Beitrag G: Christian Jolk, Björn Zindler, Harro Stolpe, Roman Wössner, Andreas Abecker

Planning and Decision Support Tools for Integrated Water Resource Management on River Basin Level in South Africa on the Example of the Middle Olifants Sub-Basin

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Abstract

This paper presents methods and software tools for GIS-based planning and decision support in Integrated Water Resources Management. The approach results from the BMBF-funded research project "Integrated Water Resources Management in the Pilot Region Middle Olifants River, South Africa - MOSA". The tools developed provide an overview of quaternary river basins in order to identify hot-spot areas with increased problem intensity with regard to water quality and with a priority need for action.

Zusammenfassung

In diesem Beitrag werden Methoden und Softwaretools zur GIS-basierten Planung und Entscheidungsunterstützung im Integrierten Wasserressourcenmanagement vorgestellt. Der Ansatz resultiert aus dem BMBF-Projekt "Integrated Water Resources Management in the Pilot Region Middle Olifants River, South Africa - MOSA". Die entwickelten Instrumente ermöglichen einen Überblick über Flussteileinzugsgebiete vierter Ordnung, um Hot-Spot-Gebiete mit erhöhter Problemintensität in Bezug auf die Wasserqualität und mit einem vorrangigen Handlungsbedarf zu identifizieren.

1 Objectives

South Africa is facing major challenges in the water sector. The uneven distribution of the water body network and of precipitation leads to water supply shortages especially in the dry season. The water infrastructure and the management of water supply and wastewater treatment are in deficit. The rapid industrial growth, the progressing urbanization and the industrially organized agriculture lead to increasing water demand and water quality problems. The problems are increased by the fact that South Africa has locations with significant touristic value.

Considering these challenges, different stakeholders, such as local and regional authorities, NGOs, industry, and scientists, are searching for solutions to establish a holistic and sustainable development of the water sector in the future. The integrated approach of the R&D project MOSA, sponsored by the German Federal Ministry of Education and Research (BMBF), helps to analyze and solve water-management related problems in the Middle Olifants sub-basin.

The main project goal was to develop Planning and Decision Support Tools for Integrated Water Resources Management (IWRM) on river basin level with the focus on water quality issues. The Planning and Decision Support Tools (PDST) evaluate the water resources and facilitate the identification and prioritization of sub catchments with increased problem intensity and a necessity for action through IWRM measures. The PDST improve and support decision processes of South African decision makers in the water sector toward a cost-, time- and target-oriented approach.

The Middle Olifants sub-basin is a river basin with stressed water resources. The water quality faces numerous challenges that require an efficient water management in the future. The Water Quality Report of the Department of Water Affairs [Van Veelen 2011] and the Planning Level Review of Water Quality in South Africa [DWA 2011] provide an assessment of the water quality in the Olifants river basin in compliance with the existing conditions in the area. According to the reports, the following water quality problems arise in the Middle Olifants sub-basin and the Steelport:

- Increased salinity and eutrophication of dams and rivers by return flows from agriculture and mining, as well as discharge from wastewater treatment plants
- Increased toxicity due to presence of pesticides and herbicides in the water bodies
- Erosion caused by poor agricultural practice and overgrazing in rural areas
- Groundwater contamination due to inadequate wastewater treatment and leakages from landfills and waste disposals
- High concentrations of sulphate and low pH values in surface water due to the influence of mining, power plants and industry

- Despite the fact of limited data in some parts of the sub-basin, increased heavy metal concentrations are expected

Particular emphasis in the development of the PDST has been laid on the integration of existing knowledge and experiences of South African stakeholders. The limited data availability and quality as well as the uneven distribution of data among different authorities and institutions influenced the development of the PDST.

2 Research Design and Activities

Since the International Conference on Water and the Environment and the United Nations Conference on Environment and Development in 1992, IWRM attracted worldwide attention, see, e.g., Agenda 21 [UNCED 1993]. According to the Global Water Partnership (GWP), IWRM is “a process which promotes the coordinated development and management of water, land and related resources in order to maximize economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems and the environment” [GWP 2000].

The overall objective of IWRM is “to satisfy the freshwater needs of all countries for their sustainable development”. With the focus on water planning, IWRM should include “the development of interactive databases, forecast models and economic planning models appropriate to the task of managing water resources in an efficient and sustainable manner will require the application of new techniques such as geographical information systems and expert systems to gather, assimilate, analyze and display multisectoral information and to optimize decision-making.” [UNCED 1993].

3 Administration / laws

In order to discuss the water quality issues on a national level the Department of Water Affairs (DWA) published the series “Water Resources Planning System Series” [DWAF 2006a, b]. This series deals with political processes, strategies and management tools for assessing the water quality.

According the statement of the DWAF [DWAF 2006b] “Integrated water quality management should be implemented in a cyclical process aimed at continual improvement (fundamental to the principle of adaptive management). This cycle occurs at a number of different levels. They range from individual (local) source and resource management initiatives (short-term) through re-consideration of the catchment management strategy (medium-term) to re-consideration of the resource directed measures and vision (long-term)."

Following the DWA [DWA 2011] "water quality planning is directed at addressing the following key issues facing water resource management:

- Balancing the degree to which water, and water quality, is used (e.g. for socio-economic development) with the degree of protection of water resources as natural systems (for current and future generations) requires both political and scientific considerations.
- The nature of the imbalance between the requirement for and supply of water and water quality is such that equitable allocation of these resources is not possible without management intervention.
- Resource directed management of water quality requires certain specialist skills, while decision-making is often complex and may have to be based on uncertain or incomplete data and information.
- Consistent nationwide application of legislation relating to management of water quality is essential."

To assess the water quality according to the National Water Resource Strategy [DWAF 2004a; DWAF 2004b] and the Resource Directed Management of Water Quality [DWAF 2006a, b], the approaches adopted in these reports are, on the one hand, resource-oriented measures to protect water resources and, on the other hand, measures to control the pollution sources.

An assessment of the water quality of all river basins in South Africa is reported in a study of the DWA [DWA 2011]. This study provides information on the assessment of point and diffuse sources, the environmental conditions of the river basins as well as the impact of human activities on water resources and ecosystems.

The PDST presented in this paper follow the strategy of the DWAF [DWAF 2004a; DWAF 2004b] and improve and specify the methodology of the DWA [DWA 2011] on the example of the Middle Olifants sub-basin.

4 Project area

The investigated Middle Olifants sub-basin is located in the provinces Limpopo, Gauteng and Mpumalanga in the Northeast of South Africa.

Starting at the outlet of the Loskop Dam the Olifants flows in northern direction until it joins the Flag Bohilo Dam. Larger tributaries in this river section are the Moses and the Elands. After the Olifants leaves the Flag Boshilo Dam, it is deflected to Northeast by the Wolkenberg Mountains. At the confluence of the Steelport and the Olifants, the middle river section of the Olifants ends.

The massif of the Wolkenberg Mountains consists mainly of intrusive rocks. Furthermore, extensive sheets of basalt are located in the Springbok Flats, an area in the western part of the Middle Olifants sub-basin. Quaternary deposits can be found in the river valleys and the flood plains. In particular, the basalts are aquifers with high yield.

A large part of the Middle Olifants sub-basin is used for agriculture. Predominately maize is grown in rain-fed agriculture. Soybean, cotton, vegetable, citrus fruits, wheat and tobacco are grown on irrigated fields. Large irrigated areas are found in the river valleys of the Olifants, the Elands and the Moses in close proximity to Loskop Dam and Flag Boshilo Dam. Rain-fed agriculture is found primarily in the Springbok Flats or in areas east of the Olifants.

