

# SMART Research using Linked Data – Sharing Research Data for Integrated Water Resources Management in the Lower Jordan Valley

Benedikt Kämpgen<sup>1</sup>, David Riepl<sup>2</sup>, and Jochen Klinger<sup>3</sup>

<sup>1</sup> Institute AIFB, Karlsruhe Institute of Technology, Germany,  
[benedikt.kaempgen@kit.edu](mailto:benedikt.kaempgen@kit.edu)

<sup>2</sup> Disy Informationssysteme GmbH, Karlsruhe, Germany  
[david.riepl@disy.net](mailto:david.riepl@disy.net)

<sup>3</sup> Institute of Applied Geosciences, Karlsruhe Institute of Technology, Germany  
[jochen.klinger@kit.edu](mailto:jochen.klinger@kit.edu)

**Abstract.** In the region of the Lower Jordan River a steadily increasing population has access only to constantly decreasing natural freshwater resources. Integrated Water Resources Management (IWRM) considers social, economical and ecological objectives when deciding over long-term strategies in a study area. IWRM is collaborative and knowledge intensive, but missing operational guidelines and data management challenges hinder decision makers and scientists to make the decision process transparent and research results comparable. In this work, we formalise the IWRM domain in an OWL ontology; use Linked Data and multidimensional modelling based on the RDF Data Cube Vocabulary to build a knowledge base with research data; and present exploratory interfaces on top of integrated IWRM data. From an application of this SMART Knowledge Base approach for Wadi Shueib, Jordan, we identify challenges to make scientists share research data and to model the water resources domain.

## 1 Introduction

Numerous regions of the world face immense pressure and competition on their natural freshwater resources<sup>4</sup>. Different from other water resources management methods, Integrated Water Resources Management (IWRM) considers social, economical and ecological objectives simultaneously when deciding over long-term strategies in a study area [1]. IWRM processes are collaborative and knowledge intensive: Data in the IWRM domain is complex often having many dimensions or leaving a long provenance trail from sensors over analyses to reports; is available from distributed sources such as research publications, dataset catalogs, and official documents; is heterogeneous since coming from social, economical and ecological domains; and may contain semi-structured information such as maps and free text.

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<sup>4</sup> <http://politics.slashdot.org/story/13/02/13/1731237/nasa-huge-freshwater-loss-in-the-middle-east>

To handle this information complexity, applied IWRM projects and case studies usually use multi-thematic information systems to share data between their interdisciplinary modelling tools. Although these systems are capable of providing raw data on the one hand and highly aggregated model outputs on the other, they fail to support collaborating scientists. As a consequence, IWRM researchers often only collaborate informally and within small groups using email and spreadsheets. Assumptions or research data between such groups are rarely shared or aligned, so that research results are not comparable. Thus, we are interested in the following research questions: How to make the decision process transparent for third-parties so that results can be re-used in other decisions and collaborated upon? How to define operational guidelines for scientists contributing to IWRM processes? How to foster collaboration among stakeholders? How to increase interoperability between systems used for IWRM, e.g., data storage and access platforms, water simulation systems and decision support tools? After introducing a scenario of IWRM analyses in Section 2, we present the SMART Knowledge Base approach with the following contributions in Section 3:

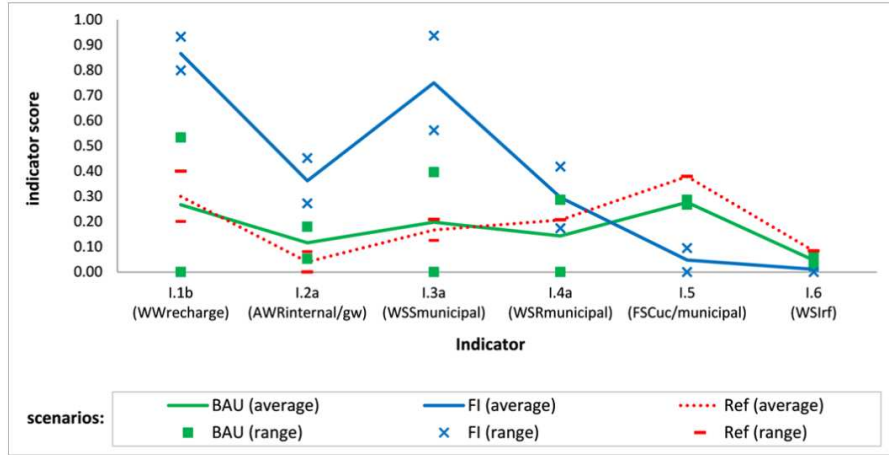
- We formalise the IWRM knowledge and decision support domain in an OWL ontology reusing the RDF Data Cube Vocabulary.
- We use Linked Data to represent, extract, integrate and load community-created research and sensor data into a knowledge base for browsing and expressive queries.
- We present consumption tools on top of this IWRM knowledge base that allows scientists to share and re-use research data.

