Designing a Web-Based Application for Process-Oriented Risk Management of Drinking-Water Catchments According to the Water Safety Plan Approach

Jonas Gottwalt[1], Andreas Abecker[1], Friederike Brauer[2], Thilo Fischer[2], David Riepl[1], Vanessa Rojas[1] and Sebastian Sturm[2]

[1] Disy Informationssysteme GmbH, Karlsruhe, Germany
[2] DVGW-Technologiezentrum Wasser (TZW), Karlsruhe, Germany
andreas.abecker@disy.net

Abstract. The methodological foundations and a Web-based software prototype for risk management at the catchment level of a drinking-water supply chain are presented. The system follows the WHO's Water Safety Plan approach. Robustness and a good effort-benefit ratio are gained by a semi-quantitative risk assessment approach. Additional intelligence is brought into the system by exploiting geodata layers and geodata processing for assessing the vulnerability of the water resources in a given geographic area.

Keywords: Water Safety Plan, Risk Management, Geodata Application

1 Motivation and Objectives

"Ensure availability and sustainable management of water and sanitation for all" is declared as a human right and represents the sixth sustainable development goal (SDG) of the United Nations. Unsafe water, sanitation and hygiene (WASH) are some of the most critical public health challenges in the world. It is estimated that 1.8 billon people rely on fecal contaminated drinking-water resources. Inadequate access to drinking-water leads to death of an estimated 502,000 people every year. Diarrheal diseases caused by inadequate WASH, such as cholera and dysentery, are responsible for approximately 1,000 child deaths per day [1].

The first efforts to establish drinking-water quality standards started in the 1950s and focused on end-product testing to guarantee the safety of drinking-water. This approach resulted in a decrease of the very widespread waterborne diseases. However, end-product testing based on spot samplings, has several limitations. For example, detection systems for microbial contamination cannot securely detect the multitude of pathogens. Further, by the time of detecting a contamination, drinking-water may already have been consumed. Moreover, only a small sample of the total delivered drinking-water can be analyzed. Hence, end-product testing in drinking-water supplies can highlight, but not prevent potential hazards for human health and additional approaches to improve drinking water safety are required [2,3].

These experiences were considered in the formulation of the third edition of the WHO guidelines for drinking-water quality (GDWQ), which introduces a holistic risk management approach to consistently ensure the safety of drinking-water [4]. This so-called *Water Safety Plan (WSP)* approach allows to systematically highlight risks in the drinking-water supply chain and offers a systematic procedure to manage those risks and to prevent the supply system from contaminations [5].

Until now, the implementation of WSPs is usually performed on paper. Sometimes basic software support by text processing or spreadsheets is available [6,7]. Practical experience has shown the high effort of creating and maintaining the documentation for implementing a WSP. Technical operators state that risk assessment and documentation is "time-consuming paper work" [8]. The WSP approach considers four stages of water supply systems: catchment area, water treatment, distribution system, and water consumer. Risk management on a catchment scale is facing particular challenges where conventional methods do not provide sufficient support. This includes a multitude of stakeholders involved in catchment processes, a high number of different land-use activities, the complex flow of substances within a catchment area and the large size of drinking-water catchments [9].

Hence, the goal of the work presented in this paper was the development and validation of a software tool for a more efficient implementation of the WSP risk management. The software concept to be developed considers the WSP sub-component "system assessment" on the scale of drinking-water catchments. The software prototype should be developed as a web-based application including interactive map components.

In this paper the prototype is presented. In Section 2, the methodological background is presented, namely the foundations of the Water Safety Plan approach, the WSP activity "system assessment", the specific challenges of working at the catchment area level, and the specific semi-quantitative approach applied in this work. Section 3 sketches the software development process and some principles of system design and then presents the realized prototype. Section 4 sketches the development status and first evaluations, while Section 5 summarizes and discusses some potential future work.

2 Methodological Background

2.1 Objectives and Content of a WSP

The objective of a WSP is "to consistently ensure the safety and acceptability of a drinking water supply" [6]. The GDWQ describe the objective of a WSP as follows: "The primary objectives of a WSP in ensuring good drinking-water supply practice are

- the prevention or minimization of contamination of source waters,
- the reduction or removal of contamination through treatment processes,
- and the prevention of contamination during storage, distribution and handling of drinking-water."

To achieve these objectives, the WSP approach comprises three components, (i) system assessment, (ii) operational monitoring, (iii) management and communication.

2.2 The WSP component "system assessment"

System assessment includes five consecutive steps as shown in Fig. 1.

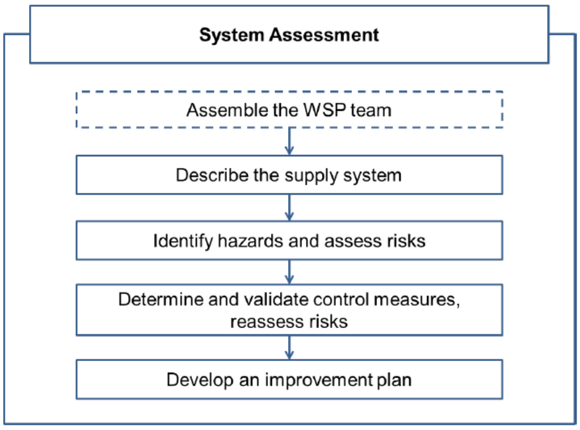

Fig. 1. Steps of the WSP component "system assessment" [5,6].