Main water users are the agriculture for irrigation purposes and the rural and urban population for drinking water supply. Other important water users are hydro-electrical power stations and mines.

5 Methods

The applied method follows the basic ideas of risk assessment for water quality. It is based on concepts for the ecological risk analysis which have been originally developed in Germany, for example by Kiemstedt and Bachfischer [Kiemstedt & Bachfischer 1977] and which have been completed later during the further development according to the European Law of Environmental Impact Assessment from 1985 and amended in 1997, 2003 and 2009 [EC 2011]. Comparing to the European concept, the Environmental Protection Agency in the United States published their Guidelines for Ecological Risk Assessment in 1998 [EPA 1998].

The developed method consists of a contamination risk assessment (water quality). The basic idea for the contamination risk assessment is to combine *contamination potentials* (originating from land uses) and the *sensitivity of natural resources* (here of water resources) which results in a *contamination risk*. Two-dimensional matrices are used to aggregate the contamination potential and the sensitivity of water resources into the risk. The matrices are applied to determine the risk on a scale with the classes “low”, “medium” and “high” [Jolk 2010; Greassidis 2011; Zindler 2012].

The quaternary catchments are the spatial basis on which PDST are being applied. The PDST are instruments to spatially identify and prioritize contamination risks (e.g., diffuse agricultural contamination sources or industrial point sources). The Contamination Risk Tool is used for risk assessment of water quality aspects (groundwater and surface water). The Ranking Tool identifies quaternary catchments with high problem intensities and priority need for IWRM measures.

The PDST are GIS-based. They enable the user to visualize single current situations, the contamination risk assessment and the prioritization (ranking) of quaternary catchments.

5.1 Contamination Risk Tool

The Contamination Risk Tool is used to analyze the contamination risk of water resources in a quaternary catchment. The method described below is based on the estimation of the sensitivity of water resources (groundwater and surface water) and the classification of contamination potentials from different sources, developed in a preceding R&D project about IWRM in Vietnam.

The method has been transferred to and adapted on South African conditions. Based on the currently higher data resolution in South Africa the methodology was further developed in order to increase the accuracy of the conclusions. As already stated above, the basic idea can easily be summarized by the equation:

Sensitivity of water resources + *Contamination potential of polluters*

= *Contamination risk*

The contamination risk assessment is being conducted and evaluated for *three contamination paths of pollutants* that affect the water resources:

- *Infiltration (into groundwater)*: Solute pollutants from diffuse and point sources directly infiltrate into the groundwater (e.g., nitrate from agricultural sources, domestic wastewater, industrial wastewater, mine water)
- *Erosive runoff (into surface water)*: Pollutants from diffuse sources are being transported by (erosive) runoff into the surface water (e.g., phosphate and pesticides from fields adsorbed to sediments or organic matter).
- *Direct discharge (into surface water)*: Pollutants from point sources are being discharged into the surface water (e.g., domestic wastewater, industrial wastewater, mine water, seeping landfills).

The *contamination potential* describes the ability of a certain polluter to negatively affect the water resources. It is graded into four classes (no, low, medium, high). Only the most relevant polluters for the evaluation of contamination risks in each path have been selected for closer evaluation [Zindler 2012 (with reference to South African conditions)].

The *sensitivity of water resources* describes the relative ease of a contaminant applied on or near the land surface to migrate into the water resource. It is a function of different natural characteristics. The sensitivity is graded into five classes (no, low, medium, high, very high). If more than one parameter is being considered to assess a sensitivity class, matrices help to aggregate different class values into a final class. Parameters considered to assess the sensitivity of groundwater are the aquifer type and areas with an intense use of groundwater. The sensitivity of surface water is assessed according to the parameters of potential soil erosion and the ecological status. The specific regional characteristics of the different project areas are considered [Zindler 2012 (with reference to South African conditions)].

The tool identifies hot spot quaternary catchments regarding the risk of contamination for water resources and helps decision makers to analyze contamination potentials from different sources.

The following subsections give an overview of the combinations leading to the qualitative water risk assessment and the resulting available maps. These maps are compiled in a planning atlas. Disy developed a web-viewer version of the atlas [Jolk 2010; Greassidis 2011; Zindler 2012].

5.1.1 Contamination path 1: infiltration of contaminants into groundwater

Contamination path 1, groundwater sensitivity

The resource sensitivity of groundwater is established for the uppermost groundwater aquifer, also taking into consideration groundwater use.

Groundwater resource sensitivity is classified based on runout and groundwater use (e.g., solid rock with high runoff (basalt) = high groundwater resource sensitivity or solid rock with low runoff (granite) = low groundwater resource sensitivity) [Barnard & Baran 1999] [Du Troit et al. 1998; Du Troit et al. 1999; Du Troit et al. 2003]. The runout evaluation of the uppermost groundwater aquifer was carried out based on the hydraulic conductivity classes in hydrological cartography for North Rhine Westphalia NRW [LANUV NRW 2010]. Overlying strata above the groundwater aquifers were not included in the consideration, as these cannot be safely assessed in the chosen scale of 1:800.000. As the protective effect of overlying strata is ignored, the classification of resource sensitivity lies within secure margins.

Areas with high groundwater use (wells) are characterized by high resource sensitivity. This characterization is based on existing risks through contaminant inflow due to unprofessional well construction or well use. A further justification for this characterization is the special need for protection of the directly used groundwater resource.

Contamination path 1, contamination potential

a) Contamination potential of diffuse sources through infiltration of agricultural contaminants

For agricultural areas, a contamination potential through infiltration of nutrients is assumed. The nutrient availability potential is differentiated according to different land use classes [Moolman et al. 1999]. The agricultural areas were defined based on the South African National Land-Cover Database [Fairbanks et al. 2000]. All agricultural areas are classified due to their nutrient availability potential in three contamination potential classes (high, medium and low) [Moolman et al. 1999].

b) Contamination potential of diffuse sources through infiltration of settlement wastewater

Settlements are assumed to have a contamination potential through wastewater infiltration. There are wastewater treatment plants in the Middle Olifants sub-basin but because of the improper operation of the plants and the predominant renovation backlog it could be expected that wastewater is infiltrating.

Settlement density and the location of single houses are used as a basis to classify contamination potential. It is assessed by using topographical maps of South Africa (1:50.000).

The classification of contamination potentials from diffuse sources through wastewater infiltration is carried out according to settlement classes in three grades (e.g., Metropolitan area = high contamination potential or rural scattered = low contamination potential).

c) Contamination potential of point sources through infiltration of contaminants

For point sources such as commercial, industrial facilities and mines, a contamination potential through infiltration of contaminants is assumed. It is considered that most of these facilities do not yet take sufficient actions for groundwater protection.

A comprehensive registry with applied substances is not yet available or still being set up by the authorities. For an initial evaluation on river basin level the topographical maps of South Africa (1:50.000) as well as data of the Ministry of Mineral Resources were used.

By analyzing aerial images an exact site localization of the point sources has been done. All locations were assigned by a sphere of influence (500 m) along the lines of the EU Water Framework Directive [Raschke & Menzel 2005].

The classification of the contamination potential classes is based on the production branches and the types of mineral being exploited in the different mines (e.g., clay dumps = low contamination potential or PGM mines = high contamination potential) [Gauteng Department of Agriculture, Environment and Conservation 2008].

Contamination path 1, groundwater contamination risk

The groundwater contamination risk is the result of the aggregation of groundwater resource sensitivity and the corresponding contamination potential. Figure 1 shows an example of the aggregation matrices which have been developed for each intersection operation respectively.