In Section 4, we apply the approach to our scenario. Then, we reflect on the solution (Section 5), describe related work (Section 6) and conclude (Section 7).

## 2 Sustainable Management of Available Water Resources in the Lower Jordan Valley

In the region of the Lower Jordan River in the Middle East, a steadily increasing population has access only to constantly decreasing natural freshwater resources. On the quest for more sustainable, equitable and efficient solutions, the IWRM approach postulates a holistic assessment of available water resources as well as the consideration of social, ecological and economic impacts of long-term planning scenarios [1]. Scientists and decision makers from Israel, Jordan, Palestine and Germany from the SMART project try to establish IWRM approaches for Sustainable Management of Available Water Resources with Innovative Technologies (SMART) for countries bordering the Lower Jordan<sup>5</sup>.

Figure 1 illustrates the possible result of an IWRM decision process. Here, a set of alternative Water Management strategies to improve the situation in the Lower Jordan valley (scenarios: BAU, FI, Ref) are compared regarding multiple, partly conflicting evaluation criteria (indicators: e.g., “Waste Water Recharge Ratio” / WWrecharge). Determining the preferable scenario in an IWRM process is a multi-criteria decision analysis (MCDA) problem defined as follows:



**Fig. 1.** Illustration of IWRM process result: decision matrix with normalised indicators values for scenarios in Wadi Shueib in 2025 [4].

**Problem formulation.** After instantiating a decision process, decision makers define IWRM objectives that are to be optimised in a specific region during the process, e.g., to “Increase volume of captured and treated wastewater”.

**Domain modelling.** Domain experts from social, economical and ecological sciences define indicators to evaluate the grade of reaching an IWRM objective within a water strategy, e.g., the “Waste Water Recharge Ratio”. Also, scenarios need to be selected, i.e., descriptions of a development pathway leading towards a future state of the study area at a defined planning horizon such as 2025. Scenarios should be consistent and plausible (internal factors, e.g., climate change) and propose implementable actions (external factors, e.g., building a new well).

**Model execution.** Based on the assumptions in the domain model, experts create analyses to estimate indicator values for scenarios. For expert analyses, various data sources such as publications (e.g., Water Strategy Jordan), encyclopedias (e.g., BMBF Water Glossary, FAO on Agricultural and Farm Systems) and basic indicator values (e.g., sensor records) are relevant. The collaborative web-based Knowledge Management System *Dropedia*<sup>6</sup> developed by partner KIT is read open to the entire IWRM community; SMART project members have write access to describe, discuss, and share research data. To archive and share climate sensor data, partner UFZ provides SMART members Web-based access to an Oracle database (*SMART-DB*). To implement and simulate domain models, decision makers create or import indicator values from documents or *SMART-DB* to the Water Evaluation And Planning software (WEAP). However, data sources and tools use different identifiers. Thus, for comparing information, domain experts often need additional efforts such as manually copy-pasting of tables with tools such as Microsoft Excel.

