Jul 1st, 12:00 AM

The informatics of the hydrological modelling system JGrass-NewAge

G. Formetta

Andrea Antonello

S. Franceschi

Olaf David

R. Rigon

International Environmental Modelling and Software Society (iEMSs)
2012 International Congress on Environmental Modelling and Software
Managing Resources of a Limited Planet, Sixth Biennial Meeting, Leipzig, Germany
R. Seppelt, A.A. Voinov, S. Lange, D. Bankamp (Eds.)
http://www.iemss.org/society/index.php/iemss-2012-proceedings

The informatics of the hydrological modelling system JGrass-NewAge

G.Formetta[a], A.Antonello[b], S.Franceschi[b], O. David[c] and R.Rigon[a]

[a]*University of Trento, 77 Mesiano St., Trento, I-38123 (formetta@ing.unitn.it, riccardo.rigon@ing.unitn.it)*

[b]*Hydrologis S.r.l., Bolzano, BZ, Italy (info@hydrologis.com)*

[c]*Depts. of Civil and Environmental Engineering and Computer Science, Colorado State University, Fort Collins, CO 80523 USA (odavid@colostate.edu)*

Abstract: This paper describes the structure of JGrass-NewAge: a system for hydrological forecasting and management at the basin scale. It is based on the Geographic Information System uDig and composed of two parts: (i) the system for data and result visualization based on JGrass and (ii) the modelling components. The latter are implemented as OMS3 components, which can be connected or excluded at runtime, according to the needs of who runs the model, and work seamlessly inside the uDig ver.1.3.1 spatial toolbox. Compared to other models which are built upon monolithic code, JGrass-NewAge allows for having multiple modelling solutions for the same process, provided they share the same input and outputs. Since sound hydrological modelling requires a proper definition of a digital watershed model, this paper presents and discusses an implementation based on uDig .

***Keywords**:* Hydrological modelling, digital watershed model, Object Modelling System

1 INTRODUCTION

Environments models are solvers of mass, momentum, and energy conservation, expressed with an acceptable degree of simplification as equations or rules.
Equations have been usually implemented in monolithic software tools (e.g. Rizzoli et al. [2005]) that, once deployed, remain fully in the responsibility of the original developers. Such practice is precluding rapid reuse and advancement in science. Any single step of a research outcome should, at least in principle, be reproducible. In fact, with the traditional approach to structure of the independent revisions, external improvement is nearly impossible even if the code would be available. Alteration and modification of models is practically impossible by other scientists.
To overcome these difficulties, researchers that rely on computational techniques as part of their day-to-day activities would need “reproducible research systems” (RRS) apt to be inspected in detail, making it easier to document any step during research from data preparation to output analyses performed, and, at the same time, working collaboratively.
To obtain such goals, commercial programming practices were promoted, such as concepts of object oriented programming as represented in encapsulation, data abstraction, delegation, inheritance, and other principles.
Moreover, as a requirement a RRS infrastructure should include not only the computational cores but also visualization and data-processing tools necessary to synthesize knowledge from volume of inputs and outputs.
Many of such computer infrastructures were designed and built with these requirements in mind (e.g. Wesselung et al. [1996], Argent [2005], Rizzoli et al.

