Appendix A: Supplemental tables for the paper: "A Data Model to Manage Data for Water Resources Systems Modeling"

Table A1: Summary of reviewed water resources data management systems and models

#	Data management system	Name/description
1	Arc Water Utilities Data Model (Grise et al., 2001)	Maintain comprehensive water distribution, sewer, and stormwater records; coordinate and plan capital projects; and improve the operation of utility networks.
2	Arc Hydro (Maidment, 2002)	Delineates watersheds, groundwater and subsurface geo-processing tools, analyzes hydro geometric networks, manage time series data, and configure and export data to numerical models
3	ODM1 (Horsburgh et al., 2008)	A relational model for environmental and water resources data
4	NFCP (Optimal Solutions Ltd, 2009)	Natural Flow Computation Program
5	HEC-DSS (USACE, 2009)	database system designed to efficiently store and retrieve scientific data that is typically sequential
6	Arc Irrigation Data Model (Armstrong, 2010)	Provide a generic template data model to the Irrigation District clients
7	WISKI (Gál, 2010)	Enterprise Data Management application for environmental monitoring data
8	Hydro-Platform (Harou et al., 2010)	Linking water resource network models to an open data management platform
9	RiverML (Jackson, 2014)	Standardizing the Communication of River Model Data
10	Hydra (Knox et al., 2014)	An open-source software platform for water, energy and/or logistics system data management, visualization, model building and model sharing
11	WaDE 0.2 (Larsen and Young, 2014)	Sharing water planning and use data
12	Arc River (Kim et al., 2015)	A GIS-based relational data model for multi-dimensional representation of river hydrodynamics and morphodynamics
13	ODM2 (Horsburgh et al., 2016)	information model and supporting software ecosystem for feature-based earth observations
	Modeling software	**Name/description**
14	MODSIM 8.3.2 (Labadie, 1995)	River Basin Management Decision Support System
15	AQUATOOL (Andreu et al., 1996)	AQUATOOL, a generalized decision-support system for water-resources planning and operational management
16	EPANET 2.00.12 (Rossman, 2000)	Hydraulic and Water Quality Behavior of Water Distribution Piping Systems
17	RiverWare 6.5.2 (Zagona et al., 2001)	A Generalized Tool for Complex Reservoir System Modeling
18	Water-Strategy-Man (Manoli et al., 2001)	Water demand and supply analysis using a spatial decision support system
19	WAS 4.0 (Fisher et al., 2002)	Water Allocation System. The Middle East Water Project
20	CALVIN (Jenkins et al., 2004)	California Value Integrated Network
21	TOPNET (Bandaragoda et al., 2004)	Networked version of TOPMODEL
22	WEAP 2016.01 (Yates et al., 2005)	Water Evaluation And Planning system
23	GSSHA 6.1 (Downer and Ogden, 2006)	Gridded Surface/ Subsurface Hydrologic Analysis
24	ResSim 3.1 (USACE,2007)	Analyze and improve reservoir operations
25	OASIS (HydroLogics, 2009)	Generalized program for modeling the operations of water resources systems
26	SWMM 5.1.007 (Rossman, 2010)	Storm Water Management Model
27	IRAS (Matrosov et al., 2011)	Interactive River-Aquifer Simulation Program
28	HOBBES (Lund et al., 2013)	Bottom up approach to improve and organize the data for water modeling efforts in California
29	ArcSWAT 2012.10.19 (Winchell et al., 2007)	Predict the effect of management decisions on water, sediment, nutrient and pesticide yields with reasonable accuracy on large, ungaged river basins.
30	Source IMS (Welsh et al., 2013)	Source- Integrated Modelling System (IMS)
31	AdHydro (Lai et al., 2013)	Physics-based, high-resolution, distributed water resources model for simulating large watersheds
32	GoldSim 11.1 (GoldSim Technology Group LLC, 2014)	Monte Carlo Simulation Software for Decision and Risk Analysis
33	Basins (US EPA, 2015)	Better Assessment Science Integrating point & Non-point Sources
	OpenAgua (David Rheinheimer, 2018)	open source, web-based decision support system for water planning
34	**Data standards and initiatives**	**Name/description**
35	OpenMI (Gregersen et al., 2007)	Open Modelling Interface
36	HY-Features (OGC, 2012)	Common Hydrologic Feature Model
37	DCMI (DCMI, 2013)	Dublin Core Metadata Initiative
38	CSDMS (Peckham et al., 2013)	Community Surface Dynamics Modeling System
39	WRC (Elag and Goodall, 2013)	Water Resources Component
40	Prov-dm (Moreau and Missier, 2013)	World Wide Web Consortium Provenance Working Group
41	HydroShare (Morsy et al., 2017)	HydroShare metadata framework for environmental models