<sup>5</sup> <http://www.iwr-smart2.org/>

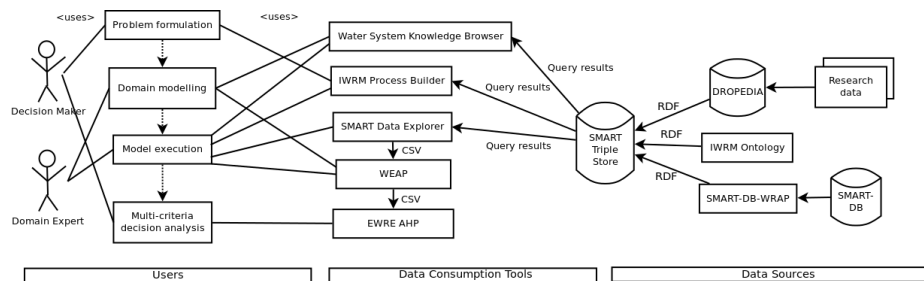
<sup>6</sup> <http://dropedia.iwr-smart2.org/>

**Multi-criteria decision analysis (MCDA).** Finally, the decision makers create a decision matrix such as illustrated in Figure 1 with the information provided by the domain experts for input in an MCDA tool. The typical MCDA approach is for the decision makers to assign weights to criteria (indicators) and afterwards to use an algorithm to rank the decision alternatives (scenarios) w.r.t. the criteria and weights. SMART partner EWRE provides a tool to compute the rank with an Analytical Hierarchy Process (AHP) [5].

The following requirements are derived from this scenario: Domain experts and decision makers need to explicitly establish decision processes and transparently decide upon and share “objectives”, “indicators” and “scenarios” (Requirement 1). Domain experts should be able to identify, integrate and re-use research data from expert analyses, e.g., the calculation or estimation of a single value, a literature study, and a complex model application (Requirement 2).

### 3 SMART Knowledge Base Approach

As illustrated in Figure 2, the components of the *SMART Knowledge Base* (SKB) roughly can be divided into IWRM relevant data sources and data consumption tools. Consumption tools access data via a SMART triple store that is filled in advance or on-demand with data from the data sources. In the following, we describe the components in more detail. Main *IWRM relevant data sources* are an IWRM ontology, a web-based knowledge management system Dropedia and the SMART-DB for climate sensor data.

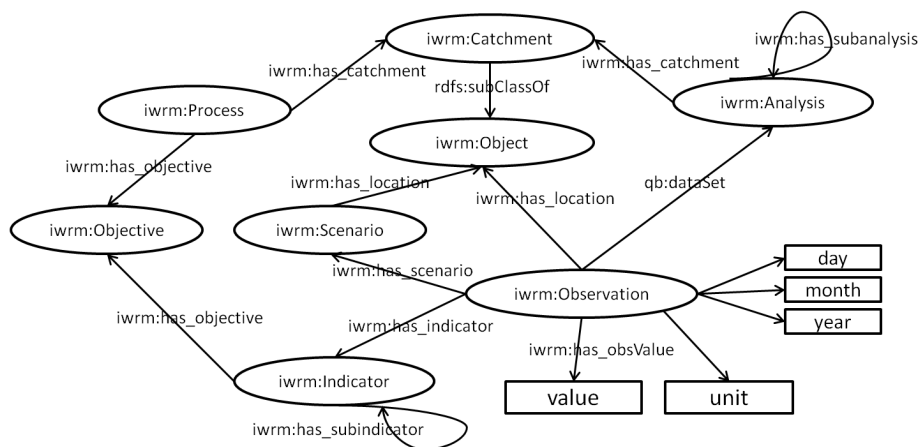


**Fig. 2.** Diagram illustrating use-case and architecture of SMART Knowledge Base.

**IWRM Ontology:** See Figure 3 for an illustration of the ontology as graph with concepts and common properties between instances of those concepts. Note, the illustration only contains the most important concepts and properties of the IWRM ontology. The IWRM ontology is implemented in Dropedia, the collaborative knowledge management system of SMART. As a semantic wiki, Dropedia allows browsing of URIs for both the ontology `iwrm` and the `dropedia` namespaces<sup>7</sup>. In the ontology, any IWRM process has objectives and a location. Objectives are linked from indicators which can quantify the performance of a

<sup>7</sup> <http://dropedia.iwr-smart2.org/index.php/Special:URIResolver/>

scenario. Values of indicators for specific scenarios are given by IWRM observations. Besides indicator and scenario, observations specify a recording date, a measurement location as well as the value and unit. Observations are derived within expert analyses. To model multidimensional observations and analyses, we re-use the W3C-standardised *RDF Data Cube Vocabulary* (QB).