[2005]). Among those that specifically target the support of hydrological modelling are the Spatial Modelling Environment (SME, Maxwell and Costanza [1997]), The Invisible Modelling Environment (TIME, http://www.toolkit.net.au/Tools/TIME) and hydrological derivative tools like, E2 (Argent et al. [1999]), OpenMI (http://www.openmi.org/), Moore and Tindall [2005]), and the Object Modelling System (OMS, Kralisch et al. [2005]).
Many of the above frameworks requires a quite relevant paradigm shift in programming that not all scientists, even if proficient modellers, are willing to make, hence their diffusion among scientist was less than enthusiastic.
Thus, making the transition to modern programming environments easier, some projects recently tried to reduce the invasiveness of frameworks. (Lloyd, 2010). Especially the third version of OMS and the MARS project (http://mars.jrc.ec.europa.eu/mars/About-us/AGRI4CAST) revealing promising perspectives.
Preferable tools for the visualization of hydrological processes have been for a long time Geographic Information Systems (GIS) (Maidment [1993]; Grayson et al. [1992]). However, traditional GIS are usually designed for loading static information layers. They are not designed to interact with the dynamical modelling (e.g. Burrough et al. [1998]; Wesselung et al. [1996]), thus, making it more difficult, if not impossible, to adequately interact with model inputs and results, hence being part of an effective RRS.
The frameworks listed above, offer a component-oriented way to allow a GIS to easily interact with models. In fact, they advocate for separating the model elements, including the I/O, into independent modules, each of them with a specified way to interact with the others through specified interfaces. Through such interfaces the modules can communicate and exchange data at run-time.
The time is right for GIS and hydrological model components to constitute a pool of interoperable tools that can be mixed together for obtaining a software system exactly tailored to a Earth's science task.
This paper describes an open source deployment of such a RRS system, based on the GIS uDig, OMS3, GEOtools and Java programming.

2 THE DEPLOYMENT OF JGRASS-NEWAGE AND THE JGRASS TOOLS

The JGrass-NewAge system represents an attempt to provide for the above concepts and tools, and fit them into the hydrologist's view. To achieve the needs of a RRS, JGrass-NewAge is built upon two main parts: (i) the GIS uDig (http://code.google.com/p/jgrass/) which managing geospatial data, models, visualizes inputs and results, and (ii) the OMS toolbox referred to in uDig as the ''Spatial toolbox''. These two parts can easily be connected with an geospatial database, as well as other middleware as shown in fig.(1).

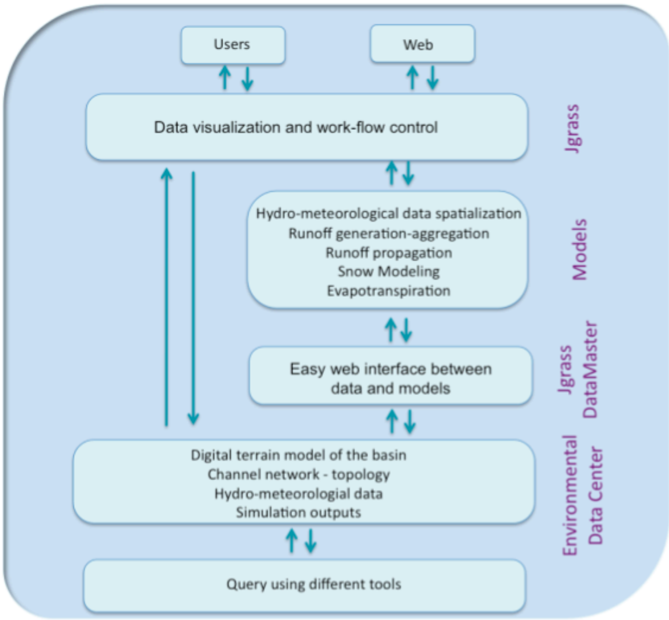

Figure 1. Structure of NewAge, as deployed for “River Adige basin Authority”.

The GIS interface is built on uDig 1.3.1 (http://udig.refractions.net/) as shown in fig.(2); the interface contains not only elements for visualization of maps, but also tools for data manipulation (editing), map printing, connection with remote databases and servers.

