Spatially Explicit Integrated Modeling System (SEIMS)

User Manual

Version alpha-0.2

Liang-Jun Zhu, Junzhi Liu, Cheng-Zhi Qin, A-Xing Zhu

02/10/2019

State Key Lab of Resources and Environmental Information System,
Institute of Geographic Sciences and Natural Resources Research,
China Academy of Science, Beijing, 100101, China

Key Laboratory of Virtual Geographic Environment (Nanjing Normal University),
Ministry of Education, Nanjing 210023, China

Department of Geography, University of Wisconsin-Madison, Madison, WI 53706, USA

This page is intentionally left blank.

Table of Contents

List of Figures

List of Tables

Section 1. Introduction

This section is a brief introduction of the SEIMS (short for Spatially Explicit Integrated Modeling System). In the current pre-released version, this section is not yet finished. Please refer to Zhu et al. (Environ. Model. Softw., under review) for more information.

1:1. What is SEIMS?

SEIMS (Spatially Explicit Integrated Modeling System) is an integrated, modular, parallelized, fully-distributed watershed modeling system, which is also designed for scenario analysis, especially for evaluating and optimizing BMP scenarios.

SEIMS can be used to build a specific watershed model of a single watershed for long-term or storm-event simulation. Multiple watershed processes could be considered, e.g., hydrological processes, soil erosion, nutrient cycling, and plant growth.

- SEIMS is a fully-distributed watershed modeling system, in which grid cells with hydrological connection are used as basic simulation units within each subbasin. Support for using irregularly shaped fields, such as hydrologic response units (Arnold et al., 1998) and patches (Tague and Band, 2004), as basic simulation units is under development.
- SEIMS is a multiple watershed processes integrated modular system, to which model developers could easily add their own modules (algorithms) of hydrology, soil erosion, nutrient cycling, plant growth, and BMP management, etc.
- SEIMS is a parallelized modeling system, which takes fully use of the parallelizability at both the subbasin level and the basic simulation unit level (e.g., grid cell) simultaneously. Developers can easily implement parallelized watershed model in a nearly serial programming manner.
- SEIMS is a configurable watershed modeling system, in which users can easily specify their modules, and outputs.
- SEIMS is developed by C++ with the support of GDAL, mongo-c-driver, OpenMP and MPI libraries. Python is used to organize various workflows as utility tools, e.g., preprocessing, post-processing, parameter sensitivity analysis, auto-calibration, and scenario analysis. SEIMS can be compiled by common used C++ compiler (e.g. MSVC 2010+, GCC4.6+, Intel C++ 12+, and Clang 8.0+) and run on multiple parallel computing platforms (e.g., multi-core computer, and symmetric multiprocessing (SMP) clusters).
- SEIMS, which uses several open source technologies (e.g., GDAL, mongo-c-driver), is also open-sourced at Github (https://github.com/lreis2415/SEIMS).

1:1.1 Key procedures

The following points are commonly used procedures to build a watershed model and perform scenario analysis based on SEIMS. The details of each procedures will be elaborated in “Section 2 Get started”.

- *Install the prerequisite software and libraries*
- *Download and install SEIMS*
- *Prepare data (climate, spatial, and observations, etc.) of the study area*
- *Build database for SEIMS-based model by data preprocessing scripts*

- *Set up a SEIMS-based model according to model objectives and run model*
- *Postprocessing, e.g., analyze, plot and graph outputs*
- *(Optional) Parameter sensitivity analysis*
- *(Optional) Automatic calibration*
- *(Optional) Scenario analysis, e.g., BMP scenarios optimization for reducing soil erosion*

1:1.2 Publications

1:1.2.1 Watershed modeling framework

Zhu, L.-J., Liu, J., Qin, C.-Z., Zhu, A-X., **2019**. A modular and parallelized watershed modeling framework. *Environmental Modelling & Software* (*under review*).

Liu, J., Zhu, A-X., Qin, C.-Z., Wu, H., Jiang, J., **2016**. A two-level parallelization method for distributed hydrological models. *Environmental Modelling & Software* 80, 175–184. doi: 10.1016/j.envsoft.2016.02.032

Liu, J., Zhu, A-X., Liu, Y., Zhu, T., Qin, C.-Z., **2014**. A layered approach to parallel computing for spatially distributed hydrological modeling. *Environmental Modelling & Software* 51, 221–227. doi: 10.1016/j.envsoft.2013.10.005

Liu, J., Zhu, A-X., Qin, C.-Z., **2013**. Estimation of theoretical maximum speedup ratio for parallel computing of grid-based distributed hydrological models. *Computers & Geosciences* 60, 58–62. doi: 10.1016/j.cageo.2013.04.030

1:1.2.2 BMPs scenario analysis

Zhu, L.-J., Qin, C.-Z., Zhu, A-X., Liu, J., Wu, H., **2019**. Effects of different spatial configuration units for spatial optimization of watershed best management practices scenarios. *Water* 11(2), 262. doi: 10.3390/w11020262

Qin, C.-Z., Gao, H.-R., Zhu, L.-J., Zhu, A-X., Liu, J.-Z., Wu, H., **2018**. Spatial optimization of watershed best management practices based on slope position units. *Journal of Soil and Water Conservation* 73(5), 504–517. doi: 10.2489/jswc.73.5.504

Wu, H., Zhu, A-X., Liu, J., Liu, Y., Jiang, J., **2018**. Best Management Practices Optimization at Watershed Scale: Incorporating Spatial Topology among Fields. *Water Resource Management* 32, 155–177. doi: 10.1007/s11269-017-1801-8

Wu, H., Liu, Y., Liu, J., Zhu, A-X., **2014**. Representation of Agricultural Best Management Practices in a Fully Distributed Hydrologic Model: A Case Study in the Luoyugou Watershed. *Journal of Resources and Ecology* 5(2), 179–184. doi: 10.5814/j.issn.1674-764X.2014.02.011

1:1.3 Support

SEIMS is an open source software. Support is provided through the Github issues and Email of developers.

- SEIMS issues: https://github.com/lreis2415/SEIMS/issues

- Emails of developers:
  - Dr. Liang-Jun Zhu (zlj@lreis.ac.cn)
  - Dr. Junzhi Liu (liujunzhi@njnu.edu.cn)

1:2. Why SEIMS?

In the current pre-released version, this part is not yet written, please refers to Zhu et al. (Environ. Model. Softw., under review) to get the necessary information.

1:3. Terminology

SEIMS Main Program – The executable program (`seims_mpi` for MPI&OpenMP version, `seims_omp` for OpenMP version or `seims` for serial version) which would read all configuration files, load all configured modules and input data (includes climate, spatial data, and management data, etc.), and outputs specified outputs.

SEIMS Module – A dynamic link library file (i.e., `.dll` on Windows, `.so` on Unix-like systems, or `.dylib` on macOS) file which follows SEIMS module APIs and could be loaded by SEIMS main program. A SEIMS module is corresponding to one watershed subprocess.

SEIMS-based watershed model – A SEIMS-based watershed model consists of one version of SEIMS main program (i.e., OpenMP version or MPI&OpenMP version), several customized SEIMS modules, and the watershed database. A SEIMS-based watershed model is prepared as a folder (e.g., `demo_youwuzhen30m_longterm_model`) which consists of several SEIMS configuration files, e.g., the `config.fig` file designed to define the selected SEIMS modules and the execution orders during the simulation of the watershed model.

1:4. References

Abbaspour, K.C., Rouholahnejad, E., Vaghefi, S., Srinivasan, R., Yang, H., Kløve, B., 2015. A continental-scale hydrology and water quality model for Europe: Calibration and uncertainty of a high-resolution large-scale SWAT model. J. Hydrol. 524, 733–752. https://doi.org/10.1016/j.jhydrol.2015.03.027

Arnold, J.G., Moriasi, D.N., Gassman, P.W., Abbaspour, K.C., White, M.J., Srinivasan, R., Santhi, C., Harmel, R.D., Van Griensven, A., Van Liew, M.W., 2012. SWAT: Model use, calibration, and validation. Trans. ASABE 55, 1491–1508. https://doi.org/10.13031/2013.42256

Arnold, J.G., Srinivasan, R., Muttiah, R.S., Williams, J.R., 1998. Large area hydrologic modeling and assessment part I: Model development. J. Am. Water Resour. Assoc. JAWRA 34, 73–89. https://doi.org/10.1111/j.1752-1688.1998.tb05961.x

Band, L.E., Tague, C.L., Brun, S.E., Tenenbaum, D.E., Fernandes, R.A., 2000. Modelling watersheds as spatial object hierarchies: structure and dynamics. Trans. GIS 4, 181–196. https://doi.org/10.1111/1467-9671.00048

Bieger, K., Arnold, J.G., Rathjens, H., White, M.J., Bosch, D.D., Allen, P.M., Volk, M., Srinivasan, R., 2016. Introduction to SWAT+, A Completely Restructured Version of the Soil and Water Assessment Tool. J. Am. Water Resour. Assoc. JAWRA 53, 115–130. https://doi.org/10.1111/1752-1688.12482

Campolongo, F., Cariboni, J., Saltelli, A., 2007. An effective screening design for sensitivity analysis of large models. Environ. Model. Softw., Modelling, computer-assisted simulations, and mapping of dangerous phenomena for hazard assessment 22, 1509–1518. https://doi.org/10.1016/j.envsoft.2006.10.004

Chen, S., Zha, X., 2016. Evaluation of soil erosion vulnerability in the Zhuxi watershed, Fujian Province, China. Nat. Hazards 82, 1589–1607. https://doi.org/10.1007/s11069-016-2258-4

Chen, Z.-B., Z.-Q. Chen, and H. Yue. 2013. Comprehensive research on soil and water conservation in granite red soil region: A case study of Zhuxi watershed, Changting County, Fujian province. Beijing, Science Press. (*in Chinese*)

Clark, M.P., Bierkens, M.F.P., Samaniego, L., Woods, R.A., Uijlenhoet, R., Bennett, K.E., Pauwels, V.R.N., Cai, X., Wood, A.W., Peters-Lidard, C.D., 2017. The evolution of process-based hydrologic models: historical challenges and the collective quest for physical realism. Hydrol. Earth Syst. Sci. 21, 3427–3440. https://doi.org/10.5194/hess-21-3427-2017

Cukier, R.I., Levine, H.B., Shuler, K.E., 1978. Nonlinear sensitivity analysis of multiparameter model systems. J. Comput. Phys. 26, 1–42. https://doi.org/10.1016/0021-9991(78)90097-9

David, O., Ascough II, J.C., Lloyd, W., Green, T.R., Rojas, K.W., Leavesley, G.H., Ahuja, L.R., 2013. A software engineering perspective on environmental modeling framework design: The Object Modeling System. Environ. Model. Softw., Thematic

Issue on the Future of Integrated Modeling Science and Technology 39, 201–213. https://doi.org/10.1016/j.envsoft.2012.03.006

Deb, K., Pratap, A., Agarwal, S., Meyarivan, T., 2002. A fast and elitist multiobjective genetic algorithm: NSGA-II. IEEE Trans. Evol. Comput. 6, 182 – 197. https://doi.org/10.1109/4235.996017

Formetta, G., Antonello, A., Franceschi, S., David, O., Rigon, R., 2014. Hydrological modelling with components: A GIS-based open-source framework. Environ. Model. Softw. 55, 190–200. https://doi.org/10.1016/j.envsoft.2014.01.019

Foster, I., 1995. Designing and Building Parallel Programs: Concepts and Tools for Parallel Software Engineering. Addison-Wesley Longman Publishing Co., Inc., Boston, MA, USA.

Freeze, R.A., Harlan, R.L., 1969. Blueprint for a physically-based, digitally-simulated hydrologic response model. J. Hydrol. 9, 237–258. https://doi.org/10.1016/0022-1694(69)90020-1

Hill, C., DeLuca, C., Balaji, Suarez, M., Silva, A. da, 2004. The Architecture of the Earth System Modeling Framework. Comput. Sci. Eng. 6, 18–28. https://doi.org/10.1109/MCISE.2004.1255817

Hold-Geoffroy, Y., Gagnon, O., Parizeau, M., 2014. Once you SCOOP, no need to fork, in: Proceedings of the 2014 Annual Conference on Extreme Science and Engineering Discovery Environment. ACM, Atlanta, GA. https://doi.org/10.1145/2616498.2616565

Iman, R.L., Shortencarier, M.J., 1984. Fortran 77 program and user's guide for the generation of Latin hypercube and random samples for use with computer models (No. NUREG/CR-3624; SAND-83-2365). Sandia National Labs., Albuquerque, NM (USA). https://doi.org/10.2172/7091452

Karypis, G., Kumar, V., 1998. A Fast and High Quality Multilevel Scheme for Partitioning Irregular Graphs. SIAM J. Sci. Comput. 20, 359–392. https://doi.org/10.1137/S1064827595287997

Kneis, D., 2015. A lightweight framework for rapid development of object-based hydrological model engines. Environ. Model. Softw. 68, 110–121. https://doi.org/10.1016/j.envsoft.2015.02.009

Leavesley, G.H., Markstrom, S.L., Viger, R.J., 2006. USGS modular modeling system (MMS)--precipitation-runoff modeling system (PRMS), in: Singh, V.P., Frevert, D.K. (Eds.), Watershed Models. CRC Press, Boca Raton, FL., pp. 159–177.

Liu, J., Zhu, A.-X., Liu, Y., Zhu, T., Qin, C.-Z., 2014. A layered approach to parallel computing for spatially distributed hydrological modeling. Environ. Model. Softw. 51, 221–227. https://doi.org/10.1016/j.envsoft.2013.10.005

Liu, J., Zhu, A.-X., Qin, C.-Z., 2013. Estimation of theoretical maximum speedup ratio for parallel computing of grid-based distributed hydrological models. Comput. Geosci. 60, 58–62. https://doi.org/10.1016/j.cageo.2013.04.030

Liu, J., Zhu, A.-X., Qin, C.-Z., Wu, H., Jiang, J., 2016. A two-level parallelization method for distributed hydrological models. Environ. Model. Softw. 80, 175–184. https://doi.org/10.1016/j.envsoft.2016.02.032

Liu, Y.B., 2004. Development and application of a GIS-based distributed hydrological model for flood prediction and watershed management. Vrije Universiteit Brussel, Belgium.

Liu, Y.B., Gebremeskel, S., De Smedt, F., Hoffmann, L., Pfister, L., 2003. A diffusive transport approach for flow routing in GIS-based flood modeling. J. Hydrol. 283, 91–106. https://doi.org/10.1016/S0022-1694(03)00242-7

Maringanti, C., Chaubey, I., Popp, J., 2009. Development of a multiobjective optimization tool for the selection and placement of best management practices for nonpoint source pollution control. Water Resour. Res. 45, W06406. https://doi.org/10.1029/2008WR007094

Moore, R.V., Tindall, C.I., 2005. An overview of the open modelling interface and environment (the OpenMI). Environ. Sci. Policy, Research & Technology Integration in Support of the European Union Water Framework Directive 8, 279–286. https://doi.org/10.1016/j.envsci.2005.03.009

Moriasi, D.N., Arnold, J.G., Van Liew, M.W., Bingner, R.L., Harmel, R.D., Veith, T.L., 2007. Model evaluation guidelines for systematic quantification of accuracy in watershed simulations. Trans. ASABE 50, 885–900. https://doi.org/10.13031/2013.23153

Morris, M.D., 1991. Factorial Sampling Plans for Preliminary Computational Experiments. Technometrics 33, 161–174. https://doi.org/10.1080/00401706.1991.10484804

Neitsch, S.L., Arnold, J.G., Kiniry, J.R., Williams, J.R., 2011. Soil and Water Assessment Tool Theoretical Documentation, Version 2009. Texas A&M University System, College Station, Texas, USA.

O'Callaghan, J.F., Mark, D.M., 1984. The extraction of drainage networks from digital elevation data. Comput. Vis. Graph. Image Process. 28, 323–344. https://doi.org/10.1016/S0734-189X(84)80011-0

Peckham, S.D., Hutton, E.W.H., Norris, B., 2013. A component-based approach to integrated modeling in the geosciences: The design of CSDMS. Comput. Geosci., Modeling for Environmental Change 53, 3–12. https://doi.org/10.1016/j.cageo.2012.04.002

Qin, C.-Z., 2015. Cuda/GPU, in: Shekhar, S., Xiong, H., Zhou, X. (Eds.), Encyclopedia of GIS. Springer International Publishing, Cham, pp. 1–7. https://doi.org/10.1007/978-3-319-23519-6_1606-1

Qin, C.-Z., Gao, H.-R., Zhu, L.-J., Zhu, A.-X., Liu, J.-Z., Wu, H., 2018. Spatial optimization of watershed best management practices based on slope position units. J. Soil Water Conserv. 73, 504–517. https://doi.org/10.2489/jswc.73.5.504

Qin, C.-Z., Zhan, L.-J., Zhu, A.-X., Zhou, C.-H., 2014. A strategy for raster-based geocomputation under different parallel computing platforms. Int. J. Geogr. Inf. Sci. 28, 2127–2144. https://doi.org/10.1080/13658816.2014.911300

Qin, C.-Z., Zhu, A.-X., Pei, T., Li, B., Zhou, C., Yang, L., 2007. An adaptive approach to selecting a flow‐partition exponent for a multiple‐flow‐direction algorithm. Int. J. Geogr. Inf. Sci. 21, 443–458. https://doi.org/10.1080/13658810601073240

Rouholahnejad, E., Abbaspour, K.C., Vejdani, M., Srinivasan, R., Schulin, R., Lehmann, A., 2012. A parallelization framework for calibration of hydrological models. Environ. Model. Softw. 31, 28–36. https://doi.org/10.1016/j.envsoft.2011.12.001

Tague, C.L., Band, L.E., 2004. RHESSys: regional hydro-ecologic simulation system-an object-oriented approach to spatially distributed modeling of carbon, water, and nutrient cycling. Earth Interact. 8, 1–42. https://doi.org/10.1175/1087-3562(2004)8<1:RRHSSO>2.0.CO;2

Tarboton, D.G., 2016. Terrain Analysis Using Digital Elevation Models (TauDEM 5.3.7). http://hydrology.usu.edu/taudem/ (accessed 19 October 2016).

Vivoni, E.R., Mascaro, G., Mniszewski, S., Fasel, P., Springer, E.P., Ivanov, V.Y., Bras, R.L., 2011. Real-world hydrologic assessment of a fully-distributed hydrological model in a parallel computing environment. J. Hydrol. 409, 483–496. https://doi.org/10.1016/j.jhydrol.2011.08.053

Wagener, T., Boyle, D.P., Lees, M.J., Wheater, H.S., Gupta, H.V., Sorooshian, S., 2001. A framework for development and application of hydrological models. Hydrol. Earth Syst. Sci. 5, 13–26. https://doi.org/10.5194/hess-5-13-2001

Wang, H., Fu, X., Wang, G., Li, T., Gao, J., 2011. A common parallel computing framework for modeling hydrological processes of river basins. Parallel Comput. 37, 302–315. https://doi.org/10.1016/j.parco.2011.05.003

Wang, H., Fu, X., Wang, Y., Wang, G., 2013. A High-performance temporal-spatial discretization method for the parallel computing of river basins. Comput. Geosci. 58, 62–68. https://doi.org/10.1016/j.cageo.2013.04.026

Wang, S., Armstrong, M.P., 2009. A theoretical approach to the use of cyberinfrastructure in geographical analysis. Int. J. Geogr. Inf. Sci. 23, 169–193. https://doi.org/10.1080/13658810801918509

Wenderholm, E., 2005. Eclpss: a Java-based framework for parallel ecosystem simulation and modeling. Environ. Model. Softw. 20, 1081–1100. https://doi.org/10.1016/j.envsoft.2004.06.006

Wu, H., Zhu, A.-X., Liu, J., Liu, Y., Jiang, J., 2018. Best Management Practices Optimization at Watershed Scale: Incorporating Spatial Topology among Fields. Water Resour Manage 32, 155–177. https://doi.org/10.1007/s11269-017-1801-8

Wu, Y., Li, T., Sun, L., Chen, J., 2013. Parallelization of a hydrological model using the message passing interface. Environ. Model. Softw. 43, 124–132. https://doi.org/10.1016/j.envsoft.2013.02.002

Yalew, S., van Griensven, A., Ray, N., Kokoszkiewicz, L., Betrie, G.D., 2013. Distributed computation of large scale SWAT models on the Grid. Environ. Model. Softw. 41, 223–230. https://doi.org/10.1016/j.envsoft.2012.08.002

Yang, J., 2011. Convergence and uncertainty analyses in Monte-Carlo based sensitivity analysis. Environ. Model. Softw. 26, 444–457. https://doi.org/10.1016/j.envsoft.2010.10.007

Zhan, C.-S., Song, X.-M., Xia, J., Tong, C., 2013. An efficient integrated approach for global sensitivity analysis of hydrological model parameters. Environ. Model. Softw. 41, 39–52. https://doi.org/10.1016/j.envsoft.2012.10.009

Zhang, X., Beeson, P., Link, R., Manowitz, D., Izaurralde, R.C., Sadeghi, A., Thomson, A.M., Sahajpal, R., Srinivasan, R., Arnold, J.G., 2013. Efficient multi-objective calibration of a computationally intensive hydrologic model with parallel computing software in Python. Environ. Model. Softw. 46, 208–218. https://doi.org/10.1016/j.envsoft.2013.03.013

Zhao, G., Bryan, B.A., King, D., Luo, Z., Wang, E.L., Bende-Michl, U., Song, X., Yu, Q., 2013. Large-scale, high-resolution agricultural systems modeling using a hybrid approach combining grid computing and parallel processing. Environ. Model. Softw. 41, 231–238. https://doi.org/10.1016/j.envsoft.2012.08.007

Zitzler, E., Thiele, L., 1999. Multiobjective evolutionary algorithms: a comparative case study and the strength Pareto approach. IEEE Trans. Evol. Comput. 3, 257–271. https://doi.org/10.1109/4235.797969

Zitzler, E., Thiele, L., Laumanns, M., Fonseca, C.M., da Fonseca, V.G., 2003. Performance assessment of multiobjective optimizers: An analysis and review. IEEE Trans. Evol. Comput. 7, 117–132. https://doi.org/10.1109/TEVC.2003.810758

Section 2. Get started

SEIMS is mainly written by C++ with the support of GDAL (Geospatial Data Abstraction Library, https://www.gdal.org/), mongo-c-driver (https://github.com/mongodb/mongo-c-driver), OpenMP (Open Multi-Processing) and MPI (Message Passing Interface), while Python is used for organizing the utility tools such as data preprocessing, postprocessing, parameter sensitivity analysis, auto-calibration, and BMP (Best Management Practices) scenarios analysis.

SEIMS is designed to be an open-source, cross-platform, and high-performance integrated watershed modeling framework. Theoretically, SEIMS can be compiled by common used C/C++ compiler (e.g. Microsoft Visual C++ 2010+, GCC 4.6+, and Intel C++ 12.0+) as 32-bit or 64-bit programs and run on mainstream Operation Systems (e.g. Windows, Linux, and macOS).

In order to save the length of this manual, the software environments with Windows 10 64bit, Microsoft Visual C++ 2013 (MSVC 2013 for short), and Python 2.7.15 are selected for example. For the demo of parallel computing, a Linux cluster with IBM Platform LSF for workload management is adopted.

Users are encouraged to follow this manual step by step to get started with SEIMS, including download and installation, understanding the data preparation of the demo watershed, preprocessing and running the user-configured SEIMS-based watershed model, postprocessing, parameter sensitivity analysis, auto-calibration, and BMPs scenario analysis, etc.

2:1. Download and installation

2:1.1 Download

SEIMS is hosted on Github (https://github.com/lreis2415/SEIMS). SEIMS is dependent on several open-source software, e.g., GDAL (https://www.gdal.org/) and mongo-c-driver (https://github.com/mongodb/mongo-c-driver). Currently, there are no compiled binaries for distribution, but only through source code.

Users are encouraged to download and install (means compile from the source code) SEIMS manually. Generally, the `master` branch of SEIMS repository (https://github.com/lreis2415/SEIMS/tree/master) is the relative stable version, while the `dev` branch reflects the latest development changes.

Users can use `git` to clone the repository or download the compressed `zip` file directly.

- *Clone the single `master` branch using `git`.*
  1. *Download and install `git` from https://gitforwindows.org/.*
  2. *Open or create a local directory without spaces in File Explorer, e.g., `D:\demo`, right-click in the space and select "Git Bash Here". Then, enter the following two commands to configure your basic settings of `git`, i.e., the `username` and `email` of your Github account.*

     ```
     $ git config --global user.name "Your Name"
     $ git config --global user.email "email@example.com"
     e.g.,
     $ git config --global user.name "crazyzlj"
     $ git config --global user.email "crazyzlj@gmail.com"
     ```

  3. *If it is the first time to use `git` in your computer, a SSH key should be created and added to your Github account.*

     First, type the following command to generate a SSH key and store to your user directory, e.g., `C:/Users/XXX/.ssh/id_rsa.pub`

     ```
     $ ssh-keygen -t rsa -C "email@example.com"
     ```

     Then, copy the content of this file and add to your Github account ("Settings" -> "SSH and GPG keys" -> "New SSH key").

  4. *Clone a single branch, e.g., the `master` branch (Figure 2:1-1).*

     ```
     $ git clone git@github.com:lreis2415/SEIMS.git --branch master
     --single-branch
     ```

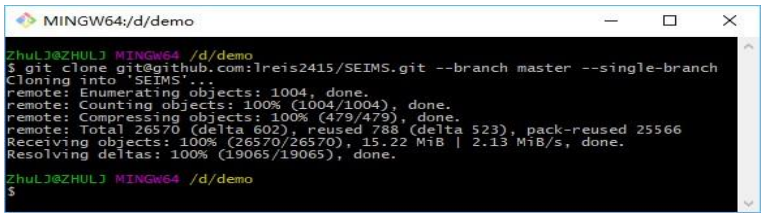


Figure 2:1-1 Clone the single master branch of SEIMS repository using Git Bash command

- *Alternatively, users can download the compressed `zip` file (e.g., the `zip` file of the `master` branch, https://github.com/lreis2415/SEIMS/archive/master.zip) directly and then decompress it to a local directory without spaces, e.g., `D:\demo`.*

Now, the source code of SEIMS should be located in `D:\demo\SEIMS` such as Figure 2:1-2.

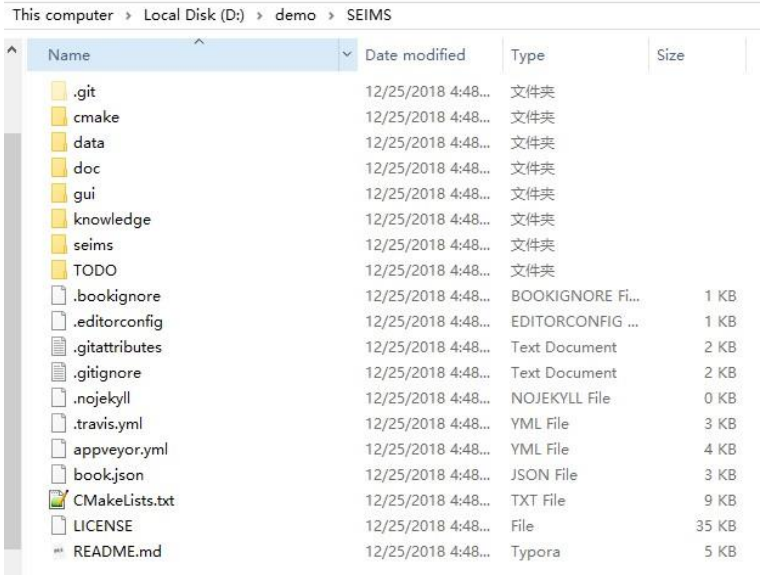


Figure 2:1-2 Directory tree of SEIMS source code

2:1.2 Prerequisite software and libraries

Several software and libraries are required to compile and run SEIMS successfully.

- *Software*
  1. *C/C++ compiler with partial support for C++11, e.g., MSVC 2010+, GCC 4.6+, Intel C++ 12.0+, and Clang 8.0+*
  2. *CMake 3.1+*
  3. *Python 2.7.x or 3.x*
  4. *MongoDB (community) server*
- *Libraries*
  5. *MPI implementation for C/C++, e.g., MS-MPI v6+, MPICH, OpenMPI or Intel MPI*
  6. *GDAL 1.x or 2.x for C/C++ and Python*
  7. *mongo-c-driver 1.5+ for C/C++*
  8. *third-party Python packages*

The following instructions are prepared and tested on Windows 10 64bit.

2:1.2.1 Microsoft Visual C++ (MSVC)

SEIMS uses several features of C++11 such as `nullptr` and `auto` keywords. Therefore, the minimum support version is MSVC 2010. Microsoft Visual Studio is a powerful IDE based on Microsoft Visual C++. If you don't want to install Microsoft Visual Studio, the Visual C++ build tools can allow you to build C++ libraries and applications targeting Windows desktop, which are the same tools that you find in Microsoft Visual Studio. Even though, Visual Studio is still highly recommended. Unless stated, the following MSVC refers to Microsoft Visual Studio.

If you want to develop parallel applications based on MPI, MSVC 2010 is the best choice since it is the last MSVC version that integrated the MPI cluster debugger. MPI cluster debugger is the most convenient and powerful tools on Windows to debug MPI-based parallel applications. More details about MPI cluster debugger can be found in https://docs.microsoft.com/en-us/previous-versions/visualstudio/visual-studio-2010/dd560809(v=vs.100). Otherwise, MSVC 2013 and 2015 are both recommended. All these MSVC versions can be downloaded from https://visualstudio.microsoft.com/vs/older-downloads/.

This manual takes "Microsoft Visual Studio 2013 update 5" as an example.

2:1.2.2 CMake

CMake 3.1+ is used to build the C/C++ project of SEIMS such as Microsoft Visual Studio solution (`*.sln`). CMake can be downloaded from the official site https://cmake.org/download/. The installer is something like `cmake-3.x.x-win64-x64.msi` for Windows64-x64.

After the installation of CMake, please add the path of CMake executable, e.g., `C:\Program Files (x86)\CMake\bin`, to the system variable `PATH`. In such a way, we can run CMake in CMD (Command Prompt) directly by typing `cmake` rather than the absolute path.

2:1.2.3 Python

The utility tools of SEIMS is compatible with Python 2.7.x and 3.x versions. Download from https://www.python.org/downloads/windows/ and install to a local location, e.g., Python 2.7.15 x86-64 version installed at `D:\demo\python27`. Same to CMake, please add the paths of Python, e.g., `D:\demo\python27; D:\demo\python27\Scripts` to the system variable `PATH`.

`Pip` (https://pypi.org/project/pip/), the PyPA (Python Packaging Authority, https://www.pypa.io/en/latest/) recommended tool for installing Python packages, should be installed right after the installation of Python. If `pip` has been selected and installed along with Python, this step will perform an update for `pip`.