**Fig. 3.** Illustration of IWRM ontology as graph with concepts and common properties between instances of concepts.

If populated, the links between individuals in the ontology allow for follow-your-nose browsing similar to common Web browsing and provide the schema for querying the data using SPARQL.

**Research data as Linked Data in Dropedia:** Dropedia is based on the Open Source semantic wiki software, Semantic MediaWiki, which combines ease of use and collaboration functionalities of the well-known MediaWiki software with flexible support to capture and use structured information via Semantic Web technologies. Users can fill in forms to populate the IWRM ontology and to make such data available as Linked Data in RDF, e.g., about `dropedia:Wadi.Shueib`. Structured information can be queried directly within Dropedia and visualised, e.g., as tables. Measurements are represented with “sub-objects”. Also, users can upload and display KML files as well as link from the map to specific wiki pages with background information.

**Climate sensor measurements as Linked Data from SMART-DB-WRAP:** We now present a wrapper that publishes SMART-DB data as Linked Data for integration in the SMART Knowledge Base; SMART-DB-WRAP provides a URI for the `smart-db` namespace<sup>8</sup>, is based on a Google-App-Engine and on-the-fly translates XML from a Web interface to SMART-DB (HYDROS-MART, developed by partner UFZ) into an RDF representation using the IWRM ontology. Any record is contained in a dataset, has been created by a specific

<sup>8</sup> <http://smartdbwrap.appspot.com/>

project, has been recorded at a specific location, e.g., “AM0530” (“Baqqouria Spring” in Dropedia), and measures a certain analysis object / indicator, e.g., “Q” (“Mean Discharge”). Table 1 shows example mappings between objects and URIs identifying those entities in Linked Data (abusing CURIE syntax).

**Table 1.** Example mappings between objects, data sources and URIs

Object	URI
Wadi Shueib as referred to in Dropedia	<code>dropedia:Wadi_Shueib</code>
Shorea Spring as referred to in Dropedia	<code>dropedia:Shorea_Spring</code>
Shorea Spring as referred to in SMART-DB <sup>9</sup>	<code>smart-db:/id/location/AM0528</code>
Average Discharge in Dropedia	<code>dropedia:Annual.Average.Discharge</code>
Average Discharge from SMART-DB	<code>smart-db:/id/analysisobject/Q</code>
Dataset of locations from SMART-DB	<code>smart-db:/id/location/ds</code>
Dataset of indicators from SMART-DB	<code>smart-db:/id/analysisobject/ds</code>
Dataset of Mean Discharge for Shorea Spring from SMART-DB	<code>smart-db:/id/location-dataset/AM0528/Q</code>

**SMART Triple Store:** The challenge remains that SMART-DB and Dropedia use different identifiers for the same objects, e.g., AM0530 vs. Baqqouria Spring and Q vs. Mean Discharge. Integrating both data sources would mean to allow queries on both data sources simultaneously considering identical elements. From an Excel sheet provided by our partner UFZ, we manually inserted identifiers from SMART-DB to Dropedia locations from which automatically `owl:sameAs` links between location URIs in Dropedia and location URIs in SMART-DB were created. Then, we automatically and regularly fill a triple store with up-to-date data from the data sources using LDSpider<sup>10</sup>. LDSpider starts with a seed list of locations in Dropedia. Via above `owl:sameAs` links LDSpider reaches the same locations in SMART-DB. Crawled data is then inserted in the triple store. We select a triple store that not only provides a SPARQL 1.1 endpoint for expressive queries (e.g., aggregations), but also is able to evaluate our `owl:sameAs` links and fully integrates Dropedia and SMART-DB. Note, it is not the goal to permanently duplicate information from SMART-DB and other data sources, but to provide unified access and integration capabilities for selected data. The following *data consumption tools* access data from the store.

The **Water System Knowledge Browser** is implemented as a set of pages in Dropedia with which users get overviews of and can explore the knowledge base by visiting catchments, water resources, demand sites and many other aspects of the water system in the Lower Jordan Valley. The SPARK extension allows Dropedia pages to issue SPARQL queries to the triple store and to display results in tables and diagrams.

