Application of a novel cascade-routing and infiltration concept with a Voronoi unstructured grid in MODFLOW 6, for an assessment of surface-water/groundwater interactions in a hard-rock catchment (Sardon, Spain). Hydrogeology Journal, 30(3), 899–925. <https://doi.org/10.1007/s10040-021-02430-z>.

<sup>34</sup> Serrano-Hidalgo, C., Guardiola-Albert, C., Heredia, J., Tenreiro, F. J. E., & Naranjo-Fernández, N. (2021). Selecting suitable modflow packages to model pond–groundwater relations using a regional model. Water (Switzerland), 13(8). <https://doi.org/10.3390/w13081111>.

<sup>35</sup> Aghlmand, R., & Abbasi, A. (2019). Application of MODFLOW with Boundary Conditions Analyses Based on Limited Available Observations: A Case Study of Birjand Plain in East Iran. Water, 11(9). <https://doi.org/10.3390/w11091904>.

<sup>36</sup> Ostad, K., & Askari, A. (2019). Effect of management strategies on reducing negative impacts of climate change on water resources of the Isfahan – Borkhar aquifer using MODFLOW. February, 611–631. <https://doi.org/10.1002/rra.3463>.

<sup>37</sup> Almuhaylan, M. R., Ghumman, A. R., Al-Salamah, I. S., Ahmad, A., Ghazaw, Y. M., Haider, H., & Shafiquzzaman, M. (2020). Evaluating the Impacts of Pumping on Aquifer Depletion in Arid Regions Using MODFLOW, ANFIS and ANN. Water, 12(8). <https://doi.org/10.3390/w12082297>.

<sup>38</sup> Wei, X., Bailey, R. T., Records, R. M., Wible, T. C., & Arabi, M. (2019). Comprehensive simulation of nitrate transport in coupled surface-subsurface hydrologic systems using the linked SWAT-MODFLOW-RT3D model. Environmental Modelling & Software, 122, 104242. <https://doi.org/https://doi.org/10.1016/j.envsoft.2018.06.012>.

<sup>39</sup> Shepley, M. G., Whiteman, M. I., Hulme, P. J., & Grout, M. W. (2012). Introduction: groundwater resources modelling: a case study from the UK. In The Geological Society London (Ed.), Groundwater Resources Modelling: A Case Study from the UK. (Vol. 51, Issue 4, p. 379). <https://doi.org/10.1111/gwat.12073>.

<sup>40</sup> Whiteman, M. I., Maginness, C. H., Farrell, R. P., Gijsbers, P. J. A., & Ververs, M. (2012). The National Groundwater Modelling System: Providing wider access to groundwater models. In Groundwater Resources Modelling: A Case Study

using the MODFLOW software (Harbaugh, 2005<sup>41</sup>). Recent examples include the Caribbean region, where groundwater recharge to a complex aquifer system on the island of Tobago has been investigated, using to MODFLOW to better understand the hydrogeology of the island's aquifers for groundwater resources management (Boutt et al., 2021<sup>42</sup>).

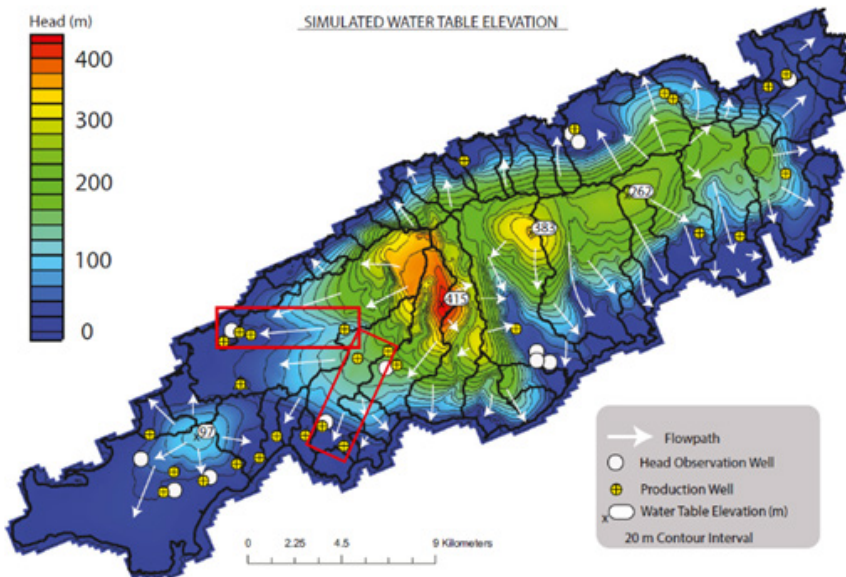


Figure 3.4: Simulated water-table elevation representing mean annual conditions (Boutt et al., 2021)<sup>42</sup>

**Advantages and Limitations:** HR Wallingford has in-house expertise in using MODFLOW and related packages. The advantages of using a MODFLOW is the applicability in terms of the widely applied approach and the expertise that will make the development of a model relatively easy. However, MODFLOW is a data-intensive software and requires a level of detail that could not be easily achieved due to gaps in data and knowledge of the aquifers. It will also make the development of an island-scale model of both Saint Kitts and Nevis challenging.