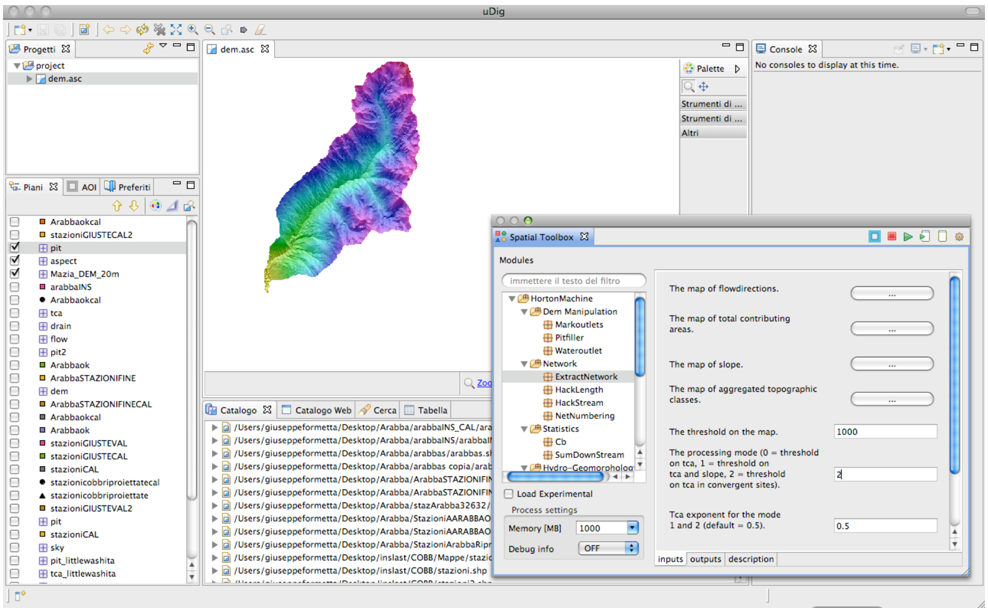

Figure 2. The GIS interface of NewAge implemented in uDig. uDig is based on the Eclipse Rich Client Platform.

The uDig spatial toolbox window is depicted in fig.(2). Its interface allows the execution of models and components of JGrass-NewAge. Tabs in this window contain the data input, data output, and control of the execution flow.
The uDig Spatial Toolbox contains all the tools for the management of raster maps (import, export, manipulation) and provides the geomorphological analysis packages necessary to prepare the input data for JGrass-NewAge.

The Spatial Toolbox interface, as well as the documentation of any tool, is automatically generated by parsing the meta data information contained in the Java annotations provided by the underline OMS3.

The Java based, object-oriented modelling framework OMS3 treats models and components as plain objects with meta data provided by means of annotations David et al. [2002]). Creating a modelling object is very easy, there are no interfaces to implement, no classes to extend and polymorphic methods to overwrite; no framework-specific data types need to replace common native language data types. There is only the use of annotations to specify and describe "points of interest" for existing data fields and methods for the framework.
The models in OMS3 are ‘’components assemblies’’. Each component is a self contained unit implemented with a standard, well defined purpose and interface in mind.
Finally, simulations (model applications with data) can be executed individually from the graphical interface or they can be linked together in the uDig console.
The first use case requires the uDig Spatial Toolbox installation (fig.(2)), the model selection from the “Modules” interface and filled out input field forms.
The second option requires the OMS3 scripting knowledge which allows the user to select and run the models.
Jgrasstools, uses also Open GIS Consortium (OGC) GEOtools libraries (htttp://www.geotools.org). In fact, to pass entire matrixes of spatial data, JGrass-NewAge implemented an OGC grid coverage service: a tool that allows a burst in efficiency, and clean handling of spatial data. Specifically, GridCoverage are objects (in the meaning of object oriented programming) that contain a matrix of numbers, and the information required to define their spatial localization as well as various metadata. All of them are treated and implemented in a standard way. JGrass-NewAge also uses OGC features and related OGC services to implement vector objects necessary for the components.
Moreover, the main structure of the JGrass-NewAge model is based on the Eclipse Rich Client (RCP) interface and services provided by uDig, the extensive use of GEOtools, and a modelling strategy based on OMS3. This structure can easily be connected to a geographic database that provides the appropriate data of input. Furthermore it could serve for the storage of the geospatial components' output.