Sensitivity groundwater	Very high	No	Very high	Very high	Very high
	High	No	Medium	High	High
	Medium	No	Low	Medium	High
	Low	No	Low	Low	Medium
Path 1 - Contamination risk agriculture		None	Low	Medium	High
		Contamination potential agriculture			

Figure 1: Path 1 – Groundwater contamination risk through infiltration of agricultural contaminants

Figure 2 depicts the groundwater contamination risk due to infiltration of agricultural contaminants in the Middle Olifants sub-basin.

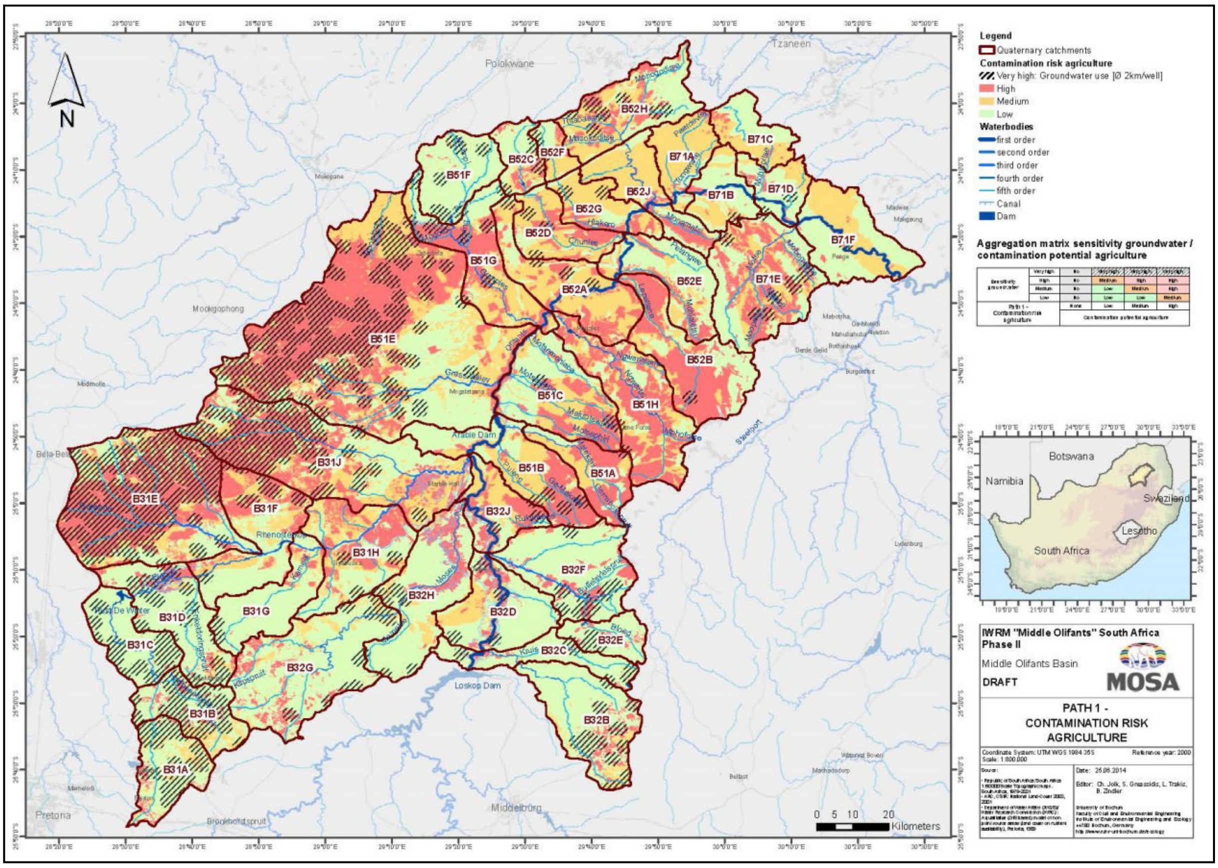

Figure 2: Path 1 – Groundwater contamination risk due to infiltration of agricultural contaminants

5.1.2 Contamination path 2: erosive runoff and/or erosive discharge of contaminants into surface waterbodies

Contamination path 2, surface water sensitivity

Erosion

To analyze the erosive runoff and/or erosive discharge of contaminants into surface water bodies, the methodology of Moolman [Moolman et al. 1999] is used to estimate the sediment availability potential. The sediment availability potential is calculated by aggregating the wash-off potential with the sediment production potential.

A GIS-based intersection of Moolman [Moolman et al. 1999] was used to calculate the sediment production potential.

Water withdrawal

Starting from the analysis of the drinking water withdrawals at dams and the surface water, areas have been identified in which water contaminations can have a negative impact on the reservoirs and drinking water abstraction points. Detailed information on water withdrawals are available from the studies "Development of a reconciliation strategy for all towns in the Northern Region", at the municipal level, commissioned by the Department of Water Affairs (Directorate: National Water Resources Planning).

Ecological status

Potentially sensitive areas could be identified based on a study [Nel & Driver 2012] by the Council for Science and Industrial Research (CSIR) and the South African National Biodiversity Institute (SANBI) on environmental protection areas.

Regarding the research of Nel, both aquatic ecosystems and wetlands as well as fish sanctuaries and protection areas with priority are included in the sensitivity analysis. The most important context in which the “Freshwater Ecosystem Priority Areas“ (FEPAS) can be institutionalized is the development of the Resource Quality Objectives (RQOs) which, according to DWAF [DWAF 2004a; DWAF 2004b], has to be designated on the national level. It should also be noted that the DWA acknowledges the FEPAS to derive the RQOs [Nel et al. 2011]. The ultimate definition of the RQOs was not completed at the time the report was written [DWA 2014].

FEPA regions include, on one hand, the current and planned fish sanctuaries with a good ecological status (Ecological Category A or B) as well as wetland cluster and, on the other hand, the categories “Fish Support Area" and "Upstream management area".

Fish sanctuaries within a region with an ecological category worse than B are called "Fish Support Areas". "Upstream Management Areas" are sub quaternary catchments where human activity must be controlled in order to prevent the degradation of downstream FEPAS and "Fish Support Areas" [Nel et al. 2012].

The evaluation of surface waterbody resource sensitivity was categorized as “very high”, “high”, “medium” and “low”.

Contamination path 2, contamination potential

- Contamination potential of diffuse sources through erosive runoff of agricultural contaminants

For agricultural areas, a contamination potential through infiltration of nutrients is assumed. The nutrient availability potential is differentiated according to different land use classes [Moolman 1999]. The agricultural areas were defined based on the South African National Land-Cover Database [Fairbanks 2000]. All agricultural areas are classified due to their nutrient availability potential in three contamination potential classes (high, medium and low).

Contamination path 2, surface waterbody contamination risk

As shown in figure 3, the surface waterbody contamination risk results from an aggregation of the erosion and the contamination potential from diffuse agricultural sources due to erosive runoff of agricultural contaminants and the surface waterbody resource sensitivity (ecological status).

Sensitivity surface water - Erosion	Very high	No	Very high	Very high	Very high
	High	No	Medium	High	High
	Medium	No	Low	Medium	High
	Low	No	Low	Low	Medium
Contamination potential agriculture - Erosion		None	Low	Medium	High
		Contamination potential agriculture			

Sensitivity surface water	Very high	No	Very high	Very high	Very high
	High	No	Medium	High	High
	Medium	No	Medium	Medium	High
	Low	No	Low	Medium	High
Path 2 - Contamination risk agriculture		None	Low	Medium	High
		Contamination potential agriculture - Erosion			

Figure 3: Path 2 – Surface waterbody contamination risk due to erosive runoff of agricultural contaminants

Figure 4 depicts the surface waterbody contamination risk due to diffuse discharge of agricultural contaminants.