The **IWRM Process Builder** allows to find IWRM studies in the Lower Jordan Valley on regional and local scales. Decision makers define objectives

<sup>9</sup> [http://www2.ufz.de/smarthydro/smartquery?location\\_data=AM0528](http://www2.ufz.de/smarthydro/smartquery?location_data=AM0528)

<sup>10</sup> <http://code.google.com/p/ldspider/>

for an IWRM problem; scientists create a domain model, e.g., define locations, indicators and scenarios, and further investigate the model in analyses.

The **SMART Data Explorer** provides an exploratory interface to analyse numeric data from SKB. For that, all instances of `iwrM:Observation` from Dropedia and SMART-DB are integrated in one single Data Cube `dropedia:-SMART-DB-DSD` with location, scenario, date, indicator (analysis object) and unit as dimensions and AVG and COUNT of `smart:obsValue` as measures. The SMART Data Explorer uses Saiku as frontend to issue OLAP operations such as slice and dice and as backend OLAP4LD that translates OLAP operations to SPARQL queries on the triple store [3]. Excel or CSV exports of indicator values can be imported to WEAP.

## 4 An IWRM process for Wadi Shueib, Jordan

In this section, we describe a case study conducted by one of the authors applying the SKB approach to a representative IWRM process in Wadi Shueib, Jordan [4]. From the SKB start page<sup>11</sup>, data sources and consumption tools can be visited. Also, information about the implementation and case study are given. The SMART Triple Store is based on Open Virtuoso version 06.01.3127 and runs on a AMD Athlon(tm) 64 Processor 3000+ with 2G memory with Ubuntu Linux. Crawling on average takes less than 60min. Currently, 6 IWRM processes, 7 objectives, 22 indicators, 22 scenarios and 27 analyses are described in Dropedia.

**Problem formulation:** In the case study [4], the “Wadi Shueib IWRM Decision Process” (`dropedia:Wadi_Shueib_IWRM_Analysis`) is motivated by the National Water Strategy of Jordan<sup>12</sup>. The water strategy defines objectives, e.g., `dropedia:Increase_volume_of_captured_and_treated_wastewater`.

**Domain modelling:** Basic provenance information such as the analysis area (`dropedia:Wadi_Shueib`) and the authors of the process are given. The analysis area already is further described, e.g., by the exact geo-spatial and political origin, important buildings within the area, and synonymous area names. Now, the domain expert selects indicators from discussions with other domain experts. For instance, to evaluate the increased volume of captured and treated wastewater, the “Municipal Waste Water Treatment Ratio” relates the assumed volume of total waste water produced with the amount of municipal waste water treated in centralised and decentralised treatment facilities.

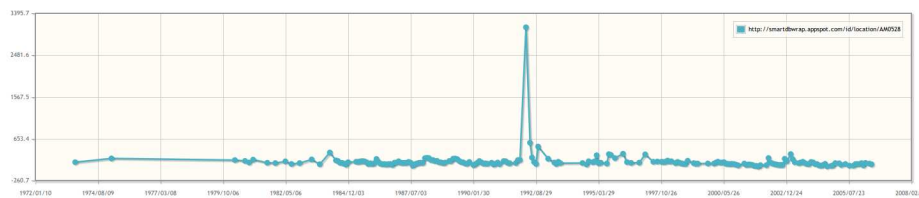
Also, the domain expert defines or reuses scenarios, e.g., “Wadi Shueib Business as Usual (BAU)”, the water strategy implementation according to the current plans of the Jordanian national water strategy. This scenario includes the reduction of physical and administrative supply network losses and a sewer rehabilitation and connection program in As-Salt. Whereas in the BAU scenario, further implementation of the water strategy either is regarded as not feasible until 2025 or is hampered by slow political decision making, the “Full Imple-

<sup>11</sup> [http://dropedia.iwrM-smart2.org/index.php/SMART\\_Knowledge\\_Base](http://dropedia.iwrM-smart2.org/index.php/SMART_Knowledge_Base)

<sup>12</sup> [http://www.joriew.eu/uploads/private/joriew\\_org-jordan\\_national\\_water\\_strategy.pdf](http://www.joriew.eu/uploads/private/joriew_org-jordan_national_water_strategy.pdf)

mentation (FI)” scenario assumes that all obstacles are overcome and the full range of stated implementation approaches is realised.