### 3.4.3 Aquimod

**Type of model:** Lumped-catchment groundwater model.

**Description:** Aquimod is a simple, lumped-catchment groundwater model. It simulates groundwater-level time series at a point by linking simple algorithms of soil drainage, unsaturated-zone flow and groundwater flow. It takes time series of rainfall and potential evapotranspiration as input and produces a time series of groundwater level. Hydrographs of flows through the outlets of the groundwater store are also generated, which can potentially be related to river flow measurements (Mackay et al., 2014<sup>43</sup>). The main features of the Aquimod software include:

- Fast simulation of groundwater level time-series;

from the UK. (Vol. 364, Issue 1, pp. 49–63). Geological Society, London, Special Publications. <https://doi.org/10.1144/SP364.5>.

<sup>41</sup> Harbaugh, A. W. (2005). MODFLOW-2005, The U.S. Geological Survey Modular Ground-Water Model—the Ground-Water Flow Process. In U.S. Geological Survey Techniques and Methods 6-A16. U.S. Geological Survey.

<sup>42</sup> Boutt, D. F., Allen, M., Settembrino, M., Bonarigo, A., Ingari, J., Demars, R., & Munk, L. A. (2021). Groundwater recharge to a structurally complex aquifer system on the island of Tobago (Republic of Trinidad and Tobago). *Hydrogeology Journal*, 29(2), 799–818. <https://doi.org/10.1007/s10040-020-02289-6>.

<sup>43</sup> Mackay, J. D., Jackson, C. R., & Wang, L. (2014b). A lumped conceptual model to simulate groundwater level time-series. *Environmental Modelling & Software*, 61, 229–245. <https://doi.org/10.1016/j.envsoft.2014.06.003>.

- Flexible time-stepping;
- Monte Carlo parameter sampling;
- Modular structure with multiple process representations;
- Choice of objective functions to evaluate model efficiency.

**Application:** AquMod can be applied to groundwater catchments, with observation boreholes containing observed groundwater level time-series data. It can be calibrated against these data and used to provide information on the behaviour of groundwater levels beyond observational records. The model has been used in this way for a number of applications, including reconstructing groundwater level records (Figure 3.5), long term projections of groundwater levels under climate change and forecasting groundwater levels into the near future using meteorological forecasts (Jackson et al., 2015<sup>44</sup>; Mackay et al., 2015<sup>45</sup>; Mackay et al., 2014<sup>43</sup>).

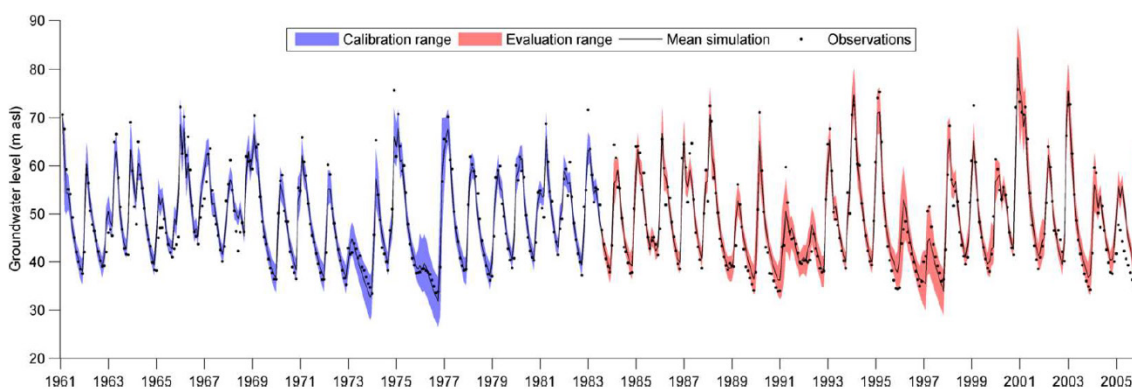


Figure 3.5: Example of groundwater level time-series simulation using AquMod

**Advantages and Limitations:** The simple structure of AquMod makes it easy to use in comparison to more complex physically-based distributed models, and therefore should be accessible to those users who are new to the field of groundwater / hydrological modelling. However, several limitations need to be taken into account: catchment areas are lumped into a single area characterised by data from a groundwater level borehole; each input variable (e.g. soil type and rainfall) and output variable (e.g. groundwater level) are spatially uniform over the study area and spatial heterogeneity cannot be represented; it needs observed groundwater level time-series to calibrate the model and corresponding rainfall and potential evapotranspiration (PET) data to drive the model; rainfall recharge is the only type of recharge considered and does not take into account other sources of recharge such as lateral groundwater flows across the catchment boundary (Mackay et al., 2015<sup>45</sup>).

### 3.4.4 GISGroundwater

**Type of model:** add-in to ArcGIS.

**Description:** GISGroundwater is an add-in to ArcGIS that models the depth to groundwater beneath the land surface. It calculates the elevation of the groundwater table for unconfined aquifers. For aquifers that are confined by overlying impermeable rock, it calculates the elevation of the groundwater surface, i.e. the level groundwater will rise to in a borehole.

<sup>44</sup> Jackson, C. R., Bloomfield, J. P., & Mackay, J. D. (2015). Evidence for changes in historic and future groundwater levels in the UK. *Progress in Physical Geography*, 39(1), 49–67. <https://doi.org/10.1177/0309133314550668>.