The "description of the drinking-water supply" should provide an overview and a comprehensive understanding of the entire supply system, including catchment, treatment, storage and distribution. This step should provide all necessary information to identify potential hazards and hazardous events, and result in a flow diagram, for example. Typical documents supporting the description of the system are general plans, plans of catchment and water reserve, pipe plans, plans of control measures, descriptions of treatment plants and its spatial location, to name just a few [7].

In the step "hazard identification and risk assessment", all hazards and hazardous events of the supply system will be identified and prioritized. A hazard according to the WSP approach "is a biological, chemical, physical or radiological agent that has the potential to cause harm", while a hazardous event "is an incident or situation that can lead to the presence of a hazard" [5]. The identified hazards and hazardous events will be prioritized by risk assessment to get a summary of which hazards and hazardous events are more important than others. Risk assessment covers the determination and combination of "likelihood of occurrence (LO)" and "severity of consequences (SC)" of hazards and hazardous events which results into the risk (Table 1). [5] defines risk as "the likelihood of identified hazards causing harm in exposed populations in a specified time frame, including the magnitude of that harm and/or the consequences". Determined risks will be categorized by a ranking. Table 1 demonstrates the process of risk assessment by the mean of a risk matrix. It defines risk by the combination of LO and SC. Table 2 is an example of a risk classification approach which refers to a semi-quantitative risk assessment method.

Table 1. Example of a semi-quantitative scoring matrix for risks [5].

Likelihood	Severity of consequences				
	Insignificant	Minor	Moderate	Major	Catastrophic
Almost certain	5	10	15	20	25
Likely	4	8	12	16	20
Moderately likely	3	6	9	12	15
Unlikely	2	4	6	8	10
Rare	1	2	3	4	5

Table 2. Example of a classification schema for risk ranking [5].

Risk score	< 6	6 – 9	10 – 15	> 15
Risk rating	Low	Medium	High	Very high

2.3 Challenges in catchment risk management

Holistic drinking-water risk management starts with catchment management. The term “raw water” stands for untreated natural water sources, including ground water and various types of surface water such as rivers and lakes [9]. The quality of raw water entering the supply system is relevant for the safety of the entire supply system. High-quality raw water reduces the overall risks and reduces the costs of the water treatment processes.

But there are specific challenges in risk management at the catchment scale. For example, water suppliers often have only limited influence on the catchment activities, because the catchment areas are usually not fully owned by water suppliers. A high number of stakeholders from different fields has influence on the water resources. This requires collaboration between the different stakeholders such as (i) public health authorities, (ii) local authorities responsible for catchment management aspects like land-use planning or urban development, (iii) agriculture and further land users, etc.

A further challenge is the wide spatial extent that catchments usually have, with a number of uncontrolled aspects of the natural system influencing the quality of raw water. Examples are land use activities such as agriculture in which fertilizers and pesticides can contaminate water sources. Another example is the discharge of untreated waste water of industrial plants into water bodies. Further factors may be contaminated sites or natural factors such as vegetation cover, geological conditions, climate components etc. The high number of possible hazardous events and hazards implies a huge challenge in catchment risk management. To meet this challenge the application of Geographic Information Systems (GIS) is recommended [10]. GIS enable a quick overview about the catchment and can simplify the process of hazard identification and risk assessment.

The kinds of hazardous events and hazards occurring in catchments as well as the necessary control measures differ from those of other stages in the water-supply chain. The intervals, for example, in which a hazardous event in a catchment occurs, are longer compared to the water-treatment stage. For this purpose, risk assessment for catchments provides specific scale tables, where for example, the interval of likelihood of occurrence can be defined (cp. Table 3). Examples for catchment specific hazards and hazardous events are given in the literature [3,9].

The impact that hazards have on catchment water bodies is difficult to estimate because of complex flows of substances in catchments. Soils and water bodies, for instance, have natural retention characteristics to reduce harmful influences on raw water [9]. General WSP guidelines such as [2,5,7,11] do not provide sufficient support to meet the complex challenges of catchment risk management. Tools in the literature such as tables, flow diagrams and catchment sketches often neglect the complexity of catchment risk management. Against this backdrop a series of guidance documents and standards particularly for catchment risk management were developed [3,9,12,13,14]. The following subsection will focus on this aspect.

2.4 Risk assessment approaches on a catchment scale

In general, there are qualitative, semi-quantitative and quantitative risk assessment approaches. *Qualitative approaches* describe risks by subjective evaluation. Hazards and hazardous events can be analyzed and prioritized based on the expertise opinion of the WSP team, for example. *Semi-quantitative approaches* consider a number of easily measurable parameters and use indexes or scoring methods. *Quantitative risk* assessment is based on measurement data and algorithms [9]. The problem of quantitative approaches for catchment risk management: The wider the extent of the catchment, the more difficult is the computation of risk, because of availability and comparability of data. Hence, the GDWQ recommend the application of qualitative and semi-quantitative methods for the implementation of risk assessment. In our work, we followed the semi-quantitative approach – which may require more effort compared to qualitative methods, on one hand, but, on the other hand, is more suitable to meet the complex challenges of catchment risk management.