Table A2: Fourteen common required metadata elements for data values in WaMDaM. Other data types like time series, and multi-column attributes have additional specific metadata.

#	Element	Definition	Example
1	Resource type	The name of a collection of object types for a specific model	WEAP
2	Master Network	The name of a collection of scenarios in a specific area with a spatial reference	Lower Bear River Network
3	Connections	The relations of how data values are connected through their instances with others across system components of a water management system	Blacksmith Fork diversion supplies Hyrum reservoir
4	Scenario	The name of a specific configuration of instances, their metadata, and data values that represent management decisions across system components	Base Case Lower Bear River
5	Object Typology	Node, link, network	Node
6	Object Type	A generic type of water system component that can be replicated as instances with specific local data	Reservoir
7	Instance	A system component that represents a node or link instance “where”	Hyrum
8	Organization	The institution where the person who provided or generated the attribute’s data value is affiliated with. “who”	Utah Water Research Lab
9	Person (people)	The individual who provided or generated the attribute’s data value. “who”	David Rosenberg
10	Source	The origin of the attribute’s data value	Lower Bear WEAP Model
11	Method	The procedure used to generate attribute data values. “how”	WEAP Manual
12	Unit	The unit of measurement of attribute data values	Acre
13	Attribute	The qualitative descriptive characteristic of a data value “what”	Surface area
14	Attribute Data Type	One of the seven means to store data value(s): time series, multi-column arrays, numeric or descriptive parameters, seasonal parameters, electronic files	Numeric value
15	Data Value	The numeric or categorical value(s)	480

Table A3: Supported attribute data types, their definitions, and examples in water resources systems models (Requirement #5)

Data type	Definition	Example and use
Numeric	numeric values	Dam elevation is 450 feet.
Seasonal	parameter values over specified time periods	Water right parameter can have 20 acre-feet in winter and 5 acre-feet in summer or a water demand can take 10 cfs at day and 5 cfs at night. Modelers may optionally register the season name with a controlled term. For each record of season name and value, there is a season order field to preserve the seasons and values order as they are entered which can also be used to sort the season values.
Categorical	Categorical values	Reservoir purpose of “irrigation,” “hydropower generation,” or “flood control”. Or True or false values that indicate dual system operational status e.g., “open”, “closed”
Free text	any text values	Dam release rule stored as block of text, a script, or a description of a system
Time series	numerical values for specified times/dates	Stream discharge, evaporation, inflow, demand, supply
Multi-attribute series	paired numeric values for two or more attributes (i.e., columns)	Reservoir volume and surface area that change with elevation. Water cost that changes with demand month of the year.
Electronic file	physical file to attach to the database	Images, PDF documents, NetCDF and shape-files. They are stored as Binary Large OBject (BLOB) in the database.