- *Download `get_pip.py` from https://bootstrap.pypa.io/get-pip.py to a local directory, e.g., `D:\demo`*
- *Open a CMD (`Start->Windows System->Command Prompt`), and enter the following command.*

`python d:\demo\get-pip.py`

- *The latest version of* `pip` *is now installed or updated! Most Python packages can be installed by running* `pip install <package name>` *in a CMD window.* `Pip` *also support the installation of offline compiled binary file, i.e., the* `*.whl` *format file which is the new standard built-package format for Python (https://pypi.org/project/wheel/) by running* `pip install </path/to/whl-file-of-package>`*.*

***Note**:*

1. If ArcGIS has been installed on the computer, the 32-bit and 64-bit versions of Python may also installed at the path of `C:\Python27\ArcGIS10.3` *and* `C:\Python27\ArcGISx6410.3`*, respectively, so to support the* `arcpy`*. However, we still recommend installing an independent Python so to avoid the confusion of Python packages that may affect the work of* `arcpy`*.*

2. Only one specific path of Python should be existed in the `PATH` *environment. When users want to use a different version of Python, the absolute path (e.g.,* `D:\demo\python27\python.exe`*) should be used instead of the single name of* `python`*.*

2:1.2.4 MongoDB server

Given the requirements of flexible data structures, elastic scalability, and high performance, a widely-used NoSQL database, MongoDB (https://www.mongodb.com), was adopted to manage all kinds of data in SEIMS.

The free available version of MongoDB server is MongoDB community server which can be downloaded from the official website, such as the previous stable release version 3.6.9 https://fastdl.mongodb.org/win32/mongodb-win32-x86_64-2008plus-ssl-3.6.9-signed.msi.

2:1.2.4.1 Installation and simple test

- *Install the MongoDB community server (take* `mongodb-win32-x86_64-2008plus-ssl-3.2.3-signed.msi` *as example) to a local directory without spaces, e.g.,* `D:\MongoDB`*.*
- *Create a new directory named* `logs` *(e.g.,* `D:\MongoDB\logs`*) to store journal files.*
- *Create a new directory named* `db` *(e.g.,* `D:\MongoDB\db`*) to store data.*
- *Open a CMD as administrator and run the following commands:*

  `D:\MongoDB\bin\mongod.exe --dbpath=D:\mongodb\db`
- *The last line printed in the CMD windows should be like:*

  `Tue Oct 09 11:50:55 [websvr] admin web console waiting for connections on port 27017`

  This means MongoDB server has started successfully and the port `27017` *is occupied by MongoDB.*
- *DO NOT close the current CMD window and open a new one as administrator, and run the following commands:*

  `D:\MongoDB\bin\mongo.exe`

If the last line is `connecting to: test`*, the connection to MongoDB is successful. The default database named* `test` *is connected.*

- *Continue to test:*

```
01 use test
02 db.foo.save({hello:0})
03 db.foo.find()
```

If something like `{ "_id" : ObjectId("5c222fdff492e1436718e00b"), "Hello" : 0 }` *showed in the last line, the key-value data (i.e., key is* `hello` *and value is* `0`*) has been inserted into the newly created collection* `foo` *in* `test` *database successfully.*

- *Enter* `exit` *to leave MongoDB.*

2:1.2.4.2 Register MongoDB as system service

As is shown in previous section, a CMD window MUST be active to keep the running of MongoDB server, which is tedious. Therefore, we wish to set MongoDB as system service and start it along with Windows system, so that we do not need to start it manually each time after restarts of Windows system.

- *Open a CMD as administrator and enter the following commands:*

```
cd D:\MongoDB\bin\mongo.exe --dbpath=D:\MongoDB\db --
logpath=D:\MongoDB\logs\mongodb.log --install --serviceName "MongoDB"
```

- *If something like "*`Tue Oct 09 12:05:15 Service can be started from the command line with 'net start MongoDB'`*" showed in the console window, the service has been successfully registered.*
- *Now, a simple command* `net start MongoDB` *is enough to start MongoDB server.*
- *Next, we need to set the* `MongoDB` *service as automatically start service along with Windows system.*

```
D:\MongoDB\bin\mongod --install --serviceName "MongoDB" --
serviceDisplayName "MongoDB" --logpath D:\MongoDB\logs\mongodb.log --
logappend --dbpath D:\MongoDB\db --directoryperdb
```

- *If no errors occurs, the automatically start service has been set successfully!*

2:1.2.4.3 MongoDB GUI

In order to view, query, and update data stored in MongoDB, a user-friendly and efficient GUI is urgently needed.

Robo 3T is what we need (https://robomongo.org/download). Download the proper version for your system and install it.

Open Robo 3T and connect to the `localhost:27017` (i.e., `127.0.0.1:27017`). The key-pair data inserted in 2:1.2.4.1 can be found (Figure 2:1-3).

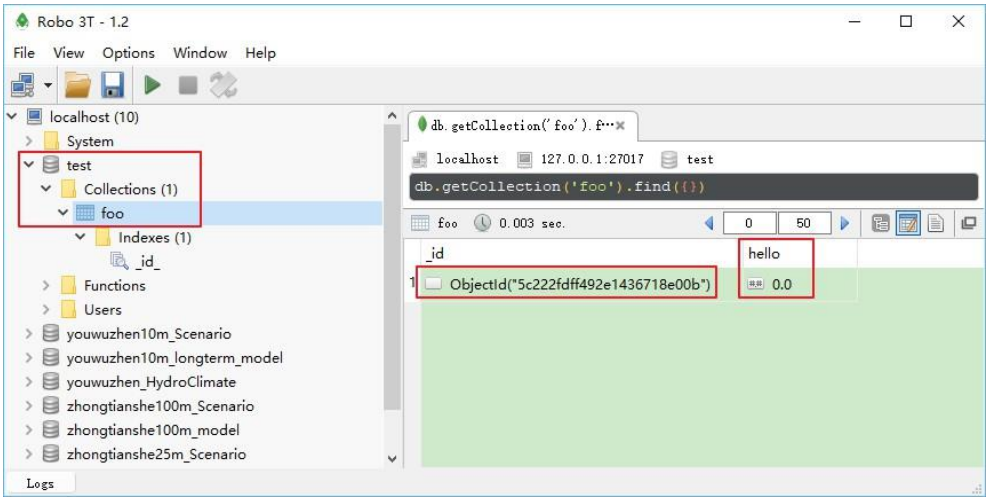


Figure 2:1-3 Screenshot of Robo 3T – a user-friendly and efficient MongoDB GUI

2:1.2.5 Microsoft MPI (MS-MPI)

Microsoft MPI (MS-MPI) is a Microsoft implementation of the MPI (Message Passing Interface, https://www.mpi-forum.org/) standard for developing and running parallel applications on the Windows platform. MS-MPI v6 and later versions are recommended.

Download MS-MPI (two installer files are required, i.e., `msmpisdk.msi` and `MSMpiSetup.exe`) from Microsoft download center, e.g., https://www.microsoft.com/en-us/download/details.aspx?id=47259 for MS-MPI v6, and install to the default locations. By default, the environment variables of MS-MPI will be set automatically. Open `System->Advanced system settings->Environment variables->System variables` to make sure the following variable-value pairs are existed. If not, please add them manually with the correct paths of your computer.

```
MSMPI_BIN=C:\Program Files\Microsoft MPI\Bin\
MSMPI_INC=C:\Program Files (x86)\Microsoft SDKs\MPI\Include\
MSMPI_LIB32=C:\Program Files (x86)\Microsoft SDKs\MPI\Lib\x86\
MSMPI_LIB64=C:\Program Files (x86)\Microsoft SDKs\MPI\Lib\x64\
```

2:1.2.6 GDAL library for C/C++ and Python

Download the pre-compiled library is the most convenient and successful way to install GDAL library for both C/C++ and Python.

2:1.2.6.1 GDAL for C/C++

The “GISInternals support site” (http://www.gisinternals.com/index.html) maintained by Tamas Szekeres is the most famous site that provides compiled GDAL library by MSVC on Windows platform. Users should pick up the exact version according to your compiler and OS architecture, e.g., I have MSVC 2013 (`_MSC_VER=1800`) installed on Windows 10-64bit and I want `GDAL-1.11.4` to compile 64-bit applications, so I should download the `release-1800-x64-gdal-1-11-4-mapserver-6-4-3.zip` and `release-1800-x64-gdal-1-11-4-mapserver-6-4-3-libs.zip` from archived releases (http://www.gisinternals.com/archive.php).

- *Unzip these two* `zip` *files to the same directory path without spaces, e.g.,* `C:/GDAL`*. The directory tree of GDAL should like Figure 2:1-4.*

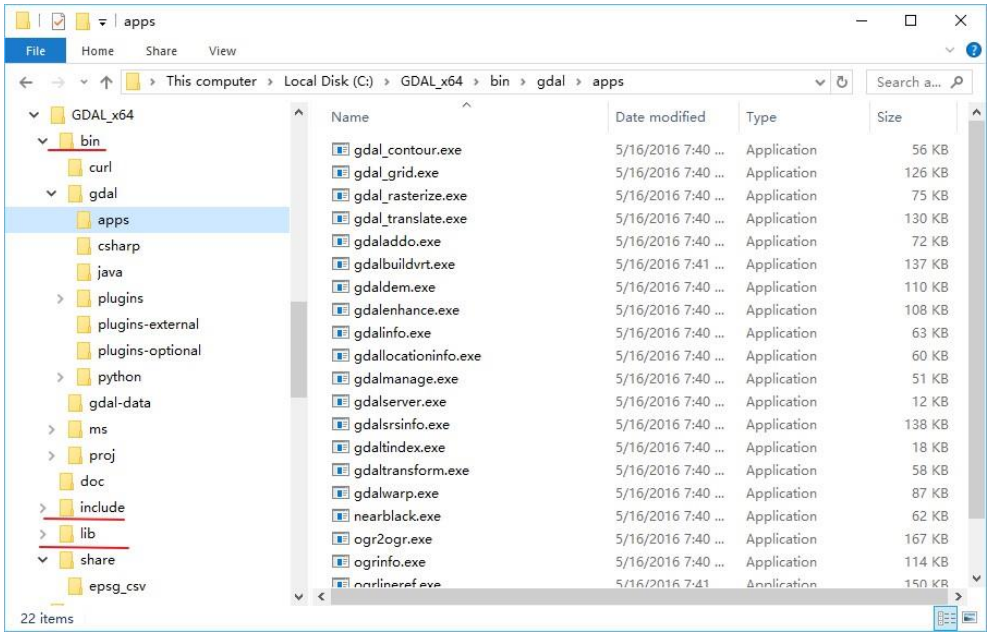


Figure 2:1-4 Directory tree of the compiled GDAL library

- *Open* `Advanced System Properties->Environment variables`*, create several new system variables under the* `System variables` *pane:*

  ```
  GDAL_DIR=C:\GDAL
  GDAL_DATA=C:\GDAL\bin\gdal-data
  GDAL_PATHS=C:\GDAL;C:\GDAL\bin;C:\GDAL\bin\proj\apps;C:\GDAL\bin\gdal\apps;C:\GDAL\bin\ms\apps;C:\GDAL\bin\curl;
  ```

- *Then, append* `%GDAL_PATHS%` *to the end of the system variable* `PATH`*.*
- *The GDAL library for C/C++ has been installed, as well as executable utility tools of GDAL, e.g.,* `gdalinfo`*. Open a new CMD window, and enter*

  `gdalinfo --version`*,*

  something like `GDAL 1.11.4, released 2016/01/25` *should be printed.*

2:1.2.6.2 GDAL for Python

Although the "GISInternals support site" also provides the GDAL Python bindings (e.g., `GDAL-1.11.4.win-amd64-py2.7.msi`), it may not work properly for unknown reason. So, the site of "Unofficial Windows Binaries for Python Extension Packages (https://www.lfd.uci.edu/~gohlke/pythonlibs/)" maintained by Christoph Gohlke is highly recommended to download the compiled binaries of Python packages (i.e., `*.whl` files), not only the GDAL but also almost the commonly used packages.

Please read the instructions at the head of this website very carefully.

- *Select 32- (*`win32`*) or 64-bit (*`win_amd64`*) binaries of packages according to the bit version of Python, not the version of your Windows. In other words, even if the Windows is 64-bit, the Python can be 32- or 64-bit.*

- *Select the correct version according to the version number of Python, e.g.,* `cp27-cp27m` *for Python 2.7.x,* `cp34-cp34m` *for Python 3.4.x, ex analogia.*
- *Install Microsoft Visual C++ Redistributable packages first, since many binaries cannot run without them, i.e., Microsoft Visual C++ 2008 (x64, x86, and SP1 for CPython 2.7), Visual C++ 2010 (x64 and x86 for CPython 3.4), or the Visual C++ 2017 (x64 or x86 for CPython 3.5, 3.6, and 3.7).*
- *Install numpy+mkl (https://www.lfd.uci.edu/~gohlke/pythonlibs/#numpy), e.g.,* `numpy-1.15.4+mkl-cp27-cp27m-win_amd64.whl`.

```
01 d:\demo>d:\demo\python27\scripts\pip install numpy-1.15.4+mkl-cp27-
cp27m-win_amd64.whl
02 Processing .\numpy-1.15.4+mkl-cp27-cp27m-win_amd64.whl
03 Installing collected packages: numpy
04 Successfully installed numpy-1.15.4+mkl
```

- *Install GDAL (https://www.lfd.uci.edu/~gohlke/pythonlibs/#gdal), e.g.* `GDAL-2.2.4-cp27-cp27m-win_amd64.whl`.

```
01 d:\demo>d:\demo\python27\scripts\pip install GDAL-2.2.4-cp27-
cp27m-win_amd64.whl
02 Processing .\gdal-2.2.4-cp27-cp27m-win_amd64.whl
03 Installing collected packages: GDAL
04 Successfully installed GDAL-2.2.4
```

- *(Optional) Install Esri's FileGDB API 1.3 or FileGDB 1.5 if you want to use the* `FileGDB` *plugin for GDAL. Otherwise, just delete the* `ogr_FileGDB.dll` *located in* `D:\demo\python27\Lib\site-packages\osgeo\gdalplugins` if the related errors occurred.
- *Open a CMD window and enter the following commands to test if the GDAL package for Python is successfully installed.*

```
01 d:\demo>d:\demo\python27\python
02 Python 2.7.15 (v2.7.15:ca079a3ea3, Apr 30 2018, 16:30:26) [MSC
v.1500 64 bit (AMD64)] on win32
03 Type "help", "copyright", "credits" or "license" for more
information.
04 >>> import osgeo
05 >>> osgeo.__version__
06 '2.2.4'
07 >>> from osgeo import ogr
08 >>> from osgeo import osr
09 >>> from osgeo import gdalconst
10 >>> from osgeo import gdal_array
11 >>> from osgeo import gdal
```

As we can see, the version of GDAL library for Python in my computer is `2.2.4`*, which means the GDAL version for C/C++ (which is* `1.11.4`*) and Python are not necessarily the same.*

2:1.2.7 mongo-c-driver library

The mongo-c-driver library for MongoDB (https://github.com/mongodb/mongo-c-driver) is adopted by SEIMS to handle data Input/Output (IO) with MongoDB. Since mongo-c-driver is still under active and continuous development, the building method and API (Application Program Interface) functions may different with versions. So, for the most compatibility, the version of 1.6.1 is recommended, since SEIMS is mainly developed and tested based on mongo-c-driver 1.5.x ~ 1.6.x.

- *Download the released file and decompress it to a local directory, e.g.,* `D:\demo\mongo-c-driver-1.6.1`
- *Open* `VS2013 Developer Command Prompt`*, and enter the following commands (start with '>' symbol) in order. Assume that the desired destination of compiled libraries and headers of mongo-c-driver is* `C:\mongo-c-driver`*.*

```
01 >cd D:\demo\mongo-c-driver-1.6.1
02 # 1. Configure, build, and install libbson first.
03 # Note that, in the latest version, libbson is no need to be built
separately.
04 #  Please visit http://mongoc.org/libmongoc/current/installing.html
for more information.
05 >cd src\libbson
06 >cmake -DCMAKE_INSTALL_PREFIX=C:\mongo-c-driver -G "Visual Studio
12 2013 Win64"
07 >msbuild.exe ALL_BUILD.vcxproj /p:Configuration=RelWithDebInfo
08 >msbuild.exe INSTALL.vcxproj /p:Configuration=RelWithDebInfo
09 # 2. Go back to the root folder, configure, build, and install
mongoc
10 >cd ..\..
11 >cmake -DCMAKE_INSTALL_PREFIX=C:\mongo-c-driver -
DBSON_ROOT_DIR=C:\mongo-c-driver -G "Visual Studio 12 2013 Win64" -
DCMAKE_PREFIX_PATH=C:\mongo-c-driver\lib\cmake -
DENABLE_AUTOMATIC_INIT_AND_CLEANUP:BOOL=OFF -DENABLE_SSL=WINDOWS -
DENABLE_SASL=SSPI
12 # Use Windows Native TLS, rather then OpenSSL in case of strange
link errors
13 # Use Windows Native SSPI, rather then Cyrus SASL
14 >msbuild.exe ALL_BUILD.vcxproj /p:Configuration=RelWithDebInfo
15 >msbuild.exe INSTALL.vcxproj /p:Configuration=RelWithDebInfo
```

  Notes:

  1. *If* `msbuild.exe` *cannot be found by CMD, please find it in the path of* `.NetFramework`*, e.g.,* `C:\Windows\Microsoft.NET\Framework64\v4.0.30319\msbuild.exe`*.*
  2. *If you want to build the 32-bit mongo-c-driver libraries, please replace the generator "*`Visual Studio 12 2013 Win64`*" to "*`Visual Studio 12 2013`*".*

- *Now, mongo-c-driver has been built and installed, the directories of* `bin`*,* `include`*, and* `lib` *can be found in the root directory of mongo-c-driver, i.e.,* `C:\mongo-c-driver`*.*

- *Create two new system variables:*

  `MONGOC_ROOT=C:\mongo-c-driver`
  `MONGOC_LIB=C:\mongo-c-driver\bin`
- *Then, append* `%MONGOC_LIB%` *to the end of the system variable* `PATH`*.*

2:1.2.8 Python packages for SEIMS utility tools

SEIMS utility tools written by Python require several third-party packages. Except for Numpy and GDAL that have been installed in Section 2:1.2.6.2, there is one more package should be installed manually, i.e., PyGeoC (short for **Py**thon for **GeoC**omputation, https://github.com/lreis2415/PyGeoC). PyGeoC is designed to provide commonly used functions for Geocomputation, e.g., watershed delineation workflow based on TauDEM. Besides, other required packages can be installed automatically by `pip`.

- *The installation of PyGeoC*
  1. *Get the latest version of PyGeoC from the* `master` *branch (https://github.com/lreis2415/PyGeoC/tree/master) and save to a local directory, e.g.* `D:\demo\PyGeoC`*.*

     Alternatively, users are recommended to clone the `master` *branch using* `git`*. With* `git`*, users can easily get the latest changes of PyGeoC by the command of '*`git pull origin master`*'.*
  2. *Open a CMD windows as administrator and using the following command to install:*

     `D:\demo\PyGeoC\reinstall.bat`

     The `reinstall.bat` *script also accepts one input argument to specify the exact directory path of Python, e.g.:*

     `D:\demo\PyGeoC\reinstall.bat D:\demo\python27`
  3. *Wait for a moment, PyGeoC and its dependencies will be installed automatically, the messages of success are something like:*

     ```
     Successfully installed PyGeoC-0.3.0 backports.functools-lru-cache-
     1.5 cycler-0.10.0 future-0.17.1 kiwisolver-1.0.1 matplotlib-2.2.3
     pyparsing-2.3.0 python-dateutil-2.7.5 pytz-2018.7 typing-3.6.6
     ```
- *The installation of other required packages*

  `pip install -r D:\demo\SEIMS\seims\requirements.txt`

  Wait for a moment, the required packages and their dependencies will be installed automatically, the messages of success are something like:

  ```
  Successfully installed configparser-3.5.0 SALib-1.2 Shapely-
  1.6.4.post2 argparse-1.4.0 deap-1.2.2 decorator-4.3.0 greenlet-0.4.15
  networkx-2.2 pandas-0.23.4 pymongo-3.7.2 pyzmq-17.1.2 scipy-1.2.0
  scoop-0.7.1.1
  ```

  Note: If you want to use the Python which is not the default version on your computer, please use the absolute path of `pip` *to install packages, e.g.,* `D:\demo\python27\Scripts\pip`*.*

Now, the Python environment for SEIMS has been set up!

2:1.3 Test of the C/C++ building environment

Now, we have set up the C/C++ building environment for SEIMS, i.e., MSVC 2013, MS-MPI v6, GDAL 1.11.4, and mongo-c-driver 1.6.1. In case of any unpredictable omissions or errors, users are highly recommended to test the C/C++ building environment by compiling the **C**ommon **C**ross-platform **G**eographic-computing **L**ibrary (`CCGL`, https://github.com/crazyzlj/CCGL) and running its unit test. `CCGL` has been integrated into SEIMS and no additional download is required.

Please follow the steps below to compile `CCGL` and run its unit test.

- *Open a new `VS2013 Developer Command Prompt`, and navigate to the directory of `CCGL`, e.g., `D:\demo\SEIMS\seims\src\ccgl`.*
- *Build the Visual Studio solution by CMake with the support of Google Test (i.e., `-DUNITTEST=1`), such as Figure 2:1-5.*

```
>cd D:\demo\SEIMS\seims\src\ccgl
>d:
>mkdir build
>cd build
>cmake -G "Visual Studio 12 2013 Win64" -DUNITTEST=1 ..
>msbuild.exe ALL_BUILD.vcxproj /p:Configuration=RelWithDebInfo
>msbuild.exe INSTALL.vcxproj /p:Configuration=RelWithDebInfo
```

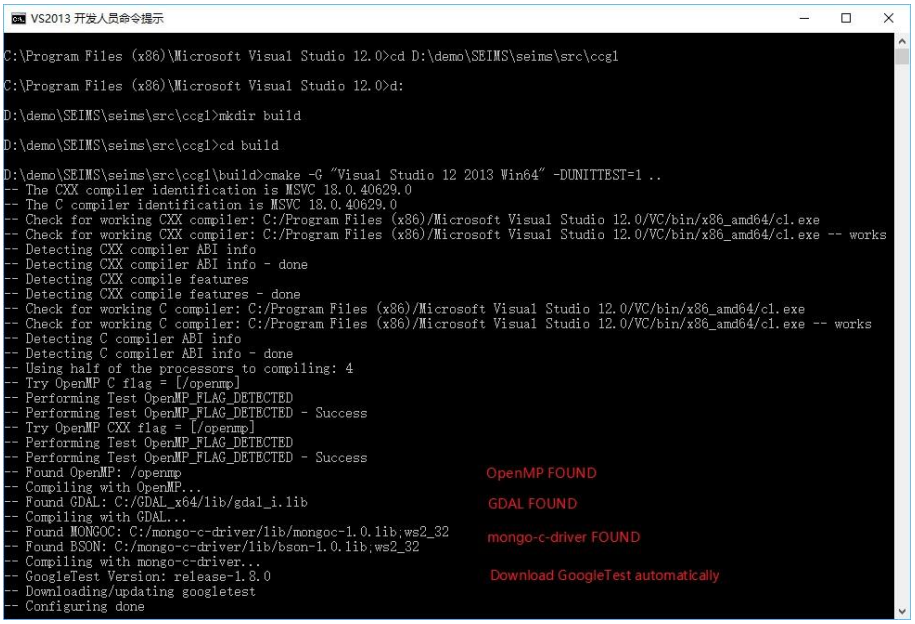


Figure 2:1-5 Building Visual Studio solution of CCGL library by CMake

- *Then, navigate to the binary directory of `CCGL` and run its unit test.*

```
>cd ../bin
>UnitTests_CCGL.exe
```

- *The final results should be like Figure 2:1-6.*

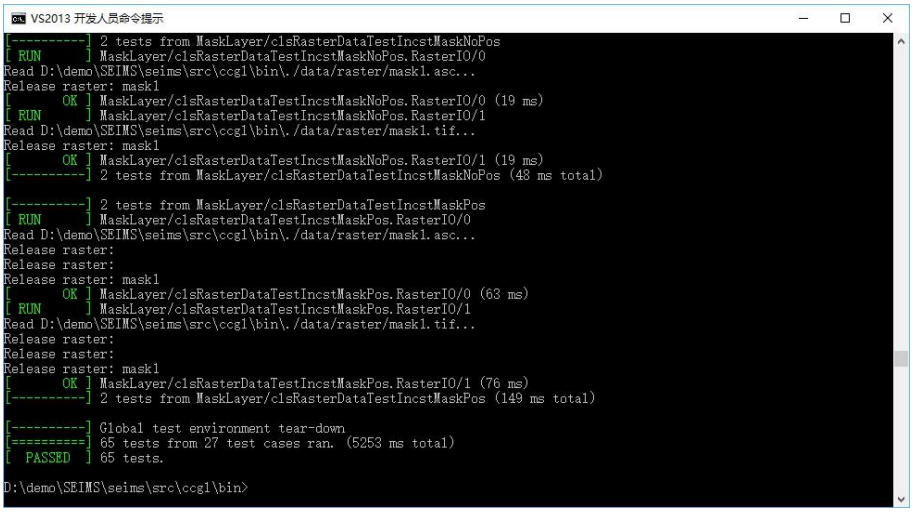


Figure 2:1-6 Unit test results of CCGL (Common Cross-platform Geographic-computing Library)

If any `FAILED` tests occurred, you should check the settings of prerequisite software and libraries in Section 2:1.2 carefully. If you do not sure what the errors mean, please contact the developers for supports (see Section 1:1.3).

2:1.4 Installation of SEIMS

As stated earlier, SEIMS is mainly written by C++ and Python. Python is an interpreted language which means the source code can be executed directly under the Python environment without any manual compilation. Therefore, the installation of SEIMS is the compilation and installation of C++ applications.

The C++ applications of SEIMS not only include the main programs and modules for watershed modeling, but also the integrated programs for preprocessing such as watershed delineation by TauDEM (http://hydrology.usu.edu/taudem/taudem5/index.html) and static task scheduling with the graph of subbasins by METIS (http://glaros.dtc.umn.edu/gkhome/metis/metis/overview). All the C++ applications are organized by CMake and can be built, compiled, and installed at one time.

- *Open a new* `VS2013 Developer Command Prompt`*, and navigate to the directory of SEIMS, e.g.,* `D:\demo\SEIMS`*.*
- *Build the Visual Studio solution by CMake and compile the whole SEIMS solution by* `msbuild.exe`*.*

```
>cd D:\demo\SEIMS
>d:
>mkdir build
>cd build
>cmake -G "Visual Studio 12 2013 Win64" ..
>msbuild.exe ALL_BUILD.vcxproj /p:Configuration=Release
>msbuild.exe INSTALL.vcxproj /p:Configuration=Release
```

- *After the compilation and installation, all executables and libraries are installed at the default location, i.e.,* `D:\demo\SEIMS\bin`*.*

- *The complete SEIMS includes C++ applications located in* `D:\demo\SEIMS\bin` *and Python utility tools located in* `D:\demo\SEIMS\seims` *such as* `preprocess`, `postprocess`, `parameters_sensitivity`, `calibration`, *and* `scenario_analysis` *(Figure 2:1-7).*

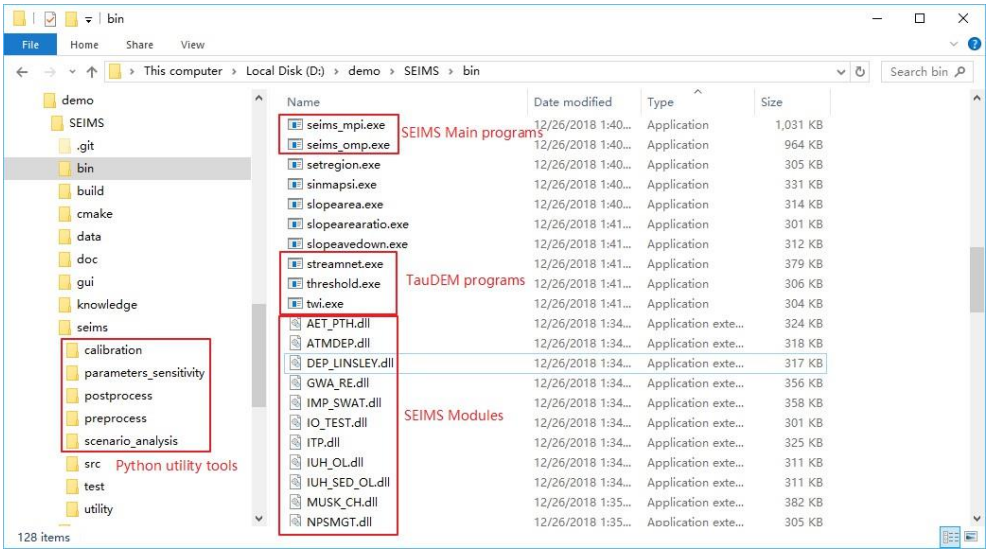


Figure 2:1-7 Directory tree of C++ applications and Python utility tools of SEIMS

- *Enter* `D:\demo\SEIMS\bin\seims_omp.exe` *in a CMD window, the help information of SEIMS main program will be shown such as Figure 2:1-8. More details of running SEIMS will be introduced in "Section 2:4 Running a SEIMS-based watershed model".*

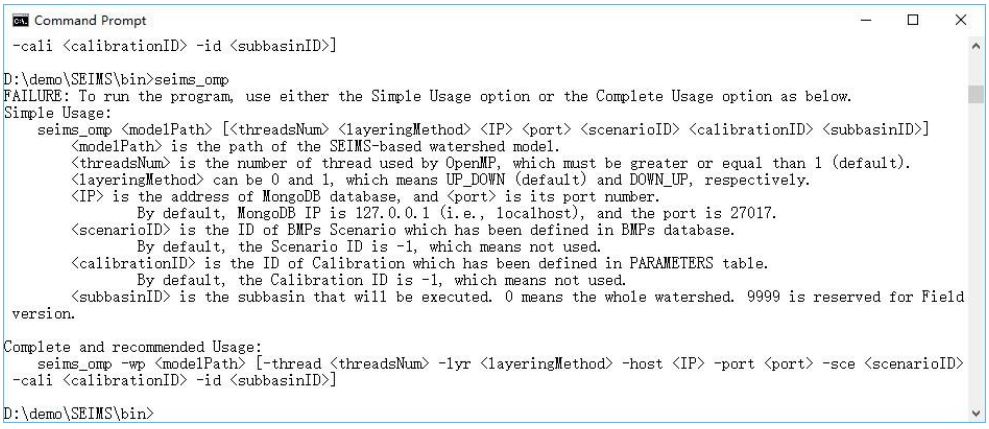


Figure 2:1-8 Usage of the OpenMP version of SEIMS main program

2:2. Data preparation of demo watershed

In simple terms, watershed modeling is to simulate the behavior of watershed such as runoff, soil erosion, and nutrient transfer using the empirical or physical formulas based on the geographic information data (e.g., digital elevation model [DEM], landuse map, and soil map), meteorological data, and management data, etc. Thus, data collection and preparation is the first key step for watershed modeling.

As a demo, data from the Youwuzhen watershed, Changting County, Fujian province, China is selected for long-term (i.e., daily time-step) simulation.