Semi-quantitative risk assessment can be divided into the steps (i) risk analysis, which describes the processes of determining likelihood of occurrence and severity of consequences of a particular hazardous event and (ii) risk prioritization, which is the categorization or ranking of the analyzed risks. Risk is defined as the product of likelihood of occurrence and severity of consequences of a specific hazard and hazardous event. This relationship can be schematically expressed in a risk matrix (Table 1). The resulting risk can be categorized with the objective to separate unimportant from important hazards, applied by a risk ranking schema (Table 2). Semi-quantitative risk analysis requires the definition of what likelihood of occurrence and severity of consequences means (see Table 3 and Table 4). This can be different for different catchments. Usually, ordinal scales with three or five classes will be applied. This allows for the implementation of relative ranking even if detailed information is missing. This approach reduces the subjectivity and makes the process of risk analysis more transparent.

Class	Weighting	Interval
very low	1	Less frequently than once every 10 years
Low	2	Once every 6–10 years
moderate	3	Once every 2–5 years
High	4	Between every 1 and 2 years
very high	5	Once per year or more frequently

Table 4. Scale for severity of consequences.

Class	Weighting	Description
very low	1	Insignificant or no impact on public health
Low	2	Short term, not health-related non-compliance, or aesthetic impact
moderate	3	Significant aesthetic issues, long-term non-compliance, but not health related; occasional interruption of supply
High	4	Potential long-term health effect, acute health effect of minor impact; frequent or regular interruption of supply
very high	5	Acute public health impact; that is, with potential for severe health effects; no water available

2.5 Catchment risk assessment taking into account vulnerability

Risk assessment within the WSP approach has the objective to prioritize hazards and hazardous events to differentiate between less and more important hazardous events in the water supply. However, using standard semi-quantitative risk assessment at the catchment level may lead to a high number of hazardous events marked with a high risk. In order to make possible further prioritization, the aspect of *"vulnerability"* has been included in addition: Catchments have the natural capacity to protect water resources from harmful impacts. Soils, for example, can absorb hazards and prevent the infiltration of harmful substances into water bodies. Vulnerability describes the degree of susceptibility of raw water which depends on catchment-specific protective effects [9]. Fig. 2 illustrates these ideas using an example. Besides soil there are further parameters which determine the degree of inherent protection of a catchment. These include geomorphological conditions such as connections of water bodies, geology, topography and degree of vegetation cover. Hazards can either get directly into surface water by emission of a point source, such as waste water of industrial plants or diffuse sources. Manure, for example, distributed on farmland can be removed by precipitation and run off into a water body. If hazards seep into ground, they can be absorbed, degraded or get into surface water bodies by interflow. In the water body itself, hazards can be degraded, or they can sediment and reduce the harmful effects. The risk of a hazardous event for raw water is the target figure in our risk assessment approach (Fig. 2).

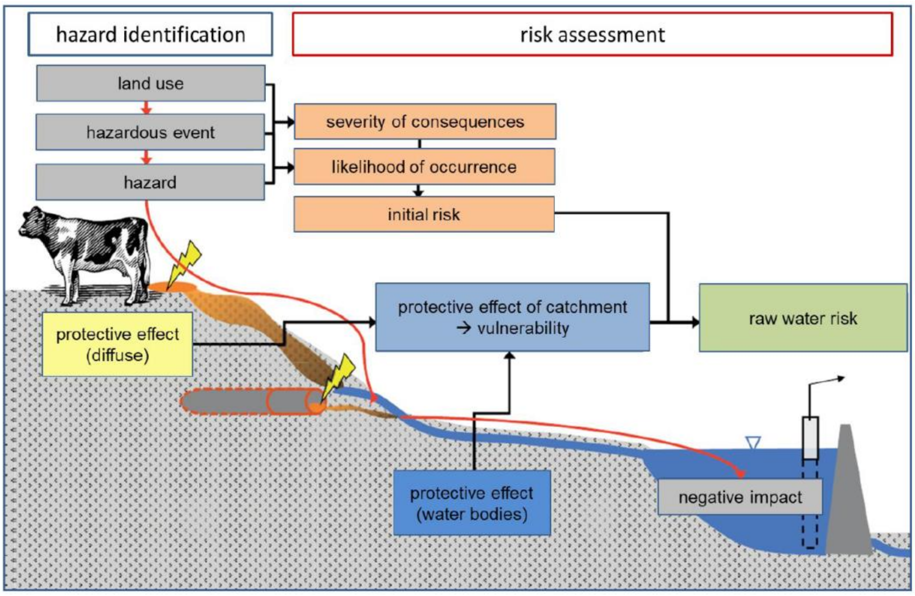

Fig. 2. Schematic illustration of the risk assessment approach of [13].