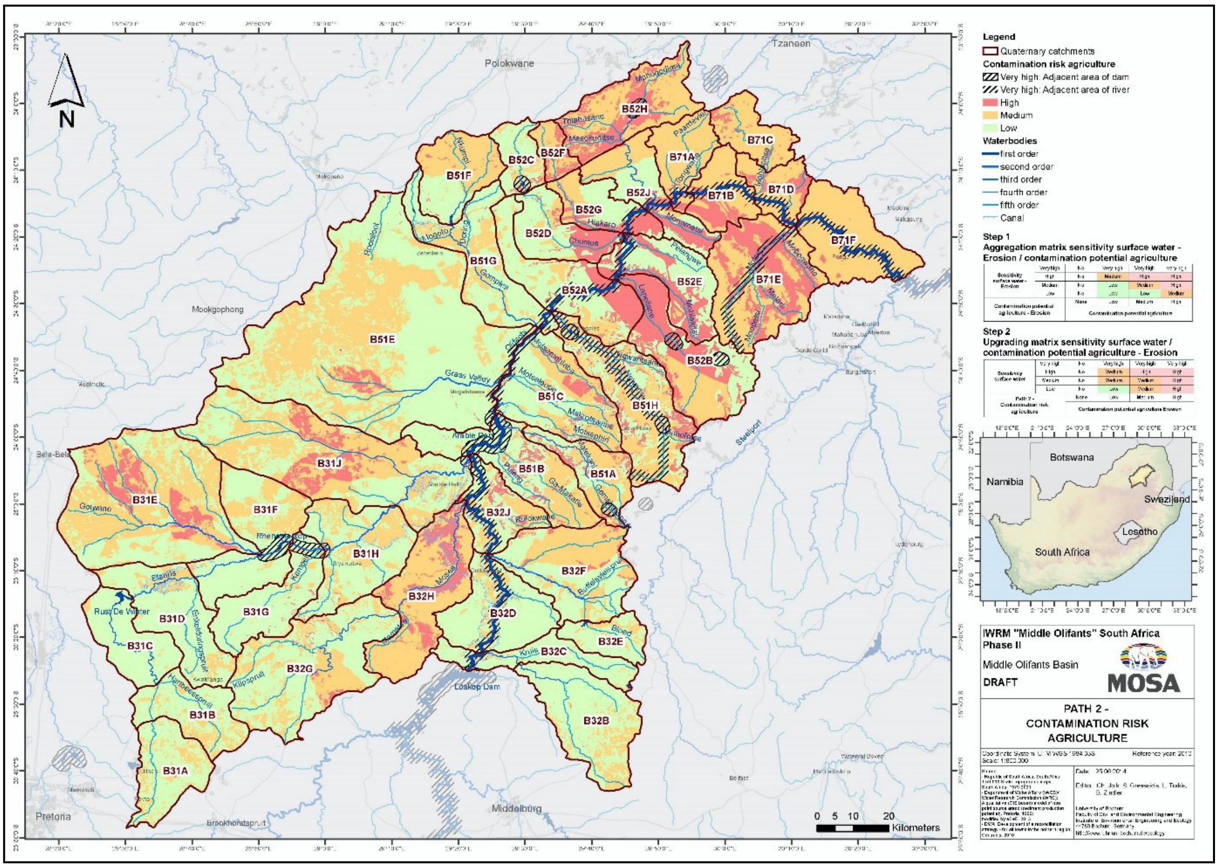

Figure 4: Path 2 – Surface waterbody contamination risk due to diffuse discharge of agricultural contaminants

5.1.3 Contamination path 3: direct discharge of contaminants into surface waterbodies

Contamination path 3, surface water use sensitivity

The surface water use sensitivity follows the same approach as the surface water sensitivity (path 2) for the ecological status.

In addition to this, the use of surface water (drinking water abstraction points at dams and surface water) as well as the environmental protection status were taken into account. Detailed information on water withdrawals are available from the studies "Development of a reconciliation strategy for all towns in the Northern Region", at the municipal level, commissioned by the Department of Water Affairs (Directorate: National Water Resources Planning).

Starting from the analysis of the drinking water withdrawals at dams and the surface water, areas have been identified, in which water contaminations can have a negative impact on the reservoirs and drinking water abstraction points.

Contamination path 3, contamination potential

a) Contamination potential due to direct discharge of wastewater from settlements

Settlements are assumed to have a contamination potential through direct discharge of wastewater. There are wastewater treatment plants in the Middle Olifants sub-basin but because of the improper operation of the plants and the predominant renovation backlog it could be expected that untreated wastewater is discharged into the rivers.

Based on the evaluation of the wastewater treatment plants in the Middle Olifants sub-basin by the Green Drop Report [DWA 2012] and studies of REMONDIS [REMONDIS 2012] the classification of the contamination potential could be done. The cartographic data are based on the topographic maps of South Africa at a scale of 1:50,000.

According to the wastewater treatment plants performance from low to high, the contamination potential is classified respectively into high to low. Downstream effects are included in the evaluation and the worst case is assumed. The wastewater load is considered to be constant and self-cleaning processes of the rivers are not considered.

b) *Contamination potential due to discharge of wastewater from point sources*

For point sources a contamination potential through direct discharge of contaminants is assumed. It is considered that most of these facilities do not yet take sufficient actions for surface water protection.

By analyzing aerial images an exact site localization of the point sources has been done. All locations were assigned which are located in a 200 m distance to the next river, along the lines of the EU Water Framework Directive [Raschke & Menzel 2005].

The classification of the contamination potential classes is based on the production branches and the types of mineral being exploited in the different mines (e.g., clay dumps = low contamination potential or PGM mines = high contamination potential) [Gauteng Department of Agriculture, Environment and Conservation 2008].

Contamination path 3, surface waterbody contamination risk

The surface waterbody contamination risk is the result of the aggregation of contamination potential and resource sensitivity for surface waterbodies. The emphasis here lies in drinking water applications and the ecological protection status. As an example of the general approach, figure 5 represents the aggregation to establish the contamination risk due to wastewater discharge from settlements.

Sensitivity surface water	Very high	No	Very high	Very high	Very high
	High	No	Medium	High	High
	Medium	No	Low	Medium	High
	Low	No	Low	Low	Medium
Path 3 - Contamination risk settlements		None	Low	Medium	High
		Contamination potential settlements			

Figure 5: Path 3 – Contamination risk for surface waterbodies due to discharge of wastewater from settlements

Figure 6 depicts the resulting contamination risk for surface waterbodies due to wastewater discharge from settlements.