2:2.1 Basic conventions of file formats

Basically, the input data of SEIMS-based watershed model includes two categories such as spatial data and plain text.

2:2.1.1 Spatial data

Spatial data includes raster data and vector data. Theoretically, all formats of raster (https://www.gdal.org/formats_list.html) and vector (https://www.gdal.org/ogr_formats.html) data supported by GDAL are acceptable for SEIMS. Even though, the most commonly used GeoTIFF and ESRI Shapefile are highly recommended for raster and vector data, respectively.

- *Please make sure all spatial data have the same projected coordinate system, **NOT** geographic coordinate system.*
- *The spatial extents of different raster data are not necessarily the same. However, the gridded cells at the same location are preferably coincident. Otherwise, the raster data will be interpolated based on the DEM data which may cause undesired distortion.*

2:2.1.2 Plain text

Except for the spatial data, almost all the other data can be provided as plain text. The basic conventions of plain text are designed as:

- *The line starts with number sign (‘`#`’) will be regarded as a comment line and ignored by SEIMS. However, there is one exception when the first line of one plain text file is for recording the time-system and timezone, e.g., `#LOCALTIME 8` means date time recorded in the current file is east 8th district time and `#UTCTIME` means Coordinated Universal Time which is also known as Greenwich Mean Time (GMT).*
- *The first valid line is headers if needed.*
- *Comma (‘`,`’) is the delimiter for values within each data line.*
- *En dash (‘`-`’) is the primary delimiter within each value while colon (‘`:`’) is the secondary delimiter.*

For example, the following plain text

```
# This line is a comment.
SUBSCENARIO,NAME,LANDUSE,PARAMETERS
1, Closing measures,7-16,Interc_max:Maximum Interception
Capacity:AC:1-Conductivity:Soil hydraulic conductivity:RC:3.5
```

can be parsed as a Python data structure of dictionary like:

```
demo_dict = {
    'SUBSCENARIO': 1,
    'NAME':'Closing measures'
    'LANDUSE': [7, 16],
    'PARAMETERS': [
        ['Interc_max', 'Maximum Interception Capacity', 'AC', 1],
        ['Conductivity', 'Soil hydraulic conductivity', 'RC', 3.5]
    ]
}
```

2:2.2 Spatial data

The demo data named Youwuzhen watershed (~5.39 km^2) is located in Changting County of Fujian province, China (Figure 2:2-1). It belongs to the typical red-soil hilly region in southeastern China and suffers from severe soil erosion. The study area has hills with steep slopes (up to 52.9° and with an average slope of 16.8°) and broad alluvial valleys. The elevation ranges from 295.0 m to 556.5 m. The landuse types are mainly forest (59.8%), paddy field (20.6%), and orchard (12.8%) (Figure 2:2-2). Soil types in the study area are red soil (78.4%) and paddy soil (21.6%) which can be classified as *Ultisols* and *Inceptisols* in US Soil Taxonomy, respectively (Figure 2:2-3).

In order to improve the computational efficiency for demonstration in this manual, the DEM (`ywzdem30m.tif`), landuse (`ywzlanduse30m.tif`), and soil (`ywzsoil30m.tif`) map are all unified to be of 30 m resolution.

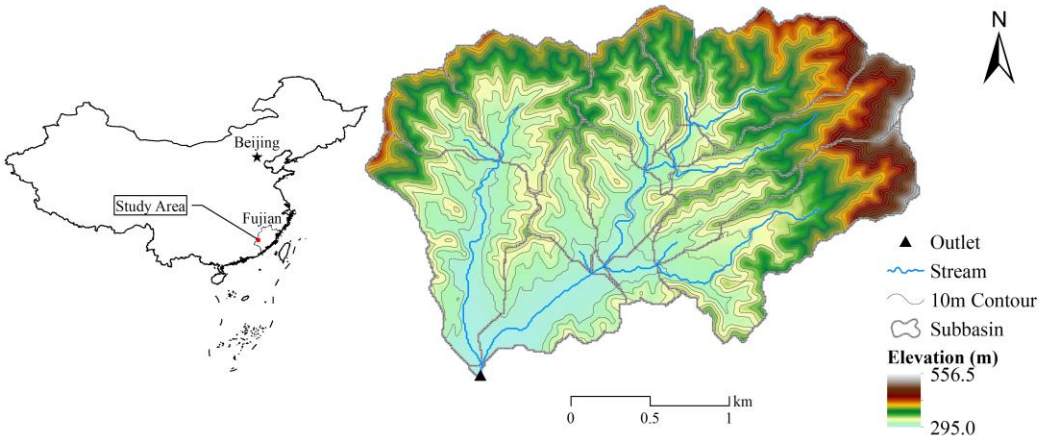


Figure 2:2-1 Location of the demo watershed named Youwuzhen watershed

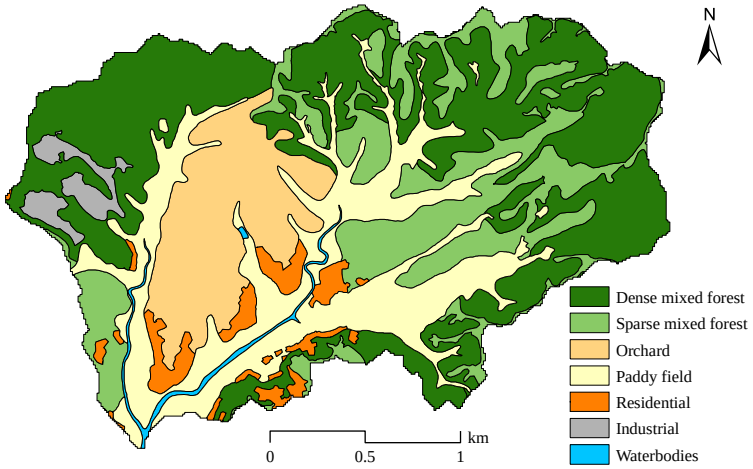


Figure 2:2-2 Landuse map of the Youwuzhen watershed

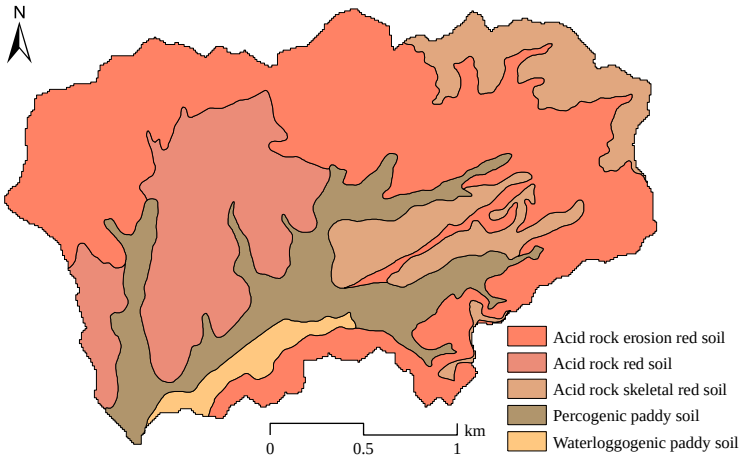


Figure 2:2-3 Soil map of the Youwuzhen watershed

The outlet location (i.e., as vector point) of the Youwuzhen watershed is prepared as ESRI Shapefile. If the outlet data cannot be predetermined, the location (i.e., center of the gridded cell) with largest flow accumulation will be marked as the outlet of the current study area.

In the current version of SEIMS, the Thiessen polygon of meteorological stations and precipitation stations that covers the entire watershed should also be provided as vector polygon data, e.g., `thiessen_meteo.shp` and `thiessen_pcp.shp`, respectively. The attributes of each polygon should include the unique ID (`ID`) which is coincident with station ID introduced in the following section (2:2.3.1), station name (`Name`), X and Y coordinates under the projected coordinate system (`LocalX` and `LocalY`), latitude and longitude under the WGS84 coordinate system (`Lat` and `Lon`), and altitude (`Elevation`).

***TODO**: The requirements of the Thiessen polygon of meteorological stations and precipitation stations should be removed since the spatial information of these stations presented as plain text (see Section 2:2.3.1) can provide similar information.*

All these spatial data are located in `SEIMS\data\youwuzhen\data_prepare\spatial`.

2:2.3 Precipitation data

The annual average precipitation of the Youwuzhen watershed is 1697.0 mm and intense short-duration thunderstorm events contribute about three-quarters of annual precipitation from March to August.

2:2.3.1 Spatial information of precipitation station

The fields of spatial information of precipitation station are shown in Table 2:2-1.

Table 2:2-1 Fields of precipitation station

Field name	Datatype	Description
`StationID`	Integer	Unique station ID
`Name`	String	Station name
`LocalX`	Float	X coordinates (unit: m) under the projected coordinate system
`LocalY`	Float	Y coordinates (unit: m)
`Lat`	Float	Latitude (unit: degree) under the WGS84 coordinate system
`Lon`	Float	Longitude (unit: degree)
`Elevation`	Float	Altitude (unit: m)

For example, `SEIMS\data\youwuzhen\data_prepare\climate\Sites_P.csv`,

```
StationID,Name,LocalX,LocalY,Lon,Lat,Elevation
81502750,HeTianZhan,39444759.232,2840563.152,116.4,25.683333,298
```

2:2.3.2 Records of precipitation data

The first line is to state the time-system and timezone (see Section 2:2.1.2). If not provided, `#UTCTIME` will be regarded as the default.

The fields and formats of precipitation data are shown in Table 2:2-2.

Table 2:2-2 Fields and formats of precipitation data item

Field name	Datatype	Description
`DATETIME`	Datetime string	Date time with the format of `YYYY-MM-DD HH:MM:SS`
`StationIDs`	Float	Precipitation value for each Station IDs. Multiple stations can be `StationID1`,`StationID2`, … `StationIDN`

Thus, the records of precipitation data is something like (`SEIMS\data\youwuzhen\data_prepare\climate\ pcp_daily.csv`):

```
#UTCTIME
DATETIME,81502750
2012-01-01 00:00:00,0
2012-01-02 00:00:00,0
2012-01-03 00:00:00,9.00
2012-01-04 00:00:00,16.50
2012-01-05 00:00:00,16.00
2012-01-06 00:00:00,1.50
```

2:2.4 Meteorological data

The Youwuzhen watershed is characterized by a mid-subtropical monsoon moist climate and has an annual average temperature of 18.3 ℃.

The format of meteorological station is the same as that of precipitation station (see Section 2:2.3.1), e.g., `SEIMS\data\youwuzhen\data_prepare\climate\Sites_M.csv`.

Same to precipitation data, the first line of meteorological data text is to state the time-system and timezone (see Section 2:2.1.2). If not provided, `#UTCTIME` will be regarded as default. The fields and formats of meteorological data are shown in Table 2:2-3.

Note that there are no fixed order of these fields.

Table 2:2-3 Fields and formats of meteorological data item

Field name	Datatype	Description
`StationID`	Integer	Station ID
`DATETIME`	Datetime string	Date time with the format of `YYYY-MM-DD HH:MM:SS`
`TMAX`	Float	Maximum temperature (unit: degC)
`TMIN`	Float	Minimum temperature (unit: degC)
`TMEAN`	Float	(Optional) Mean temperature (unit: degC)
`RM`	Float	Relative moisture (unit: %)
`WS`	Float	Wind speed (unit: m/s)
`SR` or `SSD`	Float	Solar radiation (units: MJ/m2/day) or sunshine duration hour (unit: hr)
`PET`	Float	Potential evapotranspiration (mm)

Thus, the records of meteorological data is something like (`SEIMS\data\youwuzhen\data_prepare\climate\ meteo_daily.csv`):

```
#LOCALTIME 8
StationID,DATETIME,TMEAN,TMAX,TMIN,RM,WS,SSD
58911,2012-01-01 20:00:00,10.0 ,13.6 ,7.8 ,76 ,1.2 ,1.2
58911,2012-01-02 20:00:00,10.6 ,15.7 ,7.0 ,73 ,0.7 ,1.5
58911,2012-01-03 20:00:00,7.1 ,12.0 ,4.6 ,89 ,1.6 ,0.0
58911,2012-01-04 20:00:00,3.9 ,6.6 ,2.5 ,78 ,1.7 ,0.0
```

Besides, the units of each type of data should also be provided, e.g., `SEIMS\data\youwuzhen\data_prepare\climate\Variables.csv`.

***TODO**: In the current version of SEIMS, the units should be the same as Table 2:2-3. However, some unit convert functions should be added in the future to make SEIMS more compatible with common used units.*

2:2.5 Observed data

The periodic site-monitoring streamflow, sediment, or nutrient data collected within the watershed are regarded as observed data. The observed data is organized as one site information file and several data files corresponding to the number of monitoring sites and monitoring variables.

2:2.5.1 Spatial information of monitoring sites

The fields of spatial information of monitoring sites are shown in Table 2:2-4.

Table 2:2-4 Fields of observed data

Field name	Datatype	Description
`StationID`	Integer	Unique station ID
`Name`	String	Station name
`Type`	String	Monitoring variables, use En dash as separator for multiple variables. Avoid En dash in each single `Type`.
`Unit`	String	Units of monitoring variables, use En dash as separator for multiple units. Avoid En dash in each single `Unit`.
`LocalX`	Float	X coordinates (unit: m) under the projected coordinate system
`LocalY`	Float	Y coordinates (unit: m)
`Lat`	Float	Latitude (unit: degree) under the WGS84 coordinate system
`Lon`	Float	Longitude (unit: degree)
`Elevation`	Float	Altitude (unit: m)
`isOutlet`	Integer	Types of monitoring site: 1: The outlet of watershed 2: The outlet of one subbasin 3: The junction of multiple subbasins 0: Other spatial location

For example, `SEIMS\data\youwuzhen\data_prepare\observed\SiteInfo.csv`:

```
StationID,Name,Type,Lat,Lon,LocalX,LocalY,Unit,Elevation,isOutlet
1,hetianzhan,SED,25.680207,116.406401,440409.511725,2841541.17804,g/L,280,1
1,hetianzhan,Q,25.680207,116.406401,440409.511725,2841541.17804,m3/s,280,1
```

Note that the observed data is primarily used for postprocessing such as matching to the corresponding simulated values. Thus, the `Type` should be accord with the output of SEIMS-based watershed model. All the currently available outputs can be found in `SEIMS\seims\preprocess\database\AvailableOutputs.csv`. For example, if the total nitrogen data is monitored, the type should be `CH_TN` according to the value of the `FILENAME` field (obviously, not include the suffix, e.g., '`.txt`') in the output item of total nitrogen amount in reach:

```
MODULE_CLASS,OUTPUTID,DESCRIPTION,UNIT,TYPE,STARTTIME,ENDTIME,INTERVAL,INT
ERVAL_UNIT,SUBBASIN,FILENAME,USE
NutrientTransport,CH_TN,total nitrogen amount in reach,kg,NONE,1970-01-01
00:00:00,1970-01-01 00:00:00,-9999,-9999,ALL,CH_TN.txt,0
```

2:2.5.2 Records of observed data

Similar to the format of precipitation data, the first line is optionally to state the time-system and timezone (see Section 2:2.1.2). If not provided, `#UTCTIME` will be regarded as the default.

The fields and formats of observed data are shown in Table 2:2-5.

Table 2:2-5 Fields and formats of observed data item

Field name	Datatype	Description
`StationID`	Integer	Station ID
`DATETIME`	Datetime string	Date time with the format of `YYYY-MM-DD HH:MM:SS`
`Type`	String	Monitoring variable
`VALUE`	Float	Monitoring value of current variable at the current date time

Thus, the records of observed data is something like (`SEIMS\data\youwuzhen\data_prepare\observed\observed_Q.csv`):

```
#UTCTIME
StationID,DATETIME,Type,VALUE
1,2012-01-14 00:00:00,Q,0.1615
1,2012-01-15 00:00:00,Q,0.578
1,2012-01-16 00:00:00,Q,0.4317
```

2:2.6 Lookup tables

Lookup tables, including crop, fertilizer, tillage, lanuse, soil, and urban, are adopted from SWAT and predefined in `SEIMS\seims\preprocess\database`. Parameters specific to study areas can be appended to these lookup tables or prepared in separate files in `SEIMS\data\youwuzhen\data_prepare\lookup`.

The details of the most common used lookup tables are as follows.

2:2.6.1 Soil properties

Soil properties include physical properties and chemical properties. The fields and descriptions are shown in Table 2:2-6. The optional parameters can be omitted.

Note that the `SEQN` and `NAME` may not consistent with soil types (`SOILCODE`), so that to represent heterogeneity of the same soil type according to different landcover or topographic positions. However, the `SEQN` MUST be consistent with the values in soil map, i.e., `ywzsoil30m.tif`. The soil properties of multiple layers are concatenated with En dash ('`-`') as described in Section 2:2.1.2.

Table 2:2-6 Fields and description in lookup table of soil properties

Field name	Datatype	Unit	Description
`SEQN` or `SOILCODE`	Integer	-	Unique identifier of soil map
`NAME`	String	-	Soil name
`SOILLAYERS`	Integer	-	Number of soil layers
`SOL_Z`	Float array	mm	Depth from soil surface to bottom of layer
`SOL_OM`	Float array	%	Organic matter content
`SOL_CLAY`	Float array	%	Clay content, d < 0.002 mm
`SOL_SILT`	Float array	%	Silt content, 0.002 mm < d < 0.05 mm
`SOL_SAND`	Float array	%	Sand content, 0.05 mm < d < 2 mm
`SOL_ROCK`	Float array	%	Rock fragment content, d > 2 mm
`SOL_BD`	Float array	Mg/m3	Moist bulk density, value ranges 1.1 ~ 1.9
`SOL_AWC`	Float array	mm	Available water capacity
`SOL_ZMX`	Float	mm	(Optional) Maximum rooting depth of soil profile
`ANION_EXCL`	Float	-	(optional) Fraction of porosity (void space) from which anions are excluded, default is 0.5

Field name	Datatype	Unit	Description
SOL_CRK	Float	-	(optional) Potential or maximum crack volume of the soil profile expressed as a fraction of the total soil volume.
SOL_K	Float array	mm/hr	(optional) Saturated hydraulic conductivity
SOL_WP	Float array	mm	(optional) Wilting point
SOL_FC	Float array	mm	(optional) Field capacity
SOL_POROSITY	Float array	-	(optional) Porosity
SOL_USLE_K	Float array	-	(optional) USLE K factor
SOL_ALB	Float	-	(optional) Albedo when soil is moist
ESCO	Float	-	(optional) Soil evaporation compensation factor, the default is 0.95
SOL_NO3	Float array	g/kg	(optional) concentration of nitrate
SOL_NH4	Float array	g/kg	(optional) concentration of ammonium-N in soil
SOL_ORGN	Float array	g/kg	(optional) concentration of organic nitrogen
SOL_ORGP	Float array	g/kg	(optional) concentration of organic phosphorus
SOL_SOLP	Float array	g/kg	(optional) concentration of soluble phosphorus

Thus, the lookup table of soil properties of specific study area is something like (SEIMS\data\youwuzhen\data_prepare\lookup\soil_properties_lookup.csv):

```
SEQN,SNAM,SOILLAYERS,SOL_ZMX,SOL_Z,SOL_BD,SOL_OM,SOL_CLAY,SOL_SILT,SOL_SAND,SOL_ROCK,SOL_WP,SOL_FC,SOL_POROSITY,SOL_K,SOL_AWC,SOL_NO3,SOL_NH4,SOL_ORGN,SOL_SOLP,SOL_ORGP
201,WNT,3,600,200-400-600,1.5-1.57-1.45,2.31-0.84-0.84,15.66-17.36-20.94,13.8-17.31-22.23,52.25-44.6-35.9,18.29-20.73-20.93,0.12-0.14-0.18,0.21-0.24-0.31,0.44-0.41-0.45,26.16-11.43-7.87,0.1-0.1-0.13,0.004-0.002-0.002,0-0-0,0.164-0.079-0.077,0.005-0.002-0.001,0.047-0.018-0.012
```

2:2.6.2 Initial landcover parameters

Some parameters of landcover at the beginning of simulation should be defined. The fields and descriptions are shown in Table 2:2-7.

Table 2:2-7 Fields and descriptions in the lookup table of initial landcover parameters

Field name	Datatype	Unit	Description
LANDUSE_ID	Integer	-	Landuse ID
IGRO	Integer	-	Land cover status: 0-none growing; 1-growing
LANDCOVER	Integer	-	ICNUM, Land cover ID number (required when IGRO

Field name	Datatype	Unit	Description
or ICNUM			is 1)
LAI_INIT	Float	-	Initial leaf area index (required when IGRO is 1)
BIO_INIT	Float	kg/ha	Initial biomass (required when IGRO is 1)
PHU_PLT	Float	degC	Number of heat units to bring plant to maturity (required when IGRO is 1)
EPCO	Float	-	Plant uptake compensation factor, 0.01 ~ 1
RSDIN	Float	kg/ha	Initial residue cover
CURYR_INIT	Float	year	Initial age of trees
CHT	Float	m	Initial canopy height
DORMI	Float	-	Dormancy status code: 1 - growing and 0 - dormancy
USLE_P	Float	-	Conservation practice management factor of USLE

Thus, the lookup table of initial landcover parameters of specific study area is something like (SEIMS\data\youwuzhen\data_prepare\lookup\landcover_initial_parameters.csv):

```
LANDUSE_ID,IGRO,LANDCOVER,LAI_INIT,BIO_INIT,PHU_PLT,EPCO,RSDIN,
CURYR_INIT,CHT,DORMI,USLE_P
33,0,33,0,0,0,1,100,0,0,0,0.084
4,1,4,2,200,0,1,200,2,2,0,0.8
8,1,8,3,1000,0,1,300,5,5,0,0.8
6,1,6,2,600,0,1,200,3,2,0,0.8
18,0,18,0,0,0,0,0,0,0,0,1
104,0,-9999,0,0,0,0,0,0,0,0,1
106,0,-9999,0,0,0,0,0,0,0,0,1
```

2:2.7 Management practices data

There are three different types of Best Management Practices (BMPs) supported or will be supported by SEIMS.

- *Reach BMPs: BMPs that attached to specific reaches and will change the characters of the reach, such as point source, stream flow diversion, reservoir, riparian wetland, and riparian buffer, etc.*
- *Areal structural BMPs: BMPs that are corresponding to a specific structure in the watershed and will change the characters of the specified locations, such as grass waterway, filter strip, pond, isolated wetland, terrace, overland flow diversion, tile drain management, and urban management, etc.*
- *Areal non-structure BMPs: BMPs that are NOT corresponding to a specific structure in the watershed and will change the characters of the specified locations, such as plant management.*

In this section, the organization of BMP scenario is firstly presented, then followed by the detail parameter settings of different BMPs. In the current version of this user manual, plant management and general areal structural BMP are introduced as an example. More BMPs should be updated in the future version.

2:2.7.1 BMP scenario

A BMP scenario is a collection of different BMPs which will be applied to an SEIMS-based watershed model to affect watershed behaviors.

There can be many different BMP scenarios for the BMP scenarios analysis based on one watershed model. Each BMP scenario is identified using a unique integer `ID`. For each BMP of one scenario, the location and parameters must be specified. For reach BMPs, the location is the reach ID. For two areal BMPs, the location is the areas identified by a raster data, i.e., the so-called BMP configuration units. The BMP parameters are defined in separate plain text files, in which different combinations of parameters are allowed and distinguished by unique ID, i.e., `SUBSCENARIO`. The fields and descriptions of BMP scenario table are shown in Table 2:2-8.

Table 2:2-8 Fields and descriptions of BMP scenario table

Field name	Datatype	Description
`ID`	Integer	Unique ID of BMP scenario
`NAME`	String	Scenario name
`BMPID`	Integer	Predefined BMP ID (e.g., `SEIMS\data\youwuzhen\scenario\BMP_index.csv`)
`SUBSCENARIO`	Integer	Sub-scenario ID of BMP defined in specific BMP parameters
`DISTRIBUTION`	String	The format is `<Type>|<Filename>`. `<Type>` may be `REACH` or `RASTER` for reach BMP and areal BMP, respectively. `<Filename>` is the corresponding reach table name or raster filename. For example, `RASTER|LANDUSE` means the configuration of the current areal BMP is based on landuse types.
`COLLECTION`	String	The name of the plain text file that defines the BMP parameters (e.g., `SEIMS\data\youwuzhen\scenario\plant_management.csv`)
`LOCATION`	Integer array	Location values of `DISTRIBUTION` for configuring BMP, e.g., 33 means the BMP will be configured on the landuse use type of 33. Multiple location values are separated by En dash.

Thus, the BMP scenarios table of specific study area is something like (SEIMS\data\youwuzhen\data_prepare\scenario\BMP_scenarios.csv):

```
ID,NAME,BMPID,SUBSCENARIO,DISTRIBUTION,COLLECTION,LOCATION
0,base,12,0,RASTER|LANDUSE,plant_management,33
```

The scenario ID of 0 named base includes one BMP with the BMPID of 12 which is plant management according to BMP_index.csv. The configuration unit of this BMP is based on LANDUSE map and the landuse of 33 will be configured. The parameters of this BMP can be loaded from plant_management.csv and the SUBSCENARIO of 0 will be applied.

2:2.7.2 Plant management

By drawing lessons from the SWAT model, a total of 15 different types of plant management operations are considered in the BMP module of SEIMS. A combination of several plant management operations (e.g., plant, fertilize, harvest, etc.) is regarded as a SUBSCENARIO of plant management practices such as the crop rotation practices with rice and winter wheat. Each management operation of one SUBSCENARIO has the same fields such as Table 2:2-9.

Plant management practices are scheduled according to heat units and/or operation date from local experiences. The operation can be performed if either of the conditions is met. For example, the plant operation is set at 5th, May or HUSC greater or equal to 0.2. If the BASE_HU is used and the HUSC which represents the fraction of annual total heat units (HU) has reached 0.2 at 1st, May, then the plant operation will occur since the HUSC condition is first met than MONTH/DAY.

The type of plant management operation simulated is identified by the code given for the field MGT_OP. The different codes for MGT_OP are:

1. *Plant/beginning of growing season. Initializes the growth of a specific landcover/plant type.*
2. *Irrigation operation. Applies water to the location.*
3. *Fertilizer application. Adds nutrients to the soil.*
4. *Pesticide application. Applies a pesticide to the plant and/or soil.*
5. *Harvest and kill operation. Harvest the portion of the plant designated as yield, removes the yield from the location and converts the remaining plant biomass to residue on the soil surface.*
6. *Tillage operation. Mix the upper soil layers and redistributes the nutrients/chemicals/etc. within those layers.*
7. *Harvest only operation. Harvest the portion of the plant designated as yield and removes the yield from the location, but allows the plant to continue growing. This operation is used for hay cuttings.*
8. *Kill/ending of growing season. Stop all plant growth and covert all plant biomass to residue.*
9. *Grazing operation. Remove plant biomass and allow simultaneous application of manure.*

10. *Auto irrigation initialization. Initialize auto irrigation within the location. This operation applies water whenever the plant experiences a user-specified level of water stress.*
11. *Auto fertilization initialization. Initialize auto fertilization within the location. This operation applies nutrients whenever the plant experiences a user-specified level of nitrogen stress.*
12. *Street sweeping operation. Remove sediment and nutrient build-up on impervious areas in the location. This operation can only be used when the urban build up/wash off routines are activated for the location.*
13. *Release/impound. Release or impound water for rice or other plants.*
14. *Continuous fertilization. Apply fertilizer/manure to the soil surface on a continuous basis.*
15. *Continuous pesticide. Apply pesticides to the soil surface on a continuous basis*
16. *Burning operation. Remove the user-specified portion of pant biomass from the location.*

The parameters of different plant management operations are listed in Table 2:2-10. Please refers to SWAT 2012 Input/Output Documentation[1] for more details of each parameters.

Note that, in order to simulate the water level changes in different growth stages of paddy rice, the parameters of the release/impound operation are expanded than SWAT, i.e., maximum ponding depth (`MAX_PND`), minimum fitting depth (`MIN_FIT`), and maximum fitting depth (`MAX_FIT`).

Table 2:2-9 Fields and descriptions of plant management practices

Field name	Datatype	Description
`SUBSCENARIO`	Integer	Unique sub-scenario ID in current BMP parameters table
`NAME`	String	Sub-Scenario name, e.g., `Crop_rotation`
`LANDUSE_ID`	Integer	Landuse type that the `SUBSCENARIO` can be applied
`SEQUENCE`	Integer	Sequence No. of the plant management related operations of the `SUBSCENARIO`, start from 1
`YEAR`	Integer	Year No. of the `SUBSCENARIO`, start from 1
`MONTH`	Integer	Month of the operation takes place
`DAY`	Integer	Day of the operation takes place
`BASE_HU`	Boolean	Use (1) the fraction of annual total heat units (`HU`) or the

[1] Arnold, J.G.; Kiniry, J.R.; Srinivasan, R.; Williams, J.R.; Haney, E.B.; Neitsch, S.L. Soil and Water Assessment Tool 2012 Input/Output Documentation; Texas Water Resources Institute, 2012, p257-296.

Field name	Datatype	Description
		fraction of total heat units of a plant to reach maturity (PHU) (0)
HUSC	Float	Heat unit scheduling for operation expressed as the fraction of PHU or the fraction of HU if BASE_HU=1
MGT_OP	Integer	Management operation number
MGT<N>	Float array	Operation related parameters. <N> ranges from 1 to 10. Multiple location values are separated by Comma.

Table 2:2-10 Parameters defined for plant management operations

NAME	OP	MGT1	MGT2	MGT3	MGT4	MGT5	MGT6	MGT7	MGT8	MGT9	MGT10
Plant	1	PLANT_ID	NONE	CURYR_MAT	HEAT_UNITS	LAI_INIT	BIO_INIT	HI_TARG	BIO_TARG	CNOP	NONE
Irrigate	2	NONE	IRR_SC	NONE	IRR_AMT	IRR_SALT	IRR_EFM	IRR_SQ	NONE	NONE	IRR_NO
Fertilize	3	FERT_ID	NONE	NONE	FRT_KG	FRT_SURFACE	NONE	NONE	NONE	NONE	NONE
Pesticide	4	PEST_ID	NONE	NONE	PST_KG	PST_DEP	NONE	NONE	NONE	NONE	NONE
Harvest & Kill	5	NONE	NONE	NONE	CNOP	HI_OVR	FRAC_HARVK	NONE	NONE	NONE	NONE
Tillage	6	TILL_ID	NONE	NONE	CNOP	NONE	NONE	NONE	NONE	NONE	NONE
Harvest Only	7	NONE	NONE	NONE	HARVEFF	HI_BMS	HI_RSD	NONE	NONE	NONE	NONE
Kill	8	NONE	NONE	NONE	NONE	NONE	NONE	NONE	NONE	NONE	NONE
Grazing	9	GRZ_DAYS	MANURE_ID	NONE	BIO_EAT	BIO_TRMP	MANURE_KG	NONE	NONE	NONE	NONE
Auto Irrigation	10	WSTRS_ID	IRR_SCA	NONE	AUTO_WSTRS	IRR_EFF	IRR_MX	IRR_ASQ	NONE	NONE	IRR_NOA
Auto Fertilize	11	AFERT_ID	NSTRESS	NONE	AUTO_NSTRS	AUTO_NAPP	AUTO_NYR	AUTO_EFF	AFRT_SURFACE	NONE	NONE
Sweep	12	NONE	NONE	NONE	SWEEPEFF	FR_CURB	NONE	NONE	NONE	NONE	NONE
Release/Impound	13	IMP_TRIG	**MAX_PND**	**MIN_FIT**	**MAX_FIT**	NONE	NONE	NONE	NONE	NONE	NONE
Cont. Fertilize	14	FERT_DAYS	CFRT_ID	IFRT_FREQ	CFRT_KG	NONE	NONE	NONE	NONE	NONE	NONE
Cont. Pesticide	15	IPST_ID	PEST_DAYS	IPST_FREQ	CPST_KG	NONE	NONE	NONE	NONE	NONE	NONE
Burning	16	NONE	NONE	NONE	BURN_FRLB	NONE	NONE	NONE	NONE	NONE	NONE

Note: NONE *means the reserved position for further potential parameters and the default value is 0.*

2:2.7.3 General areal structural BMP

Generally, the areal structural BMP takes effects by modifying watershed modeling related parameters on the locations that configured with BMP. Thus, a general table for areal structural BMP is designed as shown in Table 2:2-11, which basically includes spatial parameters (e.g., suitable `LANDUSE` and `SLPPOS`), environmental effectiveness parameters (e.g., `PARAMETERS` and `EFFECTIVENESS`), and economic benefits (e.g., `CAPEX`, `OPEX`, and `INCOME`).