3 THE DIGITAL WATERSHED MODEL (DWM)

Catchment information in Jgrasstools is organized as a Digital Watershed Model (DWM) which concepts are derived from other implementations such as of ArcHydro (Maidment [2002]) and the ideas behind the Hydrologic Information system (http://his.cuahsi.org/) of CUASHI. The Jgrasstools DWM contains spatial data of the basin in terms of projection, geospatial resolution, any sub-partition of the watershed, sub basins, hillslope or HRU (Ross et al. [1979], Flugel [1995]), and additional metadata, respectively. In addition, the core hydro-meteorological data and other ancillary data for soils, vegetation cover, land-use, satellite, and aerial photos are stored.
It also contains the forcing data, the parameters of the models, and the geometrical/topological structure of the basin.
Geospatial data include geometries (Shapefiles) of the river network, water bodies, a suitable sub-grid parameterization of the area. It is based on a hillslope-channel partition (e.g. Formetta et al. [2011]) and the anthropic features (such as intakes, outtakes) relevant for modelling.
Shapefiles do not contain any topology information. Therefore, JGrass-NewAge DWM was extended with topology information which is derived by enumerating the river network structure according to a generalized Pfafstetter numbering scheme (e.g. Verdin and Verdin [1999], Furst and Horhan [2009]).
The main goal of the Pfafstetter numbering scheme (PNS) presented in is to propose a numbering scheme of the watershed based on the natural river network topology.

4 RUNNING A MODELLING SOLUTION IN JGRASS-NEWAGE

The model components implemented in NewAge are shown in Figure 4. Some of them were already discussed in detail in Formetta et al. [2011], including a meteorological forcing interpolation model, a energy balance and evapotranspiration model, a runoff generation and aggregation model, a channel flow model, and finally auto-calibration models.

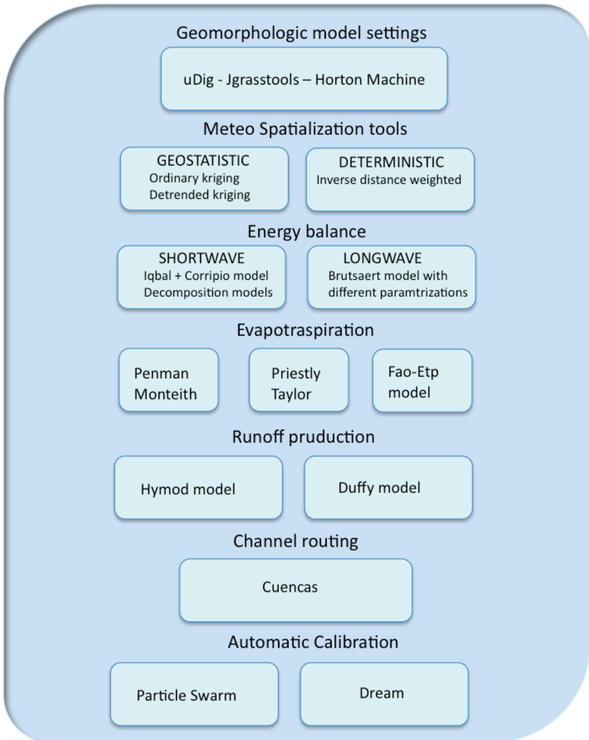

Figure 4. Interacting NewAge-OMS3 components.