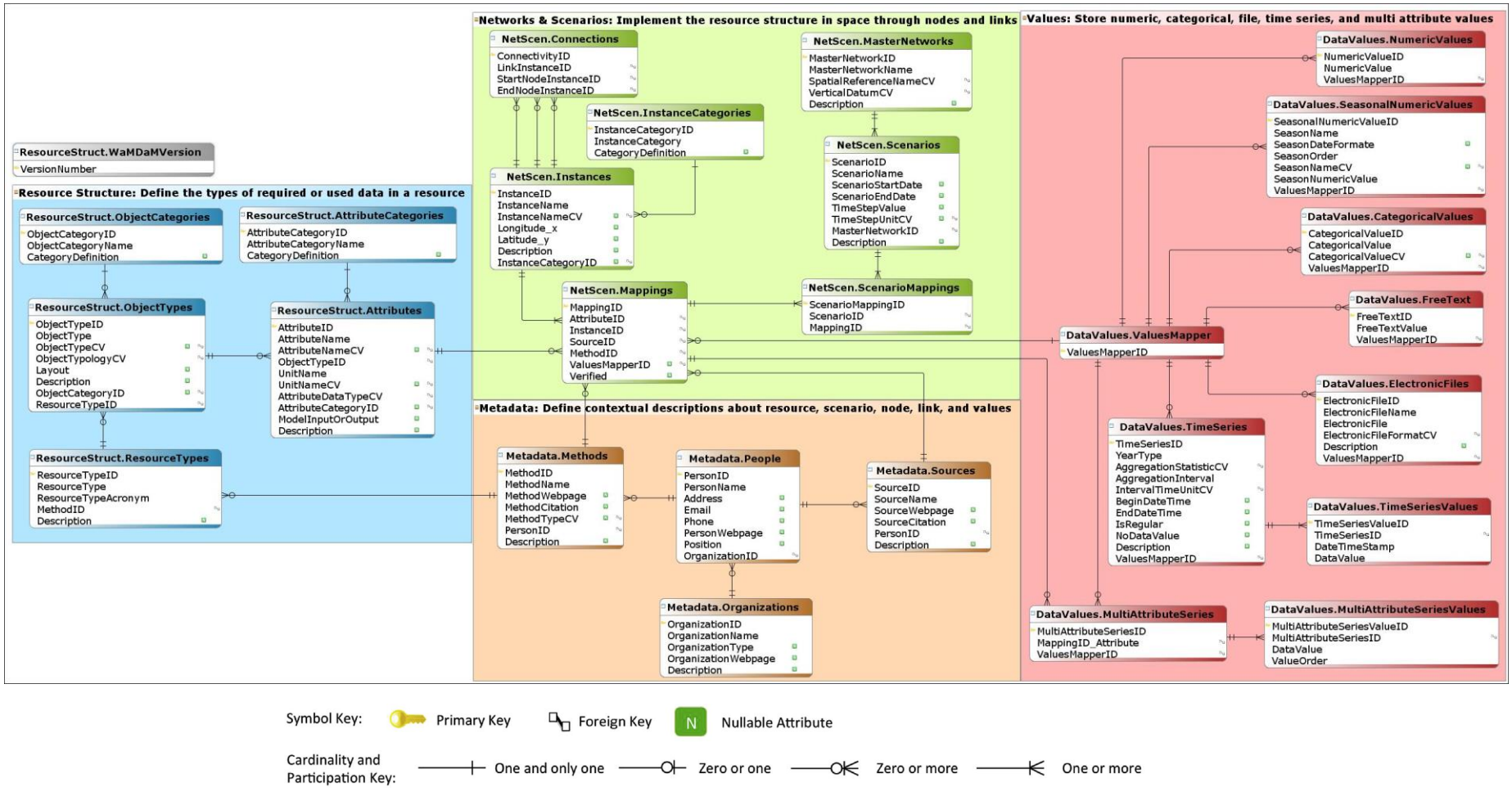

Figure A4: WaMDaM logical model tables grouped into the design requirements ResourceType (#1), Networks and Scenarios (#2&3), Metadata (#4), and Data Values (#5). The diagram uses the crow's foot notation for relationship cardinality and participation. An interactive html copy is available at http://schema.wamdam.org/diagrams/01_WaMDaM.html. . Controlled vocabularies tables (#6) are not shown here for simplicity and can be viewed at http://schema.wamdam.org/diagrams/03_CVs.html. Each column name (field) that ends with "CV" indicates that the term is a controlled vocabulary.

References

Andreu, J., Capilla, J., Sanchís, E., 1996. AQUATOOL, a generalized decision-support system for water-resources planning and operational management. Journal of Hydrology 177(3) 269-291.

Armstrong, L., 2010. ArcGIS Irrigation Data Model. ESRI Water/Wastewater and Water Resources Team, Redlands, Ca.

Bandaragoda, C., Tarboton, D.G., Woods, R., 2004. Application of TOPNET in the distributed model intercomparison project. Journal of Hydrology 298(1–4) 178-201.