It is difficult to estimate the catchment-specific degree of inherent protection. For implementing the vulnerability concept in risk assessment, a geodata layer can be processed. Parameters such as soil characteristics and vegetation characteristics will be processed by weighting and spatial intersection. The result is a geodata layer in which each coordinate in the catchment has a specific vulnerability. Depending on the type of water which is used for abstraction of the water supply, vulnerability describes either surface-water vulnerability (like in Fig. 2) or ground-water vulnerability.

2.6 Risk assessment approach for the planned software application

The first value to be determined is the "initial risk" which still neglects spatial location and existing control measures of hazards and hazardous events (Table 5). The leachate at the hazardous event location is subject of risk analysis. It is calculated by the multiplication of LO and SC. The reason for that is that the effectiveness of a control measure should be considered critically.

In the second step of risk assessment, vulnerability is used to do further prioritization. Vulnerability works like a filter. Hazards and hazardous events located on places with high vulnerability will have an unchanged initial raw-water risk compared to its initial risk. However, hazards and hazardous events which are located on places with low vulnerability will have a reduced initial raw-water risk compared to the initial risk. Hazards and hazardous events which are still classified as high will be considered in detail in the following step.

In the third step, risks should be analyzed again, that time taking into account the effectiveness of existing control measures. The resulting indicator is called "residual risk". If control measures and vulnerability are considered, the resulting indicator is termed "initial raw water risk". This value describes the risk of a hazard and hazardous event to raw water at the location of water abstraction [12,13,14]. Risk can be reduced by the introduction and optimization of control measures such as reduced use of fertilizers in agriculture.

Table 5. Overview of indicators applied in the risk assessment process.

Term of indicator	Abbreviation	Calculation of the indicator
Likelihood of occurrence	LO	Semiquantitative assessment
Severity of consequences	SC	Semiquantitative assessment
Vulnerability	V	Quantitative calculation
Initial risk	R_I	R_I = LO * SC
Initial raw water risk	R_{IRW}	R_{IRW}= R_I * V
Residual risk	R_R	R_R= LO * SC (taking into account CM)
Residual raw water risk	R_{RRW}	R_{RRW} =R_R * V (taking into account CM)

3 The WSP Tool Prototype

3.1 Concepts and realization approach

Requirements engineering was based on analyzing WSP documents and on 3 stakeholder workshops with 3 TZW[1] domain experts for water safety plans. Requirements engineering, use-case definition and GUI design for the software prototype was done in several iterations with GUI mockups and rapid prototyping. In the beginning of the requirements elicitation process, observation methods were useful for better understanding the risk management processes in practice [15]. Fig. 3 shows the context and the system boundaries of the software prototype to be built. Several instruments have been used for requirements documentation, namely business process modeling, use cases, glossary, mockups, data flow chart and data modeling. A couple of the resulting of the resulting models are shown in the following. The remaining models, in particular the use cases, can be found in [15].

For designing the system and realizing the prototype, the to-be-supported WSP activities have been modelled as businesses processes, with their sub-activities, input and output documents and data. Fig. 4 presents the resulting model. Based on the input-/output-data of these business processes, an Entity-Relationship-Model as a conceptual model for all system-relevant objects has been developed, and a logical

[1] TZW (Technologiezentrum Wasser) - the German Water Centre – is part of DVGW e.V., the German Gas and Waterworks Association. TZW is a non-profit and independent institution with more than 150 employees performing close-to-application research and scientific advice regarding drinking-water supply. TZW experts provided the domain knowledge fort he software tool presented in this paper.

data model as well as a physical data model for the software prototype has been derived from that.

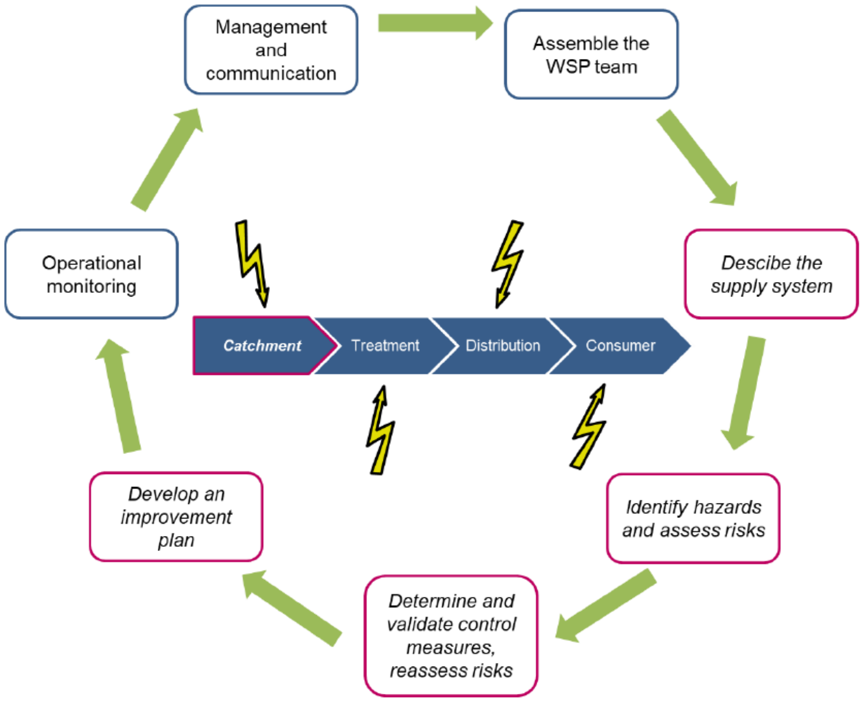

Fig. 3. System boundaries and context: System components are labeled by magenta frames. The entire WSP process forms the system context. The flashes symbolize hazards and hazardous events compromising the water supply.