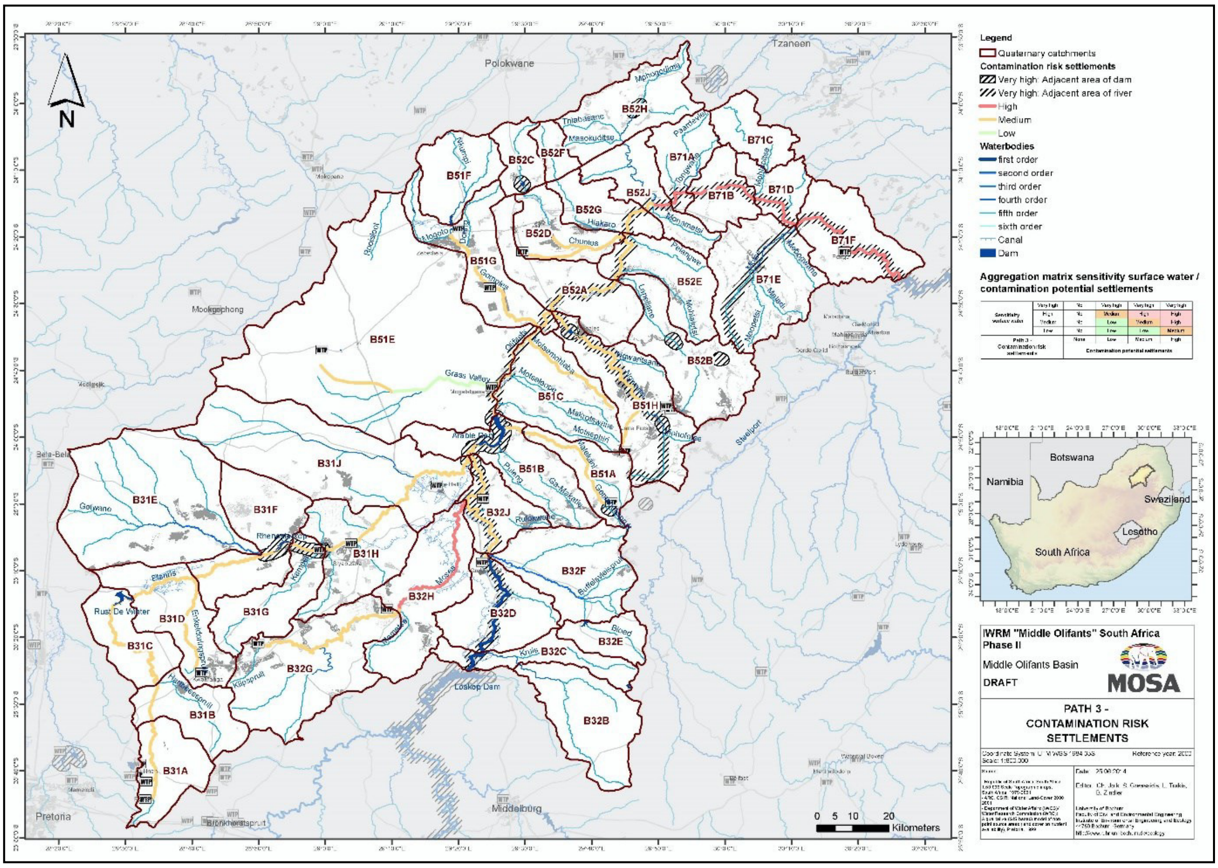

Figure 6: Path 3 – Contamination risk for surface waterbodies due to discharge of wastewater from settlements

5.2 Ranking Tool

The Ranking Tool processes the results of the Contamination Risk Tool (aggregated on quaternary catchment basis) in order to prioritize the problem intensities of quaternary catchments within a river basin regarding their water quality issues.

For this ranking, the percentage of areas with a “very high” or “high” contamination risk of the entire quaternary catchment respectively the location of point sources and their contamination risk were joined up and divided into three ranking classes. Initially this was done separately for each contamination path. Within each of the contamination paths a ranking was carried out for each contamination risk (e. g., figure 7).

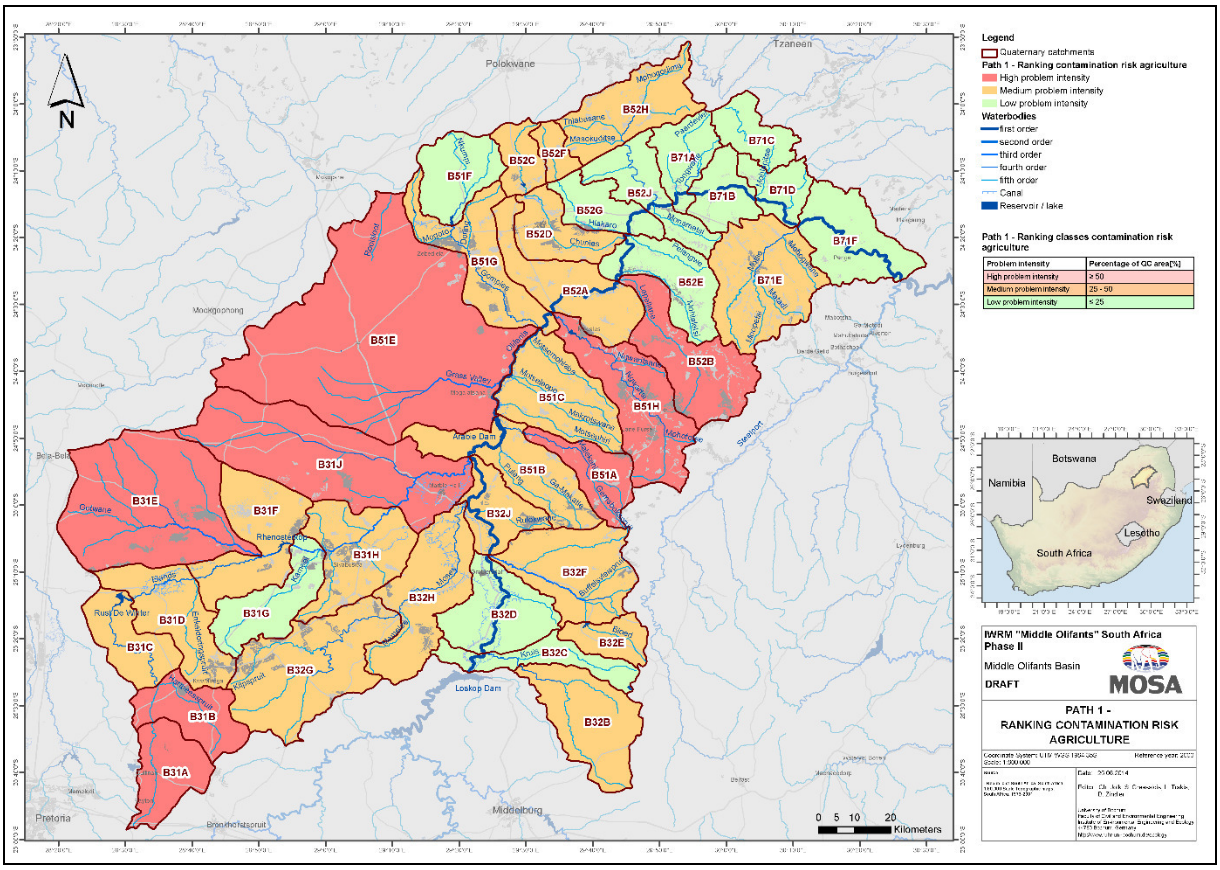

Figure 7: Result of ranking: contamination risk for the groundwater stemming from agriculture

5.3 Software implementation

A software tool based on the methodological approach combines a spatial data warehouse system and a Web-based Geographic Information System (Web-GIS). The solution is implemented using the Disy Cadenza platform [Vogel et al. 2010] for spatial reporting solutions. Disy Cadenza is usually applied as follows (see figure 8):

- Existing spatial geodata and factual data as well as information from manifold heterogeneous existing sources (databases, existing GIS, files, geodata services) can be imported and stored in a unified and harmonized spatial Data Warehouse.
- The process of filling the Data Warehouse with incoming data may comprise operations for selecting the project-relevant data from different sources, checking or improving data quality, transforming data such that syntactic and semantic integrity and consistency is achieved, and loading the data into one or more specific data schemata which facilitate human understanding or which enable more efficient execution of analytics functions etc. The totality of such

data-manipulation operations is called ETL process (extract – transform – load operations, cp. [Schrauth et al. 2017]).

- Cadenza allows building up a repository of operation sequences for querying, analyzing and processing the data in the Data Warehouse and for finally visualizing und publishing the analysis results as thematic maps, business diagrams, predesigned PDF reports, etc. The so-defined data-analysis workflows in the repository can be managed with the help of a fine-grained user and rights management.
- The Cadenza functionalities and results can be accessed through a desktop tool (Cadenza Professional), a Web-GIS (Cadenza Web), a Tablet-based mobile solution (Cadenza Mobile) and through OGC-compliant geodata Web services.