<sup>45</sup> Mackay, J. D., Jackson, C. R., Brookshaw, A., Scaife, A. A., Cook, J., & Ward, R. S. (2015). Seasonal forecasting of groundwater levels in principal aquifers of the United Kingdom. *Journal of Hydrology*, 530, 815–828. <https://doi.org/10.1016/j.jhydrol.2015.10.018>. Mangin.

The tool is based on a mathematical model that simulates groundwater flow, with inputs about the area of interest as a series of GIS raster layers and shapefiles. For example, amongst other things, the user defines properties of an aquifer such as: how permeable the rock is the locations of rivers and pumping wells the amount of rainfall seeping downwards to the water table from the land surface. On running the model, the tool adds a raster layer to the GIS project, which then plots the elevation of the groundwater level surface (Wang et al., 2014). An example of how groundwater levels are represented in ArcMap is shown in Figure 3.6.

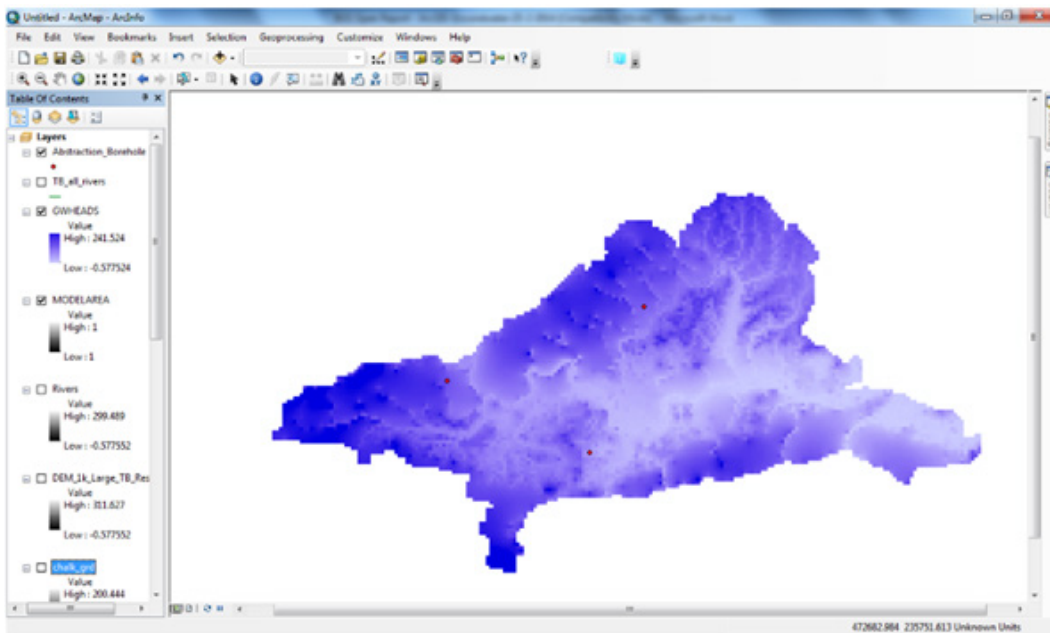


Figure 3.6: Groundwater levels produced by BGS GISGroundwater

**Application:** The application of this tool has been limited. Examples of this is the validation of the GISGroundwater by the British Geological Survey (BGS) against analytical solutions to groundwater-head profiles for a range of aquifer configurations (Wang et al., 2016<sup>46</sup>); or the study to develop a catchment-scale integrated numerical method to investigate the nitrate lag time in the groundwater system, and the Eden Valley, UK (Wang et al., 2013<sup>47</sup>).

**Advantages and Limitations:** The use of GIS groundwater flow model is a valuable tool to do preliminary analysis of groundwater flow models to evaluate hydrogeological conceptual models. This would be useful for non-experts in groundwater modelling but will not generate the outputs required for the tool compared to other more complex semi-distributed or distributed models. And although it is relatively easy to use, it needs ArcGIS, which is not openly accessible to the public.

### 3.4.5 ZOOMQ3D

**Type of model:** Numerical finite-difference model.

**Description:** ZOOMQ3D is a numerical finite-difference model, which simulates groundwater flow in aquifers. The program is used to investigate groundwater resources and to make predictions about possible

<sup>46</sup> Wang, L, Jackson, C R, Pachocka, M, Kingdon, A. 2016. A seamlessly coupled GIS and distributed groundwater flow model. Environmental Modelling & Software, Vol. 82, 1–6.

<sup>47</sup> Wang, L, Butcher, A S, Stuart, M E, Goody, D C, Bloomfield, J P. 2013. The nitrate time bomb: a numerical way to investigate nitrate storage and lag time in the unsaturated zone. Environmental Geochemistry and Health, Vol. 35(5), 667–681.

future changes in their quantity and quality. It incorporates a mesh refinement procedure which aids the solution of problems related to scale (Figure 3.7).