**Model execution:** Based on the assumptions in the domain model, the domain expert selects suitable analyses or creates own analyses leading to the computation of required indicators for the given planning scenarios. To find expert analyses the domain expert can use the keyword search functionality. Also, analyses are linked to knowledge objects and can be browsed in the `dropedia:Water_System_Knowledge_Browser` and the `dropedia:IWRM_Process_Builder`. SMART-DB identifies Shorea Spring with “AM0528” and provides for example water discharge numbers from 1973 to 2006; see Figure 4 for a screenshot. Note, a very high discharge number of around  $687m^3/h$  in 1992 may indicate an incorrect sensor record in the SMART-DB.



**Fig. 4.** Line chart of water discharge records in  $m^3/h$  of Shorea Spring over years from SMART-DB.

In addition, based on data records from SMART-DB of Shorea Spring from 1995 to 2005 the domain expert computes an overall average annual discharge as an estimation for future years; see Figure 5 for a screenshot of the values documented in Dropedia.

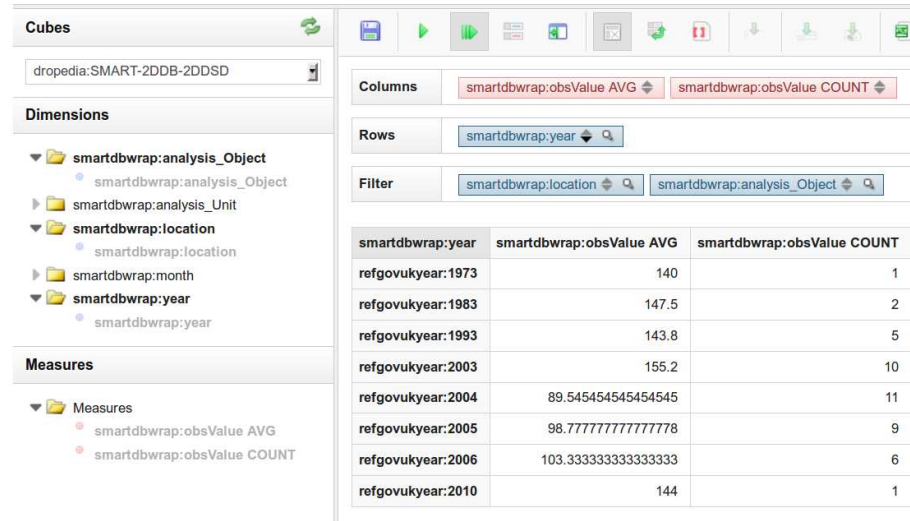
Smart:analysis	Smart:day	Smart:obsValue	Smart:analysis	Smart:location	Comment	Scenario
Average Annual Discharge	<a href="http://reference.data.gov.uk/id/day/1995-12-31">http://reference.data.gov.uk/id/day/1995-12-31</a>	143.8	m³/h	Shorea Spring	based on 10-year monthly measurements	Status Quo
Average Annual Discharge	<a href="http://reference.data.gov.uk/id/day/2005-12-31">http://reference.data.gov.uk/id/day/2005-12-31</a>	143.8	m³/h	Shorea Spring	based on 10-year monthly measurements	Status Quo
Average Annual Discharge	<a href="http://reference.data.gov.uk/id/day/2010-12-31">http://reference.data.gov.uk/id/day/2010-12-31</a>	143.8	m³/h	Shorea Spring	based on 10-year monthly measurements	Status Quo

**Fig. 5.** Interface for expert analysis on Shorea Spring 10-year average discharge.

The domain expert uses the SMART Data Explorer to explore, compare and analyse numeric assumptions from other analyses. For instance, the decision



maker can ask for the average annual discharge for Shorea Spring over time, see Figure 6. Note, Dropedia and SMART-DB data are integrated, since both “Shorea Spring” and “Mean Discharge” are identified differently in SMART-DB and Dropedia but displayed together. Figure 5 showed how estimated discharge observations for 1995, 2005 and 2010 can be documented in Dropedia; an overview of actual sensor values from SMART-DB was shown in Figure 4. Both number of observations and the average are shown; we see that for some values we have many more observations than for others. Note, loading time for Saiku may take several minutes due to large queries to populate the interface.