Fig. 5 depicts the main elements of the conceptual E-R-Model, without attributes. It is denoted in Martin's widespread Crow's Foot notation [16]. The simple notation of the E-R-Model makes it an appropriate tool for communication between developers and non-database experts such as domain experts in early stages of the design process [17]. An entity type is an abstraction of a real-world object, on which information should be stored. In the risk-management domain, a "control measure", e.g., was modeled as an entity type. Also, "hazard", "event", "risk" and "risk analysis", for example, were modeled as entity types (Fig. 5). A special form of entity type is the weak entity type. A weak entity type is an entity type which depends on other entity types. For example, "hazardous event" comprises "hazard" and "event" (Fig. 5). Hazardous events cannot exist without "hazard" or "event". Entity types have associated attributes. A "control measure", for instance, has a "control measure name" and an "affected type of hazard". The entity type "hazard" has attributes such as "hazard name", "type of hazard" and "description" (not shown in Fig. 5). Relationship types represent a connection between entity types. For example, a "control measure" "acts against" a specific "hazardous event" and a "hazardous event" "has one" "hazard" (Fig. 5).

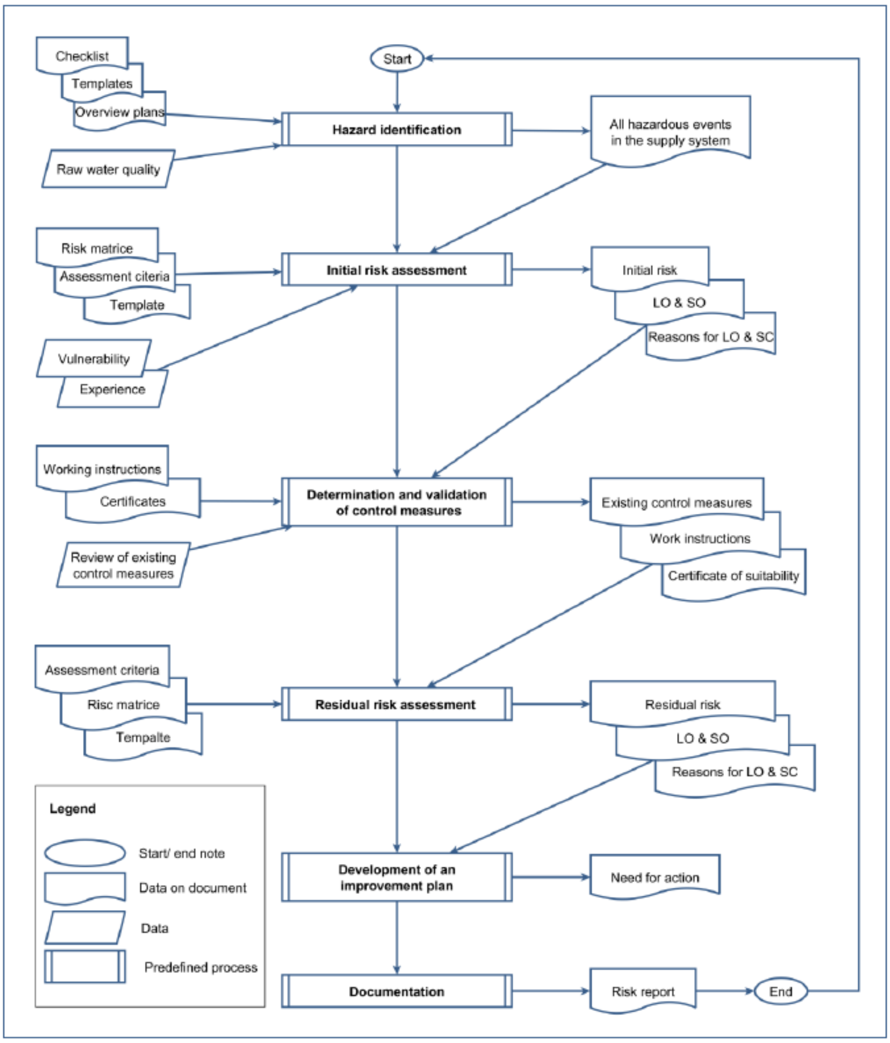

Fig. 4. Business process model of selected WSP main activities.