It applies a quasi-three-dimensional finite-difference approximation to the general three-dimensional governing partial differential groundwater flow equation. A model, based on the above equation, incorporating appropriate boundary and initial conditions, would be truly three-dimensional. ZOOMQ3D takes a simplifying approach to the solution of the three-dimensional equation by recognising that in many aquifers it is possible to identify a layered structure. If the layers are aligned parallel to the horizontal coordinate axes, then the three-dimensional equation can be integrated vertically across the layer to produce an equation which describes the flow within a layer and its interactions with adjacent layers (Jackson & Spink, 2004<sup>48</sup>).

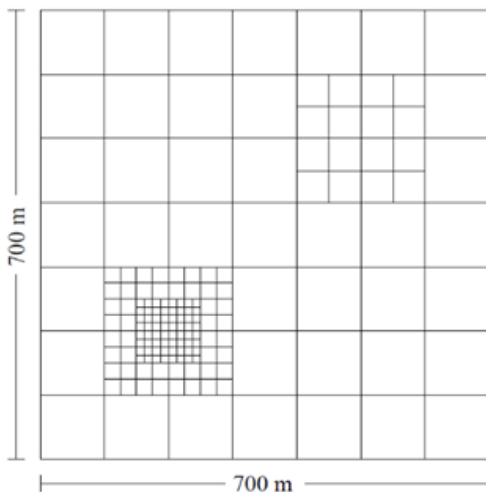


Figure 3.7: Example of a ZOOMQ3D mesh composed of four grids: the coarsest base grid, two child grids (on grid level 2) and one grandchild grid (on grid level 3)

**Application:** ZOOMQ3D has been mainly applied to UK water resources (Mansour et al., 2008<sup>49</sup>; Jackson et al., 2011<sup>50</sup>; Jackson et al., 2012<sup>51</sup>).

**Advantages and Limitations:** The less widely application of the model will limit its use to a wider set of study areas. It will also need an independent recharge modelling effort to use in conjunction with the groundwater model and will not be able to provide the set of outputs needed for the tool.

### 3.4.6 BGS GW

**Type of model:** Semi-distributed groundwater flow model.

**Description:** BGS GW is a semi distributed groundwater flow model that simulates groundwater head fluctuations across a series of linked groundwater units (GWUs) that can simulate the groundwater flows and heads under confined or unconfined conditions. Each GWU is a lumped system with hydraulic properties which can be varied accordingly to hydrogeological understanding or through optimisation. By linking multiple units horizontally and vertically, one can introduce simplified representations of three-dimensional heterogeneity (Figure 3.8).

<sup>48</sup> Jackson, C. R., & Spink, A. E. F. (2004). User's manual for the groundwater flow model ZOOMQ3D (p. 94).

<sup>49</sup> Hughes, A. G., Mansour, M. M., & Robins, N. S. (2008). Evaluation of distributed recharge in an upland semi-arid karst system: The West Bank Mountain Aquifer, Middle East. *Hydrogeology Journal*, 16(5), 845–854. <https://doi.org/10.1007/s10040-008-0273-6>.

<sup>50</sup> Jackson CR, Meister R and Prudhomme C (2011) Modelling the effects of climate change and its uncertainty on UK Chalk groundwater resources from an ensemble of global climate model projections. *Journal of Hydrology* 399(1–2): 12–28.

<sup>51</sup> Jackson CR (2012) Future flows and groundwater levels: R-Groundwater model summary Science Report/Project Note – SC090016/PN6. British Geological Survey Commissioned Report CR/12/105 N.

**Application:** Similar to ZOOMQ3D model, it has been used mainly as a tool to study groundwater processes and for water resources management in the UK. Mansour et al., (2013<sup>52</sup>) used BGS GW to improve the simulation of groundwater processes in the Thames Basin; or applied to a complex multi-aquifer groundwater system at a national scale in the UK (Pachocka et al., 2015).

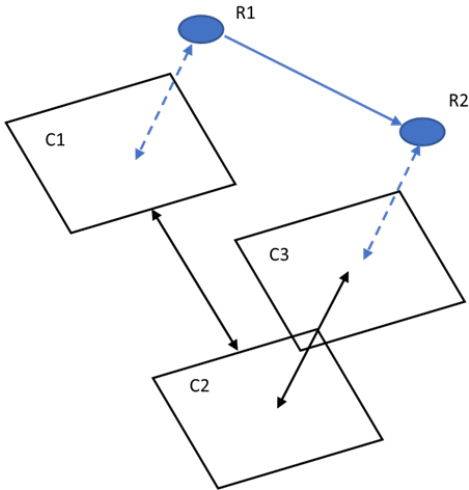


Figure 3.8: Example of how groundwater units connect between each other and with defined river nodes in BGS GW

**Advantages and Limitations:** Although BGS GW is a relatively simple modelling tool, it could provide a realistic representation of the certain hydrogeology. However as this has not been tested on a wider scale, it would be difficult to predict its behaviour for different areas of interest. It will also need a recharge model input to the model, and with the current version, it will not provide the needed outputs for the tool.

### 3.4.7 Statistical groundwater model

**Type of model:** Multiple linear regression approach.

**Description:** A simple lumped model based on the FAO56 method (Allen et al., 1998) is applied to calculate groundwater recharge. The recharge model generates a monthly time series of soil moisture deficit (SMD), runoff and recharge. The subsequent Multiple Linear Regression (MLR) approach is based on the relationship between groundwater annual minima and relative recharge totals for dry and normal years rather than the absolute values. Statistical groundwater models are based on the relationship between recharge and observed groundwater levels can be developed using MLR analysis. The MLR analysis is applied to the annual minimum groundwater level and lags of seasonal or monthly recharge. An example of how the statistical groundwater model, developed by HR Wallingford, is applied to certain sites (particularly in the UK) is shown in Figure 3.9.