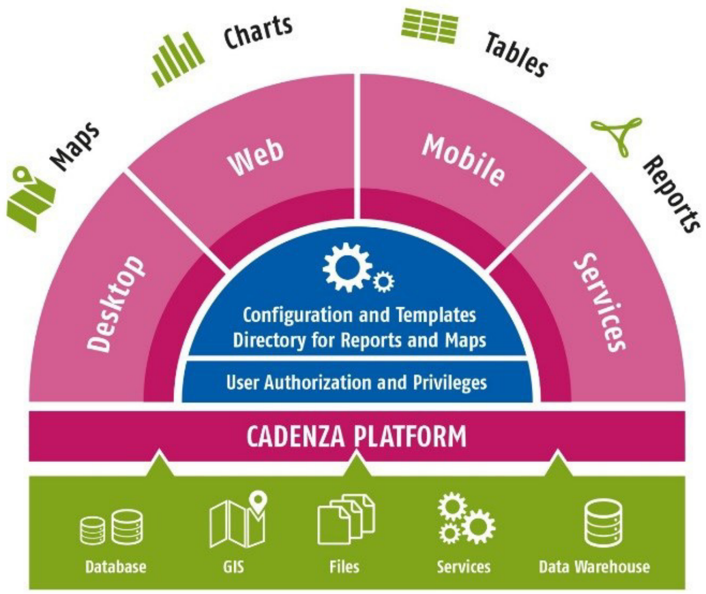

Figure 8: Elements of the Cadenza software platform for spatial data warehousing and spatial reporting solutions

The above-presented risk assessment method has been implemented using Cadenza as follows (see figure 9, from left to right):

- Raw geodata from the South-African government, needed to assess the contamination paths 1, 2 and 3, were loaded into the geodata warehouse. As part of the ETL processes, data quality was checked and necessary scale and representation changes were done. The geodata warehouse is based on PostgreSQL/PostGIS. Data is load into an application-specific DB-schema.

- The computations of contamination potential, resource sensitivity and contamination risk were implemented as part of the ETL processes, as well as the ranking of quaternary catchments according to their priority for action needs. Concretely, these processes were realized through stored database procedures in the data warehouse (Groovy scripts and PL/pgSQL functions).
- The data warehouse then contains all basic as well as all derived parameters required for IWRM planning and decision making. This information was visualized as thematic maps that are provided to end users in the South-African public administration through their Web browsers with the help of the Cadenza Web-GIS. Furthermore, all the thematic maps visualized in the Web-GIS can also be exported for offline-use during on-site operations using a tablet and the Cadenza Mobile tool [Otterstätter at al. 2014; Lübke et al. 2016].
- Another feature, implemented with the help of the Cadenza Report Generator tool, is the possibility to preconfigure a document template for collecting all the information available in the system for a certain region. At any time when up-to-date information about this area is required, the report generation can be run and a bulletin for the region in quest can be created on demand.

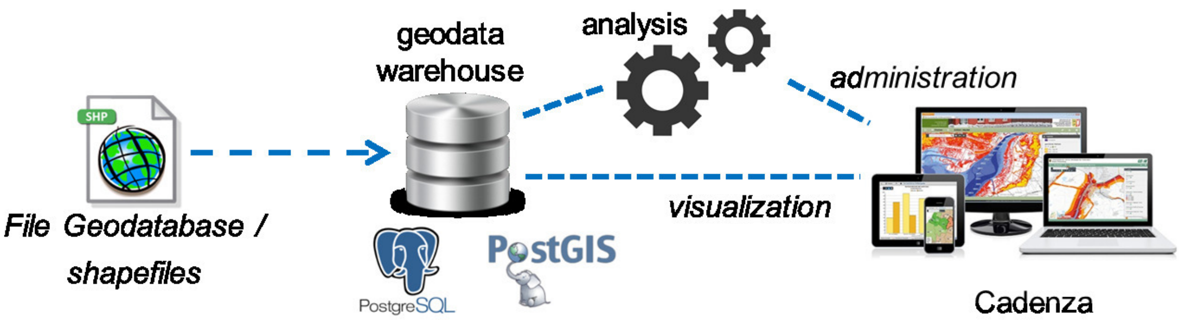

Figure 9: Simplified data-flow of the realized software solution

As an example, figure 10 shows the DB tables stored in the data warehouse for the realization of the computations regarding contamination path 1, infiltration of contaminants into groundwater, caused by agriculture, diffuse sources in settlements and point sources. The tables with a red exclamation mark contain input data whereas all the other tables are derived by GIS operations or automated risk assessment and ranking procedures, based on the qualitative decision tables as shown, e.g. in figure 1.

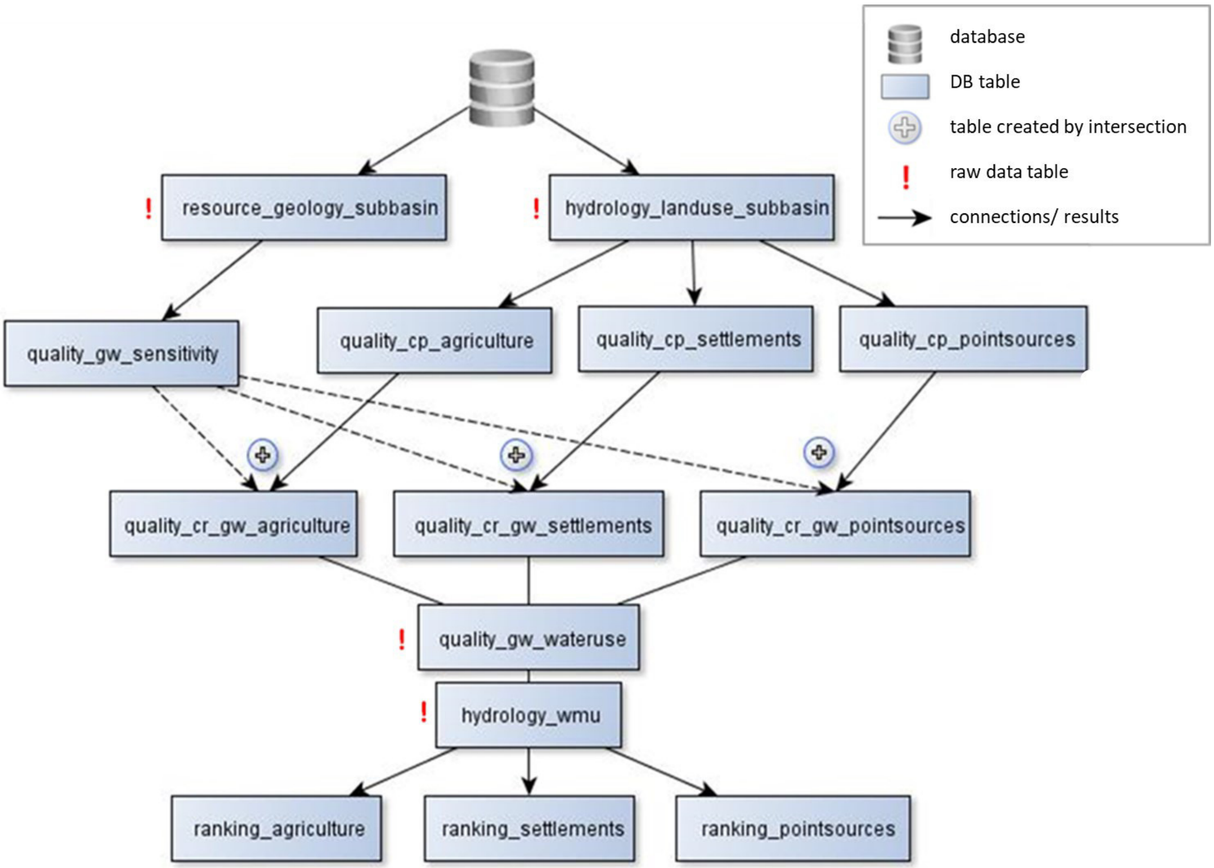

Figure 10: Database tables used for the realization of contamination path 1, infiltration of contaminants into groundwater, caused by agriculture, settlements and point sources