Note that, fields of the general areal structural BMP can be extended or modified by users according to the requirements of scenario analysis. These fields will be used in the predefined scenario analysis program (e.g., `SEIMS\seims\scenario_analysis\spatialunits`) or other scenario analysis program developed based on the base class in SEIMS (`SEIMS\seims\scenario_analysis`).

Table 2:2-11 Fields and descriptions of general areal structural management practices

Field name	Datatype	Description
`SUBSCENARIO`	Integer	Unique sub-scenario ID in current BMP parameters table
`NAME`	String	Sub-Scenario name, e.g., `closing measures (CM)`
`DESC`	String	Description of BMP
`REFERENCE`	String	Literature reference
`LANDUSE`	String	Suitable landuse types, default is 'ALL'. Multiple landuse types are concatenated by En dash, e.g., '6-8'.
`SLPPOS`	String	Suitable slope positions, default is 'ALL'. Multiple slope position tags are concatenated by En dash, e.g., '4-16'.
`PARAMETERS`	String	Spatial parameters that the BMP affects, the format MUST be: `NAME1:DESC1:CHANGE1:IMPACT1-NAME2:DESC2:CHANGE2:IMPACT2-` where, `NAME` is the parameter's ID, which MUST be one of the `GridFS` file in `SPATIAL` collection in MongoDB, `DESC` is the corresponding description, `CHANGE` is the change method (`VC`,`RC`, or `AC`. `VC`: replace, `RC`: multiply, and `AC`: add), `IMPACT` is the impact value.
`EFFECTIVENESS`	Integer	Overall environmental effectiveness (e.g., reducing soil erosion) grade, range from 1 to 5, with higher-numbered grades representing better effectiveness
`CAPEX`	Float	Initial implementation cost per km^2
`OPEX`	Float	Annual maintenance cost per km^2
`INCOME`	Float	Annual benefit per km^2

One of the general areal structural management practices of the Youwuzhen watershed prepared in

`SEIMS\data\youwuzhen\data_prepare\scenario\areal_struct_management.csv` is as follows:

```
SUBSCENARIO,NAME,DESC,REFERENCE,LANDUSE,SLPPOS,PARAMETERS,EFFECTIVE
NESS,CAPEX,OPEX,INCOME
1,fengjin, CM (closing measures),Qin et al (2018),8-6,1-
4,OM:Organic matter:RC:1.22-Density:bulk density:RC:0.98-
Porosity:Total porosity:RC:1.02-USLE_K:USLE soil
erodibility:RC:1.01-Conductivity:Soil hydraulic
conductivity:RC:0.81-FieldCap:Soil field capacity:RC:1.02-
Wiltingpoint:Wiltingpoint:RC:1.02-SOL_AWC:Soil available
water:RC:1.02-SOL_UL:Soil saturated water:RC:1.02-SOL_CBN:Soil
carbon content:RC:1.22-USLE_P:USLE practice
factor:RC:0.9,3,15.5,1.5,2.0
```

,

which can be parsed as a Python data structure of dictionary like:

```
01 demo_dict = {'NAME': 'fengjin',
02              'DESC': 'CM (closing measures)',
03              'REFERENCE': 'Qin et al (2018)',
04              'LANDUSE': [8, 6],
05              'SLPPOS': [1, 4],
06              'PARAMETERS': [
07                             {'NAME': 'OM',
08                              'DESC': 'ORGANIC MATTER',
09                              'CHANGE': 'RC',
10                              'IMPACT': 1.22
11                              },
12                             {'NAME': 'DENSITY',
13                              'DESC': 'BULK DENSITY',
14                              'CHANGE': 'RC',
15                              'IMPACT': 0.98
16                              }
17                             ],
18              'EFFECTIVENESS': 3,
19              'CAPEX': 15.5,
20              'OPEX': 1.5,
21              'INCOME': 2,
22              }
```

.

2:3. Data preprocessing for watershed modeling

Data preprocessing for watershed modeling is a workflow to extract spatial parameters from various spatial data (e.g., DEM, landuse, and soil map), organize plaintext data (e.g., precipitation and meteorological data, site-monitoring data, and BMP scenarios data), and import these data into MongoDB database of the study area.

2:3.1 Simple usage

For simple usage, open a CMD window, enter the following commands to run the data preprocessing of the Youwuzhen watershed.

```
01 >cd D:\demo\SEIMS\seims\test
02 >D:
03 >python demo_preprocess.py -name youwuzhen
```

The end of runtime logs of the data preprocessing was shown in Figure 2:3-1.

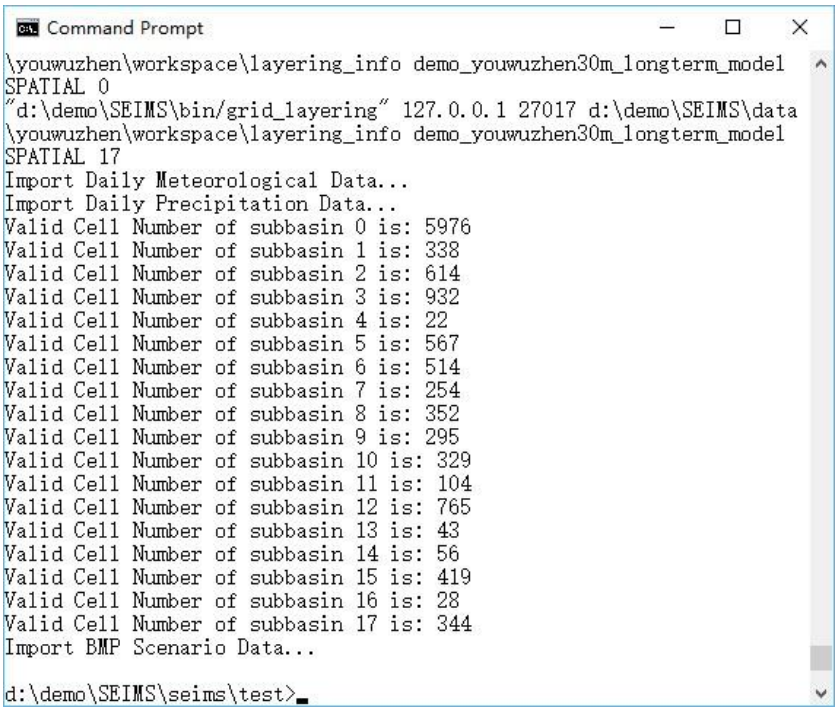


Figure 2:3-1 Runtime logs of data preprocessing for watershed modeling of the Youwuzhen watershed

After running the simple usage, the input configuration file for data preprocessing (`preprocess.ini`) is generated in the directory of intermediate data (i.e., `SEIMS\data\youwuzhen\workspace`, Figure 2:3-2) and the data for watershed modeling has been imported into MongoDB (Figure 2:3-3). The details of the configuration file, advanced usage, intermediate data, and watershed modeling databases will be introduced in the following sections.

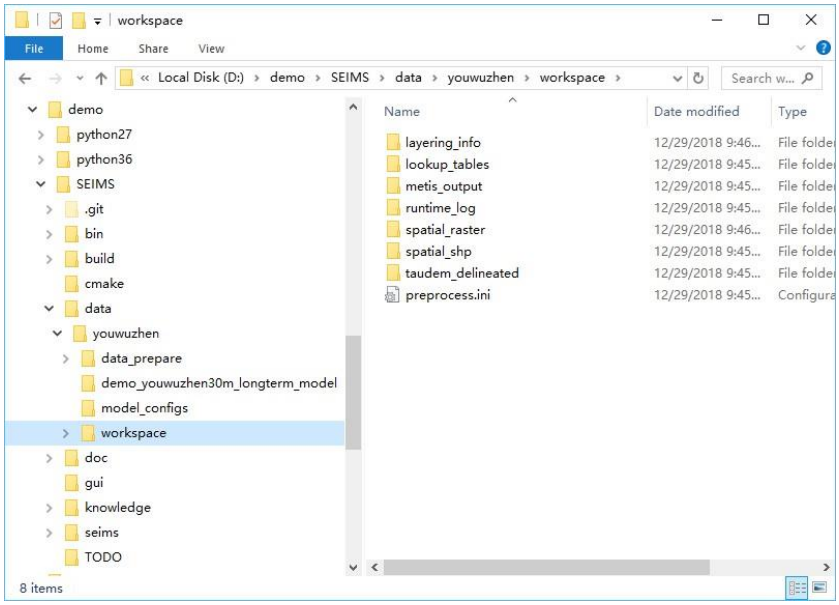


Figure 2:3-2 Directory tree of intermediate data of the Youwuzhen watershed after data preprocessing

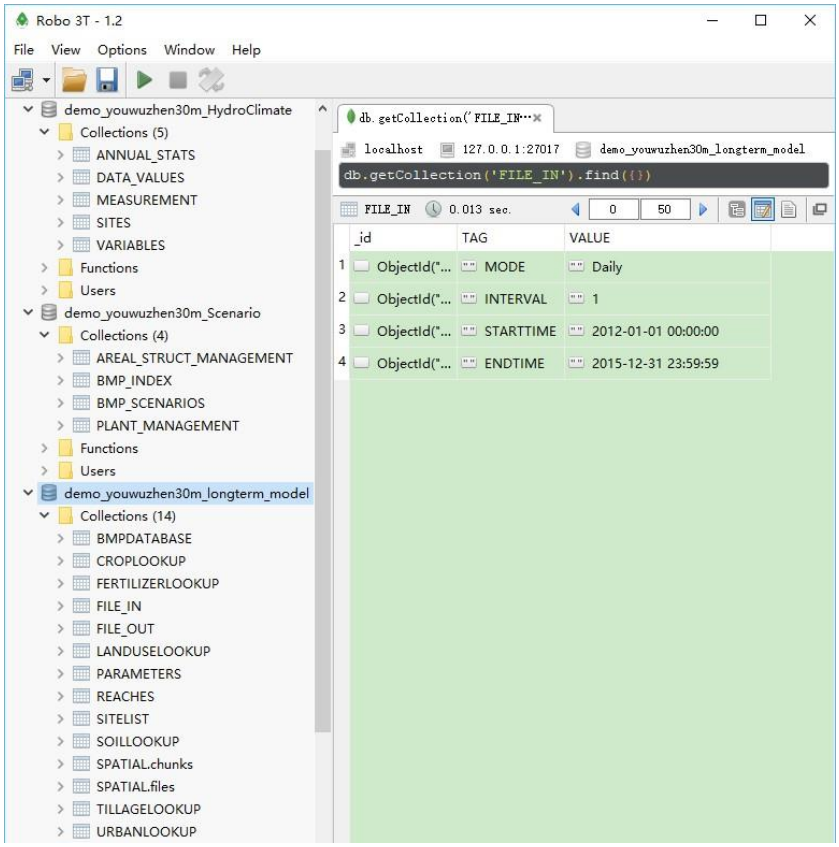


Figure 2:3-3 Screenshot of the watershed modeling databases of the Youwuzhen watershed

2:3.2 Configuration file of data preprocessing

Actually, the simple usage of the data preprocessing includes two steps such as generating the configuration file according to the local paths of SEIMS and executing data preprocessing by the advanced usage which will be introduced in the next section.

SEIMS takes the INI file as the format of configuration files. `INI` files are plain text files with a basic structure composed of sections and options (an option is a pair of property and value). Semicolons (‘`;`’) or number sign (‘`#`’) at the beginning of the line indicate a comment which will be ignored. Figure 2:3-4 showed the data preprocessing configuration content of Youwuzhen watershed.

```
[PATH]
PREPROC_SCRIPT_DIR = d:\demo\SEIMS\seims\preprocess
CPP_PROGRAM_DIR = d:\demo\SEIMS\bin
MPIEXEC_DIR = None
BASE_DATA_DIR = d:\demo\SEIMS\data\youwuzhen
CLIMATE_DATA_DIR = d:\demo\SEIMS\data\youwuzhen\data_prepare\climate
SPATIAL_DATA_DIR = d:\demo\SEIMS\data\youwuzhen\data_prepare\spatial
MEASUREMENT_DATA_DIR = d:\demo\SEIMS\data\youwuzhen\data_prepare\observed
BMP_DATA_DIR = d:\demo\SEIMS\data\youwuzhen\data_prepare\scenario
MODEL_DIR = d:\demo\SEIMS\data\youwuzhen\demo_youwuzhen30m_longterm_model
TXT_DB_DIR = d:\demo\SEIMS\data\youwuzhen\data_prepare\lookup
WORKING_DIR = d:\demo\SEIMS\data\youwuzhen\workspace
[MONGODB]
HOSTNAME = 127.0.0.1
PORT = 27017
ClimateDBName = demo_youwuzhen30m_HydroClimate
BMPScenarioDBName = demo_youwuzhen30m_Scenario
SpatialDBName = demo_youwuzhen30m_longterm_model
[CLIMATE]
HydroClimateVarFile = Variables.csv
MeteoSiteFile = Sites_M.csv
PrecSiteFile = Sites_P.csv
MeteoDataFile = meteo_daily.csv
PrecDataFile = pcp_daily.csv
thiessenIdField = ID
[SPATIAL]
dem = ywzdem30m.tif
outlet_file = outlet_beijing1954.shp
PrecSitesThiessen = thiessen_pcp.shp
MeteoSitesThiessen = thiessen_meteo.shp
landuseFile = ywzlanduse30m.tif
landcoverInitFile = landcover_initial_parameters.csv
soilSEQNFile = ywzsoil30m.tif
soilSEQNText = soil_properties_lookup.csv
field_partition_thresh = 15
[OPTIONAL_PARAMETERS]
D8AccThreshold = 35
np = 4
D8DownMethod = Surface
dorm_hr = -1.
T_base = 0.
imperviousPercInUrbanCell = 0.3
defaultLanduse = 33
defaultSoil = 201
```

Figure 2:3-4 Configuration content for data preprocessing of the Youwuzhen watershed

The configuration file for data preprocessing, such as that of the Youwuzhen watershed shown in Figure 2:3-4, includes five sections, i.e., `PATH`, `MONGODB`, `CLIMATE`, `SPATIAL`, and `OPTIONAL_PARAMETERS`. Several property-value pairs (i.e., options) are included within each section. The names of sections and properties should not be changed. Note that section and property names are not case sensitive in the Windows implementation.

- *`PATH`: Full paths of executables, data, and intermediate workspace.*
  1. `PREPROC_SCRIPT_DIR`*: The path of Python scripts of data preprocessing.*
  2. `CPP_PROGRAM_DIR`*: The install directory of SEIMS C/C++ applications.*
  3. `MPIEXEC_DIR`*: The directory path of the MPI executable, i.e.,* `C:\Program Files\Microsoft MPI\Bin`*. If it has been added to the environment path, the value can be* `None` *or commented.*
  4. `BASE_DATA_DIR`*: The base data directory of the study area.*
  5. `CLIMATE_DATA_DIR`*: (Optional) The path of climate data which include precipitation data (Section 2:2.3) and meteorological data (Section 2:2.4). If not specified (means the option line is commented), SEIMS will try to find climate data in* `BASE_DATA_DIR\data_prepare\climate`*.*
  6. `SPATIAL_DATA_DIR`*: (Optional) The path of spatial data (Section 2:2.1.1). If not specified, SEIMS will try to find spatial data in* `BASE_DATA_DIR\data_prepare\spatial`*.*
  7. `MEASUREMENT_DATA_DIR`*: (Optional) The path of observed data (Section 2:2.5). If not specified, SEIMS will try to find observed data in* `BASE_DATA_DIR\data_prepare\observed`*.*
  8. `BMP_DATA_DIR`*: (Optional) The path of BMP scenarios data (Section 2:2.7). If not specified, SEIMS will try to find scenario data in* `BASE_DATA_DIR\data_prepare\scenario`*.*
  9. `MODEL_DIR`*: The model path of the study area which includes several configuration files for the watershed modeling. For data preprocessing, the* `file.in` *and* `file.out` *are required, the calibrated parameters* `param.cali` *is optional. Details of the file structure of model folder will be introduced in Section 2:4.2.*
  10. `TXT_DB_DIR`*: (Optional) The path of additional lookup tables (Section 2:2.6). If not specified, SEIMS will try to find lookup tables in* `BASE_DATA_DIR\data_prepare\lookup`*.*
  11. `WORKING_DIR`*: (Optional) Workspace for intermediate data. If not specified, SEIMS will use the default path of* `BASE_DATA_DIR\workspace`*.*
- *`MONGODB`: MongoDB related settings.*
  1. `HOSTNAME`*: IP address of MongoDB server, e.g., 127.0.0.1 (i.e., localhost).*
  2. `PORT`*: Port of MongoDB server, e.g., 27017 by the default.*
  3. `SpatialDBName`*: Name of the main spatial database of the study area created in MongoDB server (Figure 2:3-3). The name* ***MUST*** *be the same with the folder name of* `MODEL_DIR`*.*

4. `ClimateDBName`: *Name of the hydro-climate database created in MongoDB server (Figure 2:3-3).*
5. `BMPScenarioDBName`: *Name of the BMP scenarios database created in MongoDB server (Figure 2:3-3).*

- `CLIMATE`: *Filenames of climate data located in* `CLIMATE_DATA_DIR`.
  1. `HydroClimateVarFile`: *Types and Units of climate data variables (Section 2:2.4).*
  2. `MeteoSiteFile`: *The spatial information of meteorological station (Section 2:2.4).*
  3. `PrecSiteFile`: *The spatial information of precipitation station (Section 2:2.3.1)*
  4. `MeteoDataFile`: *The meteorological data (Section 2:2.4).*
  5. `PrecDataFile`: *The precipitation data (Section 2:2.3.2).*
  6. `thiessenIdField`: *(Optional) The field ID in the Thiessen polygon files of climate sites (Section 2:2.2), the default is* `ID`.
- `SPATIAL`: *Filenames of spatial data located in* `SPATIAL_DATA_DIR` *and* `TXT_DB_DIR`.
  1. `dem`: *The original DEM data.*
  2. `outlet_file`: *(Optional) The outlet of the study area.*
  3. `PrecSitesThiessen`: *The Thiessen polygon file of precipitation stations.*
  4. `MeteoSitesThiessen`: *The Thiessen polygon file of meteorological stations.*
  5. `landuseFile`: *The raster file of landuse types.*
  6. `landcoverInitFile`: *The lookup table of initial landcover parameters (Section 2:2.6.2).*
  7. `soilSEQNFile`: *The raster file of soil sequences.*
  8. `soilSEQNText`: *The lookup table of soil properties (Section 2:2.6.1).*
  9. `field_partition_thresh`: *(Optional) Threshold values for the delineation of hydrologically connected fields (Wu et al., 2018). Multiple thresholds can be specified such as* `10,15,20`. *The partitioned fields named* `fields_<threshold>.tif` *(e.g.,* `fields_15.tif`*) will be imported into the main spatial database (i.e.,* `SpatialDBName`*). In the meantime, a* `json` *formatted file named* `connected_field_units_updown_<threshold>.json` *will be generated in the* `MODEL_DIR`*, which describes the upstream and downstream relationships of fields and landuse information, etc. The hydrologically connected fields can be used as BMP configuration units for BMP scenarios analysis (see Section 2:8).*
- `OPTIONAL_PARAMETERS`: *Optional parameters.*
  1. `D8AccThreshold`: *Flow accumulation threshold for stream and subbasin delineation, the default is 0. In such circumstance, the determination of threshold will be performed by the drop analysis function of TauDEM automatically.*
  2. `np`: *Number of processes for MPI-based parallel computing of C++ applications, e.g., TauDEM functions. The default is 4.*
  3. `D8DownMethod`: *Calculation method of distance down to a stream, the available values are* `pythagoras`, `horizontal`, `vertical`, *and* `surface`, *or* `p`, `h`, `v`, *and* `s` *for simplification, respectively. The default is* `surface` *or* `s`. *More information can be referred to* http://hydrology.usu.edu/taudem/taudem5/help53/DInfinityDistanceDown.html.

4. `dorm_hr`*: Day length threshold hours for dormancy, the default is -1.*
5. `T_base`*: Base temperature (degC) for heat unit calculation, the default is 0.*
6. `imperviousPercInUrbanCell`*: Impervious percent in urban units, the default is 0.3.*
7. `defaultLanduse`*: The default landuse type for* `NoData` *area.*
8. `defaultSoil`*: The default soil sequence type for* `NoData` *area.*

2:3.3 Advanced usage

The Python scripts of data preprocessing are located in `SEIMS/seims/preprocess`. The prefix of script names are distinguished by functionality, i.e., '`sd_`' for the spatial discretization of watershed (e.g., the delineation of subbasins), '`sp_`' for the extraction of spatial parameters (e.g., landuse and soil related parameters according to the database of SWAT model and additional lookup tables, Section 2:2.6), '`hydro_`' for the data processing of hydrology and climate data, and '`db_`' for the input and/or output of MongoDB database. The `main.py` is the entrance for the entire workflow of data preprocessing. Each script can be executed independently though the unified format:

`python <script_name> -ini </path/to/configuration-file>`.

For example, to run the entire workflow:

```
01 >cd D:\demo\SEIMS\seims\preprocess
02 >python main.py -ini
D:\demo\SEIMS\data\youwuzhen\workspace\preprocess.ini
```

If the BMP scenarios related data needs to be updated, there is only need to run the script of importing BMP scenarios data into MongoDB, i.e.,

```
01 >cd D:\demo\SEIMS\seims\preprocess
02 >python db_import_bmpscenario.py -ini
D:\demo\SEIMS\data\youwuzhen\workspace\preprocess.ini
```

The entire workflow of preprocessing can be conducted in two main steps, i.e., the spatial discretization of watershed (i.e., `sd_delineation.py`) and the creation of MongoDB database (i.e., `db_build_mongodb.py`). Users are highly recommended to execute `sd_delineation.py` with the `D8AccThreshold` set to 0 first to get a preliminary delineation of subbasins. The automatically delineated subbasin may too fine to get a proper spatial scale for watershed modeling. Therefore, users may want to adjust the proper threshold manually according to the flow accumulated raster (i.e., `SEIMS\data\youwuzhen\workspace\taudem_delineated\accTauD8WithWeight.tif`, more information about the intermediate data will be described in the following section). After a final threshold is determined and the value of `D8AccThreshold` in the configuration file updated, the `main.py` should be rerun for the entire preprocessing.

Note that the present implementation of data preprocessing tools is to support the currently available SEIMS modules of watershed processes. That means, if the input data of a newly developed module is not available from the database or outputs of other modules, the corresponding preprocessing tools should added. For more information, please referred to the "Section 4:1 Develop a new module of one watershed process".

2:3.4 Intermediate data of preprocessing

As is shown in Figure 2:3-2, the intermediate data of data preprocessing are organized into seven folders.

- *`taudem_delineated`: The original results and intermediate data of spatial delineation of subbasins based on TauDEM such as the flow accumulation data (`accTauD8WithWeight.tif`), the delineated subbasin data (`subbasinTauM.tif`), and the D8 flow direction masked by `subbasinTauM.tif` (`flowDirTauM.tif`), etc.*
- *`lookup_tables`: Lookup tables of landuse database based on the SWAT model used for generating landuse type related parameters.*

  ***TODO**: In the current version of SEIMS, landuse and soil type related spatial parameters (raster data) are prepared and imported into MongoDB separately as single files (i.e., GridFS in MongoDB). This solution will lead to the low performance of reading data of SEIMS main program. Therefore, in the future version, lookup tables should be used instead of separated raster- or array-based parameters.*

- *`spatial_raster`: All spatial parameters (raster data) masked by the delineated watershed boundary (i.e., `subbasinTauM.tif`).*
- *`spatial_shp`: Spatial vector data for the whole watershed and each subbasin, e.g., `reach_<N>.shp` (`N` represents the subbasin number starts from 1, while `reach.shp` is for the whole watershed), `subbasin_<N>.shp`, `basin.shp`, and `outlet.shp`.*
- *`layering_info`: The flow in and out indexes of each basic simulation units (e.g., gridded cells and irregularly shaped fields), and the routing layers of `UPDOWN` (default, layering from source) and `DOWNUP` (layering from outlet) methods based on flow direction algorithms.*
- *`metis_output`: Groups partitioned by METIS software for static task scheduling of MPI-based parallel computing at subbasin levels. For example, the results of `metis.part.4` located in `SEIMS\data\youwuzhen\workspace\metis_output\kmetis` is*

  `3 0 2 1 1 3 1 3 2 0 2 0 2 1 1 1 3`*, which means that the 17 subbasins of the Youwuzhen watershed will be distributed on four processes, i.e., subbasin IDs of (2, 10, 12), (4, 5, 7, 14, 15, 16), (3, 9, 11, 13), and (1, 6, 8, 17).*
- *`runtime_log`: Runtime logs (with prefix of '`status_`') and several input configuration files of SEIMS C++ applications (with prefix of '`config_`').*

2:3.5 Structure of the watershed modeling database

The screenshot of the structure of the watershed modeling database was shown in Figure 2:3-3. Three databases were created with the specific names in the configuration `INI` file of data preprocessing (Section 2:3.2). The preprocessed data were organized as different collections (or referred to as tables) within database.

- *`demo_youwuzhen30m_longterm_model`: Main spatial database of the study area*
  1. *Model configuration collections, such as `FILE_IN` and `FILE_OUT`.*

2. *Initial model parameters including calibration information, i.e.,* `PARAMETERS`.
3. *Reach related parameters, i.e.,* `REACHES`*, including geometric parameters, default chemical parameters, and subbasin groups for task scheduling of MPI-based parallel computing, etc.*
4. *Climate station information for each subbasin with the corresponding HydroClimate database name, i.e.,* `SITELIST`.
5. *BMP scenario database name, i.e.,* `BMPDATABASE`.
6. *Spatial parameters, i.e.,* `SPATIAL`.
7. *Lookup tables, i.e.,* `CROPLOOKUP`, `FERTILIZERLOOKUP`, `LANDUSELOOKUP`, `SOILLOOKUP`, `TILLAGELOOKUP`*, and* `URBANLOOKUP`.

- *`demo_youwuzhen30m_HydroClimate`: Hydro-climate database*
  1. *Climate and hydrology stations, i.e.,* `SITES`.
  2. *Climate data (*`DATA_VALUES`*) and hydrologic monitoring data (*`MEASUREMENT`*).*
  3. *Annual statistics of climate data, i.e.,* `ANNUAL_STATS`.
  4. *Types and units of hydro-climate variables, i.e.,* `VARIABLES`.
- *`demo_youwuzhen30m_Scenario`: BMPs scenario database*
  1. *BMP IDs, i.e.,* `BMP_INDEX`.
  2. *BMP scenarios, i.e.,* `BMP_SCENARIOS`.
  3. *Various BMPs parameters, the collection names are depend on the plain text filename located in management practices data (e.g.,* `SEIMS\data\youwuzhen\data_prepare\scenario`*), such as* `PLANT_MANAGEMENT` *and* `AREAL_STRUCT_MANAGEMENT` *in this demo study.*

2:4. Running a SEIMS-based watershed model

2:4.1 Simple usage

For simple usage, open a CMD window, enter the following commands to execute the predefined SEIMS-based watershed model of the Youwuzhen watershed (hereafter referred to as the Youwuzhen watershed model).

```
01 >cd D:\demo\SEIMS\seims\test
02 >D:
03 >python demo_runmodel.py -name yuouwuzhen
```

The simulation will be finished in a ~28 seconds (Figure 2:4-1). The predefined output information can be found in the model folder (i.e., `MODEL_DIR\OUTPUT0`), such as Figure 2:4-2.