**Application:** The statistical groundwater model has been widely applied to water resources management plans in the UK (e.g. Southeast Water, 2017-2018). Or as part of a sensitivity framework to assess the resilience of a conjunctive use system to drought (McBride et al., 2017).

**Advantages and Limitations:** This methodology, although widely applied for UK groundwater assessment, will not provide the desired outputs for the drought assessment tool.

<sup>52</sup> Mansour, M., Mackay, J., Abesser, C., Williams, A., Wang, L., Bricker, S., & Jackson, C. (2013). Integrated Environmental Modeling applied at the basin scale : Linking different types of models using the OpenMI standard to improve simulation of groundwater processes in the Thames Basin , UK . MODFLOW and More 2013: Translating Science into Practice, April 2018.

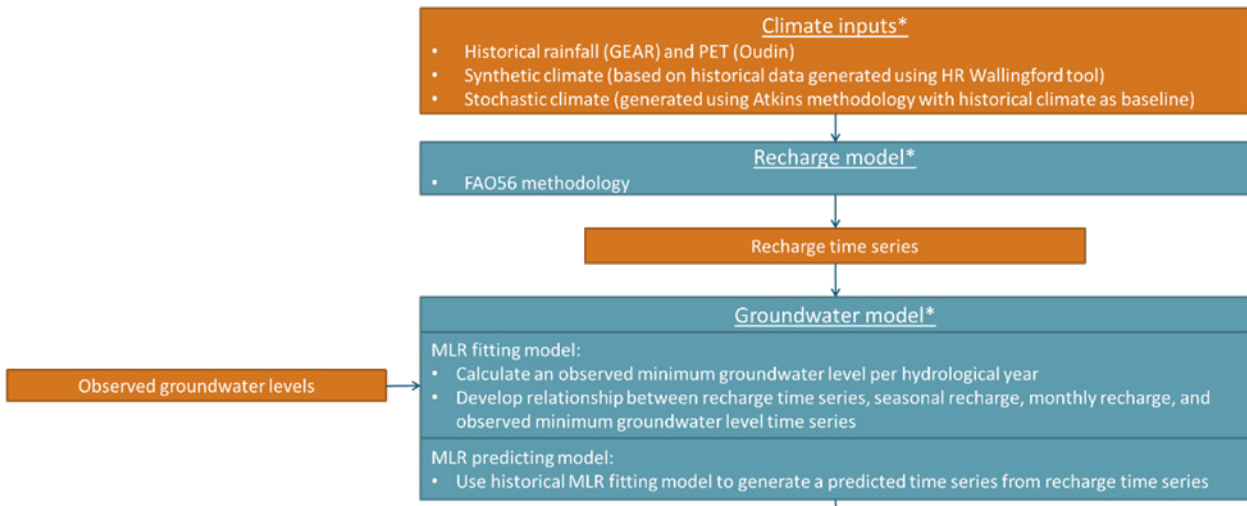


Figure 3.9: Overview of modelling methodology

### 3.4.8 Kestrel-IHM

**Type of model:** Semi-distributed groundwater flow model.

**Description:** Kestrel is a modelling framework developed by HR Wallingford via internal research funding. It consists of various modules which can be used in an integrated or independent way. The key modules are the Integrate Hydrological Model (Kestrel-IHM) and the Water Resources Model (Kestrel-WRM).

It is a computationally efficient rainfall-runoff model, incorporating multiple alternative conceptual process models and allows for spatially coherent flows to be generated across a catchment, processing abstractions and discharges spatially within the model thus enabling the impacts on individual surface water and groundwater bodies to be undertaken. The model represents groundwater as a group of aquifer response units (Figure 3.10), enabling the contributions from the underlying aquifers to be represented, but in a relatively simple manner compared to a distributed groundwater model.

**Application:** Similar to the statistical groundwater model, Kestrel-IHM has been widely applied to water resources management plans in the UK (Thames Water - UK; 2018, 2019).

**Advantages and Limitations:** Kestrel-IHM is a hydrological model that represent aquifer as "blocks", single units that do not interact between them, which is a very simplified representation of a groundwater system. The use of this modelling approach would require further code development to be adapted to this project, which limits its immediate availability and would generate time constraints.