David Rheinheimer, 2018. OpenAgua: Collaborative water system modeling for a new generation.

Downer, C.W., Ogden, F.L., 2006. Gridded Surface Subsurface Hydrologic Analysis (GSSHA) User's Manual; Version 1.43 for Watershed Modeling System 6.1. DTIC Document.

Dublin Core Metadata Initiative (DCMI), 2013. Dublin Core Metadata Element Set, Version 1.1 ANSI/NISO Z39.85-2012

National Information Standards Organization (NISO): Baltimore, MD.

Elag, M., Goodall, J.L., 2013. An ontology for component-based models of water resource systems. Water Resources Research 49(8) 5077-5091.

Fisher, F.M., Arlosoroff, S., Eckstein, Z., Haddadin, M., Hamati, S.G., Huber-Lee, A., Jarrar, A., Jayyousi, A., Shamir, U., Wesseling, H., 2002. Optimal water management and conflict resolution: The Middle East Water Project. Water Resources Research 38(11) 1243.

Gál, R., 2010. WISKI–A World Wide Used Environmental Monitoring System In: Pavel Bella, P.G. (Ed.), International Show Caves Association 6th Congress: Slovakia, Liptovský Mikuláš.

GoldSim Technology Group LLC, 2014. GoldSim User's Guide Version11.1.

Gregersen, J.B., Gijsbers, P.J.A., Westen, S.J.P., 2007. OpenMI: Open modelling interface. JOURNAL OF HYDROINFORMATICS 9(3) 175.

Grise, S., Idolyantes, E., Brinton, E., Booth, B., Zeiler, M., 2001. ArcGIS Data Models: Water Utilities. ESRI, Redlands, Ca.

Harou, J.J., Pinte, D., Tilmant, A., Rosenberg, D.E., Rheinheimer, D.E., Hansen, K., Reed, P.M., Reynaud, A., Medellin-Azuara, J., Pulido-Velazquez, M., Matrosov, E., Padula, S., Zhu, T., 2010. An open-source model platform for water management that links models to a generic user-interface and data-manager In: David A. Swayne, W.Y., A. A. Voinov, A. Rizzoli, T. Filatova (Ed.), International Congress on Environmental Modelling and Software, Modelling for Environment's Sake ed. International Environmental Modelling and Software Society (iEMSs) Ottawa, Ontario, Canada.

Horsburgh, J.S., Aufdenkampe, A.K., Mayorga, E., Lehnert, K.A., Hsu, L., Song, L., Jones, A.S., Damiano, S.G., Tarboton, D.G., Valentine, D., Zaslavsky, I., Whitenack, T., 2016. Observations Data Model 2: A community information model for spatially discrete Earth observations. Environmental Modelling & Software 79 55-74.

Horsburgh, J.S., Tarboton, D.G., Maidment, D.R., Zaslavsky, I., 2008. A relational model for environmental and water resources data. Water Resour. Res. 44(5) W05406.

Hydrologic Engineering Center (HEC) of the US Army Corps of Engineers, 2007. Reservoir System Simulation (HEC-ResSim), 3.0a ed.

HydroLogics, 2009. User Manual for OASIS WITH OCL.

Jackson, S.R., 2014. RiverML: A Harmonized Transfer Language for River Hydraulic Models, Civil, Architectural, and Environmental Engineering. University of Texas at Austin.

Jenkins, M., Lund, J., Howitt, R., Draper, A., Msangi, S., Tanaka, S., Ritzema, R., Marques, G., 2004. Optimization of California's Water Supply System: Results and Insights. Journal of Water Resources Planning and Management 130(4) 271-280.