smartdbwrap:year	smartdbwrap:obsValue AVG	smartdbwrap:obsValue COUNT
refgovukyear:1973	140	1
refgovukyear:1983	147.5	2
refgovukyear:1993	143.8	5
refgovukyear:2003	155.2	10
refgovukyear:2004	89.54545454545454	11
refgovukyear:2005	98.77777777777778	9
refgovukyear:2006	103.33333333333333	6
refgovukyear:2010	144	1

**Fig. 6.** Pivot table showing average and count of water discharge records in Shorea Spring for specific years from both Dropedia and SMART-DB.

**Multi-criteria decision analysis:** An overview of all estimated indicator values for scenarios is given on the analysis page. Note, provenance information about any single observation can be browsed from the overview. The decision maker exports such data directly from Dropedia or with the SMART Data Explorer. Figure 1 from the scenario section illustrates the decision matrix for the Wadi Shueib Process comparing different scenarios projected to 2025. Indicator values are normalised between 0 and 1; a higher score means a better performance. From the figure, the FI-alternative shows the overall best performance for most of the selected indicators; only regarding unit cost of supply and sanitation in Jordanian dinar per cubic meter, i.e., cost effectiveness, other scenarios are evaluated higher. Depending on the weights for indicators, EWRE AHP can rank the scenarios to this Wadi Shueib IWRM decision process.

## 5 Discussions and Lessons Learned

Using SKB, stakeholders are able to efficiently contribute to IWRM processes (Requirement 1): they can describe the water situation at the Lower Jordan

River in the Water System Knowledge Browser; can explicitly state, share and discuss objectives, indicators, and scenarios in the IWRM Process Builder.

Domain experts are supported in sharing their analyses (Requirement 2): analyses are published for the entire IWRM community for citations, feedback and possible future collaborations; and applications such as the SMART Data Explorer can be developed on top of published information for innovative usages.

Also, we were able to improve on our research questions: An IWRM ontology available and possible to populate on the Web simplifies and makes transparent IWRM processes for third-parties and provides a collaborative workspace for project members. Interoperability between Dropedia and the SMART-DB was demonstrated in mashups showing data from both sources.

The SKB approach benefits from Semantic Web concepts through semantics, e.g., equivalence statements using `owl:sameAs` and extensibility, e.g., new data sources can easily be added to the SMART Knowledge Base by adding new links that LDSpider would follow. If data loaded to the triple store reuse the same vocabularies such as our IWRM ontology or the RDF Data Cube Vocabulary, data may even show up in existing visualisations without additional effort. Therefore, we see potential regarding the ongoing “Open Data” trend. More and more institutions such as FigShare, DataCite and Pangea help scientists to not only publish their analysis results but also the raw (or also pre-processed) data for citations, reproduction and further analysis. If also published as Linked Data – for instance using a wrapper approach as for SMART-DB-WRAP – interoperability of the data contained in such silos can be improved.

Two main areas of possible improvements were identified:

**Usability and Training.** It proved a challenge to make scientists and decision makers share research-relevant data. There may be many reasons for this behaviour, yet, it is clear that stakeholders are especially reluctant if interfaces to data sharing platforms are not familiar and there is no clear personal benefit. The flexibility of a semantic wiki does not reach the usability of commercial products, in particular, Microsoft Excel and widely-used E-Mail clients. SKB intends to provide benefits directly to research data providers, e.g., by visualisations and integration with SMART-DB data; yet, most benefit will be achieved if there is a culture of two-way sharing and reusing of research data.

To support this aim, regular tutorials with specific cross-group analysis objectives seem necessary. SMART members will get familiar with and continuously insert new information to SKB. Also the benefits of operational guidelines and a way to make transparent SMART research results for IWRM will become clearer.