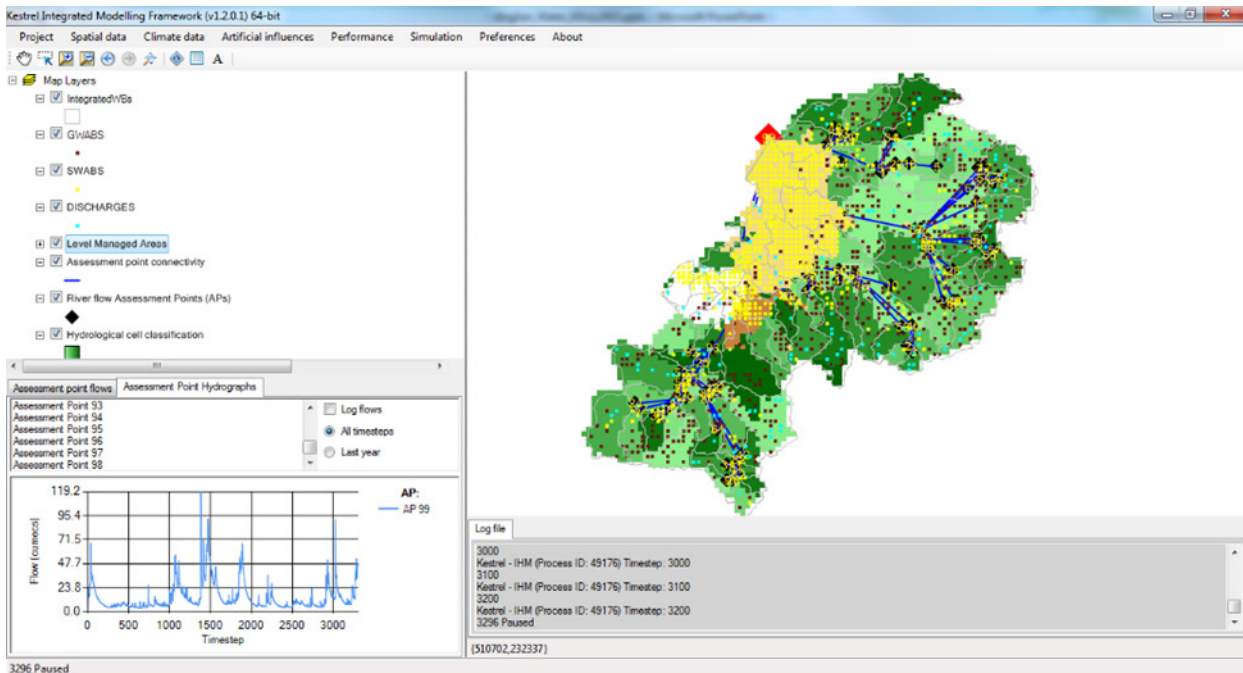


Figure 3.10: Example of the application of Kestrel-IHM to UK water resources

## 4 Discussion

### 4.1 The potential place of groundwater within drought early warning systems

When a drought occurs, there is a need to know who is affected and where water can be found and used. Drought forecasting indicators have been developed to assess different components of the hydrological cycle. The most common parameters used are precipitation, soil moisture and vegetation-related indexes. As noted from Section 3, very few operational drought early warning systems exist, where hydrological forecasting is considered. As for groundwater, even if it is considered as an indicator for hydrological drought it is often not taken into consideration when modelling tools are applied, even for highly groundwater-dependent regions. In reality though, during an emergency, groundwater is often considered as the de facto water supply.

Groundwater is often regarded as a reliable resource even if it remains poorly understood and managed. In certain countries, the lack of reliable groundwater monitoring systems, and technical capacity is causing this resource to be overlooked and not explored, though used for water supply purposes. In other countries (including St Kitts and Nevis), despite the availability of some groundwater data, gaps remain in translating monitoring data into information relevant to end-users, and in identifying groundwater impacts and interlinkages with the socio-economic and ecological systems<sup>53</sup>.

The poor understanding of groundwater systems and associated impacts exclude the possibility of integration within on-going drought early warning systems, and this is evident from the models that underpin the drought monitoring and forecasting systems described in Section 2.

In Saint Kitts and Nevis, assessing groundwater resources is crucial to determine groundwater potential for drought mitigation. Anticipation of groundwater impacts and groundwater potential are key to identify

<sup>53</sup> <https://www.un-igrac.org/stories/early-warning-systems-are-only-good-actions-they-catalyse>

possibilities for the local communities and to improve drought early action. The effectiveness of any early warning system does not rely solely on forecasting but also on the actions the forecasts catalyse.

## 4.2 Selection of model for the St Kitts and Nevis drought forecasting system

There are challenges for monitoring drought, hydrological and groundwater modeling in Saint Kitts and Nevis: complex climate dynamics near the equator, diverse topography, and lack of dense in-situ hydrological and meteorological data. In particular, soil moisture measurements are absent. This is especially problematic for the Caribbean region where water information is arguably most needed, but virtually non-existent on the ground.

With the emergence of remote sensing estimates of all components of the water cycle there is now the potential to monitor the full terrestrial water cycle from space to give global coverage and provide the basis for drought monitoring. These estimates include precipitation, evapotranspiration, temperature and vegetation data, changes in water storage, soil moisture and estimates of lake levels and river flows. However, many challenges remain in using these data, especially due to biases in individual satellite retrieved components, their incomplete sampling in time and space, and their failure to provide budget closure in concert.

A way forward is to use modeling to provide a framework to merge these disparate sources of information to give physically consistent and spatially and temporally continuous estimates of the water cycle and drought.

