Xanthos is an open-source hydrologic model, written in Python, designed to quantify and analyse global water availability. Xanthos simulates historical and future global water availability on a monthly time step at a spatial resolution of 0.5 geographic degrees. Xanthos was designed to be extensible and used by scientists that study global water supply and work with the Global Change Assessment Model (GCAM). Xanthos uses a user-defined configuration file to specify model inputs, outputs and parameters. Xanthos has been tested using actual global data sets and the model is able to provide historical observations and future estimates of renewable freshwater resources in the form of total runoff.

Keywords: Water Balance Model; Global Hydrologic Model; Runoff; River Routing; Potential Evapotranspiration (PET); Global Change Assessment Model (GCAM); Python

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(1) Overview

Introduction
Xanthos is an open-source hydrologic model written in Python, designed to quantify and analyse global water availability. Xanthos was developed at the Joint Global Change Research Institute of the Pacific Northwest National Laboratory (http://www.globalchange.umd.edu). The main objective of the model is to quantify changes in future freshwater availability under various climate change regimes, and to serve as the freshwater supply component of the Global Change Assessment Model (GCAM) [1–3]. The model has been used in previous publications to explore different climate and socioeconomic scenarios over the 21st century and assess the influence and implications of the different scenarios on regional and global water availability [4–5].

The core of Xanthos is a hydrologic model that includes modules for calculating potential evapotranspiration (PET), runoff generation, and river routing (Figure 1). The underlying equations and algorithms for the hydrologic model are described in details in Hejazi et al. [4], and Zhou et al. [7]. The model requires inputs of gridded monthly temperature and precipitation, a maximum soil water storage capacity map (assumed static over time). Using those inputs, the model calculates gridded monthly runoff, PET, actual evapotranspiration, water storage in the soil column, channel water storage, and average channel flow.

The PET module uses the Hargreaves method [6], which requires average monthly temperature and average daily temperature range in degree Celsius. The stream routing module includes a cell-to-cell river routing scheme adopted from the modified river transport model (RTM), which uses a linear advection formula [7]. The aggregation module of Xanthos provides estimates of maximum naturally-available water fluxes (mm) or volumes (billion m$^3$) monthly or annually (i.e., total monthly runoff) for each river basin. Xanthos includes an option to obtain the annual volumes (billion m$^3$/year) of renewable water resources that are accessible for human use in each basin [8], which is calculated by the accessible-water module.

Xanthos can be applied as an independent model as well as serve as the water supply component in the GCAM. The primary goals of Xanthos are:

1. Be distributed as an open-source software that can be utilized and extended by researchers who study global hydrology.
2. Make estimates of global runoff, average channel flow, actual evapotranspiration, and water storage in the soil column on a monthly time step at a spatial resolution of 0.5 geographic degrees.
3. Employ a standardized configuration and simplified input structure that is easy for the user to update.
4. Direct diagnostics on the runoff results.
To achieve the above goals, Python was selected as the programming language because of its ease of use and extensibility.

**Implementation and Architecture**

The main inputs used by Xanthos are global gridded maps of monthly climate data and common map data including basin, country and region information. The spatial resolution of the global gridded data maps is 0.5 geographic degrees. These global gridded data maps contain a total of 259,200 grid cells (360 × 720) of which 67,420 grid cells are categorized at “land grids” and are considered valid for modelling purposes. The valid grid cells are used to define a “gridded” map according to the coordinates listed in the coordinate file in the input folder. The coordinate file, including the coordinates and the indexes of the 67,420 cells on the 360 × 720 grid, is used to convert a 2D map data into a 1D vector and vice versa. To aggregate the gridded data into basin/country/region scale for outputs and diagnostics, certain commonly used global data maps such as IDs of basins/countries/regions are harmonized into the gridded format required by Xanthos. The inputs converted using the 67,420 grid cells according to the coordinate data file are called harmonized inputs.

The flowchart of Xanthos is illustrated in **Figure 2** and **Figure 3** shows the overall architecture of Xanthos. The PET calculation, runoff generation, and river routing are the core components of the hydrologic model. The gridded input files required by Xanthos can be divided into two classes, 1) monthly climate data and 2) static global maps and hydrologically related data. Xanthos majorly consists of four module packages:

1. DataReader: Configuration (class “ConfigSettings”) and import inputs (“DataLoad” module) according to user defined INI file (“IniReader” module).
2. DataWriter: Export outputs (“OUTWriter” module) by options.
3. Diagnostics: Aggregate gridded runoff results at basin/country/region scales (“Aggregation” module), perform diagnostics (“Diagnostics” module), or create time series plots (“TimeSeries” module) by options.
4. RunoffStreamGen: Calculate PET (“PETCalculation” module), calculate runoff (“RunoffGen” module) and river routing (“StreamRouting” module) using monthly water balance model, calculate accessible water (“Accessible” module).