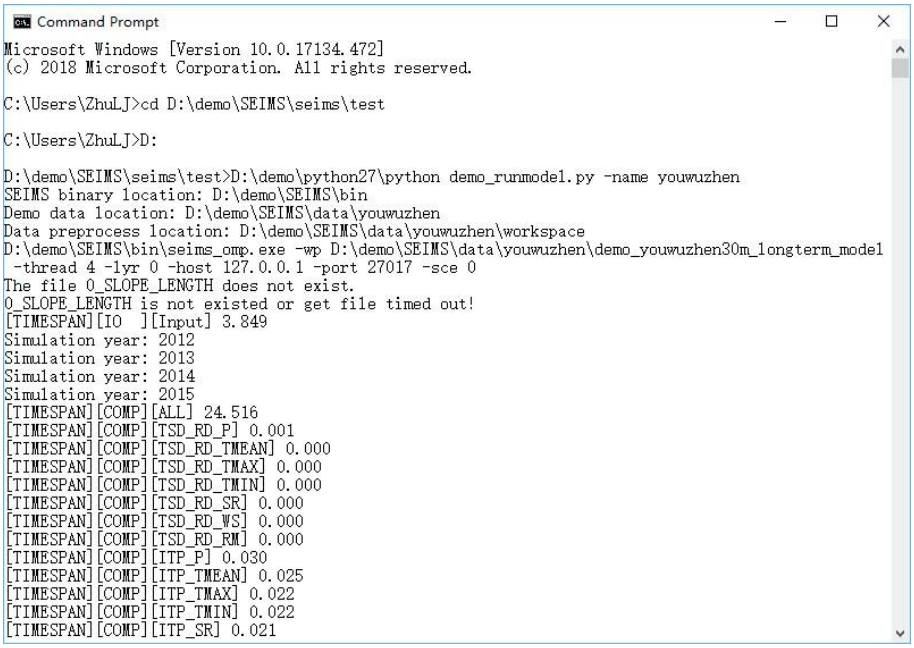


Figure 2:4-1 Simple usage of the OpenMP version of the Youwuzhen watershed model

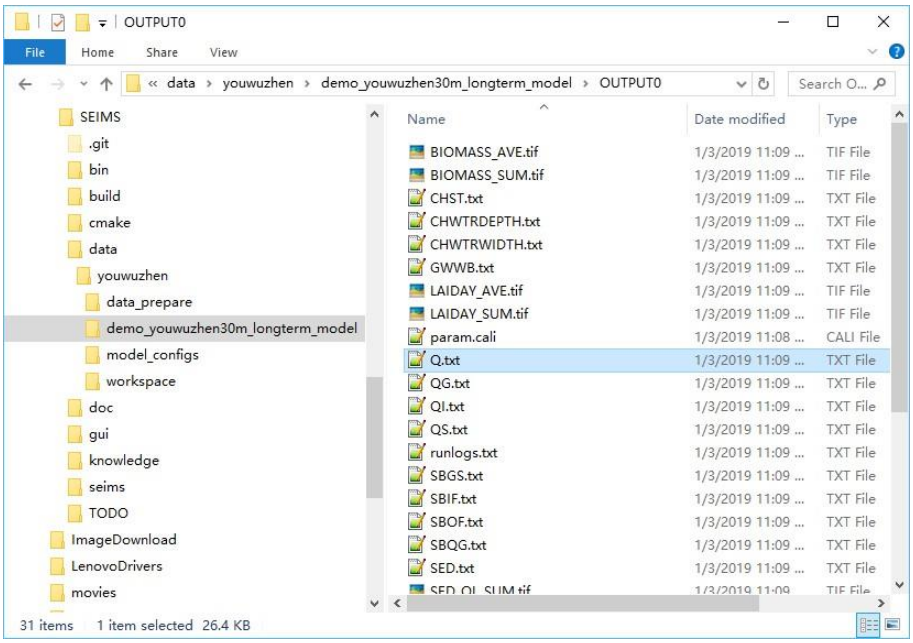


Figure 2:4-2 Predefined outputs of the Youwuzhen watershed model

2:4.2 File structure of a SEIMS-based watershed model

In simple terms, a SEIMS-based watershed model is a folder (e.g., `SEIMS\data\youwuzhen\demo_youwuzhen30m_longterm_model`) which consists of several SEIMS configuration files such as `file.in`, `file.out`, `param.cali`, and `config.fig`.

The `file.in` and `file.out` for basic model configuration are required, while `param.cali` for calibrated model parameters is optional. These three plain text files will be read and imported into the main spatial database during data preprocessing (Section 2:3.2). The MongoDB also can be updated by only running a single preprocessing Python script (i.e., `SEIMS\seims\preprocess\db_import_model_parameters.py`) when these files are changed such as during the manual calibration.

The `config.fig` file, the most important configuration file for constructing a SEIMS-based watershed model, is responsible for selecting SEIMS modules to participate in the watershed simulation, as well as specifying the simulation order of SEIMS modules.

2:4.2.1 file.in

The `file.in` file is designed to define the simulation mode with time-step and the simulation period. Different from the plain text format described in Section 2:2.1.2, the basic format is `[TAG]|[VALUE]`. Currently, there are four required `TAG`s which must appear in this file.

- `MODE`*: A string that indicates a long-term or storm event simulation. The string here can only be* `Daily` *or* `Storm` *(case insensitive).*

- `INTERVAL`*: An integer to specify the time-step (or the so-called temporal resolution) of simulation according to the simulation* `MODE`*. For long-term simulation, the unit is day, e.g.,* `INTERVAL|1` *means the time-step is one day. For storm event simulation, the unit is second, e.g.,* `INTERVAL|3600` *means the time-step is one hour. Specifically, two different time-steps can be assigned for storm event simulation considering the differences between hillslope scale processes and channel scale process. For example,* `INTERVAL|60,3600` *means that the time-step for hillslope scale processes is one minute and one hour for channel scale processes.*
- `STARTTIME`*: Starting date time of simulation with the format of* `YYYY-MM-DD HH:MM:SS`
- `ENDTIME`*: Ending date time of simulation with the format of* `YYYY-MM-DD HH:MM:SS`

For the Youwuzhen watershed model, which performs a long-term simulation with a time-step of one day and runs from Jan 1, 2012, to Dec 31, 2015, the content of `file.in` file is as follows.

```
MODE|Daily
INTERVAL|1
STARTTIME|2012-01-01 00:00:00
ENDTIME|2015-12-31 23:59:59
```

2:4.2.2 file.out

The `file.out` file is designed to define the outputs of a SEIMS-based watershed model. The format follows the plain text format described in Section 2:2.1.2. Each line is corresponding to one output variable. The available fields of each line are listed in Table 2:4-1.

Table 2:4-1 Available fields of `file.out` configuration file

Field name	Datatype	Description
`OUTPUTID`	String	Unique output identifier, e.g., `QRECH` for the streamflow at reach outlet.
`TYPE`	String	Data aggregation type for spatial data outputs, i.e., `SUM`, `AVE`, `MAX`, and `MIN`. Multiple types should be concatenated by En dash. For example, `SUM-AVE` means output the sum and average simultaneously. For time-series outputs, the `TYPE` can be `NONE`.
`STARTTIME`	Datetime string	Starting date time for the current output with the format of `YYYY-MM-DD HH:MM:SS`
`ENDTIME`	Datetime string	Ending date time for the current output with the format of `YYYY-MM-DD HH:MM:SS`
`INTERVAL`	Integer	Time-step for output. The default is `-9999`, which means the same time-step with the simulation will be used.

Field name	Datatype	Description
INTERVAL_UNIT	String	Unit for INTERVAL, can be DAY and SEC. The default is -9999, which means the same with the simulation.
FILENAME	String	Output filename with suffix, e.g., Q.txt and PET.tif.
SUBBASIN	String or Integer	Selected subbasins for output, can be ALL, OUTLET, or the subbasin IDs concatenated with En dash, e.g., 1-4-5.

Among these fields, only the OUTPUTID is required. The values of missed fields will adopted the default values defined in the available output database which can be extended by users, i.e., SEIMS\seims\preprocess\database\AvailableOutputs.csv. So, users can specify the outputs of QRECH (Streamflow at reach outlet of each time step, m^3/s) and PET (Potential evapotranspiration, mm) by simply specifying the output IDs, e.g.,

```
OUTPUTID
QRECH
PET
```

, or specifying more detail information, e.g.,

```
OUTPUTID,TYPE,STARTTIME,ENDTIME,INTERVAL,INTERVAL_UNIT,SUBBASIN
QRECH,NONE,2012-01-01 00:00:00,2015-12-31 23:59:59,1,DAY,OUTLET
PET,SUM-AVE,2012-01-01 00:00:00,2015-12-31 23:59:59,-9999,-9999,ALL
```

.

2:4.2.3 param.cali

The param.cali file is designed to define calibrated parameters. The absent of this file or a blank file is allowed and indicates the model will be executed with default parameter values. The format MUST be NAME, IMPACT, and CHANGE, while CHANGE is optional and no header line is allowed. The NAME MUST be one of the predefined list of parameters which can be extended by users, i.e., SEIMS\seims\preprocess\database\model_param_ini.csv. The CHANGE means the type of impact on the parameter, which can be RC (relative change) or AC (absolute change). The IMPACT is a float value of change, for RC, the new parameter value will be *initial_value * impact*, while for AC it is *initial_value + impact*.

Thus, three styles are accepted in param.cali file, such as:

```
Runoff_co,1.5
gw0,-50,
K_pet,-0.3,AC
```

.

2:4.2.4 config.fig

The config.fig file is designed to define SEIMS modules used in a SEIMS-based watershed model. The sequences of these modules will be the execution order during simulation. The basic order of SEIMS modules should be driver factors (i.e., climate data) related modules, modules of hillslope processes, and modules of channel and

groundwater routing processes, such as the `config.fig` content of the Youwuzhen watershed model in Figure 2:4-3. More details about the selected modules of the Youwuzhen watershed model can be found in Qin et al. (2018).

```
### Driver factors, including meteorological data and precipitation
0 | TimeSeries | | TSD_RD
0 | Interpolation_0 | Thiessen | ITP
### Surface processes
0 | Soil temperature | Finn Plauborg | STP_FP
0 | PET | PenmanMonteith | PET_PM
0 | Interception | Maximum Canopy Storage | PI_MCS
0 | Snow melt | Snowpeak Daily | SNO_SP
0 | Infiltration | Modified rational | SUR_MR
0 | Depression and Surface Runoff | Linsley | DEP_LINSLEY
0 | Hillslope erosion | MUSLE | SERO_MUSLE
0 | Plant Management Operation | SWAT | PLTMGT_SWAT
0 | Percolation | Storage routing | PER_STR
0 | Subsurface | Darcy and Kinematic | SSR_DA
0 | SET | Linearly Method from WetSpa | SET_LM
0 | PG | Simplified EPIC | PG_EPIC
0 | ATMDEP | Atomosphere deposition | ATMDEP
0 | NUTR_TF | Nutrient Transformation of C, N, and P | NUTR_TF
0 | Water overland routing | IUH | IUH_OL
0 | Sediment overland routing | IUH | IUH_SED_OL
0 | Nutrient | Attached nutrient loss | NUTRSED
0 | Nutrient | Soluble nutrient loss | NUTRMV
0 | Pothole | SWAT cone shape | IMP_SWAT
0 | Soil water | Water balance | SOL_WB
### Route Modules, including water, sediment, and nutrient
0 | Groundwater | Linear reservoir | GWA_RE
0 | Nutrient | groundwater nutrient transport | NUTRGW
0 | Water channel routing | MUSK | MUSK_CH
0 | Sediment channel routing | Simplified Bagnold equation | SEDR_SBAGNOLD
0 | Nutrient | Channel routing | NutrCH_QUAL2E
```

Figure 2:4-3 SEIMS modules involved in the demo Youwuzhen watershed model

As shown in Figure 2:4-3, different from the plain text format described in Section 2:2.1.2, the basic format for each selected SEIMS module is `[MODULE NO.]|[PROCESS NAME]|[METHOD NAME]|[MODULE ID]`, in which,

- `MODULE NO.` *could be any number*
- `PROCESS NAME` *is the name of the corresponding watershed process*
- `METHOD NAME` *is the name of the algorithm to simulate the watershed process*
- `MODULE ID` *is the ID of the SEIMS module, i.e., the file name of the corresponding dynamic library (*`dll`*,* `so`*, or* `dylib`*) file. If the module cannot be located or loaded, SEIMS will exit and report an error.*

SEIMS main program only uses the `PROCESS NAME` and `MODULE ID`, while the `MODULE NO.` and `METHOD NAME` are just designed for readability. The `MODULE ID` should match

exactly with the ID of SEIMS module. The `PROCESS NAME` may contains extra configuration information for some modules.

- *For interpolation modules, the vertical interpolation method (0 means do not perform vertical interpolation based on lapse rate, while 1 means do) must be specified as suffix of the* `PROCESS NAME`*, e.g.,*

  `0 | Interpolation_1 | Thiessen | ITP`

***TODO**: In the current version of SEIMS, the lapse rate of precipitation and temperature are defined as constants, i.e., 0.03 mm/100 m for precipitation and -0.65 degC/100 m for temperature. In the future development, the lapse rate of various meteorological variables should be allowed as inputs according to the study area.*

2:4.3 Advanced usage

The SEIMS main programs include an OpenMP version (i.e., `seims_omp`) and a version which is a hybrid of OpenMP and MPI (hereafter referred to as MPI&OpenMP version, i.e., `seims_mpi`). In the OpenMP version, parallel computing is conducted at the basic-unit level (e.g., gridded cells or irregularly shaped fields) in each module based on OpenMP. In the MPI&OpenMP version, the watershed is first decomposed into subbasins, and MPI-based parallel computation is conducted at the subbasin level. And then within each subbasin, same as the OpenMP version, OpenMP-based parallel computation is conducted at the basic-unit level.

***Note**: If OpenMP is not supported by the C/C++ compiler, the OpenMP-based parallel computing will not take affect and the executable name of SEIMS main program will be* `seims`*.*

2:4.3.1 Run with command line interface

The Command Line Interface (CLI) is the recommended way to run SEIMS-based watershed model. The invoking commands are slightly different between the OpenMP version and MPI&OpenMP version.

2:4.3.1.1 OpenMP version

As is shown in Figure 2:1-8, the complete and recommended usage of the OpenMP version of SEIMS main program is as follows.

```
seims_omp -wp <modelPath> [-thread <threadsNum> -lyr
<layeringMethod> -host <hostname> -port <port> -sce
<scenarioID> -cali <calibrationID> -id <subbasinID>]
```

In which,

1. `modelPath` *is the path of the SEIMS-based watershed model (see* `MODEL_DIR` *in the configuration file of data preprocessing, Section 2:3.2).*
2. `threadsNum` *(Optional) is the number of threads used for OpenMP-based parallel computing, which must be greater or equal than 1 (default).*

3. `layeringMethod` *(Optional) can be 0 and 1, which means the routing layering method based on flow direction algorithms of* `UPDOWN` *(default, layering from source) and* `DOWNUP` *(layering from outlet), respectively.*
4. `hostname` *is the IP address of MongoDB server. The default is 127.0.0.1 (i.e., localhost).*
5. `port` *is the port number of MongoDB server, and the default is 27017.*
6. `scenarioID` *is the ID of BMP scenario which has been defined in the* `BMP_SCENARIOS` *collection of Scenario database. By default, the* `scenarioID` *is -1, which means no scenario will be applied.*
7. `calibrationID` *is the ID (i.e., index) of calibration data which has been defined in* `PARAMETERS` *collection of the main database. By default, the* `calibrationID` *is -1, which means no calibration will be applied.*
8. `subbasinID` *is the subbasin that will be executed. 0 means the whole watershed. 9999 is reserved for Field version.*

For the Youwuzhen watershed, one of the complete usages is like:

```
01 >cd D:\demo\SEIMS\bin
02 >D:
03 >seims_omp -wp
D:\demo\SEIMS\data\youwuzhen\demo_youwuzhen30m_longterm_model
-thread 4 -lyr 1 -host 127.0.0.1 -port 27017 -sce 0
```

The runtime logs of the OpenMP version was shown in Figure 2:4-1, in which the time-consuming of data Input/Output (IO), computation of each module, and entire simulation were shown.

The output folder was created in the model directory with the folder name followed a naming format of `OUTPUT-<scenarioID>-<calibrationID>`. For example,

- `OUTPUT-1` *means no scenario and calibration ID is 1*
- `OUTPUT100` *means scenario ID is 100 and no calibration*
- `OUTPUT100-2` *means scenario ID is 100 and calibration ID is 2.*

2:4.3.1.2 MPI&OpenMP version

The MPI&OpenMP version of SEIMS main program has the same arguments with the OpenMP version but the different way of invoking it (Figure 3:1-1). The basic format to run a MPI program is:

```
mpiexec -<hostsopt> <hostfile> -n <processNum> seims_mpi -
wp <modelPath> [-thread <threadsNum> -lyr <layeringMethod>
-host <hostname> -port <port> -sce <scenarioID> -cali
<calibrationID> -id <subbasinID>]
```

In which,

1. `hostopt` *(Optional) is the identifier of the input argument of MPI to specify a host list file which is various with different MPI implementations, e.g.,* `-machinefile` *or* `-hostfile`*.*
2. `hostfile` *(Optional) is the host list file which may different with MPI implementation. For example, OpenMPI takes the format like:*

   ```
   b10n08.cluster.com slots=3 max-slots=3
   b08n01.cluster.com slots=4 max-slots=4
   b10n05.cluster.com slots=4 max-slots=4
   ```

   and IntelMPI uses:

   ```
   b10n08.cluster.com 3
   b08n01.cluster.com 4
   b10n05.cluster.com 4
   ```

3. `processNum` *(Optional) is the number of processes.*

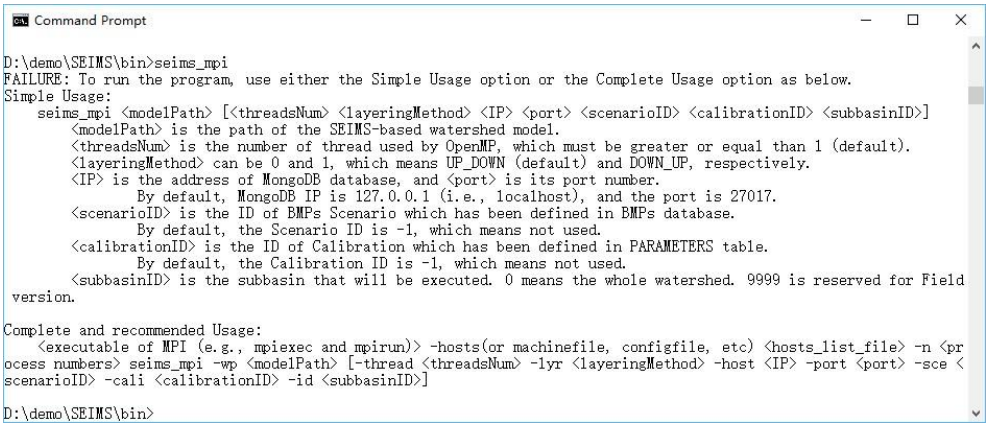


Figure 2:4-4 Usage of the MPI&OpenMP version of SEIMS main program

For the Youwuzhen watershed, one of the complete usages for the MPI&OpenMP version on Windows platform is like:

```
01 >cd D:\demo\SEIMS\bin
02 >D:
03 >mpiexec -n 4 seims_mpi -wp
D:\demo\SEIMS\data\youwuzhen\demo_youwuzhen30m_longterm_model
-thread 1 -lyr 1 -host 127.0.0.1 -port 27017 -sce 0
```

The corresponding runtime output logs was shown in Figure 2:4-5. Different from the output information of the OpenMP version (Figure 2:4-1), the maximum (`[TIMESPAN][MAX]`), minimum (`[TIMESPAN][MIN]`), and average (`[TIMESPAN][AVG]`) time-consuming of data IO, computation of all modules, and entire simulation derived from each process (i.e., four processes of MPI in this example) are given. The maximum time-consuming is the most commonly used statistics for the evaluation of parallel performance.

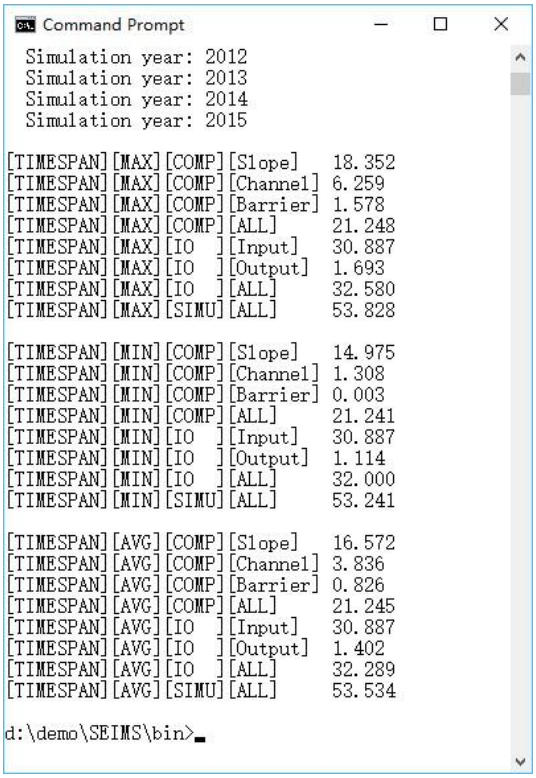


Figure 2:4-5 Runtime logs of the MPI&OpenMP version of the Youwuzhen watershed model

To demonstrate the parallel performance of the MPI&OpenMP version, a Linux cluster with IBM Platform LSF for workload management is used. One example that utilize 12 cores (i.e., 12 processes created by MPI) from 4 computing node and 2 threads per process is shown in Figure 2:4-6. A job script (i.e., `run_ywz30m_mpi_proc12_thread2.lsf` in Figure 2:4-6) was first created which includes the generation of a hosts list file that allocated by LSF and the settings of paths and commands for the execution of the Youwuzhen watershed model. Then the job script was submitted by `bsub` command. As is shown in Figure 2:4-6, four computing node (i.e., b07n04, b07n05, n09n12, and b06n14) were allocated to execute the job. According to the runtime logs, the maximum computing time of simulation among the 12 processes is 7.684 s which is much more effective than those single model runs executed on one laptop (Figure 2:4-1 and Figure 2:4-5).

More information about the parallel performance tests of a single run of the SEIMS-based watershed model can be referred to Zhu et al. (*Environ. Model. Softw.*, *under review*).

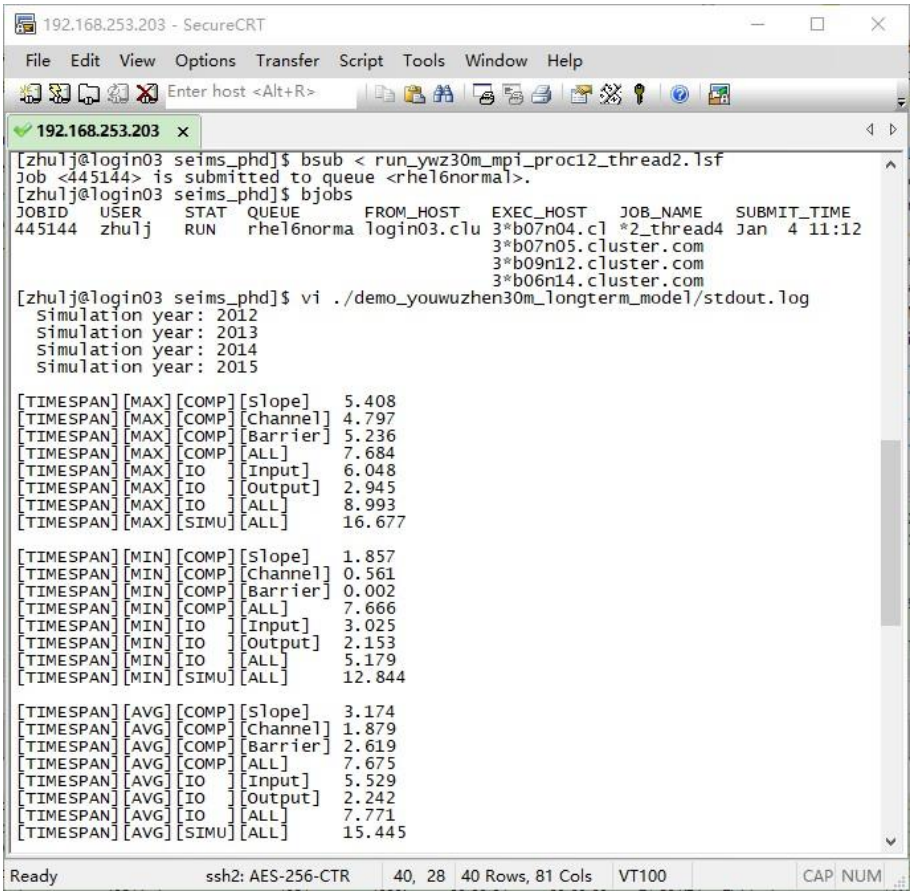


Figure 2:4-6 Run the MPI&OpenMP version of the Youwuzhen watershed model on a Linux cluster

2:4.3.2 Run with Python

Except for the CLI way, SEIMS also provides a configuration file based method to execute model with Python. Same with the simple usage of data preprocessing (2:3.2), a configuration file was also generated according to the local paths of SEIMS during the simple usage of running the Youwuzhen watershed model, such as `SEIMS\data\youwuzhen\workspace\runmodel.ini` (Figure 2:4-7).

The configuration file of running SEIMS-based watershed model, such as that of the Youwuzhen watershed model shown in Figure 2:4-7, includes several options within one section (i.e., `SEIMS_Model`) to specify the arguments of SEIMS main programs introduced in previous sections. The full list of the arguments are as follows.

- *`SEIMS_Model`:*
  1. `MODEL_DIR`*: The model path of the study area which includes several configuration files for the watershed modeling.*
  2. `BIN_DIR`*: The path of SEIMS modules and main programs, which is the same with* `CPP_PROGRAM_DIR` *defined in the configuration file of data preprocessing (Section 2:3.2) by default.*
  3. `HOSTNAME`*: IP address of MongoDB server, e.g., 127.0.0.1 (i.e., localhost).*

4. `PORT`: *Port of MongoDB server, e.g., 27017 by the default.*
5. `VERSION`: *(Optional) Version of SEIMS main program which can be* `OMP` *and* `MPI` *for OpenMP version and MPI&OpenMP version, respectively. The default is* `OMP`.
6. `MPI_BIN`: *(Optional) Full path of the executable of MPI, e.g.,* `C:\Program Files\Microsoft MPI\Bin\mpiexec.exe`.
7. `hostopt`: *(Optional) The identifier of the input argument of MPI to specify a host list file which is various with different MPI implementations, e.g.,* `-machinefile` *or* `-hostfile`.

   `hostfile`: *(Optional) The host list file which may different with MPI implementation.*
8. `processNum`: *(Optional) The number of processes, the default is 1.*
9. `threadsNum`: *(Optional) The number of threads per process, the default is 4.*
10. `layeringMethod`: *(Optional) Routing layering method based on flow direction algorithms, can be 0 or 1.*
11. `scenarioID`: *(Optional) The ID of BMP scenario.*
12. `calibrationID`: *(Optional) The ID (i.e., index) of calibration data.*
13. `subbasinID`: *(Optional) The ID of subbasin, 0 for the whole watershed and 9999 is reserved for Field version.*
14. `Sim_Time_start`: *(Optional) Starting date time of simulation with the format of* `YYYY-MM-DD HH:MM:SS`.
15. `Sim_Time_end`: *(Optional) Ending date time of simulation with the format of* `YYYY-MM-DD HH:MM:SS`. *If not specified, the starting and ending date time prepared in database (i.e.,* `FILE_IN` *collection) will be applied.*
16. `Output_Time_start`: *(Optional) Starting date time of output items with the format of* `YYYY-MM-DD HH:MM:SS`.
17. `Output_Time_end`: *(Optional) Ending date time of output items with the format of* `YYYY-MM-DD HH:MM:SS`. *If specified, the time period of all selected output IDs in* `FILE_OUT` *collection will be updated and applied.*

To run the SEIMS-based watershed model defined by the configuration file described above, please follow the unified format of running SEIMS Python scripts, e.g.,

```
01 >cd D:\demo\SEIMS\seims
02 >python run_seims.py -ini
D:\demo\SEIMS\data\youwuzhen\workspace\runmodel.ini
```

```
[SEIMS_Model]
MODEL_DIR = D:\demo\SEIMS\data\youwuzhen\demo_youwuzhen30m_longterm_model
BIN_DIR = D:\demo\SEIMS\bin
HOSTNAME = 127.0.0.1
PORT = 27017
version = OMP
mpi_bin = mpiexec
# hostopt = ...
# hostfile = ...
processNum = 2
threadsNum = 4
layeringMethod = 1
scenarioID = 0
calibrationID = -1
subbasinID = 0
# Simulation period (UTCTIME)
Sim_Time_start = 2012-01-01 00:00:00
Sim_Time_end = 2015-12-31 23:59:59
# Time period of ALL selected outputs
Output_Time_start = 2012-01-01 00:00:00
Output_Time_end = 2015-12-31 00:00:00
```

Figure 2:4-7 Configuration content for model execution of the Youwuzhen watershed model

2:4.3.3 Customize the demo Youwuzhen watershed model

To demonstrate the ability of SEIMS to construct different watershed models, a simple change is made to the Youwuzhen watershed model, i.e., replacing the Penman-Monteith method (`PET_PM`) to the Priestley-Taylor method (`PET_PT`) for the simulation of potential evapotranspiration. Note that, except for the potential evapotranspiration, the `PET_PM` module also simulates the potential plant transpiration while the `PET_PT` not, thus the module named `AET_PTH` is added for the simulation of potential plant transpiration and potential and actual soil evaporation. Meanwhile, the soil evaporation module (`SET_LM`) is no longer need. The newly customized Youwuzhen watershed model (i.e., the `config.fig` file) was shown in Figure 2:4-8.

```
### Driver factors, including climate and precipitation
0 | TimeSeries | | TSD_RD
0 | Interpolation_0 | Thiessen | ITP
### Surface processes
0 | Soil temperature | Finn Plauborg | STP_FP
0 | PET | PriestleyTaylor | PET_PT
#0 | PET | PenmanMonteith | PET_PM
0 | Interception | Maximum Canopy Storage | PI_MCS
0 | Snow melt | Snowpeak Daily | SNO_SP
0 | Infiltration | Modified rational | SUR_MR
0 | Depression and Surface Runoff | Linsley | DEP_LINSLEY
0 | Hillslope erosion | MUSLE | SERO_MUSLE
0 | Plant Management Operation | SWAT | PLTMGT_SWAT
0 | Percolation | Storage routing | PER_STR
0 | Subsurface | Darcy and Kinematic | SSR_DA
0 | AET | Hargreaves and PriestleyTaylor | AET_PTH
#0 | SET | Linearly Method from WetSpa | SET_LM
0 | PG | Simplified EPIC | PG_EPIC
0 | ATMDEP | Atomosphere deposition | ATMDEP
0 | NUTR_TF | Nutrient Transformation of C, N, and P | NUTR_TF
0 | Water overland routing | IUH | IUH_OL
0 | Sediment overland routing | IUH | IUH_SED_OL
0 | Nutrient | Attached nutrient loss | NUTRSED
0 | Nutrient | Soluble nutrient loss | NUTRMV
0 | Pothole | SWAT cone shape | IMP_SWAT
0 | Soil water | Water balance | SOL_WB
### Route Modules, including water, sediment, and nutrient
0 | Groundwater | Linear reservoir | GWA_RE
0 | Nutrient | groundwater nutrient transport | NUTRGW
0 | Water channel routing | MUSK | MUSK_CH
0 | Sediment channel routing | Simplified Bagnold equation | SEDR_SBAGNOLD
0 | Nutrient | Channel routing | NutrCH_QUAL2E
```

Figure 2:4-8 New Youwuzhen watershed model after the simple customization, i.e., replacing the Penman-Monteith method to Priestley-Taylor method for the simulation of potential evapotranspiration.

With all model parameters remain the default values, the demo Youwuzhen watershed model and the new customized model were executed respectively. Figure 2:4-9 showed the spatial distributions of average potential evapotranspiration simulated by the Penman-Monteith method (Figure 2:4-9a) and Priestley-Taylor method (Figure 2:4-9b), which have a very similar spatial pattern but different values. The differences of the simulated potential evapotranspiration can also be reflected in the simulated streamflow at the watershed outlet (Figure 2:4-10).