The interpolation of meteorological variables (air temperature, precipitation, relative humidity) for each hillslope can be handled by a deterministic (Inverse distance weighted (Cressie [1992], Goovaerts [1997], Lloyd [2005])), geostatistic (Ordinary kriging Goovaerts [1997]) or detrended Kriging (Garen et al. [1994] and Garen and Marks [2005]) approach. As a result, time series for required meteorological variables are generated for each hillslope.
The energetic budget model, presented and validated in (Formetta and Rigon [2011]) include both, shortwave and longwave radiation component calculation for each hillslope. The shortwave radiation balance (beam and diffuse components) is described in Iqbal [1983], Bird and Hulstrom [1981] and Corripio [2002]. The latter implements algorithms that take into account shades and complex topography. Shortwave radiation under generic sky conditions (all-sky) is computed according to Helbig et al. [2010] using different parameterizations approaches, as described in Erbs et al. [1982], Reindl et al. [1990] and Orgill and Hollands [1977]. The longwave radiation budget is based on Brutsaert [1982] and Brutsaert [2005].
After computing the net solar radiation for each hillslope, evapotraspiration can be modelled using three different solutions: the Fao-Evapotraspiration model (Allen et al. [1998]), the Penman-Montheit model Penman [1948] and Monteith et al. [1965]) the Priestly-Taylor model (Priestly [1959], Slatyer and McIlroy [1961], Priestley and Taylor [1972]).
Subsequently, the user can choose between two different runoff generation models: the Duffy's model (Duffy [1996]) and Hymod model (Moore [1985] and Boyle [2001]). In both cases the model is applied at each hillslope and hourly time scale.

Finally, the discharge generated at each hillslope is routed to each associated stream link according to Mantilla and Gupta [2005] and Mandapaka et al. [2009] using the indexed PNS.
All modelling components can be calibrated using one of the auto-calibration algorithms such as Particle Swarm Optimization algorithm (Kennedy and Eberhart [1995], Eberhart and Shi [2001]) and DREAM (Vrugt et al. [2009]).
Every component can be connected, parameterized, and executed either using the OMS3 console (OMS 3.1) or the OMS3 scripting mode within the uDig Spatial Toolbox.
Different components can be instantiated, initialized and connected in a sequence. In this way the modeller can build a custom hydrological model and solution by selecting different components to simulate the same hydrological processes. Processes will then use the OMS3 implicit parallelism to improve the computational efficiency in multicore or multiprocessor machines.
The complete application of the system is presented in Formetta et al. [2011], and Formetta and Rigon [2011].

4 CONCLUSION

The paper introduces the implementation of the JGrass-NewAge system. The distinguishing elements from other systems are its tight integration of a GIS with a component-oriented modelling framework system such as OMS3. Furthermore, JGrass-NewAge introduces topologic information within a DWM based on Pfafstetter numbering scheme to topologically organize any information inside the basin. It properly stores the data in a database.
Finally, JGrass-NewAge exploits the potential offered by GEOtools to manage any spatial data of the model components, which further simplifies their integration in a GIS.
We experienced that the paradigm switch from traditional programming required by the OMS3 system and GEOtools was highly rewarded. JGrass-NewAge improves maintenance of the code by employing methods of Object Oriented programming, which are adapted to the scientific research. This should facilitate the cooperation among researchers and the adoption of reproducible research strategies.
Possibly, one could argue that the use of a full GIS system is not justified for hydrological models., Instead, it could be managed by command-line interfaces or “all-in-one” environments like R, and still using object oriented technologies.
The tools of JGrass-NewAge are well suited to manage the requirements of such systems, since all river basin management tasks have inherently a “spatial” nature; therefore providing the option to span information layers produced by hydrological models with those of the municipalities, such as, roads, forestry, and infrastructure planning.

ACKNOWLEDGMENTS

The Authors thanks the project HydroAlp that support one of the Authors. The Authors thanks the reviewers, their suggestions helped to increased the quality of the paper.

REFERENCES

Allen, R., L. Pereira, D. Raes, M. Smith, et al. Crop evapotranspiration-guidelines for computing crop water requirements-fao irrigation and drainage paper 56. FAO, Rome, 300:6541, 1998.

Argent, R. A case study of environmental modelling and simulation using transplantable components. *Environmental Modelling & Software*, 20(12):1514-1523, 2005.