Xanthos can be executed in either historical or future mode. For the historical mode, the climate forcing data is taken from a historical time period (e.g. data before year 2005). As for the future mode, initial soil moisture and channel storage conditions can be taken either from
a historical case calculated by Xanthos or from other models, and the climate forcing data is for future years (e.g. 2006–2100). Xanthos allows the spin-up (model initiation by using the results from the first few years) phase by setting the years for the spin-up time.

The default outputs from the model are monthly gridded total runoff, average channel flow, potential evapotranspiration, actual evapotranspiration, and channel storage, and water storage in soil column. There are several options to output the gridded results. The default unit for these five outputs is mm/month formatted as classic NetCDF file. The alternative output format is CSV (comma-separated values). Another optional unit is billion m$^3$/month. In addition to monthly output results, there is an option for annually output results. In historical mode, two more outputs will be saved, monthly soil column moisture (mm/month) and monthly channel storage (m$^3$/month). These two files will be served as initialization data for future mode. Optional outputs include: 1) aggregated runoff by basin, country or region; 2) time series plots of runoff and average channel flow by basin, country or region; 3) runoff comparisons with other models (diagnostics, described in “Quality Control”); and 4) accessible water.

“GCAM_Hydro.py” defines the main function that integrates all the modules shown in Figure 2. “test.py” is the executable Python file connecting “config.ini” and “GCAM_Hydro.py”. A model simulation can be executed with a single command:

```
$ python test.py
```

To simplify the model run process, all the input data files are located in a separate folder from the code folders. The input folder contains:

1. Climate data files are the major user controlled inputs. There are three classic NetCDF files; 1) precipitation, 2) temperature and 3) daily maximum temperature range. Each climate data file has a size of 67,420 rows and NM (total number of months, for example, for year 1996–2005, NM = 10*12 = 120) columns.
2. Harmonized gridded global data maps and other required parameter data files required, which can be modified or replaced by the user.
3. Example data files of other models for comparison in diagnostics.
4. Example data files for accessible water.

The metadata (data source, format, related pre-processing, etc.) of all the input files are described in a document called “ReadMe_Input_Data.txt” included in the input folder.

The interface between the user and Xanthos is a configuration file, i.e., “config.ini”. One simulation requires

![Flowchart of Xanthos](image-url)
a unique configuration file. The configuration file is an INI file that is organized into six separate sections, each of which contains a few of setting parameters. The six sections are:

1. **Project (Required):** defines the major settings such as the paths of input and output folders, the output formatting, options for aggregated runoff results, an option for diagnostics, an option for time series plot, and an option for calculation of accessible water.

2. **Climate (Required):** defines the historical/future mode, paths of input climate forcing data – precipitation, temperature and daily temperature range files, and an option for initialization.

3. **GriddedMap (Required):** defines the required data maps, such as coordinates of the grids, maximum soil moisture of each grid, ID of basin/country/region for each grid.

4. **Diagnostics (Required only if “PerformDiagnostics = 1” in section 1):** defines the paths of the data files from other models (example models are described in “Quality Control” section), and the options for comparison at basin, country or region scale.

5. **TimeSeriesPlot (Required only if “CreateTimeSeriesPlot = 1” in section 1):** defines the scale for plots and the selected basin/country/region to be used for generating the plots.

6. **AccessibleWater (Required only if “CalculateAccessibleWater = 1” in section 1):** defines all the related parameters to the calculation of accessible water, such as the total reservoir capacity at basin level, and a baseflow index file.

Section 4, 5 and 6 are optional responding to the flags defined in Section 1. Default data files for inputs are included in the input folder. An output folder will be automatically generated at the path defined in the configuration file.

Xanthos was developed using Python\(^1\) (version 2.7) and related scientific libraries. NumPy\(^2\) and SciPy\(^3\) are the fundamental packages for scientific computing data processing. Matplotlib\(^4\) is a library used for 2D plotting of timer series plots and scatter plots from diagnostics. Pandas\(^5\) was used in accessible water module for data analysis. The results are able to be saved into two formats: CSV and classic NetCDF (Version 3). Classic NetCDF\(^6\) is a self-describing, machine-independent data formats for array-oriented scientific data which requires much smaller storage space [14]. By default, the input climate data files should be stored as classic NetCDF files, but they can also be stored as mat (MATLAB\(^7\) formatted) files if needed. The mat files can be read and write by input/output modules of SciPy.