For instance, the table „quality_cp_agriculture“ describes the contamination potential from agricultural activities and is created on the basis of land-use maps; the table „quality_cr_gw_settlements“ describes the contamination risk (cr) of groundwater (gw), coming from settlements – which can also be found in land-use maps. The contamination risk of groundwater caused by agriculture („quality_cr_gw_agriculture“) is derived by merging data about groundwater sensitivity and about contamination potential by agricultural activities („quality_gw_sensitivity“ and „quality_cp_agriculture“). The sensitivity again, as explaied above, can be derived from (hydro)geological maps. For assessing the urgency (ranking) of water management interventions in a certain region (water management unit, WMU, a quaternary catchment area), the water usage must also be taken into account.

To give an impression of thematic coverage and volume of information in the data warehouse, we present some facts about the data acquired for our project region:

- *Path 1: infiltration of contaminants into groundwater:*
  - 170 different sensitivity regions have been identified and about 750 geographic areas were classified as „very high“, regarding sensitivity.
  - With respect to contamination potential, ca. 40.000 land-use areas and/or agriculture-related risk areas have been identified, as well as more than 60.000 settlements and/or risk areas because of settlements, as well as about 250 point sources as risk areas.
- *Path 2: erosive runoff and/or erosive discharge of contaminants into surface waterbodies:*
  - In addition to several tens of thousands risk areas because of agricultural activities, 630 different sensitivity regions have been identified.
- *Path 3: direct discharge of contaminants into surface waterbodies:*
  - 630 different sensitivity regions have been examined.
  - Regarding the contamination potential, ca. 650 areas close to surface waterbodies and with a potential influence by settlements have been identified, as well as ca. 115 areas close to surface waterbodies and with a potential influence by point sources.
- *Geographic base data, base maps, supplementary data and material:*
  - Definition of 39 water management units.
  - 536 water bodies.
  - 160 lithological formations, 300 different soil areas, 164 biomes.
  - 1.600 drainage lines, 102 barrages and dams, further cadaster information about water supply pipes and water infrastructure.
  - 60 cities and 2.814 urban areas.
  - 23 Water Treatment Plans.
  - Average annual evaporation as well as data about population density.

The sheer amount and the diversity of relevant data – only for a relatively small *part* of South Africa – gives already an impression that – even for such a relatively coarse-grained IWRM approach at the WMU level, the operational use of such an academic result makes it indispensable to automate all processing steps as much as possible, to put automated data integration and data quality procedures in place and to continuously update and actualize the database in use. Manual data acquisition or maintenance will never be economically accepted for a continuous operational use.

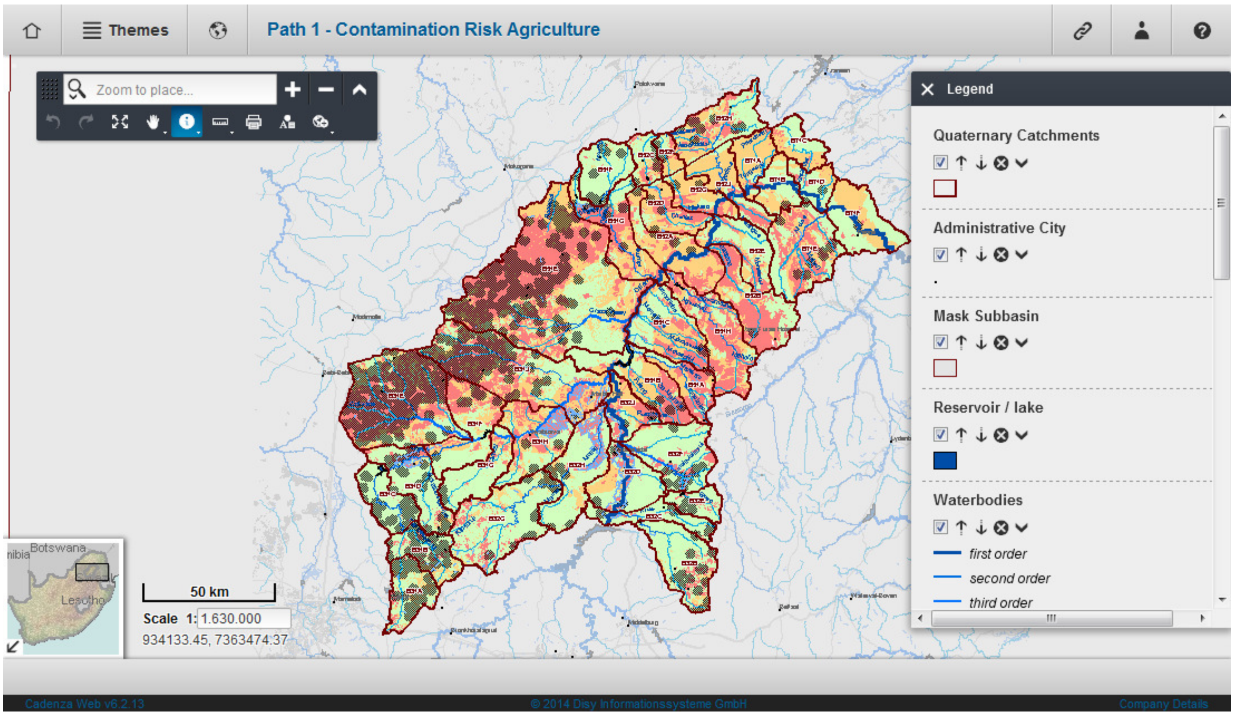

Figure 11: Web-GIS presentation of contamination risks coming from agriculture (path 1)

Figure 11 to figure 13 illustrate some of the planning maps created by the system and accessible through the Web-GIS. Figure 11 presents contamination risks caused by agriculture, shown here in combination with locations of wells. In contrast to this high-resolution visualization, Figure 12 aggregates the risk assessment at the WMU-level and shows the WMU ranking with a simple red/green/yellow colouring. The most aggregated risk-assessment visualization is shown in figure 13. Here, each WMU is presented with a red/green/yellow colour-coded overview diagram with six circle segments, each of which represents the risk ranking for one of the six paths: (1) contamination risks from agriculture through path 1; (2) contamination risks from settlements through path 1; (3) contamination risks from point sources through path 1; (4) contamination risks from agriculture through path 2; (5) contamination risks from point sources through path 3; (6) contamination risks from agriculture through path 3.