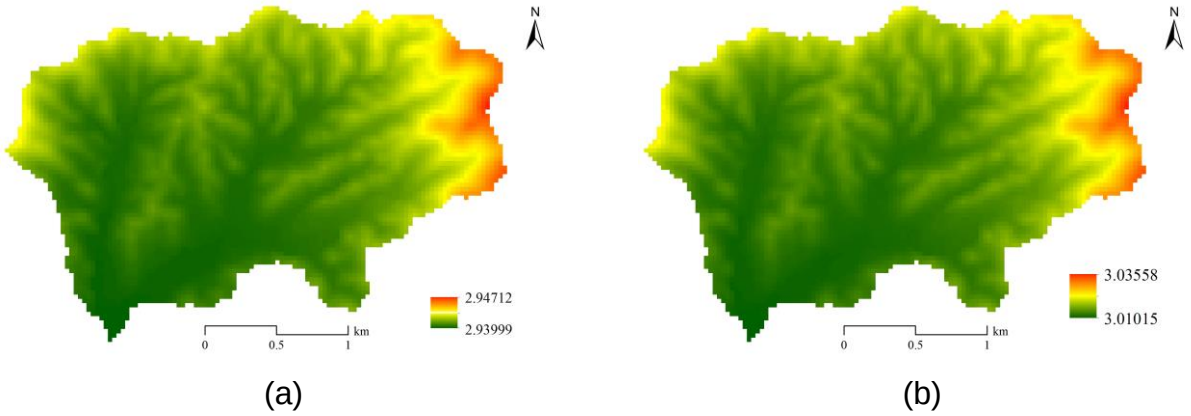


Figure 2:4-9 Spatial distributions of average potential evapotranspiration simulated by the Youwuzhen watershed model using the (a) Penman-Monteith method and the (b) Priestley-Taylor method

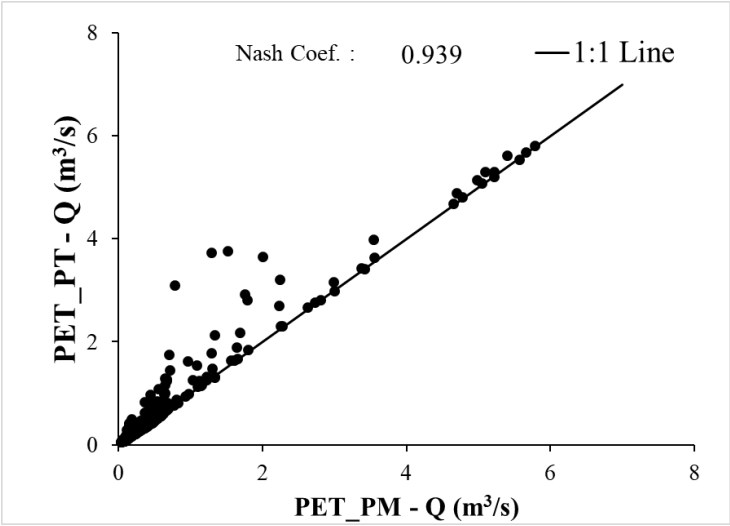


Figure 2:4-10 Differences of the streamflow (Q, m³/s) at the outlet of Youwuzhen watershed derived from the Youwuzhen watershed models using the Penman-Monteith method (PET_PM) and Priestley-Taylor method (PET_PT) for the simulation of potential evapotranspiration, respectively.

2:5. Postprocessing

After running a SEIMS-based watershed model, the postprocessing tool may be used for the calculation of model performance statistics such as Nash-Sutcliffe Efficiency (NSE), and the plotting of hydrographs of time-series data at the reach outlet such as streamflow and sediment.

2:5.1 Simple usage

For simple usage, open a CMD window, enter the following commands to execute the postprocessing of the Youwuzhen watershed model.

```
01 >cd D:\demo\SEIMS\seims\test
02 >D:
03 >python demo_postprocess.py -name youwuzhen
```

The runtime logs of postprocessing showed input paths and output model performance statistics (Figure 2:5-1).

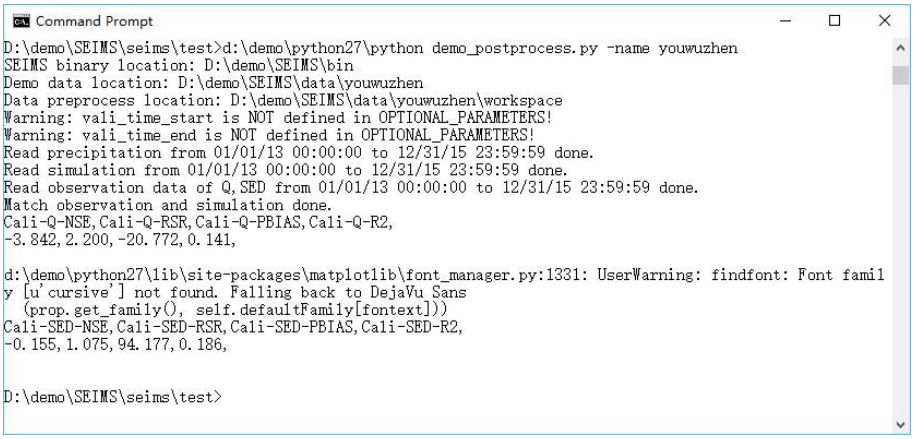


Figure 2:5-1 Runtime logs of postprocessing of the Youwuzhen watershed model

By default, the hydrographs of streamflow (e.g., `Q.txt`) and sediment (e.g., `SED.txt`) at the watershed outlet were plotted and saved as figure files with the formats of `PNG` and `PDF`, e.g., `SEIMS\data\youwuzhen\demo_youwuzhen30m_longterm_model\OUTPUT0\png\Q-2013-01-01-2015-12-31.png` (Figure 2:5-2).

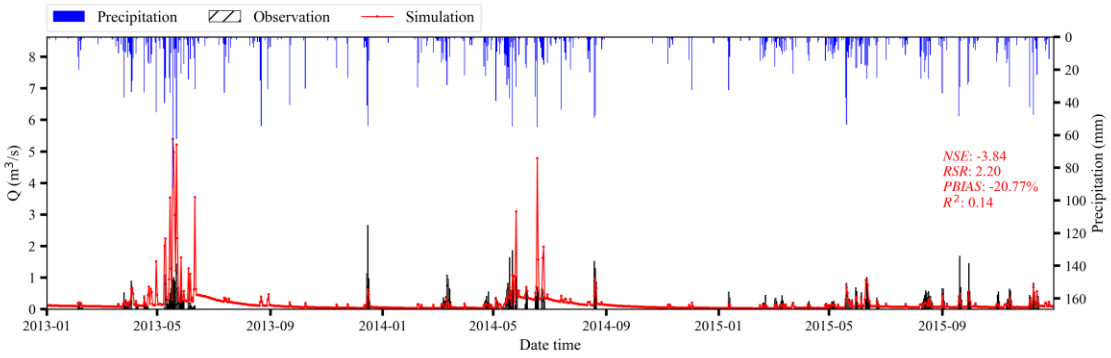


Figure 2:5-2 Hydrograph of streamflow (Q, m³/s) at the watershed outlet derived from the Youwuzhen watershed model with default model parameters

2:5.2 Configuration file of postprocessing

Same to the data preprocessing, the simple usage of postprocessing also includes generating the configuration `INI` file according to the local paths of SEIMS such as Figure 2:5-3, and executing postprocessing by the advanced usage (See Section 2:5.3).

The configuration file of postprocessing, such as that of the Youwuzhen watershed model shown in Figure 2:5-3, includes four sections, i.e., `SEIMS_Model`, `PARAMETERS`, `OPTIONAL_PARAMETERS`, and `OPTIONAL_MATPLOT_SETTING`. Among them, `OPTIONAL_PARAMETERS` and `OPTIONAL_MATPLOT_SETTING` are optional. The names of sections and options should not be changed.

- *`SEIMS_Model`: Basic settings of the SEIMS-based watershed model, including* `HOSTNAME`*,* `PORT`*,* `MODEL_DIR`*,* `BIN_DIR`*,* `scenarioID`*, and* `calibrationID`*. The meanings of these options have been introduced in Section 2:4.3.2.*
- *`PARAMETERS`*
  1. `PLOT_SUBBASINID`*: The subbasin ID to be plotted.*
  2. `PLOT_VARIABLES`*: The variables to be plotted, such as* `Q`*,* `SED`*, and* `CH_TN`*. Multiple variables can be separated by comma. Note that, the specified subbasin ID and the corresponding variables MUST be set as time-series output data in* `file.out` *(Section 2:4.2.2) and/or* `FILE_OUT` *collection of the main MongoDB database. If there is no matched observed data for the specified variable, the model performance statistics will not able to be calculated.*
- *`OPTIONAL_PARAMETERS`: (Optional) Time period of model calibration and validation. The starting and ending date times of either calibration or validation MUST be presented or omitted simultaneously.*
  1. `Cali_Time_start`*: Starting date time of model calibration with the format of* `YYYY-MM-DD HH:MM:SS`*.*
  2. `Cali_Time_end`*: Ending date time of model calibration.*
  3. `Vali_Time_start`*: Starting date time of model validation.*
  4. `Vali_Time_end`*: Ending date time of model validation.*

- *OPTIONAL_MATPLOT_SETTINGS: (Optional) Plot settings for matplotlib.*
  1. FIGURE_FORMATS*: The format(s) of output figure(s) which can be one or multiple of* PNG*,* JPG*,* TIF*,* PDF*,* EPS*,* SVG*, and* PS*. Multiple formats are separated by comma, e.g.,* PNG,JPG,EPS*.*
  2. LANG_CN*: Whether Chinese are included (*True*) or not (*False*) in labels and legend texts, etc.*
  3. FONT_TITLE*: Font title (font name) for the output figures. Below are tips to check the available fonts or use new ones.*
     a. *Get the currently available font titles by the following Python code.*

```
#! /usr/bin/env python
# -*- coding: utf-8 -*-
from matplotlib import font_manager
flist = font_manager.get_fontconfig_fonts()
font_names = list()
for fname in flist:
    try:
        font_names.append(font_manager.FontProperties(fname=fname).get_name())
    except IOError or Exception:
        continue
print(font_names)
```

     b. *To add and use a new font:*
        - *Download a font with* .ttf *format such as YaHei Mono which supports a hybrid of Chinese and English. If you have only* .ttc *formatted font file, you may want to convert it to* .ttf *file using transfonter.*
        - *Copy the font file to the font directory of matplotlib, e.g.,* D:\demo\python27\Lib\site-packages\matplotlib\mpl-data\fonts\ttf
        - *Delete the cache files of matplotlib font located in the Windows user's directory, e.g.,* C:\Users\ZhuLJ\.matplotlib*. The cache files may be* fontList.cache *and* fontList.json *for Python 2, and* fontList.py3k.cache *and* fontList-v300.json *for Python 3.*
        - *Now the new font should be available for plotting. If the new font is not rendered, it may be because matplotlib needs to refresh its font cache. Run the following Python code to rebuild it.*

```
from matplotlib import font_manager
font_manager._rebuild()
```

  4. *Font sizes of title (*TITLE_FONTSIZE*), legend (*LEGEND_FONTSIZE*), axis-tick label (*TICKLABEL_FONTSIZE*), axis label (*AXISLABEL_FONTSIZE*), and universal label (*LABEL_FONTSIZE*) in points.*
  5. DPI*: The resolution in dots (Integer) per inch, which is applied to non-vector formats.*

```
[SEIMS_Model]
HOSTNAME = 127.0.0.1
PORT = 27017
MODEL_DIR = D:\demo\SEIMS\data\youwuzhen\demo_youwuzhen30m_longterm_model
BIN_DIR = D:\demo\SEIMS\bin
scenarioID = 0
calibrationID = -1

[PARAMETERS]
PLOT_SUBBASINID = 4
PLOT_VARIABLES = Q SED

[OPTIONAL_PARAMETERS]
# Calibration period (UTCTIME)
Cali_Time_start = 2013-01-01 00:00:00
Cali_Time_end = 2015-12-31 23:59:59
# Validation period (UTCTIME)
#Vali_Time_start = 2013-01-01 00:00:00
#Vali_Time_end = 2013-12-31 23:59:59

[OPTIONAL_MATPLOT_SETTINGS]
FIGURE_FORMATS = PDF,PNG
LANG_CN = False
FONT_TITLE = Times New Roman
TITLE_FONTSIZE = 14
LEGEND_FONTSIZE = 12
TICKLABEL_FONTSIZE = 12
AXISLABEL_FONTSIZE = 12
LABEL_FONTSIZE = 14
DPI = 300
```

Figure 2:5-3 Configuration content for postprocessing of the Youwuzhen watershed model

2:5.3 Advanced usage

The Python scripts of postprocessing are located in `SEIMS/seims/postprocess`. The `main.py` is the entrance of postprocessing which can be executed though the unified format of running SEIMS Python scripts, e.g.,

```
>cd D:\demo\SEIMS\seims\postprocess
>python main.py -ini
D:\demo\SEIMS\data\youwuzhen\workspace\postprocess.ini
```

To illustrate the functionality of postprocessing, Figure 2:5-4 showed the calibration and validation of the simulated streamflow (Q, m^3/s) at the watershed outlet derived from the demo Youwuzhen watershed model with default model parameters with Chinese labels and legend texts based on `YaHei Mono` font (changes of the configuration was shown in Figure 2:5-5).

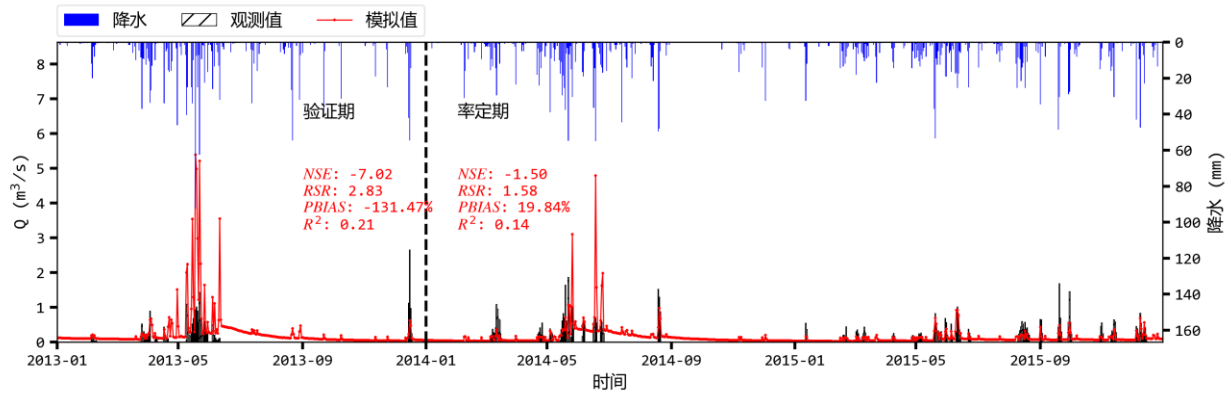


Figure 2:5-4 Calibration and validation of the simulated streamflow (Q, m³/s) at the outlet of the Youwuzhen watershed derived from the demo Youwuzhen watershed model with default model parameters using Chinese font

```
[OPTIONAL_PARAMETERS]
# Calibration period (UTCTIME)
Cali_Time_start = 2014-01-01 00:00:00
Cali_Time_end = 2015-12-31 23:59:59
# Validation period (UTCTIME)
Vali_Time_start = 2013-01-01 00:00:00
Vali_Time_end = 2013-12-31 23:59:59

[OPTIONAL_MATPLOT_SETTINGS]
FIGURE_FORMATS = PDF,PNG
LANG_CN = True
FONT_TITLE = YaHei Mono
```

Figure 2:5-5 Modification of configuration content of postprocessing to plot both calibration and validation period using Chinese font

2:6. Parameter sensitivity analysis

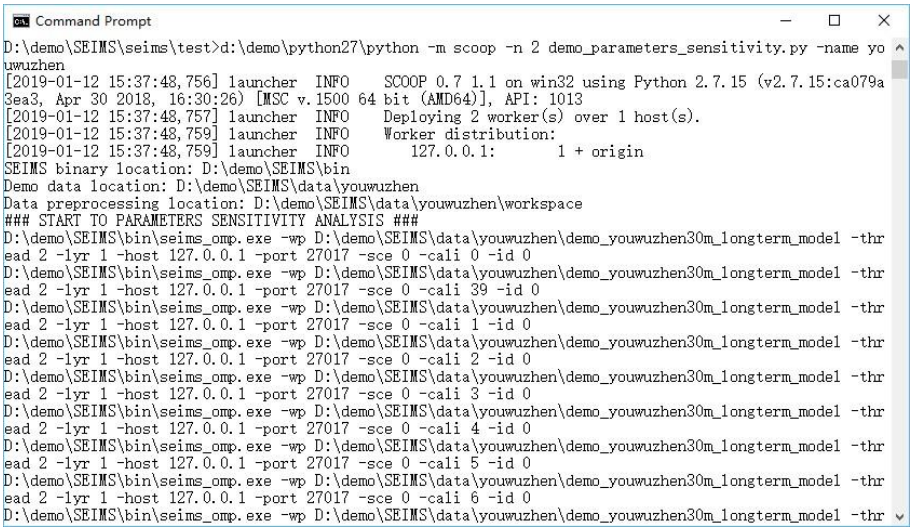
Parameter sensitivity analysis is useful for identifying the most important or influential parameters for a specified simulation target (e.g., streamflow at the watershed outlet) (Zhan et al., 2013). A typical sensitivity analysis procedure includes sampling from the value ranges of determined model inputs, evaluating the model with the generated samples and saving the interested outputs, and calculating sensitivity indices by various methods such as the Morris screening method (Morris, 1991) and FAST (Fourier Amplitude Sensitivity Test, Cukier et al., 1978). The sensitivity analysis tool in SEIMS is organized as separated functions according to these steps, which means it is easy to incorporate any sampling method and sensitivity analysis method. The most time-consuming step is repetitive model evaluations, which is parallelized at model level by parallel job management based on SCOOP (Hold-Geoffroy et al., 2014).

2:6.1 Simple usage

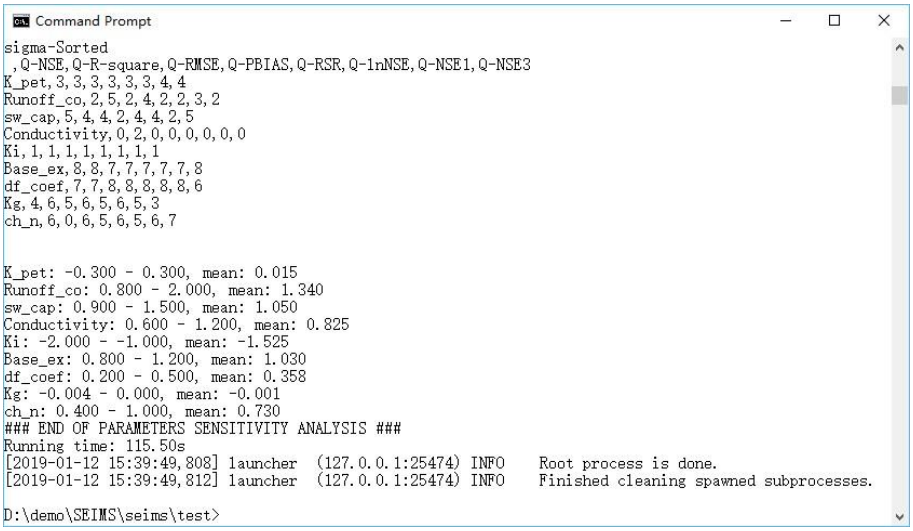
For simple usage, open a CMD window, enter the following commands to execute the predefined parameter sensitivity analysis of the Youwuzhen watershed model.

```
01 >cd D:\demo\SEIMS\seims\test
02 >D:
03 >python –m scoop –n 2 demo_parameters_sensitivity.py -name youwuzhen
```

The runtime logs of the parameter sensitivity analysis including the commands of each model run and the results of sensitivity analysis were showed in Figure 2:6-1.



(a)



(b)

Figure 2:6-1 Beginning (a) and ending (b) runtime logs of the predefined parameter sensitivity analysis of the Youwuzhen watershed model

Firstly, the sampled calibration values of selected parameters were organized as float arrays and imported as `CALI_VALUES` field into the `PARAMETERS` collection of the main spatial database. The SEIMS-based watershed model under a combination of calibrated parameters can be evaluated with the `calibrationID` argument set to the corresponding array index (start from 0) (Figure 2:6-1a). The calibration values can be queried by the following command in the console window of Robo 3T (Figure 2:6-2).

```
01 db.getCollection('PARAMETERS').find({'CALI_VALUES':{$exists:true}})
```

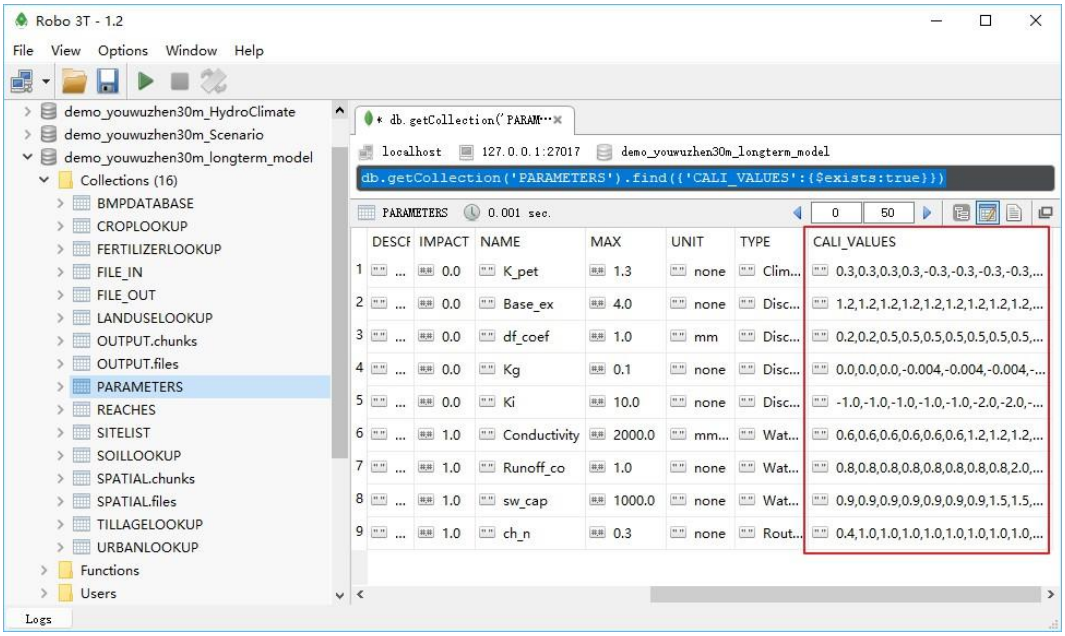


Figure 2:6-2 Sampled calibration values of selected parameters for the sensitivity analysis of the Youwuzhen watershed model

Then, all combinations of calibrated parameters were evaluated in parallel according to the workers' number of SCOOP, e.g., two workers were allocated in this simple usage (`-m scoop -n 2`). After the evaluation of each calibrated model, the interested model performance indicators will be calculated and saved. In current version of SEIMS, *NSE* (Nash-Sutcliffe efficiency), *RSR* (root mean square error-standard deviation ratio), and *PBIAS* (percent bias) (Moriasi et al., 2007) were used as model performance indicators.

Finally, the sensitivity analysis method (Morris screening method in this demo) will be executed according to the above introduced model outputs. For example, Figure 2:6-3 showed the parameter sensitivity analysis result with respect to the *NSE* of the simulated streamflow (m^3s^{-1}) at the watershed outlet. Each point in the screening plot represents one parameter of the Youwuzhen watershed model. The larger the modified means μ^* (Campolongo et al., 2007), the more sensitive the watershed response is to variation in the parameter (Yang, 2011; Zhan et al., 2013). More results can be found in the output directory, e.g., `SEIMS\data\youwuzhen\demo_youwuzhen30m_longterm_model\PSA_Morris_N4L2`.

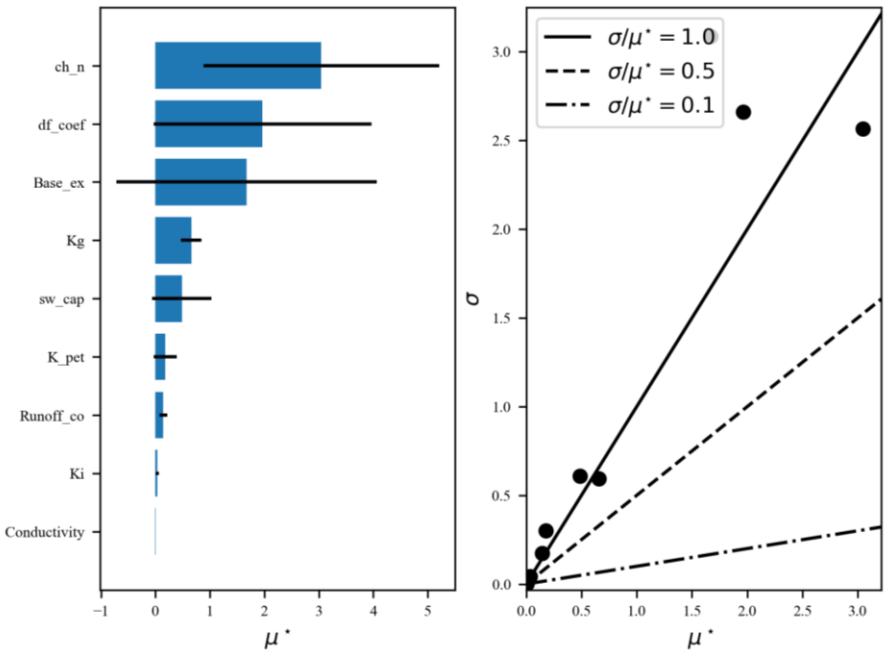


Figure 2:6-3 Parameter sensitivity analysis result with respect to the NSE of the simulated streamflow (m^3s^{-1}) at the watershed outlet

2:6.2 Configuration file of parameter sensitivity analysis

The configuration file of parameter sensitivity analysis, such as that of the Youwuzhen watershed model shown in Figure 2:6-4, includes four sections, i.e., `SEIMS_Model`, `PARAMETERS`, `OPTIONAL_PARAMETERS`, and `OPTIONAL_MATPLOT_SETTING`. Among them, `OPTIONAL_PARAMETERS` and `OPTIONAL_MATPLOT_SETTING` are optional. The names of sections and options should not be changed.

- *`SEIMS_Model`: Basic settings of the SEIMS-based watershed model, see Section 2:4.3.2 for details. Note that the OpenMP version of SEIMS main program is used by default. However, the options of `version`, `MPI_BIN`, and `processNum` are supported if the MPI&OpenMP version is wanted.*
- *`PSA_PARAMETERS`: Basic settings for parameter sensitivity analysis.*
  1. `evaluateParam`*: Simulation target(s) to be evaluated for sensitivity analysis, e.g., `Q` for streamflow, `SED` for sediment, and `CH_TN` for total nitrogen. This option is similar to `PLOT_VARIABLES` of postprocessing in Section 2:5.2. Multiple parameters should be separated by comma.*
  2. `paramRngDef`*: Filename of the definition of parameters' range. The file follows the basic plain text file format of SEIMS. Each line indicates one parameter to be analyzed with the format of `NAME, lower_bound, upper_bound`. For example, `K_pet,-0.3,0.3` means that the `impact` value of `K_pet` ranges from -0.3 to 0.3. The type of `CHANGE` is the same with that defined in `PARAMETERS` collection. Relative information please refer to Section 2:4.2.3.*
  3. `PSA_Time_start`*: Starting date time of the calculation of model performance for the sensitivity analysis with the format of `YYYY-MM-DD HH:MM:SS`.*
  4. `PSA_Time_end`*: Ending date time of the calculation of model performance for the sensitivity analysis with the format of `YYYY-MM-DD HH:MM:SS`.*
- *Sections of specific sensitivity analysis methods supported by SALib. Currently, the Morris screening method including groups and optimal trajectories (`Morris_Method`) and Fourier Amplitude Sensitivity Test (`FAST_Method`) have been integrated and tested. In the future version of SEIMS, more methods and not limited to the methods of SALib should be integrated.*
  1. *`Morris_Method`:*

     `N`*: The number of trajectories to generate.*
     `num_levels`*: The number of grid levels. The resulting samples have a row number of `(D+1)*N`, and column number of `D`, where `D` is the number of parameters.*
     `optimal_trajectories`*: The number of optimal trajectories to sample (between 2 and `N`) which can also be `None`.*
     `local_optimization`*: Flag whether to use local optimization. Speeds up the process tremendously for bigger `N` and `num_levels`. If set to `False` brute force method is used.*
  2. *`FAST_Method`:*

     `N`*: The number of samples to generate.*

`M`: *The interference parameter, i.e., the number of harmonics to sum in the Fourier series decomposition, the default is 4.*

- `OPTIONAL_MATPLOT_SETTINGS`: *Plot settings for matplotlib, see Section 2:5.2.*

```
[SEIMS_Model]
MODEL_DIR = D:\demo\SEIMS\data\youwuzhen\demo_youwuzhen30m_longterm_model
BIN_DIR = D:\demo\SEIMS\bin
HOSTNAME = 127.0.0.1
PORT = 27017
threadsNum = 2
layeringMethod = 1
scenarioID = 0
# Simulation period (UTCTIME)
Sim_Time_start = 2012-01-01 00:00:00
Sim_Time_end = 2012-03-09 23:59:59

[PSA_Settings]
evaluateParam = Q
paramRngDef = morris_param_rng-Q.def
# Objective calculation period (UTCTIME)
PSA_Time_start = 2012-02-27 00:00:00
PSA_Time_end = 2012-03-09 23:59:59

[Morris_Method]
N = 4
num_levels = 2
optimal_trajectories = None
local_optimization = True

[OPTIONAL_MATPLOT_SETTINGS]
FIGURE_FORMATS = PDF,PNG
FONT_TITLE = Times New Roman
DPI = 300
```

Figure 2:6-4 Configuration content for parameter sensitivity analysis of the Youwuzhen watershed model

2:6.3 Advanced usage

The Python scripts of parameter sensitivity analysis are located in `SEIMS/seims/parameters_sensitivity`. The `main.py` is the entrance which can be executed though the unified format of running SEIMS Python scripts, e.g.,

```
>cd D:\demo\SEIMS\seims\parameters_sensitivity
>python main.py -ini
D:\demo\SEIMS\data\youwuzhen\workspace\sensitivity_analysis.ini
```

2:7. Auto-Calibration

After parameter sensitivity analysis, a small number of the most sensitive parameters can be selected for auto-calibration. The value ranges of parameters may be the same with those defined in the parameter sensitivity analysis, or they may be narrowed by excluding values that result in an unacceptable model performance, such as in cases where *NSE* is less than zero.