**Quality Control**

This hydrologic model was tested by using different climate forcing datasets. Its ability to reproduce historical values is evaluated against observations, statistical assessments and other global hydrologic models (Figures S3 and S4 in the Supplement of [4]). The testing was completed using different operating systems: Linux Windows and Mac. To help the user get familiar with the features and functions of Xanthos, two example test cases were included with the input climate data files:

1. **Test case for a historical run of 10 years (1996–2005)** with options for aggregation, diagnostics, accessible water and time series plots, turned on. The configuration file is “config_hist.ini” and the outputs are saved in the folder of “Test_Case_Hist” (Figure 3).

2. **Test case for a future run of 15 years (2006–2020)** with the initial channel storage and soil moisture data taken from the ending values of test case A and with basic options. The configuration file is “config_futu.ini” and the outputs are saved in the folder of “Test_Case_Futu” (Figure 3).

By changing the name of the configuration file (line 19 in “test.py”), the use is able to run a certain case.

An automatically generated log file provides details of each model run. The log file lists model settings, the processing steps, and CPU cost and warnings if applicable. The log file will record each step and indicate if the model run successfully. For example, if the hydrologic simulation finished successfully, “-----Simulation has finished successfully......” will be printed into log file. When the model runs through to the end, a message will be printed. An example is:

```
# Hydrologic Model total time: 361.753000021 seconds
End of Test_Case_Futu
```

![Figure 3: The architecture of Xanthos in application.](image-url)
When the model does not run successfully, errors and warnings will be recorded in the log file. Same information will also be printed in the Python console.

The diagnostics module provides another option for the user to examine the quality of the model results of runoff. It compares the runoff results by basin scale, country scale or region scale to data sets of other models, such as the Variable Infiltration Capacity (VIC) model [9], Water Balance Model (WBM) and Water Balance Model Composite (WBMc) [10], UNH/GRDC [11–12]. Figure 4 is a scatter plot that shows an example of the plots created by the diagnostics module. If the points are below the “x = y” line, the model overestimated the runoff compared to the four models (VIC, WBM, WBMc and UNH/GRDC), and if the points are above the “x = y” line then the model underestimated the model runoff. The gridded streamflow outputs are not regulated streamflow results. They are not suitable for direct comparison with other model results (e.g. Dai’s results [13]), and are not included in diagnostics.

Xanthos is a pure python code. The user is recommended to use other tools to manage the run of Xanthos.

The modules were tested with Anaconda 2.3.0 (64-bit) on Linux.

The modules were tested using an open-source desktop Python IDE (PyDev for Eclipse) on Windows.

**Dependencies**

All the listed dependencies can be obtained by using the Python’s tool for installing packages called pip (https://pypi.python.org/pypi/pip).

- NumPy (version 1.11)
- Scipy (version 0.18)
- Matplotlib (version 2.0)
- Pandas (version 0.19)
- configobj (version 5.0.6)

**Software location**

**Archive**

Name: GitHub

Persistent identifier: https://github.com/JGCRI/xanthos/releases/tag/v1.0.0

**Licence**: BSD 2-Clause

**Publisher**: Chris R Vernon

**Version published**: v1.0.0

**Date published**: 02/08/2017

**Code repository**

Name: GitHub

Identifier: https://github.com/JGCRI/xanthos

License: BSD 2-Clause (https://github.com/JGCRI/xanthos/blob/master/LICENSE)

**Date published**: 30/05/2017
(3) Reuse potential

The Python language and the dependent library packages used are all open-source. Xanthos is highly modularized and most of the modules can be used independently by the user. The independence of the modules ensures the future development and feasibility of user contribution. For example, the current PET calculation is based on Hargreaves method. "PETCalculation" as a module can be imported into other programs to calculate monthly PET or can be replaced by the user using other methods to calculate monthly PET. Another example is the module package "DataReader", that can be utilized by the user independently to import the included input data file for other applications.

Modification of a certain step could be restricted to the corresponding module. Extension of the model is achievable by adding a new module to an existing sub-folder or a new sub-folder. Documentation is organized through intensive comments inside the python code and the example configuration file. Execution will also produce a detailed log file lists model settings, the example configuration file. Execution will also produce a detailed log file lists model settings, the example configuration file. Execution will also produce a detailed log file lists model settings, the example configuration file. Execution will also produce a detailed log file lists model settings, the example configuration file. Execution will also produce a detailed log file lists model settings, the example configuration file. Execution will also produce a detailed log file lists model settings, the example configuration file. Execution will also produce a detailed log file lists model settings, the example configuration file. Execution will also produce a detailed log file lists model settings, the example configuration file. Execution will also produce a detailed log file lists model settings, the example configuration file. Execution will also produce a detailed log file lists model settings, the example configuration file. Execution will also produce a detailed log file lists model settings, the example configuration file. Execution will also produce a detailed log file lists model settings, the example configuration file.

Xanthos is built as a part of an integrated modelling software for global water demand, supply, and scarcity, which the authors’ team is continuing to develop.

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