Argent, R., J. Perraud, J. Rahman, R. Grayson, and G. Podger. A new approach to

water quality modelling and environmental decision support systems. *Environmental Modelling & Software*, 24(7):809–818, 2009.
Bird, R. and R. Hulstrom. Simplified clear sky model for direct and diffuse insolation on horizontal surfaces. Technical report, Solar Energy Research Inst., Golden, CO (USA),1981.
Boyle, D. P. Multicriteria calibration of hydrological model. Ph.D. dissertation, Dep. of Hydrol. and Water Resour., Univ. of Ariz., Tucson, 2001.
Brutsaer t, W. Evaporation into the atmosphere: Theory, history, and applications, volume 1. *Springer*, 1982.
Brutsaer t, W. Hydrology: an introduction. Cambridge Univ Pr, 2005.
Burrough, P., R. McDonnell, P. Burrough, and R. McDonnell. Principles of geographical information systems, volume 333. Oxford university press Oxford, 1998.
Corripio, J. Modelling the energy balance of high altitude glacierised basins in the central Andes. PhD dissertation, University of Edinburgh; 2002, 2002.
Cressie, N. Statistics for spatial data. *Terra Nova*, 4(5):613–617, 1992.
David, O., S. Markstrom, K. Rojas, L. Ahuja, and I. Schneider. The object modeling system. Agricultural system models in field research and technology transfer, pages 317–331, 2002.
Duffy, C. J. A two-state integral-balance model for soil moisture and groundwater dynamics in complex terrain. *Water Resour. Res*., 32(8):2421–2434, 1996.
Eberhar t, R. and Y. Shi. Par ticle swarm optimization: developments, applications and resources. In Proceedings of the 2001 congress on evolutionary computation, volume 1,pages 81–86. Piscataway, NJ, USA: IEEE, 2001.
Erbs, D., S. Klein, and J. Duffie. Estimation of the diffuse radiation fraction for hourly, daily and monthly-average global radiation. *Solar Energy*, 28(4):293–302, 1982.
Flugel, W. Delineating hydrological response units by geographical information system analyses for regional hydrological modelling using PRMS/MMS in the drainage basin of the River Brol, Germany. *Hydrological Processes*, 9(3-4):423-436, 1995.
Formetta, G., R. Mantilla, S. Franceschi, A. Antonello, and R. Rigon. The jgrass-newage system for forecasting and managing the hydrological budgets at the basin scale: models of flow generation and propagation/routing. *Geoscientific Model Development*, 4(4): 943–955, 2011.
Formetta, G. and R. Rigon. The energy balance component in jgrass-newage infrastructure: theory and applications. *Geoscientific Model Development*, in preparation, 2011.

Furst, J. and T. Horhan. Coding of watershed and river hierarchy to suppor t gis-based hydrological analyses at different scales. *Computers & Geosciences*, 35(3):688–696, 2009.
Gamma, E. Design patterns: elements of reusable object-oriented software. Addison-Wesley Professional, 1995.
Garen, D., G. Johnson, and C. Hanson. Mean areal precipitation for daily hydrologic modeling in mountainous regions1. *JAWRA Journal of the American Water Resources Association*, 30(3):481–491, 1994.
Garen, D. and D. Marks. Spatially distributed energy balance snowmelt modelling in a mountainous river basin: estimation of meteorological inputs and verification of model results. *Journal of Hydrology*, 315(1-4):126–153, 2005.
Goovaerts, P. Geostatistics for natural resources evaluation. Oxford University Press, USA, 1997.
Grayson, R., I. Moore, and T. McMahon. Physically based hydrologic modeling: 1.a terrain-based model for investigative purposes. *Water Resources Research*, 28(10): 2639–2658, 1992.
Helbig, N., H. Lowe, B. Mayer, and M. Lehning. Explicit validation of a surface shortwave radiation balance model over snow-covered complex terrain. *Journal of Geophysical Research Atmospheres*, 115:D18113, 2010.
Iqbal, M. An introduction to solar radiation. 1983.