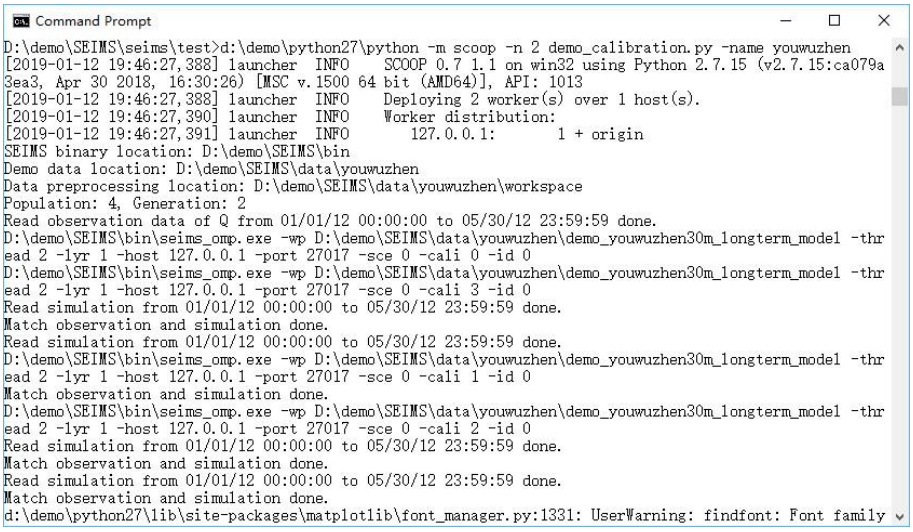
In the current version of SEIMS, the NSGA-II algorithm (Non-dominated Sorting Genetic Algorithm II) was used for auto-calibration. During NSGA-II execution, the Latin-hypercube sampling method (Iman and Shortencarier, 1984) was used to generate initial samples of calibrated parameters. The crossover and mutation operations were similar to the original implementations in NSGA-II by Deb et al. (2002).

2:7.1 Simple usage

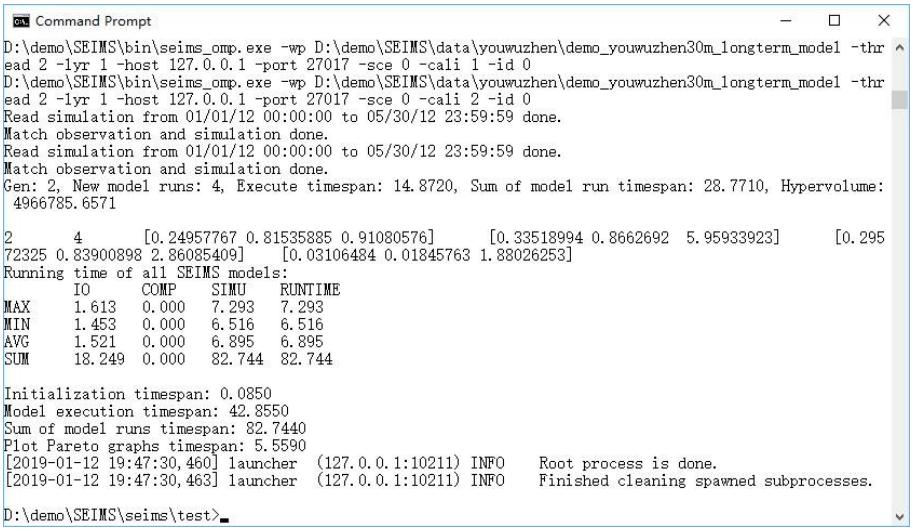
For simple usage, open a CMD window, enter the following commands to execute the auto-calibration of the streamflow modeling of the Youwuzhen watershed model.

```
01 >cd D:\demo\SEIMS\seims\test
02 >D:
03 >python –m scoop –n 2 demo_calibration.py -name youwuzhen
```

The runtime logs of auto-calibration including commands of each model run, the average model performance indicators of each generation, and the time-consuming were showed in Figure 2:7-1.



(a)



(b)

Figure 2:7-1 Runtime logs of auto-calibration of the Youwuzhen watershed model

Similar to the parameter sensitivity analysis, the calibration values of selected parameters will be generated and imported as `CALI_VALUES` field into the `PARAMETERS` collection of the main spatial database for each generation during the optimization of auto-calibration (Figure 2:7-2).

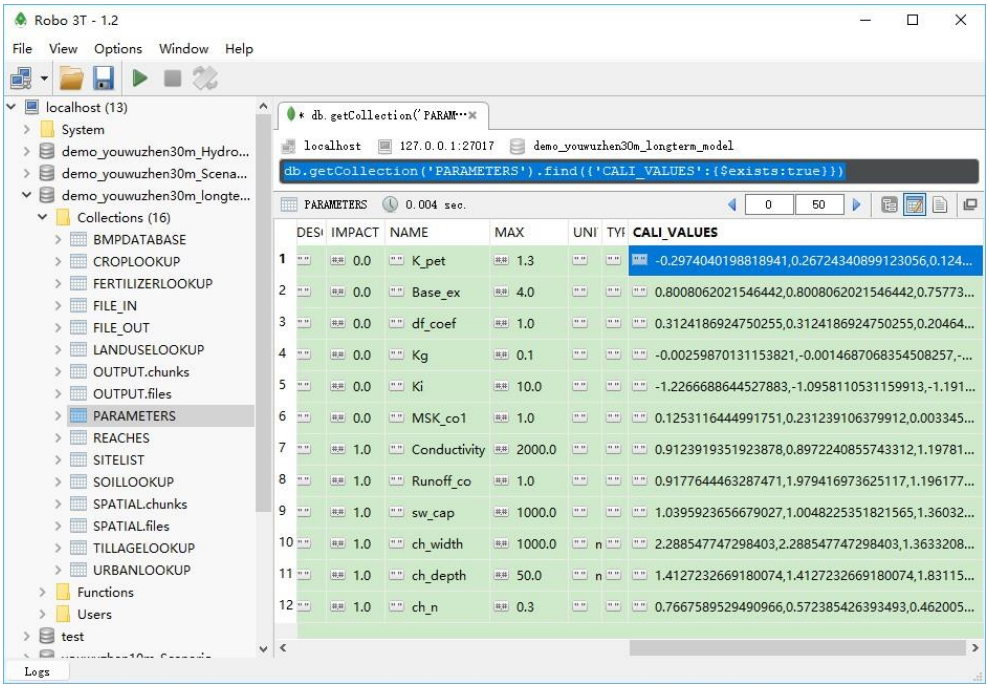
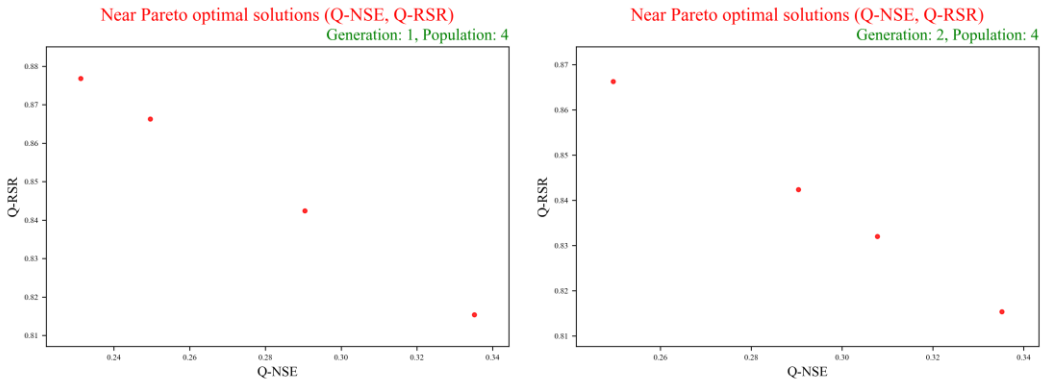


Figure 2:7-2 Calibration values of selected parameters generated during the optimization of auto-calibration of the Youwuzhen watershed model

The results of the auto-calibration can be found in `SEIMS\data\youwuzhen\demo_youwuzhen30m_longterm_model\CALI_NSGA2_Gen_2_Pop_4`. The near-optimal Pareto solutions plotted as a scatter plot can give a simple and direct interpretation of the calibration optimization processes. For example, Figure 2:7-3 showed the near optimal Pareto solutions of the 1st and 2nd generations with the objectives of maximize the *NSE* and minimize the *RSR* of the simulated streamflow at the watershed outlet, which indicated an evolutionary directory to maximum *NSE* and minimum *RSR*.



(a) (b)

Figure 2:7-3 Near optimal Pareto solutions of the 1st (a) and 2nd (b) generations with the objectives of maximize the NSE and minimize the RSR of the simulated streamflow at the watershed outlet

In the meantime, to have a better aware of the calibration results, one best solution with the maximum *NSE* of the calibration period was plotted for each generation (red dash line in Figure 2:7-4) together with the 2.5% and 97.5% levels of the cumulative distribution of the output variables (gray band in Figure 2:7-4), i.e., streamflow at the watershed outlet in this demo.

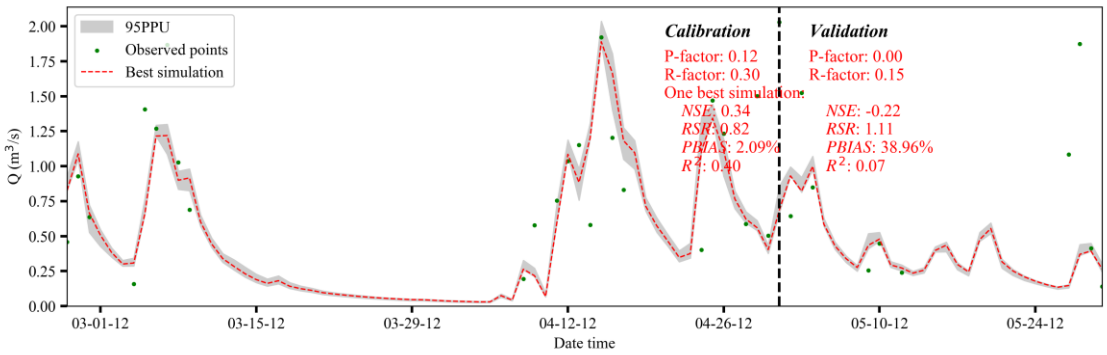


Figure 2:7-4 Auto-calibration result of streamflow (Q, m^3/s) simulation of the 2nd generation at the calibration and validation periods

2:7.2 Configuration file of auto-calibration

The configuration file of auto-calibration, such as that of the Youwuzhen watershed model shown in Figure 2:7-5, includes four sections, i.e., `SEIMS_Model`, `CALI_Settings`, `NSGA2`, and `OPTIONAL_MATPLOT_SETTING`. Among them, `OPTIONAL_MATPLOT_SETTING` is optional. The names of sections and options should not be changed.

- *`SEIMS_Model`: Basic settings of the SEIMS-based watershed model, see Section 2:4.3.2 for details. Note that the OpenMP version of SEIMS main program is used by default. However, the options of `version`, `MPI_BIN`, and `processNum` are supported if the MPI&OpenMP version is wanted.*
- *`CALI_Settings`: Basic settings for auto-calibration.*
  1. `paramRngDef`*: Filename of the definition of parameters' range for calibration. The format is the same with `paramRngDef` of parameter sensitivity analysis (Section 2:6.2).*
  2. `Cali_Time_start`*: Starting date time of the calibration period for model calibration with the format of `YYYY-MM-DD HH:MM:SS`.*
  3. `Cali_Time_end`*: Ending date time of the calibration period for model calibration with the format of `YYYY-MM-DD HH:MM:SS`.*
  4. `Vali_Time_start`*: (Optional) Starting date time of the validation period with the format of `YYYY-MM-DD HH:MM:SS` for visualization only to explore the effective of the calibrated parameters, e.g., Figure 2:7-4.*
  5. `Vali_Time_end`*: (Optional) Ending date time of the validation period with the format of `YYYY-MM-DD HH:MM:SS`. The `Vali_Time_start` and `Vali_Time_end` should be specified simultaneously.*
- *Sections of specific optimization methods for auto-calibration. Currently, the NSGA-II algorithm has been integrated and tested. In the future version of SEIMS, more methods should be integrated.*
  1. `NSGA2`*: Parameter settings of NSGA-II algorithm.*

     `GenerationsNum`*: Maximum number of generations.*
     `PopulationSize`*: Initial population size, i.e., the number of individuals.*
     `CrossoverRate`*: Crossover probability, ranges from 0 to 1. A larger crossover rate indicates a higher possibility to take place the crossover operation between two parent individuals.*
     `MutateRate`*: Mutate probability.*
     `MaxMutatePerc`*: Maximum percent of genes to be mutated.*
     `SelectRate`*: Selection rate of the evaluated and sorted individuals for each generation which is known as near-optimal Pareto solutions.*
- *`OPTIONAL_MATPLOT_SETTINGS`: Plot settings for matplotlib, see Section 2:5.2.*

```
[SEIMS_Model]
MODEL_DIR = D:\demo\SEIMS\data\youwuzhen\demo_youwuzhen30m_longterm_model
BIN_DIR = D:\demo\SEIMS\bin
HOSTNAME = 127.0.0.1
PORT = 27017
threadsNum = 2
layeringMethod = 1
scenarioID = 0
# Simulation period (UTCTIME)
Sim_Time_start = 2012-01-01 00:00:00
Sim_Time_end = 2012-05-30 23:59:59

[CALI_Settings]
# Parameters and ranges
paramRngDef = cali_param_rng-Q.def
# Calibration period (UTCTIME)
Cali_Time_start = 2012-02-27 00:00:00
Cali_Time_end = 2012-04-30 23:59:59
# Validation period (UTCTIME)
Vali_Time_start = 2012-05-01 00:00:00
Vali_Time_end = 2012-05-30 23:59:59

[NSGA2]
GenerationsNum = 2
PopulationSize = 4
CrossoverRate = 0.8
MaxMutatePerc = 0.2
MutateRate = 0.1
SelectRate = 1.0

[OPTIONAL_MATPLOT_SETTINGS]
FIGURE_FORMATS = PDF,PNG
LANG_CN = False
FONT_TITLE = Times New Roman
TITLE_FONTSIZE = 16
LEGEND_FONTSIZE = 12
TICKLABEL_FONTSIZE = 12
AXISLABEL_FONTSIZE = 12
LABEL_FONTSIZE = 14
DPI = 300
```

Figure 2:7-5 Configuration content for auto-calibration of the Youwuzhen watershed model based on NSGA-II

2:7.3 Advanced usage

The Python scripts of auto-calibration are located in `SEIMS/seims/calibration`. The `main_nsga2.py` is the entrance for the auto-calibration based on NSGA-II algorithm, which can be executed though the unified format of running SEIMS Python scripts, e.g.,

```
>cd D:\demo\SEIMS\seims\calibration
>python main_nsga2.py -ini
D:\demo\SEIMS\data\youwuzhen\workspace\calibration.ini
```

2:8. BMP scenarios analysis

Different best management practices (or beneficial management practices, BMPs for short) scenarios (i.e., spatial configurations of multiple BMPs) at the watershed scale may have significantly different environmental effectiveness, economic cost-benefit, and practicality. It is valuable for decision-making of integrated watershed management to assess the environmental effectiveness and economic cost-benefit of watershed BMP scenarios and then propose optimal ones. During the BMP scenarios analysis, each individual BMP scenario is created by automatically selecting and allocating BMPs on spatial units (known as BMP configuration units). Then the effects of the scenario on watershed behavior are simulated by watershed models. The simulation result is the basis of the automatic spatial optimization of BMP scenarios.

As a demo, one of the experiments conducted in Zhu et al. (2019) is used in this section. The hydrologically connected fields were selected as the BMPs configuration units (see Section 2:3.2 for the preparation). Four spatially explicit BMPs were considered and the BMP configuration strategy based on expert knowledge of upstream–downstream relationships (Wu et al., 2018) was adopted. The NSGA-II algorithm was integrated to achieve the spatial optimization of BMP scenarios. More information please refers to Zhu et al. (2019).

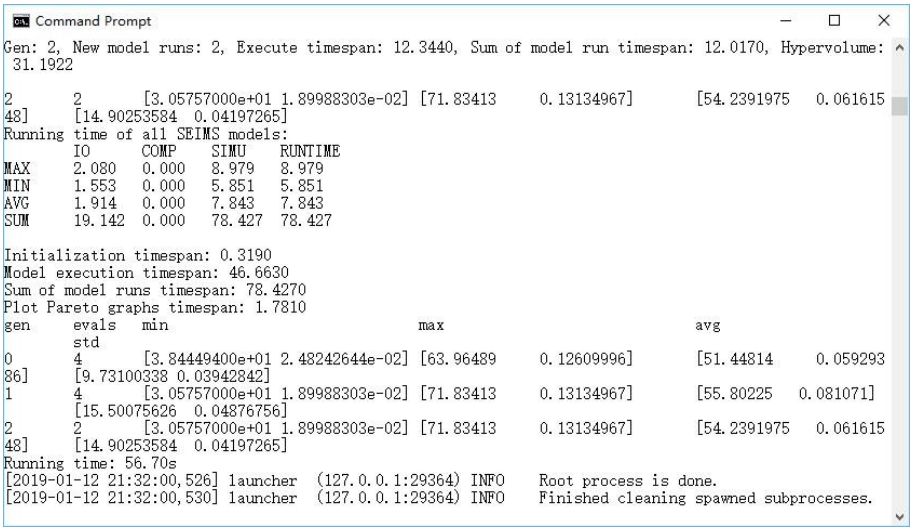
2:8.1 Simple usage

For simple usage, open a CMD window, enter the following commands to execute the predefined BMP scenarios analysis of the Youwuzhen watershed model.

```
>cd D:\demo\SEIMS\seims\test
>D:
>python -m scoop -n 2 demo_scenario_analysis.py -name youwuzhen
```

The runtime logs of scenario analysis including commands of each model run, the average objective values (i.e., environmental effectiveness and net-cost) of each generation, and the time-consuming were showed in Figure 2:8-1.

(a)



(b)

Figure 2:8-1 Runtime logs of BMP scenarios analysis of the Youwuzhen watershed model

Similar to the auto-calibration based on NSGA-II algorithm, the automatically generated BMP scenarios were imported into the `BMP_SCENARIOS` collection of the scenario database for each generation during the BMP scenarios optimization (Figure 2:8-2).

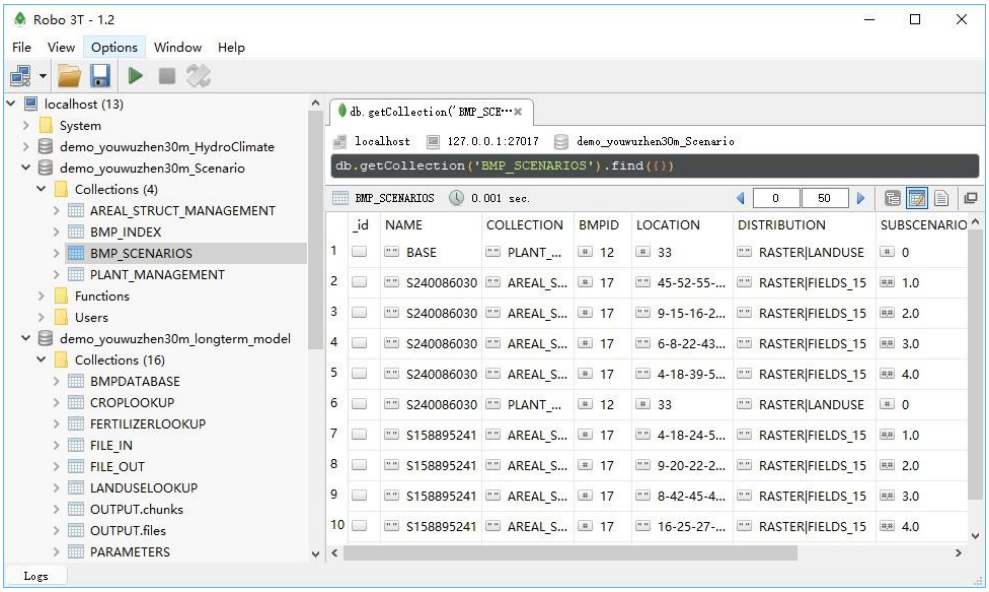


Figure 2:8-2 BMP scenarios generated during the spatial optimization of BMP scenarios

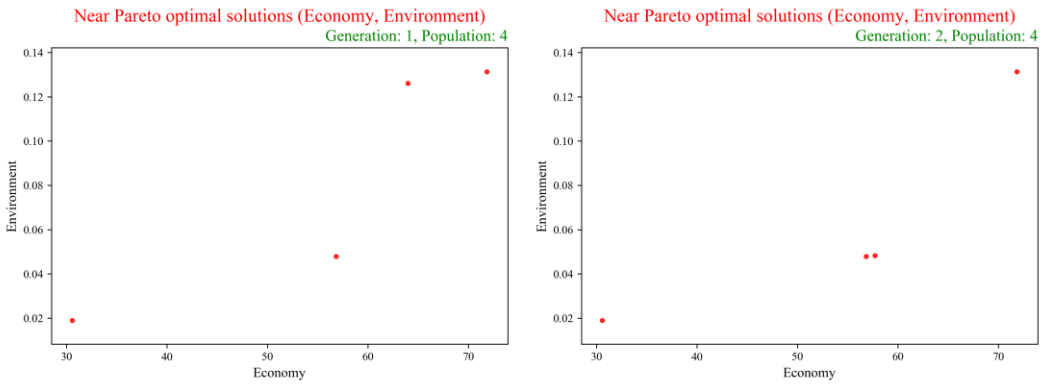
The results of the BMP scenarios analysis can be found in `SEIMS\data\youwuzhen\demo_youwuzhen30m_longterm_model\SA_NSGA2_CONNFIELD_UPDOWN_Gen_2_Pop_4` including:

- `Pareto_Economy-Environment` *folder: Near optimal Pareto plots, e.g., Figure 2:8-3 showed the near optimal Pareto solutions of the 1st and 2nd generations with the objectives of maximizing the environmental effectiveness and minimizing the economic net-cost.*
- `Scenarios` *folder: The BMP scenario information in plain text file and the corresponding spatial distribution raster file. For example, one BMP scenario information of the 2nd generation is as follows.*

```
Scenario ID: 125931440
Gene number: 72
Gene values: 0, 0, 0, 4, 0, 4, 0, 0, 0, 0, 0, 4, 0, 0, 0, 4, 0, 0, 0, 0, 2, 0, 0, 0, 0, 0, 0,
0, 0, 0, 0, 0, 0, 4, 2, 0, 0, 4, 0, 2, 4, 4, 0, 1, 1, 0, 0, 0, 0, 4, 0, 0, 2, 0, 0, 0, 0, 0, 0,
3, 0, 0, 0, 1, 0, 0, 3, 4, 0, 2, 0, 0
Scenario items:
_id NAME COLLECTION   BMPID    LOCATION DISTRIBUTION SUBSCENARIO  ID
481 S125931440   AREAL_STRUCT_MANAGEMENT   17   44-45-64 RASTER|FIELDS_15 1    125931440
482 S125931440   AREAL_STRUCT_MANAGEMENT   17   21-35-40-53-70   RASTER|FIELDS_15 2    125931440
483 S125931440   AREAL_STRUCT_MANAGEMENT   17   60-67    RASTER|FIELDS_15 3    125931440
484 S125931440   AREAL_STRUCT_MANAGEMENT   17   4-6-12-16-34-38-41-42-50-68   RASTER|FIELDS_15 4
    125931440
485 S125931440   PLANT_MANAGEMENT 12   33   RASTER|LANDUSE   0    125931440
Effectiveness:
    economy: 57.712680
    environment: 048278
```

The gene number is 72 which equals to the number of BMP configuration units, i.e., the spatial units number of `FIELDS_15`*. The gene values indicate the BMP types that configured on BMP configuration units. The value of 0 means no BMP configured. Each BMP type has one scenario item. The spatial distribution of this BMP scenario was shown in Figure 2:8-4.*

- `runtime.log` *file: Recoding the near optimal Pareto solutions of each generation.*
- `hypervolume.txt` *file: The hypervolume index of each generation.*



(a) (b)

Figure 2:8-3 Near optimal Pareto solutions of the 1st (a) and 2nd (b) generations with the objectives of maximizing the environmental effectiveness and minimizing the economic net-cost

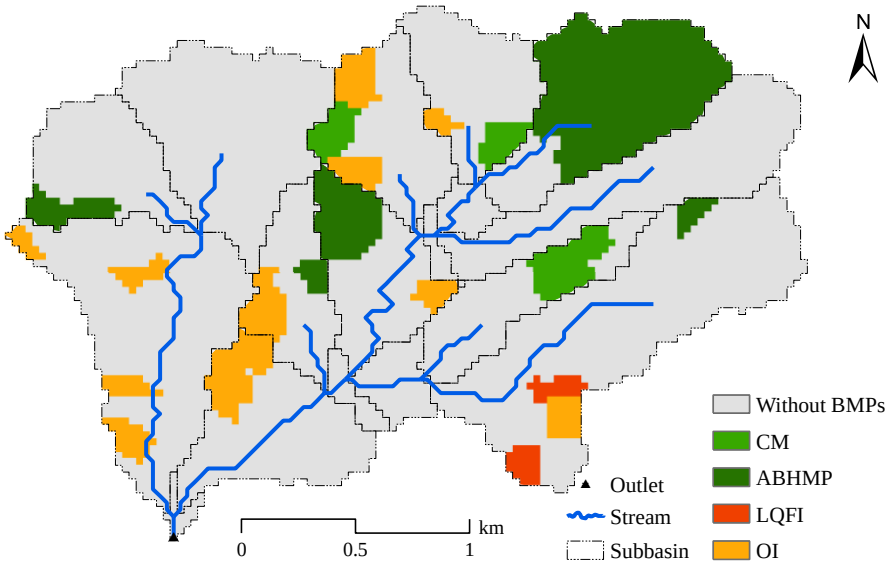


Figure 2:8-4 Spatial distribution of the selected BMP scenario of the 2nd generation of the BMP scenarios optimization

2:8.2 Configuration file of scenario analysis

The configuration file of BMP scenarios analysis, such as that of the Youwuzhen watershed model shown in Figure 2:8-5, includes five sections, i.e., `SEIMS_Model`, `Scenario_Common`, `BMPs`, `NSGA2`, and `OPTIONAL_MATPLOT_SETTING`. Among them, `OPTIONAL_MATPLOT_SETTING` is optional. The names of sections and options should not be changed.

- *`SEIMS_Model`: Basic settings of the SEIMS-based watershed model, see Section 2:4.3.2 for details. Note that the OpenMP version of SEIMS main program is used by default. However, the options of `version`, `MPI_BIN`, and `processNum` are supported if the MPI&OpenMP version is wanted.*
- *`Scenario_Common`: Common settings for scenarios analysis.*
  1. `Eval_Time_start`*: Starting date time of model evaluation with the format of `YYYY-MM-DD HH:MM:SS`.*
  2. `Eval_Time_end`*: Ending date time of model evaluation with the format of `YYYY-MM-DD HH:MM:SS`.*
  3. `worst_economy`*: Economic net-cost under the circumstance of worst scenario.*
  4. `worst_environment`*: Environmental effectiveness under the circumstance of worst scenario. The `worst_economy` and `worst_environment` are set for the calculation of hypervolume index.*
  5. `runtime_years`*: For the BMP scenarios analysis based on the evaluation of long-term environmental effectiveness of BMPs, SEIMS assumed that BMPs can reach relative stability after several years of maintenance from their first establishment.*

Therefore, the `runtime_years` *is specified for the evaluation of BMP scenario cost model.*

6. `Export_scenario_txt`*: (Optional) Output each BMP scenario as plain text file (*`True`*) or not (*`False`*). The default is* `False`*.*
7. `Export_scenario_tif`*: (Optional) Output the spatial distribution of each BMP scenario as GeoTiff raster file (*`True`*) or not (*`False`*). The default is* `False`*.*

- `BMPs`*: Application specific BMPs settings.*
  1. `BMPs_info`*: Information of selected BMP type for BMP scenarios analysis. The JSON format is used. The key is* `BMPID` *(see Section 2:2.7.1) and the value is another JSON string of the corresponding field-values (available fields can be found in Table 2:2-8). Note that, the data type of the key MUST be string, although* `BMPID` *is integer. The* `DISTRIBUTION` *and* `LOCATION` *fields can be omitted which will be defined in* `BMPs_cfg_units`*.*

```
BMPs_info = {"17":{
                    "COLLECTION": "AREAL_STRUCT_MANAGEMENT",
                    "SUBSCENARIO": [1, 2, 3, 4]
                   }
             }
```

  2. `BMPs_retain`*: Retained BMP types for generated BMP scenarios during the optimization. The format is the same with* `BMPs_info`*.*

```
BMPs_retain = {"12":{
                     "COLLECTION": "PLANT_MANAGEMENT",
                     "DISTRIBUTION": "RASTER|LANDUSE",
                     "LOCATION": "33",
                     "SUBSCENARIO": 0
                    }
               }
```

  3. `Eval_info`*: Information of model evaluation, including the* `OUTPUTID` *and the corresponding output filename (*`ENVEVAL`*) and the base value of environmental variable (*`BASE_ENV`*), e.g., the annual total amount of soil erosion. If the* `BASE_ENV` *is set to -9999, the base scenario will be firstly evaluated before the BMP scenarios analysis.*

```
Eval_info = {
              "OUTPUTID": "SED_OL",
              "ENVEVAL": "SED_OL_SUM.tif",
              "BASE_ENV": -9999
             }
```

  4. `BMPs_cfg_units`*: Information of BMP configuration units which also follows the JSON format. The* `UNITJSON` *is a file that describes the basic information of each spatial unit and spatial relationships between spatial units, e.g., the upstream and downstream relationships. In the current version, the hydrologic response units (HRUs,* `HRU`*), spatially explicit HRUs (*`EXPLICITHRU`*), hydrologically connected fields (*`CONNFIELD`*), and slope position units (*`SLPPOS`*) are supported. More details please refers to Zhu et al. (2019).*

```
BMPs_cfg_units = {"CONNFIELD": {
                                "DISTRIBUTION": "RASTER|FIELDS_15",
                                "UNITJSON": "connected_field_units_updown_15.json"
                               }
                  }
```

5. `BMPs_cfg_method`*: BMP configuration strategy used according to the characteristics of BMP configuration units, such as randomly strategy (*`RAND`*), strategy with knowledge on the suitable landuse types/slope positions of individual BMPs (*`SUIT`*), strategy based on expert knowledge of upstream–downstream relationships (*`UPDOWN`*, Wu et al. [2018]), and strategy with domain knowledge on the spatial relationships between BMPs and slope positions along the hillslope (*`HILLSLP`*, Qin et al. [2018]). More details please refers to Zhu et al. (2019).*

- *Sections of specific optimization methods for scenario analysis. Currently, the NSGA-II algorithm has been integrated and tested. In the future version of SEIMS, more methods should be integrated.*

1. `NSGA2`*: Parameter settings of NSGA-II algorithm.*

   `GenerationsNum`*: Maximum number of generations.*
   `PopulationSize`*: Initial population size, i.e., the number of individuals.*
   `CrossoverRate`*: Crossover probability, ranges from 0 to 1. A larger crossover rate indicates a higher possibility to take place the crossover operation between two parent individuals.*
   `MutateRate`*: Mutate probability.*
   `MaxMutatePerc`*: Maximum percent of genes to be mutated.*
   `SelectRate`*: Selection rate of the evaluated and sorted individuals for each generation which is known as near-optimal Pareto solutions.*

- `OPTIONAL_MATPLOT_SETTINGS`*: Plot settings for matplotlib, see Section 2:5.2.*

```
[SEIMS_Model]
MODEL_DIR = C:\z_code\Hydro\SEIMS\data\youwuzhen\demo_youwuzhen30m_longterm_model
BIN_DIR = C:\z_code\Hydro\SEIMS\bin
HOSTNAME = 127.0.0.1
PORT = 27017
threadsNum = 2
layeringMethod = 1
scenarioID = 0
# Simulation period (UTCTIME)
Sim_Time_start = 2012-01-01 00:00:00
Sim_Time_end = 2012-05-30 23:59:59

[Scenario_Common]
Eval_Time_start = 2012-02-27 00:00:00
Eval_Time_end = 2012-04-30 23:59:59
worst_economy = 300.
worst_environment = 0.
runtime_years = 8
export_scenario_txt = True
export_scenario_tif = True

[BMPs]
BMPs_info = {"17":{"COLLECTION": "AREAL_STRUCT_MANAGEMENT", "SUBSCENARIO": [1, 2, 3, 4]}}
BMPs_retain = {"12":{"COLLECTION": "PLANT_MANAGEMENT", "DISTRIBUTION": "RASTER|LANDUSE",
"LOCATION": "33", "SUBSCENARIO": 0}}
Eval_info = {"OUTPUTID": "SED_OL", "ENVEVAL": "SED_OL_SUM.tif", "BASE_ENV": -9999}
BMPs_cfg_units = {"CONNFIELD": {"DISTRIBUTION": "RASTER|FIELDS_15", "UNITJSON":
"connected_field_units_updown_15.json"}}
BMPs_cfg_method = UPDOWN

[NSGA2]
GenerationsNum = 2
PopulationSize = 4
CrossoverRate = 1.0
MaxMutatePerc = 0.2
MutateRate = 1.0
SelectRate = 1.0

[OPTIONAL_MATPLOT_SETTINGS]
FIGURE_FORMATS = PDF,PNG
LANG_CN = False
FONT_TITLE = Times New Roman
TITLE_FONTSIZE = 16
LEGEND_FONTSIZE = 12
TICKLABEL_FONTSIZE = 12
AXISLABEL_FONTSIZE = 12
LABEL_FONTSIZE = 14
DPI = 300
```

Figure 2:8-5 Configuration content for BMP scenario analysis of the Youwuzhen watershed model based on NSGA-II

2:8.3 Advanced usage

The Python scripts of scenarios analysis are located in `SEIMS/seims/scenario_analysis/spatialunits`. The `main_nsga2.py` is the entrance for the scenarios analysis based on NSGA-II algorithm, which can be executed though the unified format of running SEIMS Python scripts, e.g.,

```
01 >cd D:\demo\SEIMS\seims\scenario_analysis\spatialunits
02 >python main_nsga2.py -ini
D:\demo\SEIMS\data\youwuzhen\workspace\scenario_analysis.ini
```

Section 3. Design and implementation

This section is intended to give a detailed introduction of the design and implementation of SEIMS, which will be extended from Zhu et al. (Environ. Model. Softw., under review).