**Complex Modelling.** An initial working hypothesis stated that Semantic Web ontologies allow semi-automated IWRM analysis. WEAP provides a complex model of inter-dependent indicators in a system of water resources, demand sites and operational network elements connected by flow vectors of various types. WEAP provides algorithms to compute indicators. However, ontologies such as OWL, RDFS and Linked Data vocabularies have difficulties to represent and do reasoning over such mathematical relationships [6].

Although we were able to represent and share measurements of environmental indicators using the RDF Data Cube Vocabulary, estimating indicators still requires mostly manual effort, e.g., copy-paste from publications and spread-sheet processing in Excel. A more automatic computation of indicators will require to formalise relationships between (collections of) measurements. For instance, from assumed volumes of waste water produced in single municipalities, a total waste water discharge assumption for an area could automatically be aggregated and be re-used for a Municipal Waste Water Treatment Ratio computation. Yet, it is not clear how to represent and use such relationships between multidimensional datasets in RDF as well as how to handle conflicting definitions.

## 6 Related Work

The German-Vietnamese water-related information system for the Mekong Delta (WISDOM) project provides a web-based information system [2]. The system is based on PostgreSQL for geographical data management. Services are provided via representational state transfer (REST) and as such identify and allow access to resources similar to the Linked Data principles. However, the advantage of using REST services for efficient integration of WISDOM data sources with third-party data sources is not clear. Different from the WISDOM information system, the SKB concept is focusing on data integration and making available data for third-party usage.

In knowledge management research, wikis are widely perceived as potent knowledge management instruments. And also in the natural sciences, some organizations have recently started initiatives of which probably the most visible examples are the UNDP-initiated WaterWiki<sup>13</sup> and the IWAWaterwiki<sup>14</sup>. Different from Droppedia, such platforms do not generate self-descriptive RDF to build applications on top of structured information.

The CUAHSI Water Data Center<sup>15</sup> provides data services to communities that require access to various sources of water data to perform research. Their software stack provides tools to publish hydrologic datasets with web services as well as a metadata catalog to discover and client tools to analyse published datasets. They allow tagging of variables with the CUAHSI HIS Ontology describing concepts such as chemical, biological and physical variables. They do not use RDF and as such are limited to data complying to a fixed relational model for observation data (ODM).

The Semantic Ecology and Environmental Portal<sup>16</sup> integrates water data from different authoritative sources using Linked Data to enable pollution detection and monitoring. Their interface is able to display both geo-spatial and measurement data, but does not support collaboration on analyses as possible in Droppedia. Wiljes and Cimiano also use Linked Data to publish research results in the natural sciences. To make scientists less reluctant to share research data,

<sup>13</sup> <http://waterwiki.net>, last retrieved on 2014-03-14

<sup>14</sup> <http://www.iwaterwiki.org>, last retrieved on 2014-03-14

<sup>15</sup> <http://wdc.cuahsi.org/>, last retrieved on 2014-04-16

<sup>16</sup> <http://tw.rpi.edu/web/project/SemantEco>, last retrieved on 2014-04-16

a scientific data curator helps with the Linked Data publication process [7]. In our work, we first allow users make research data available as Linked Data without any Linked Data specificities (through Dropped and SMART-DB). Second, we have a stronger publishing argument since we describe possible applications (Dropped/SPARK, SMART Data Explorer) on top of published data.

## 7 Conclusions

The holistic IWRM approach has great potential to improve water scarcity situations in regions such as the Jordan Valley. However, IWRM is 1) lacking concrete operational guidelines to help scientists contributing to IWRM processes and 2) missing knowledge management methods and tools to share and integrate information from social, economical and ecological sciences. In this work, we try to overcome those problems via Linked Data. We have designed and developed an integrated SMART Knowledge Base that formalises the IWRM decision process using an OWL ontology, integrates research data from a semantic wiki with climate sensor records from a relational database, and allows exploring and analysing IWRM data using browsing and OLAP. We have applied the knowledge base in a IWRM decision process for the Wadi Shueib region in Jordan. Lessons learned promise to easily connect further data sources available on the Web using Linked Data, but demand a more systematic training of potential users for quantifiable improvements in the domain, and a more formal representation of indicators and scenarios for semi-automatic IWRM analysis.

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