The VIC AMBHAS model has been selected for this application. The VIC AMBHAS model is a version of VIC that includes the AMBHAS groundwater model extension. VIC is a physically based distributed hydrological model that simulates water and energy fluxes based on the hydrological process of mutual interactions among the atmosphere, vegetation and soil. It was originally developed as a land surface model, but it has mostly been used as a stand-alone hydrological model. Whilst land surface models focus on the vertical exchange of water and energy between the land surface and the atmosphere, hydrological models focus on the lateral movement and availability of water. By combining these two approaches, VIC simulations are strongly process based; this provides a good basis for climate-impact modelling. AMBHAS is a 2D lateral groundwater model. VIC calculates a groundwater recharge as a function of soil moisture and water table depth and passes this into AMBHAS. AMBHAS calculates lateral groundwater flow, groundwater baseflow and interacts with the land surface. AMBHAS feeds back the water table depth and groundwater baseflow to VIC.

The system we will develop, will rely on satellite data to drive the VIC AMBHAS model to provide near real-time estimates of precipitation, evapotranspiration, soil moisture, runoff and groundwater levels. Drought is defined in terms of anomalies of hydrologic variables relative to a long-term climatology.

This model was selected for use due to following main advantages:

1. It is a simple conceptual rainfall–runoff model that allows the spatial representation of gridded topography, infiltration rate, soil properties, climate variables, and land cover, which are important factors in modeling runoff under spatially heterogeneous conditions (Tesemma et al., 2015<sup>54</sup>);
2. It includes both infiltration and saturation excess runoff generation mechanisms, making it suitable for application to both arid and humid areas;
3. It can be conveniently and directly linked to a meteorological models or their outputs (in this case seasonal forecasting model outputs) and allows for the use of a variety of spatial resolutions for different applications;

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<sup>54</sup> Tesemma, Z. K., Wei, Y., Peel, M. C., and Western, A. W.: The effect of year-to-year variability of leaf area index on Variable Infiltration Capacity model performance and simulation of runoff, *Advances in Water Resources*, 83, 310-322, 2015.

4. One of the advantages of using VIC AMBHAS, as opposed to other hydrological or groundwater models, is that it is considering the energy balance (apart from just the water balance), which is crucial in simulating the alteration of land surface energy partitioning due to human activities such as irrigation (Ozdogan et al., 2010<sup>55</sup>; Pokhrel et al., 2012<sup>56</sup>), and consequently to understand its climate impact (e.g., Lo and Famiglietti, 2013<sup>57</sup>; Sorooshian et al., 2014<sup>58</sup>). Furthermore, models that include the energy balance are also suitable for coupling with agronomy-based crop models to dynamically simulate the changes in crop growth and productivity, including stage-dependent heat stress change under climate change (e.g., Osborne et al., 2015<sup>59</sup>). Although this is not part of the current project, it may be of interest for future work.

As mentioned in Section 4.4.1, VIC has been extensively used to evaluate drought conditions over many river basins around the world, to assess retrospective droughts<sup>60 61</sup>, to evaluate drought under a future climate<sup>62 63</sup>, and to forecast over short-term periods<sup>64 65 66</sup>. It is one of the most widely used hydrological models. It has been used in studies such as coupled regional climate model simulations (Zhu et al., 2009<sup>67</sup>; Hamman et al., 2016<sup>68</sup>), combined river streamflow and water temperature simulations (van Vliet et al., 2016<sup>69</sup>), hydrological sensitivity to climate change research (Hamlet and Lettenmaier, 1999<sup>70</sup>; Nijssen et al., 2001a<sup>71</sup>; Chegwiddden et al., 2019), streamflow simulations (Nijssen et al., 2001b<sup>72</sup>), flow regulation and

<sup>55</sup> Ozdogan, M., Rodell, M., Beaudoin, H. K., and Toll, D. L.: Simulating the Effects of Irrigation over the United States in a Land Surface Model Based on Satellite-Derived Agricultural Data, *Journal of Hydrometeorology*, 11, 171-184, doi:10.1175/2009JHM1116.1, 2010.

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<sup>63</sup> Mishra, A.K.; Singh, V.P. A review of drought concepts. *J. Hydrol.* **2010**, 391, 202–216.

<sup>64</sup> Luo, L.; Wood, E.F. Monitoring and predicting the 2007 US drought. *Geophys. Res. Lett.* **2007**, 34.

<sup>65</sup> Wood, E.F.; Chaney, N.; Sheffield, J.; Yuan, X. Development of an Experimental African Drought Monitoring and Seasonal Forecasting System: A First Step Towards a Global Drought Information System. In *AGU Fall Meeting Abstracts; American Geophysical Union: Washington, DC, USA*, 2012.

<sup>66</sup> Sheffield, J.; Wood, E.F.; Chaney, N.; Guan, K.; Sadri, S.; Yuan, X.; Olang, L.; Amani, A.; Ali, A.; Demuth, S.; et al. A drought monitoring and forecasting system for sub-Saharan Africa water resources and food security. *Bull. Am. Meteorol. Soc.* **2014**, 95, 861–882.

<sup>67</sup> Zhu, C. M., Leung, L. R., Gochis, D., Qian, Y., and Lettenmaier, D. P.: Evaluating the Influence of Antecedent Soil Moisture on Variability of the North American Monsoon Precipitation in the Coupled MM5/VIC Modeling System, *J. Adv. Model. Earth. Sy.*, 1, 13, <https://doi.org/10.3894/James.2009.1.13>, 2009.