The colors in Fig. 5 represent different domain topics. Blue means data with geographical dimension such as "hazard carrier" and "vulnerability". The orange marked model elements refer to "hazard identification". Red objects pertain to "risk assessment" and green elements cover "control measures". The relationship type "is a" refers to a generalization-specialization relationship. For example, geometry either is a point, polyline or polygon geometry, and there are four specializations of the entity type risk: initial risk, initial raw-water risk, residual risk and residual raw-water risk.

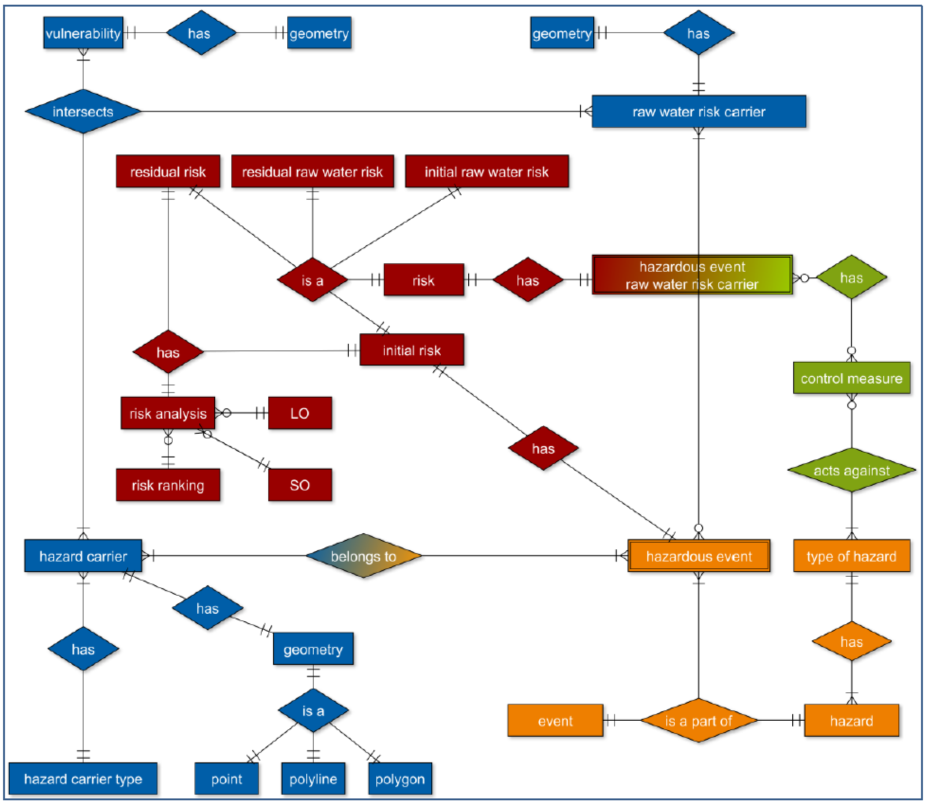

Fig. 5. Simplified ER model of the overall system to be developed (without attributes).

A PostgreSQL/PostGIS geodatabase was employed for storing all data and for realizing the geodata-layer processing for vulnerability determination. The application logic was implemented using Grails. The application logic and the GUI support the user in going through the modelled risk assessment processes in a "guided" manner, supporting data input by specific templates, pull-down menus etc., automating the semi-quantitative aggregation of input values and easily managing, updating, and inspecting all relevant data and documents. The Cadenza Web-GIS[2] has been employed for map-based visualizations of georeferenced objects and of calculated risk maps. Fig. 6 shows the overall system architecture.

[2] https://www.disy.net/en/products/cadenza/web/

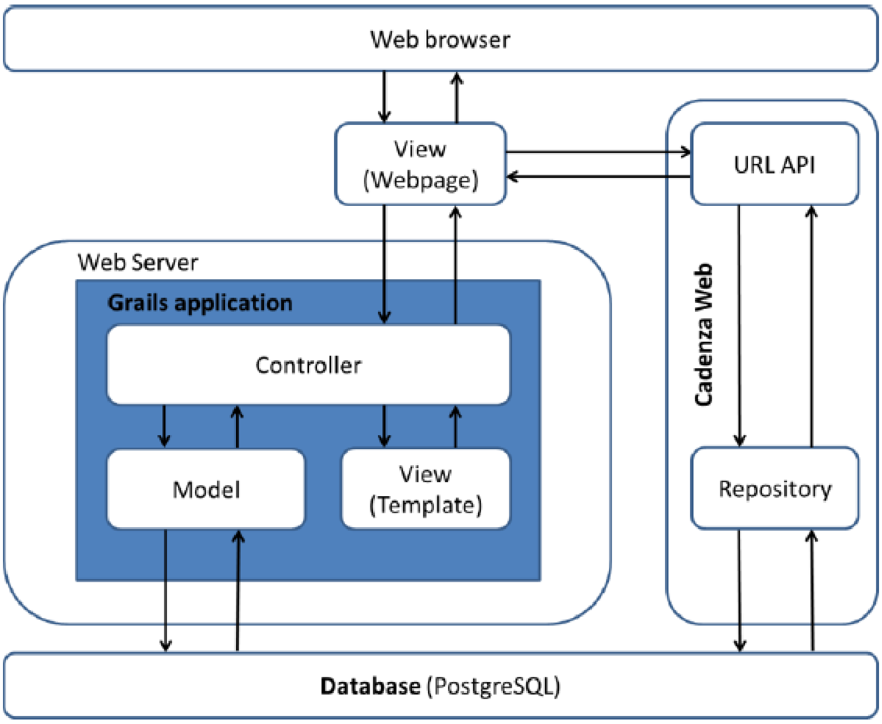

Fig. 6. High-level architectural model of the risk management application.