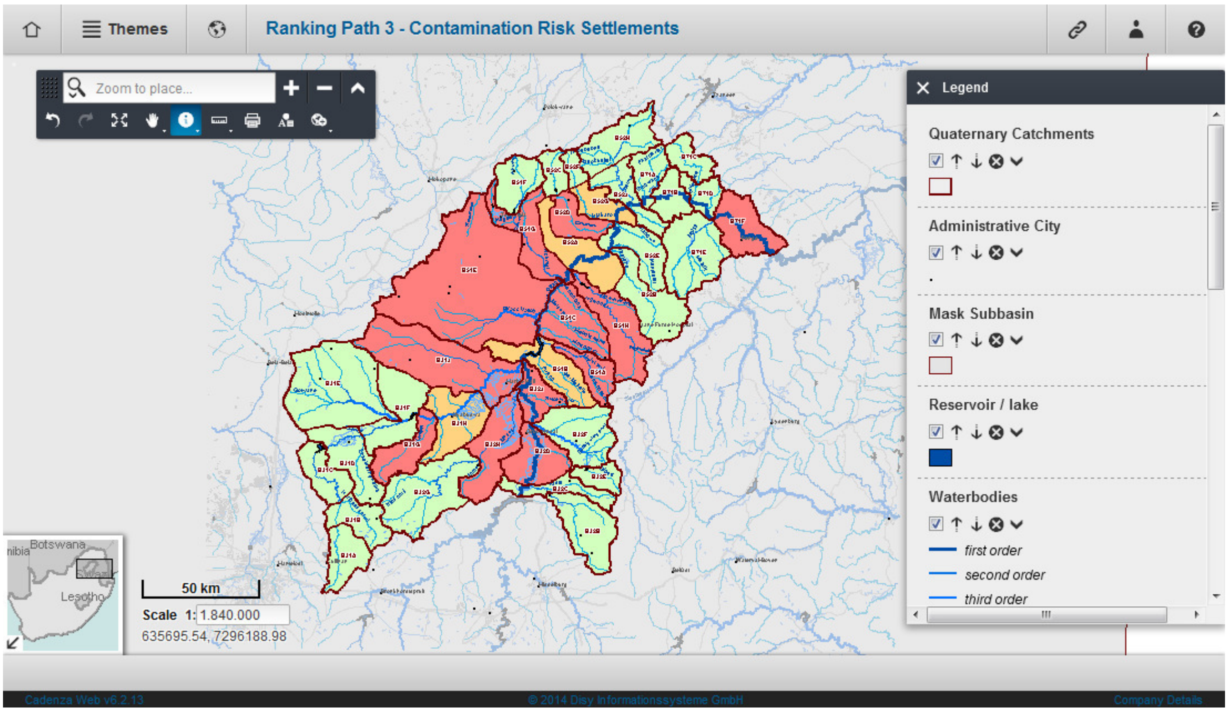

Figure 12: Web-GIS presentation of WMU ranking of contamination risk from settlements (path 3)

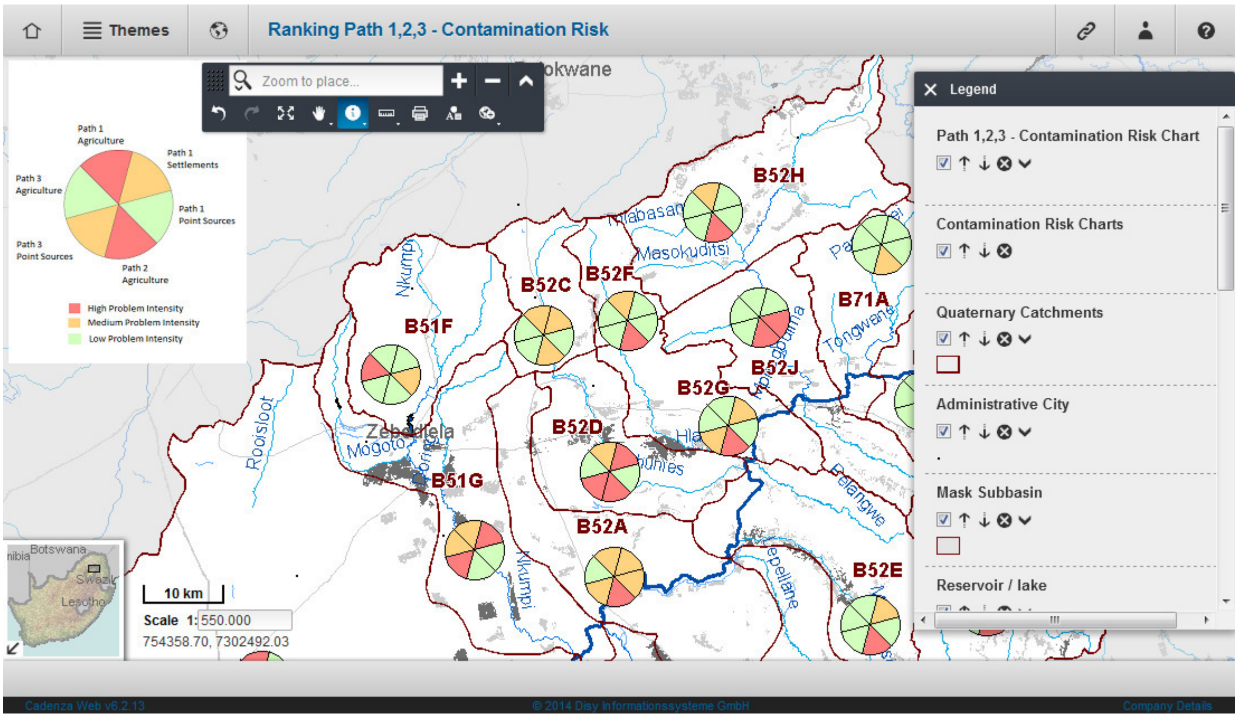

Figure 13: Combined Web-GIS presentation of six different contamination paths

All the thematic maps and planning maps created by the system can also be exported for offline usage with the Cadenza Mobile solution. This may be useful for field workers inspecting the situation on-site or acquiring or checking geographic data in-situ. Here, the offline feature is important because good Internet connection may not be available everyhwere in the hinterland.

Moreover, for each WMU, an up-to-date data summary and a set of WMU-related thematic and planning maps can, at any time, be extracted and compiled into a preconfigured PDF-report template, thus creating an always actual “WMU bulletin” for decision makers.

6 Outcome, Impact and Outlook

The application of PDST will enable South African stakeholders to make decisions on a scientific basis. The identification process enables decision makers to attend effectively to the issues with high priority ratings first. The close cooperation of the project and the South African authorities ensures a holistic implementation of the tools. Since 2015, the project implemented the Web-based system at the Department for Water and Sanitation (DWS) in Pretoria. The participation of the responsible water agency on national level guarantees a sustainable adjustment and a nation-wide transferability of the method to South African conditions.

The PDST identify quaternary catchments with higher need for action and give a structured overview of the causes. They allow for a layered, problem-orientated and efficient examination of entire river basins in South Africa. They initially use a systematic overview examination (scale approx. 1:800.000) in order to identify quaternary catchments with higher problem intensity and prioritized need for IWRM measures (“hot spots”). The next step should be the development of methods to examine these previously prioritized quaternary catchments in more depth (scale approx. 1:50.000) in order to ascertain the types, extensions and locations for necessary IWRM measures.

From the software-technological point of view, the automation of data integration, data quality assurance and risk assessment was absolutely necessary for the long-term sustainable use of the system. Feedback from local stakeholders also showed great interest for the mobile and offline GIS. Especially in developing and emerging countries, such a solution with a full-fledged mobile cadastral system could be a good tool for stepwisely completing and improving the official geo-database about water infrastructures etc. Looking at potential future RTD topics, some areas of potential interest might be (i) some standardization of data models and/or ontologies about the water sector and IWRM; (ii) coupling of coarse-grained and general models and system assessments with more fine-grained and real-time data (water quantity, water quality, water demand) or also with results from hydrologic modeling for early-warning systems, mid-term planning, model calibration, etc.; (iii) combination of IWRM planning support with scenario-based planning for designing future systems taking into consideration different potential devleopments (climatic, economic, …).

Some first steps in these directions are currently being undertaken in ongoing projects, but there is still much space for future developments.

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