Kennedy, J. and R. Eberhar t. Par ticle swarm optimization. In Neural Networks, 1995. Proceedings., IEEE International Conference on, volume 4, pages 1942-1948. IEEE, 1995.

Kralisch, S., P. Krause, and O. David. Using the object modeling system for hydrological model development and application. *Advances in Geosciences*, 4:75–81, 2005.

Lloyd, C. Assessing the effect of integrating elevation data into the estimation of monthly precipitation in great britain. *Journal of Hydrology*, 308(1-4):128–150, 2005.

Maidment, D. Gis and hydrologic modeling. *Environmental modeling with GIS*, pages 147–167, 1993.

Maidment, D. Arc Hydro: GIS for water resources, volume 1. ESRI press, 2002.

Mandapaka, P., W. Krajewski, R. Mantilla, and V. Gupta. Dissecting the effect of rainfall variability on the statistical structure of peak flows. *Advances in Water Resources*, 32(10):1508–1525, 2009.

Mantilla, R. and V. Gupta. A GIS numerical framework to study the process basis of scaling statistics in river networks. IEEE *Geoscience and Remote Sensing Letters*, 2 (4):404–408, 2005.

Maxwell, T. and R. Costanza. A language for modular spatio-temporal simulation. *Ecological modelling*, 103(2-3):105–113, 1997.

Monteith, J. et al. Evaporation and environment. In Symp. Soc. Exp. Biol, volume 19, pages 205–234, 1965.

Moore, R. The probability-distributed principle and runoff production at point and basin scales. *Hydrol. Sci. J.*, 30(1):165, 1985.

Moore, R. and C. Tindall. An over view of the open modelling interface and environment (the openmi*). Environmental Science & Policy*, 8(3):279–286, 2005.

Orgill, J. and K. Hollands. Correlation equation for hourly diffuse radiation on a horizontal surface. *Solar energy*, 19(4):357–359, 1977.

Penman, H. Natural evaporation from open water, bare soil and grass. Proceedings of the Royal Society of London. Series A. *Mathematical and Physical Sciences*, 193 (1032):120–145, 1948.

Priestley, C. Turbulent transfer in the lower atmosphere. University of Chicago Press Chicago, Ill., 1959.

Priestley, C. and R. Taylor. On the assessment of surface heat flux and evaporation using large-scale parameters. *Monthly weather review*, 100(2):81–92, 1972.

Reindl, D., W. Beckman, and J. Duffie. Diffuse fraction correlations. *Solar Energy*, 45(1): 1–7, 1990.

Rizzoli, A., M. Svensson, E. Rowe, M. Donatelli, R. Muetzelfeldt, T. Wal, F. Evert, and F. Villa. Modelling framework (SeamFrame) requirements. SEAMLESS, 2005.

Ross, B., D. Contractor, and V. Shanholtz. A finite-element model of overland and channel flow for assessing the hydrologic impact of land-use change. Journal of Hydrology, 41 (1-2):11–30, 1979.

Slatyer, R. and I. McIlroy. Practical Microclimatology., 1961.

Tarboton, D. Terrain analysis using digital elevation models (taudem). Utah State University, Logan, 2005.

Verdin, K. and J. Verdin. A topological system for delineation and codification of the Earth's river basins. *Journal of Hydrology*, 218(1-2):1–12, 1999.

Vrugt, J., C. Ter Braak, C. Diks, D. Higdon, B. Robinson, and J. Hyman. Accelerating markov chain monte carlo simulation by differential evolution with self-adaptive randomized subspace sampling. *International Journal of Nonlinear Sciences and Numerical Simulation*, 10(3):273–290, 2009.

Wesselung, C., D. Krssenberg, P. Burrough, and W. Deursen. Integrating dynamic environmental models in gis: the development of a dynamic modelling language. *Transactions in GIS*, 1(1):40–48, 1996.