3.2 Look-and-feel of the prototype system

Fig. 7 shows the main screen of the Web-based software prototype developed. The entry screen of the tool offers to the user the main activities of the modeled risk assessment process with the respective sub-activities and the resulting documents created by each process step. Clicking on an element leads the user to the respective input mask, analysis report or document.

Fig. 7. Main screen of WSP tool prototype.

The current prototype contains:

- input forms for hazardous events and control measures (which refer to geometric objects, points, lines or polygons, as potential hazard carriers – like an agricultural area or an industrial site)
- customizable scales for LO, SC, vulnerability and classification of risk
- formulas for risk analysis
- overview tables for visualizing input data, for example, hazardous events, as well as reporting features
- a GIS component for visualizing risks and vulnerability and for assigning hazardous events and control measures to hazard carriers

Fig. 8 shows the input form for adding hazardous events. Fig. 9 and Fig. 10 show the screens for editing events or the risk ranking schema, respectively.

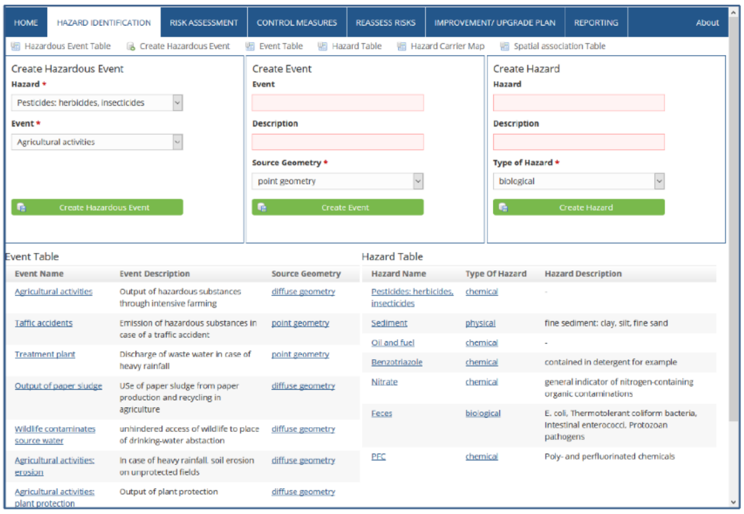

Fig. 8. Screen for adding hazardous events.

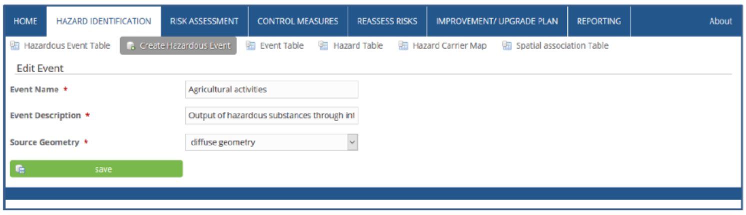

Fig. 9. Screen for editing events.

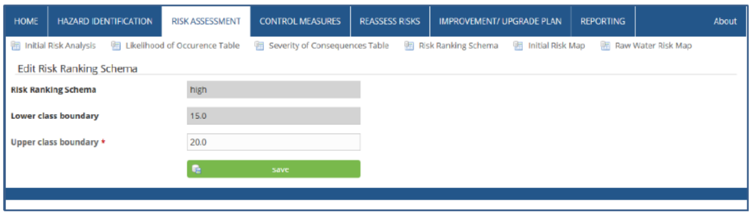

Fig. 10. Screen for editing the risk ranking schema.