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redistribution research (Voisin et al., 2018<sup>73</sup>; Zhou et al., 2018<sup>74</sup>), and most importantly real-time drought forecasting (Wood and Lettenmaier, 2006<sup>75</sup>; Mo, 2008<sup>76</sup>, Sheffield et al., 2014<sup>77</sup>).

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<sup>74</sup> Zhou, T., Voisin, N., Leng, G. Y., Huang, M. Y., and Kraucunas, I.: Sensitivity of Regulated Flow Regimes to Climate Change in the Western United States, *J. Hydrometeorol.*, 19, 499–515, <https://doi.org/10.1175/Jhm-D-17-0095.1>, 2018.

<sup>75</sup> Wood, A. W. and Lettenmaier, D. P.: A test bed for new seasonal hydrologic forecasting approaches in the western United States, *B. Am. Meteorol. Soc.*, 87, 1699–1712, <https://doi.org/10.1175/Bams-87-12-1699>, 2006.

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Table 4.1: High-level outputs of the review of models considered for the drought forecasting system

| Model name      | Incorporates groundwater<br>Yes =1<br>No = 0 |     | Suitable for areas with a paucity of hydrogeological data<br>Yes =1<br>No = 0 |     | Can be web-based<br>Yes =1<br>No = 0 |     | Can provide groundwater levels<br>Yes =1<br>No = 0 |    | Can be linked to a weather forecast<br>Yes =1<br>No = 0 |  | Can be linked to EO data<br>Yes =1<br>No = 0 |  | Complex<br>High = -1<br>Med = 0<br>Low = 1 |     | Provide desired outputs directly (Table 3.1)<br>Yes =1<br>No = 0 |  | Score (max 7) | Comments   |
|-----------------|--|-----|---|-----|--------------------------------------|-----|--|----|---|--|--|--|--|-----|--|--|---------------|--|
| VIC             | Yes  |     | Yes   |     | Yes                                  |     | Yes  |    | Yes   |  | Yes  |  | Medium                                     | Yes |  |  | 8             | This is our preferred model. It is widely used for forecasting, and meets all the other criteria. Whilst complex to set up, this will be undertaken by HR Wallingford, and hydrological updates are then straightforward.  |
| MODFLOW         | Yes  |     | No  |     | Yes                                  |     | Yes  |    | Yes   |  | Yes  |  | High                                       | No  |  |  | 4             | Whilst this is a benchmark groundwater model, a previous model in St Kitts was not maintained due to its complexity and the lack of hydrogeological data on both Islands make this an unsuitable choice. It will need to be linked to a recharge model to provide the desired outputs.                 |
| Aquimod         | Yes  | No  | No  | Yes | No                                   | No  | Low  | No |   |  |  |  |  |     |  |  | 3             | Simple lumped model that needs data for each individual borehole in the catchment that is modelled. It will not provide the desired outputs for the drought assessment tool.   |
| GISGround-water | Yes  | Yes | No  | Yes | No                                   | No  | Low  | No |   |  |  |  |  |     |  |  | 4             | This would be useful for non-experts in groundwater modelling but will not generate the outputs required for the tool compared to other more complex semi-distributed or distributed models. And although it is relatively easy to use, it needs ArcGIS, which is not openly accessible to the public. |
| ZOOMQ3D         | Yes  | No  | No  | Yes | No                                   | No  | Medium   | No |   |  |  |  |  |     |  |  | 4             | It will also need an independent recharge modelling effort to use in conjunction with the groundwater model and will not be able to provide the set of outputs needed for the tool.  |
| BGS GW          | Yes  | Yes | No  | Yes | No                                   | Yes | Medium   | No |   |  |  |  |  |     |  |  | 4             | This model has not been tested on a wider scale. It will also need a recharge model input to the model, and with the current version, it will not provide the needed outputs for the tool.   |

| Model name                     | Incorporates groundwater<br>Yes =1<br>No = 0 | Suitable for areas with a paucity of hydrogeological data<br>Yes =1<br>No = 0 | Can be web-based<br>Yes =1<br>No = 0 | Can provide groundwater levels<br>Yes =1<br>No = 0 | Can be linked to a weather forecast<br>Yes =1<br>No = 0 | Can be linked to EO data<br>Yes =1<br>No = 0 | Complex<br>High = -1<br>Med = 0<br>Low = 1 | Provide desired outputs directly (Table 3.1)<br>Yes =1<br>No = 0 | Score (max 7) | Comments  |
|--------------------------------|--|---|--------------------------------------|--|---|--|--|--|---------------|---|
| Statistical Ground-water Model | Yes  | Yes   | No                                   | Yes  | No  | No   | Low  | No   | 3             | This methodology, although widely applied for UK groundwater assessment, will not provide the desired outputs for the drought assessment tool.  |
| Kestrel                        | Yes  | Yes   | Yes                                  | Yes  | Yes   | Not directly                                 | High                                       | No   | 4             | The use of this modelling approach would require further code development to be adapted to this project, which limits its immediate availability and would generate time constraints. |



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HR Wallingford Ltd, Howbery Park, Wallingford, Oxfordshire OX10 8BA, United Kingdom  
Tel +44 (0)1491 835381, email [info@hrwallingford.com](mailto:info@hrwallingford.com)  
[www.hrwallingford.com](http://www.hrwallingford.com)