Kim, D., Muste, M., Merwade, V., 2015. A GIS-based relational data model for multi-dimensional representation of river hydrodynamics and morphodynamics. Environmental Modelling & Software 65 79-93.
Knox, S., Meier, P., Harou, J., 2014. Web service and plug-in architecture for flexibility and openness of environmental data sharing platforms, In: Ames, D.P., Quinn, N., Rizzoli, A.E. (Eds.), 7th International Congress on Environmental Modelling and Software. San Diego, California, USA.
Labadie, J., 1995. River basin network model for water rights planning, MODSIM: Technical manual. Department of Civil Engineering, Colorado State University, Fort Collins, CO.
Lai, W., Steinke, R.C., Ogden, F.L., Douglas, C., Miller, S.N., Zhang, Y., 2013. ADHydro: A Large-scale High-resolution Multi-physics Distributed Water Resources Model for Water Resources Simulations in a Parallel Computing Environment, AGU Fall Meetings: San Francisco, USA.
Larsen, S.G., Young, D., 2014. WaDE: An Interoperable Data Exchange Network for Sharing Water Planning and Use Data. Journal of Contemporary Water Research & Education(153) 33-41.
Lund, J., Josué Medellín, Samuel Sandoval, Wei Chu, Alvar Escriva, Ashley Vincent, Erik Porse, Prudentia, Zhinkalala, Timothy Nelson, Hui, R., 2013. Building Models from the Data Up: From Calvin to Hobbes: UC Davis Center for Watershed Sciences
Maidment, D.R., 2002. Arc hydro : GIS for water resources. ESRI Press, Redlands, Calif.
Manoli, E., Arampatzis, G., Pissias, E., Xenos, D., Assimacopoulos, D., 2001. Water demand and supply analysis using a spatial decision support system. Global NEST: the international Journal 3(3) 199-209.
Matrosov, E.S., Harou, J.J., Loucks, D.P., 2011. A computationally efficient open-source water resource system simulator – Application to London and the Thames Basin. Environmental Modelling & Software 26(12) 1599-1610.
Moreau, L., Missier, P., 2013. Prov-dm: The prov data model.
Morsy, M.M., Goodall, J.L., Castronova, A.M., Dash, P., Merwade, V., Sadler, J.M., Rajib, M.A., Horsburgh, J.S., Tarboton, D.G., 2017. Design of a metadata framework for environmental models with an example hydrologic application in HydroShare. Environmental Modelling & Software 93(Supplement C) 13-28.
Open Geospatial Consortium (OGC), 2012. HY_Features: a Common Hydrologic Feature Model Discussion Paper, In: Rob Atkinson, Dornblut, I. (Eds.), OGC 07-041r1. Open Geospatial Consortium Inc.
Optimal Solutions Ltd, 2009. Natural Flow Computation Program User's Manual: Calgary, Alberta.
Peckham, S.D., Hutton, E.W.H., Norris, B., 2013. A component-based approach to integrated modeling in the geosciences: The design of CSDMS. Computers & Geosciences 53(0) 3-12.
Rossman, L.A., 2000. EPANET 2: Users Manual. US Environmental Protection Agency: Cincinnati, Ohio.
Rossman, L.A., 2010. Storm water management model user's manual, version 5.0. National Risk Management Research Laboratory, Office of Research and Development, US Environmental Protection Agency.
US Army Corps of Engineers Hydrologic Information Center (HEC), 2009. HEC Data Storage System, 2.0 ed. US Army Corps of Engineers Institute for Water Resources Hydrologic Engineering Center (HEC) Davis, CA.
US EPA, 2015. BASINS 4.1 (Better Assessment Science Integrating point & Non-point Sources) Modeling Framework. National Exposure Research Laboratory: RTP, North Carolina.
Welsh, W.D., Vaze, J., Dutta, D., Rassam, D., Rahman, J.M., Jolly, I.D., Wallbrink, P., Podger, G.M., Bethune, M., Hardy, M.J., Teng, J., Lerat, J., 2013. An integrated modelling

framework for regulated river systems. Environmental Modelling & Software 39(0) 81-102.
Winchell, M., Srinivasan, R., Di Luzio, M., Arnold, J., 2007. Arc-SWAT interface for SWAT2005-User's guide. USDA Agricultural Research Service and Texas A&M Blackland Research Center, Temple, Texas.
Yates, D., Sieber, J., Purkey, D., Huber-Lee, A., 2005. WEAP21—A Demand-, Priority-, and Preference-Driven Water Planning Model. Water International 30(4) 487-500.
Zagona, E.A., Fulp, T.J., Shane, R., Magee, T., Goranflo, H.M., 2001. RiverWare: A Generalized Tool for Complex Reservoir System Modeling. JAWRA Journal of the American Water Resources Association 37(4) 913-929.