In the current pre-released version, this section is not yet finished, please refers to Zhu et al. (Environ. Model. Softw., under review) to get the necessary information.

3:1. Overall design of SEIMS

The overall architecture of SEIMS was designed as shown in Figure 3:1-1, and consists mainly of the SEIMS module library based on the modular structure, the SEIMS main programs (i.e., OpenMP version and MPI&OpenMP version), the watershed database, and utility tools for watershed model applications (such as parameter sensitivity analysis tool, and auto-calibration tool). The parallel computing middleware at multiple levels is implemented at the basic-unit level in SEIMS modules, the subbasin level in the MPI&OpenMP version of SEIMS main program, and the model level in watershed model applications, respectively. A SEIMS-based model consists of one SEIMS main program, several customized SEIMS modules, and the watershed database. Each SEIMS module inherits from the base module class (i.e., `SimulationModule`) with standard and concise interfaces (e.g., `SetData`, `GetData`, and `Execute` functions) and dependents on base modules such as `I/O` module (Figure 3:1-1). The basic-unit level parallelization is achieved using OpenMP in the execution function of each SEIMS module. The basic version of SEIMS main program, which is the OpenMP version, is responsible for loading a set of user-configured modules to build and execute a simulation workflow. The MPI&OpenMP version of SEIMS main program uses the subbasin level domain decomposition and task scheduling to create instances of the OpenMP versioned SEIMS main program for each individual subbasins and distribute them among different computing nodes with MPI-based communication, so to achieve subbasin level parallel computing. Watershed model applications that requires numerous model runs (e.g., sensitivity analysis of a watershed model) are parallelized at model level based on job management.

With the support of parallel computing, SEIMS is compatible with common operating systems (such as Windows® and Linux®) and parallel computing platforms such as personal computers with multi-core CPU (Central Processing Unit) and SMP clusters..

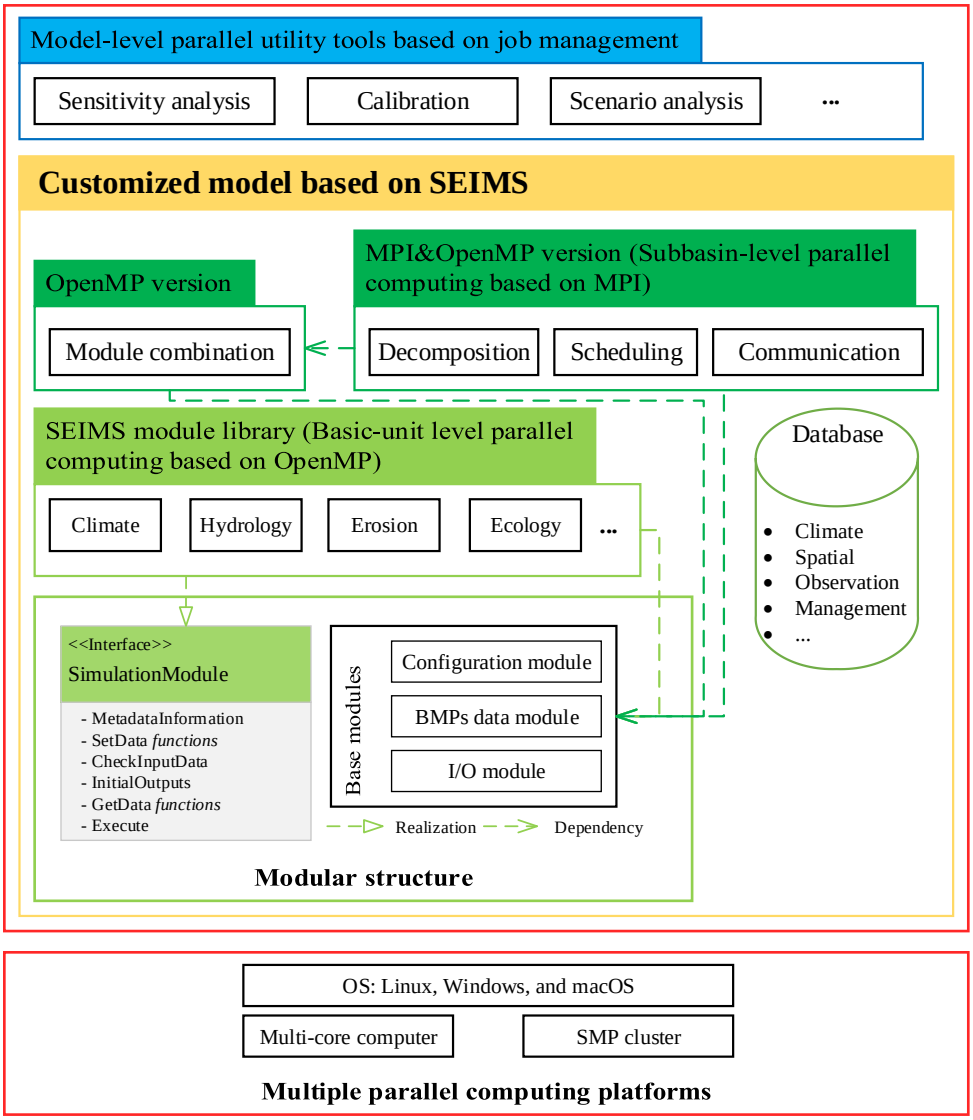


Figure 3:1-1 Architecture of Spatially Explicit Integrated Modeling System (SEIMS) which consists of the SEIMS module library, two versions of SEIMS main programs (i.e., OpenMP version and OpenMP&MPI version), the watershed database, and utility tools for watershed model applications, and can be conducted on multiple parallel computing platforms.

Section 4. Write your own code

The section presents a simple demo of developing a new module of watershed subprocess based on the SEIMS module interfaces.

4:1. Develop a new module of one watershed process

Generally, it requires three main steps to develop a new module for a specific watershed subprocess based on the SEIMS module interfaces.

- *Review the related literature and/or source code (if exists) of the watershed subprocess algorithm and figure out the input and output parameters of the algorithm as well as the specific simulation formula (or the execution code).*
- *Create new SEIMS module based on the module template and* `CMake` *structure.*
- *Open the SEIMS solution in Visual Studio or other IDEs and start to code following the recommended order of APIs.*

In this section, the simulation of potential evapotranspiration using Hargreaves method was selected as an example to demonstrate these steps.

4:1.1 Review literature and/or existing model code

Evapotranspiration is a collective term that includes all processes by which water at the earth's surface is converted to water vapor (Neitsch et al., 2011). It includes evaporation from the plant canopy, transpiration, sublimation, and evaporation from the soil. An accurate estimation of evapotranspiration is critical in the assessment of water resources and the impact of climate and land use change on those resources.

The Hargreaves method was originally derived from eight years of cool-season Alta fescue grass lysimeter data from Davis, California (Hargreaves, 1975). The Hargreaves method was implemented in the SWAT model with the improved equation (Hargreaves, 1985):

$$\lambda E_o = petco \cdot H_0 \cdot \left(T_{\max} - T_{\min}\right)^{0.5} \cdot \left(T_{avg} + 17.8\right)$$

where λ is the latent heat of vaporization (MJ kg^{-1}), E_o is the potential evapotranspiration (mm d^{-1}), *petco* is coefficient related to radiation which ranges from 0.0019 to 0.0032, H_0 is the extraterrestrial radiation (MJ m^{-2} d^{-1}), T_{max}, T_{min}, and T_{avg} are the maximum, minimum, and average air temperature for a given day (°C), respectively.

The source code of the Hargreaves method for potential evapotranspiration can be found in `etpot.f`. The following code snippet showed the core simulation code.

```
      case (2)   !! HARGREAVES POTENTIAL EVAPOTRANSPIRATION METHOD

       !! extraterrestrial radiation
       !! 37.59 is coefficient in equation 2.2.6 !!extraterrestrial
       !! 30.00 is coefficient in equation 2.2.7 !!max at surface
       ramm = 0.
       ramm = hru_rmx(j) * 37.59 / 30.

       if (tmx(j) > tmn(j)) then
         pet_day = harg_petco(hru_sub(j))*(ramm / xl)*(tmpav(j) + 17.8)*
     &                                        (tmx(j) - tmn(j))**0.5
         pet_day = Max(0., pet_day)
       else
         pet_day = 0.
       endif
```

where `ramn` is the extraterrestrial radiation which is calculated by maximum possible radiation for the day (`hru_rmx`), `hru_rmx` is a function of day of year and latitude, `xl` is the latent heat of vaporization which is calculated by the mean air temperature (`tmpav`).

The source code of the calculation of `hru_rmx` can be found in `clgen.f`.

To sum up, the simulation of potential evapotranspiration using the Hargreaves method requires the coefficient related to radiation, latitude, maximum temperature, minimum temperature, and average temperature. The simulation code can be rewritten from the FORTRAN source code of SWAT (i.e., `etpot.f` and `clgen.f`).

4:1.2 Create new SEIMS module

As introduced in previous sections, the source code of SEIMS library is located in `SEIMS/seims/src/seims_main/modules`. For the convenience of management, SEIMS modules are divided into several categories. There is one `CMakeLists.txt` file to indicate which categories are involved in the SEIMS project, i.e., `SEIMS/seims/src/seims_main/modules/CMakeLists.txt`.

```
MESSAGE(STATUS "     Compiling SEIMS_subdir: modules...")
ADD_SUBDIRECTORY(./climate)
ADD_SUBDIRECTORY(./hydrology)
ADD_SUBDIRECTORY(./hydrology_longterm)
ADD_SUBDIRECTORY(./erosion)
ADD_SUBDIRECTORY(./nutrient)
ADD_SUBDIRECTORY(./ecology)
ADD_SUBDIRECTORY(./management)
ADD_SUBDIRECTORY(./test)
```

It is worth to note that a corresponding line with the `ADD_SUBDIRECTORY()` command should be appended if a new category is added.

The template of the SEIMS module is the `template` folder located in `SEIMS/seims/src/seims_main/modules/test`, which contains four files, i.e., `CMakeLists.txt`, `api.cpp`, `template.h`, and `template.cpp`.

1. `CMakeLists.txt`*: file used to create the project for building the module executable library.*
2. `api.cpp`*: implementation file of* `MetadataInformation` *function.*

3. `template.h`*: header file that defines the module class which is inherited from the basic class of SEIMS module (i.e.,* `SimulationModule`*). The header file should be renamed with a meaningful name, such as* `PETHargreaves.h`*.*
4. `template.cpp`*: implementation file that includes* `SetData` *and* `GetData` *functions* `CheckInputData` *and* `InitialOutputs` *functions, and Execute function. The implementation file should be renamed with the same filename of the header file, such as* `PETHargreaves.cpp`*.*

Please follow these steps to create a new SEIMS module based on the module template.

1. *Copy the folder of the SEIMS module template to an existing or newly created directory of SEIMS module library, e.g.,* `modules/hydrology_longterm`*, and rename with the new module name followed the format of* `<SubprocessNameAbbr>_<AlgorithmNameAbbr>`*, e.g.,* `PET_H` *that means the simulation of potential evapotranspiration using Hargreaves method.*
2. *Open the* `CMakeLists.txt` *file in the module folder of* `PET_H` *and specify the name of the executable library (the 2nd line) and the project folder for Visual Studio or Xcode (the 10th line, which is Optional). For example, the content of the* `CMakeLists.txt` *file in the module template is as follows,*

```
01 MESSAGE(STATUS "       Compiling test_subdir: template...")
02 SET(MODNAME template)
03 PROJECT(SEIMS_MODULE_${MODNAME})
04 FILE(GLOB SRC_LIST *.cpp *.h)
05 ADD_LIBRARY(${MODNAME} SHARED ${SRC_LIST})
06 SET(LIBRARY_OUTPUT_PATH ${SEIMS_BINARY_OUTPUT_PATH})
07 TARGET_LINK_LIBRARIES(${MODNAME} common_algorithm module_setting bmps data)
08 INSTALL(TARGETS ${MODNAME} DESTINATION ${INSTALL_DIR})
09 IF (MSVC OR XCODE)
10     SET_PROPERTY(TARGET ${MODNAME} PROPERTY FOLDER "modules/test")
11 ENDIF ()
```

After modification for the `PET_H` *module,*

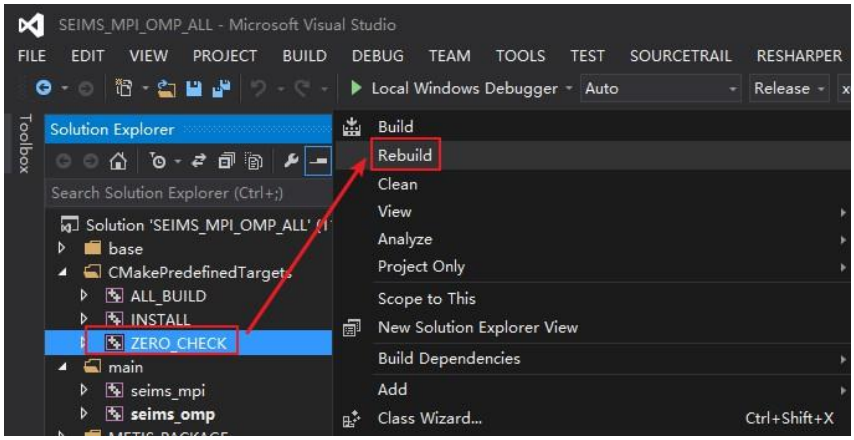
```
01 MESSAGE(STATUS "       Compiling hydrology_longterm_subdir: PET_H...")
02 SET(MODNAME PET_H)
03 PROJECT(SEIMS_MODULE_${MODNAME})
04 FILE(GLOB SRC_LIST *.cpp *.h)
05 ADD_LIBRARY(${MODNAME} SHARED ${SRC_LIST})
06 SET(LIBRARY_OUTPUT_PATH ${SEIMS_BINARY_OUTPUT_PATH})
07 TARGET_LINK_LIBRARIES(${MODNAME} module_setting common_algorithm)
08 INSTALL(TARGETS ${MODNAME} DESTINATION ${INSTALL_DIR})
09 IF (MSVC OR XCODE)
10     SET_PROPERTY(TARGET ${MODNAME} PROPERTY FOLDER "modules/hydrology_longterm")
11 ENDIF ()
```

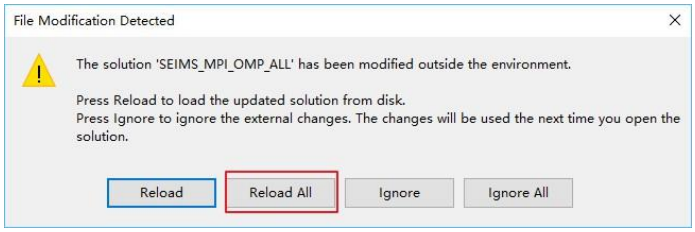
Note that, the 7th line is for specifying libraries to use when linking the current SEIMS module. If users do not sure how to determine the exact libraries, just keep the default settings in the module template.

3. *Append the* `ADD_SUBDIRECTORY()` *command of the relative directory path of the new module to the* `CMakeLists.txt` *file in its parent directory, such as* `modules/hydrology_longterm/CMakeLists.txt`*, such as,*

```
MESSAGE(STATUS "      Compiling SEIMS_subdir: hydrology_longterm...")
ADD_SUBDIRECTORY(./DEP_LINSLEY)
ADD_SUBDIRECTORY(./GWA_RE)
ADD_SUBDIRECTORY(./IUH_OL)
ADD_SUBDIRECTORY(./MUSK_CH)
ADD_SUBDIRECTORY(./PER_PI)
ADD_SUBDIRECTORY(./PER_STR)
ADD_SUBDIRECTORY(./PET_PM)
ADD_SUBDIRECTORY(./PET_PT)
ADD_SUBDIRECTORY(./PET_H)
```

4. *Rerun the CMake command as introduced in Section 2:1.4 to build the SEIMS project in which the newly created module which will be included.*
5. *Alternative to step 4, open the SEIMS solution in Visual Studio (i.e., `SEIMS/build/SEIMS_MPI_OMP_ALL.sln`), and right-click on the `ZERO_CHECK` project in `CMakePredefinedTargets` and select `Rebuild`. Then, click on `Reload All` to reload all projects of SEIMS including the newly created module.*





4:1.3 Open SEIMS solution in Visual Studio and start to code

After (re)building the SEIMS solution which includes the newly created module, the following steps are recommended to start to code.

1. *Open the header file (i.e., `PETHargreaves.h` in this demo) and rename the class name from `ModuleTemplate` to `PETHargreaves`. Also remember to change the include guard from `SEIMS_MODULE_TEMPLATE_H` to `SEIMS_MODULE_PET_H_H` or any other unique macro name in the whole SEIMS solution.*
2. *Open the `api.cpp` file and write the `MetadataInformation` function. To avoid inconsistent typing of the name, unit, and description of the same parameter/variable, the definition of all these strings are defined as macro strings in the `text.h` header file (`SEIMS/seims/src/seims_main/base/text.h`) in the current implementation of*

SEIMS. Thus, developers should search the planned variable first in the `text.h` to make sure its definition is unique.

According to the review of theory literature and source code of SWAT, eight inputs should be defined and four of them are from the database while the others are outputs of other modules.

```
// Parameters from Database (non-time series)
mdi.AddParameter(VAR_PET_HCOEF, UNIT_NON_DIM, DESC_PET_HCOEF,
Source_ParameterDB, DT_Single);
mdi.AddParameter(VAR_CELL_LAT, UNIT_LONLAT_DEG, DESC_CELL_LAT,
Source_ParameterDB, DT_Raster1D);
// Inputs from the output of other modules
mdi.AddInput(VAR_TMEAN, UNIT_TEMP_DEG, DESC_TMEAN, Source_Module, DT_Raster1D);
mdi.AddInput(VAR_TMAX, UNIT_TEMP_DEG, DESC_TMAX, Source_Module, DT_Raster1D);
mdi.AddInput(VAR_TMIN, UNIT_TEMP_DEG, DESC_TMIN, Source_Module, DT_Raster1D);
mdi.AddInput(DataType_RelativeAirMoisture, UNIT_PERCENT, DESC_RM,
Source_Module, DT_Raster1D);
```

As to the output variables of the current module, except for the potential evapotranspiration on the current day (`VAR_PET`), there are also an auxiliary output, i.e., the day length (`VAR_DAYLEN`) when calculating the maximum possible radiation for the day.

```
mdi.AddOutput(VAR_DAYLEN, UNIT_HOUR, DESC_DAYLEN, DT_Raster1D);
mdi.AddOutput(VAR_PET, UNIT_WTRDLT_MMD, DESC_PET, DT_Raster1D);
```

3. *Define the input parameters, input variables from other modules, and output variables of the current module in the header file.*

```
// Parameters from Database
int m_nCells; ///< valid units number
float m_HCoef_pet; ///< coefficient related to radiation used in Hargreaves method
float* m_cellLat; ///< latitude of each valid units
// Inputs from the output of other modules
float* m_meanTemp; ///< mean air temperature for a given day (deg C)
float* m_maxTemp; ///< maximum air temperature for a given day (deg C)
float* m_minTemp; ///< minimum air temperature for a given day (deg C)
float* m_rhd; ///< relative humidity (%)
// Output variables
float* m_dayLen; ///< VAR_DAYLEN, day length (hr)
float* m_pet; ///< VAR_PET, potential evapotranspiration on the day
```

4. *Complete the initialization (i.e., the constructor function that sets default values for all variables defined in header file) and finalization (i.e., the destructor function that releases the newly allocated memory of the current module such as array-based output variables).*

```
PETHargreaves::PETHargreaves() :
    m_nCells(-1), m_HCoef_pet(0.0023f), m_cellLat(nullptr),
    m_meanTemp(nullptr), m_maxTemp(nullptr), m_minTemp(nullptr),
    m_dayLen(nullptr), m_pet(nullptr) {
}

PETHargreaves::~PETHargreaves() {
    if (m_dayLen != nullptr) Release1DArray(m_dayLen);
    if (m_pet != nullptr) Release1DArray(m_pet);
}
```

5. *Assign values to input parameters and input variables from other modules in* `SetData` *series functions such as* `SetValue`, `Set1DData`, *and* `Set2DData`.

```
void PETHargreaves::SetValue(const char* key, const float value) {
    string sk(key);
    if (StringMatch(sk, VAR_PET_HCOEF)) m_HCoef_pet = value;
    else {
        throw ModelException(MID_PET_H, "SetValue", "Parameter " + sk +
                             " does not exist in current module.");
    }
}
```

```
void PETHargreaves::Set1DData(const char* key, const int n, float* value) {
    // Check the first dimension (m_nCells) of array-based data
    CheckInputSize(key, n);
    string sk(key);
    if (StringMatch(sk, VAR_TMEAN)) m_meanTemp = value;
    else if (StringMatch(sk, VAR_TMAX)) m_maxTemp = value;
    else if (StringMatch(sk, VAR_TMIN)) m_minTemp = value;
    else if (StringMatch(sk, DataType_RelativeAirMoisture)) m_rhd = value;
    else if (StringMatch(sk, VAR_CELL_LAT)) m_cellLat = value;
    else {
        throw ModelException(MID_PET_H, "Set1DData", "Parameter " + sk +
                             " does not exist in current module.");
    }
}
```

6. *Accomplish the validation check of data set by* `SetData` *functions in* `CheckInputData` *function and initializing necessary output variables in* `InitialOutputs` *function.*

```
bool PETHargreaves::CheckInputData() {
    CHECK_POSITIVE(MID_PET_H, m_nCells);
    CHECK_POINTER(MID_PET_H, m_maxTemp);
    CHECK_POINTER(MID_PET_H, m_meanTemp);
    CHECK_POINTER(MID_PET_H, m_minTemp);
    CHECK_POINTER(MID_PET_H, m_cellLat);
    return true;
}
```

```
void PETHargreaves::InitialOutputs() {
    CHECK_POSITIVE(MID_PET_H, m_nCells);
    if (nullptr == m_pet) Initialize1DArray(m_nCells, m_pet, 0.f);
    if (nullptr == m_dayLen) Initialize1DArray(m_nCells, m_dayLen, 0.f);
}
```

7. *Implement or transplant the actual simulation code in* `Execute` *function.*

```
int PETHargreaves::Execute() {
    CheckInputData();
    InitialOutputs();
#pragma omp parallel for
    for (int i = 0; i < m_nCells; i++) {
        /// calculate the max solar radiation
        float srMax; /// maximum solar radiation of current day
        MaxSolarRadiation(m_dayOfYear, m_cellLat[i], m_dayLen[i], srMax);
        ///calculate latent heat of vaporization(from swat)
        float latentHeat = 2.501f - 0.002361f * m_meanTemp[i];
        /// extraterrestrial radiation
        /// equation 1:1.1.6 in SWAT Theory 2009, p33
        float h0 = srMax * 37.59f / 30.0f;
        /// calculate potential evapotranspiration
        ///  equation 2:2.2.24 in SWAT Theory 2009, p133
        float petValue = m_HCoef_pet * h0
                         * pow(Abs(m_maxTemp[i] - m_minTemp[i]), 0.5f)
                         * (m_meanTemp[i] + 17.8f) / latentHeat;
        m_pet[i] = m_petFactor * Max(0.0f, petValue);
    }
    return 0;
}
```

Note that the function of calculating maximum solar radiation of current day, as a universal function, should be separated from the specific module. So the `MaxSolarRadiation` *function is defined in* `SEIMS/seims/src/seims_main/base/common_algorithm/ClimateParams.h` *and implemented in* `SEIMS/seims/src/seims_main/base/common_algorithm/ClimateParams.cpp`.

```
#include "ClimateParams.h"
```

The `#pragma omp parallel for` *is the compiler directive of OpenMP to indicate the following for-loop code region that to be executed concurrently.*

8. *Complete the* `GetData` *functions (e.g.,* `GetValue`, `Get1DData`, *and* `Get2DData`*) for output variables of current module.*

```
void PETHargreaves::Get1DData(const char* key, int* n, float** data) {
    InitialOutputs();
    string sk(key);
    *n = m_nCells;
    if (StringMatch(sk, VAR_PET)) *data = m_pet;
    else if (StringMatch(sk, VAR_DAYLEN)) *data = m_dayLen;
    else {
        throw ModelException(MID_PET_H, "Get1DData", "Parameter " + sk + " does
not exist.");
    }
}
```

9. *Build the SEIMS module by right click the project name of the current module and select* `Build` *command.*

4:1.4 Test the new SEIMS module

The newly developed `PET_H` module was tested based on the Youwuzhen watershed model customized in Section 2:4.3.3. The module configuration file is shown in Figure 4:1-1.

```
### Driver factors, including climate and precipitation
0 | TimeSeries | | TSD_RD
0 | Interpolation_0 | Thiessen | ITP
### Surface processes
0 | Soil temperature | Finn Plauborg | STP_FP
0 | PET | Hargreaves | PET_H
#0 | PET | PenmanMonteith | PET_PM
0 | Interception | Maximum Canopy Storage | PI_MCS
0 | Snow melt | Snowpeak Daily | SNO_SP
0 | Infiltration | Modified rational | SUR_MR
0 | Depression and Surface Runoff | Linsley | DEP_LINSLEY
0 | Hillslope erosion | MUSLE | SERO_MUSLE
0 | Plant Management Operation | SWAT | PLTMGT_SWAT
0 | Percolation | Storage routing | PER_STR
0 | Subsurface | Darcy and Kinematic | SSR_DA
0 | AET | Hargreaves and PriestleyTaylor | AET_PTH
#0 | SET | Linearly Method from WetSpa | SET_LM
0 | PG | Simplified EPIC | PG_EPIC
0 | ATMDEP | Atomosphere deposition | ATMDEP
0 | NUTR_TF | Nutrient Transformation of C, N, and P | NUTR_TF
0 | Water overland routing | IUH | IUH_OL
0 | Sediment overland routing | IUH | IUH_SED_OL
0 | Nutrient | Attached nutrient loss | NUTRSED
0 | Nutrient | Soluble nutrient loss | NUTRMV
0 | Pothole | SWAT cone shape | IMP_SWAT
0 | Soil water | Water balance | SOL_WB
### Route Modules, including water, sediment, and nutrient
0 | Groundwater | Linear reservoir | GWA_RE
0 | Nutrient | groundwater nutrient transport | NUTRGW
0 | Water channel routing | MUSK | MUSK_CH
0 | Sediment channel routing | Simplified Bagnold equation | SEDR_SBAGNOLD
0 | Nutrient | Channel routing | NutrCH_QUAL2E
```

Figure 4:1-1 Test the Hargreaves method for the simulation of potential evapotranspiration based on the Youwuzhen watershed model customized in Section 2:4.3.3.

The Youwuzhen watershed model was executed with all model parameters remain the default values as well. Figure 4:1-2 showed the spatial distributions of average potential evapotranspiration simulated by the Priestley-Taylor method (Figure 4:1-2a) and Hargreaves method (Figure 4:1-2b).

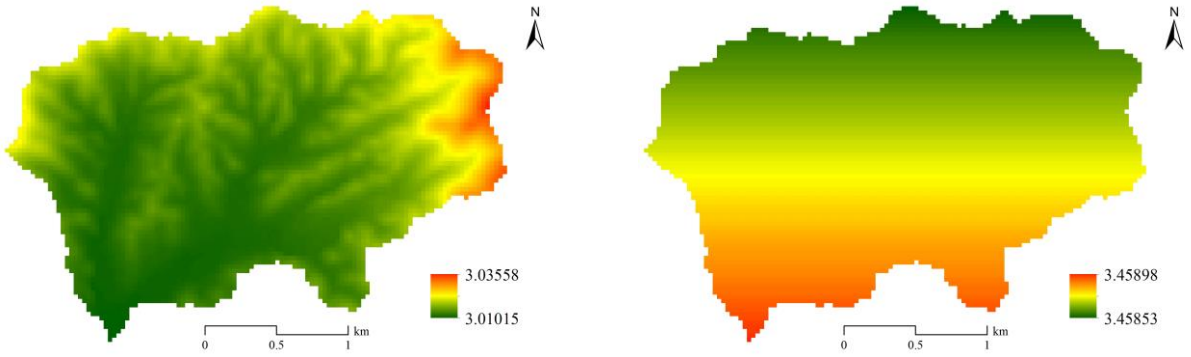


Figure 4:1-2 Spatial distributions of average potential evapotranspiration simulated by the Youwuzhen watershed model using the (a) Priestley-Taylor method and the (b) Hargreaves method