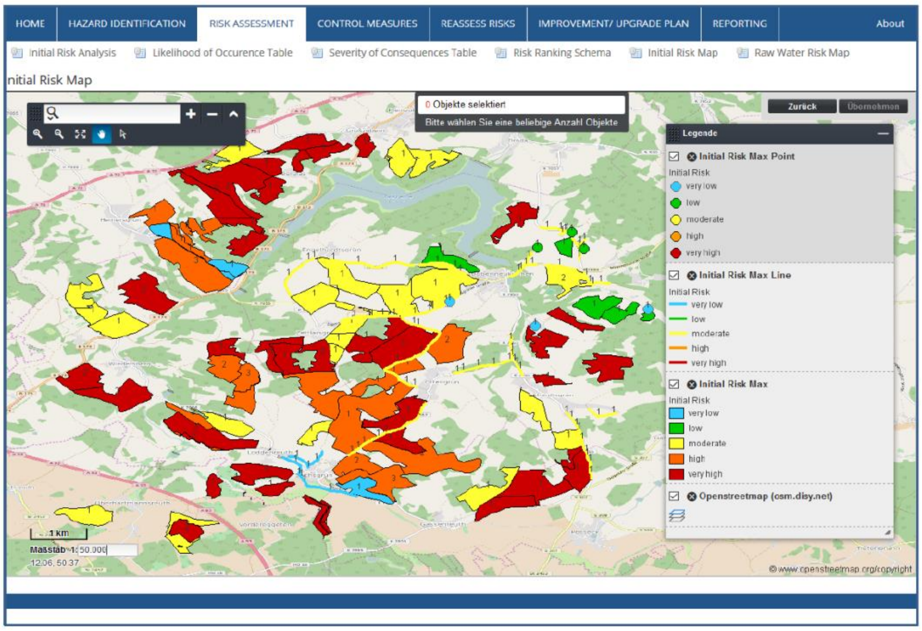

Fig. 11. Screen for map-based visualization of initial risk.

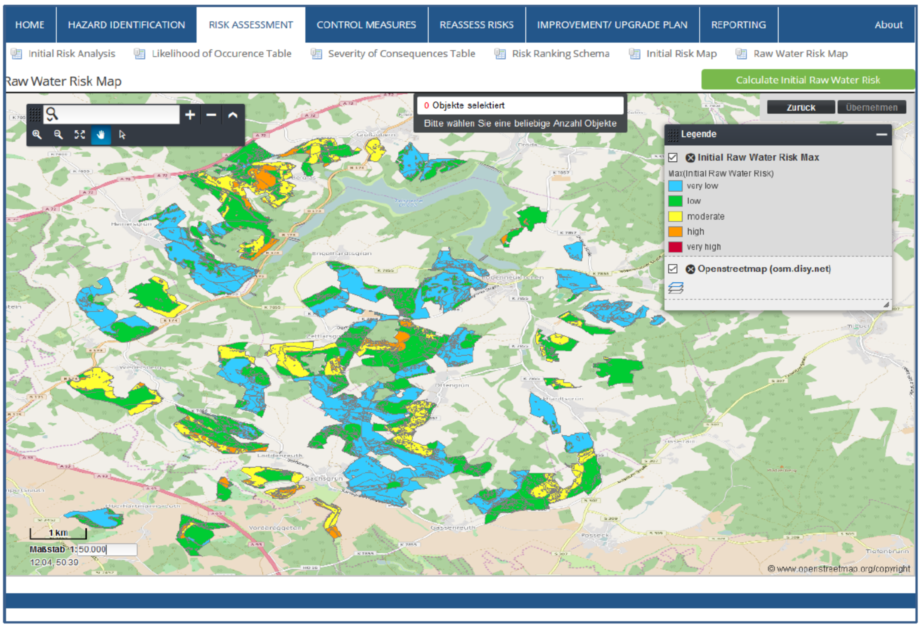

Fig. 12. Screen for map-based visualization of raw water risk.

Fig. 11 and Fig. 12 show two major map-based visualizations provided by the tool.

Fig. 11 presents in the initial-risk map all collected risks, rated according to their likelihood of occurrence and their severity of consequences. In the case that several risks are associated with the same geometry, the risk with the highest priority determines the color of the geometry and a number indicates how many risks apply here.

Fig. 12 is based on these initial risks, but in addition also considers the vulnerability of locations, leading to the raw-water risk map. The raw-water risk map is derived from the initial risk map by reducing the risk of specific areas where protective functions are prevailing. Based on such a map, control measures could be planned and prioritized in a next WSP step.

4 Evaluation of the Prototype

4.1 Usability testing

The external validation of the coded prototype was conducted as a usability test with TZW experts for WSP application.

Before the actual usability test was executed, a *pre-test* was done with just one test person not familiar with the WSP approach. The pre-test was executed to determine the duration and weaknesses of the test concept. The test concept was adopted according to the results of the pre-test. For example, the number of hazardous events the user had to identify was reduced from five to three to make the test shorter. In addition, the design of the protocol was adopted to allow more space for notes, the order of questions was changed etc.

The *usability test* involved the following *components*: Introduction, background questionnaires, task scenarios and post-test questionnaires. Transcripts and surveys can be found in [15].

To *introduce* the subject to the test, an orientation script was read aloud by the test moderator. This script provides an overview of the test procedure and test objectives. After the introduction, personal data about the test person were collected. This background questionnaire was followed by the execution of two test scenarios.

The *first scenario* concerned hazard identification, where the user had to identify three hazardous events and assign them to related hazard carriers. The results should be visualized in a map.

The *second scenario* considered risk assessment. The risk of the hazardous events identified in the first task should be estimated and prioritized. Both initial risk and initial raw water risk should be visualized in maps.

Both scenarios intended to imitate real-world use cases. The tasks were intentionally formulated rather general, so that the test persons had to find the way to solve the task on their own. The task scenarios were read aloud by the test moderator. While the user was performing the tasks he or she expressed loudly which partial step he or she is executing, what objectives he or she pursued with it, and his or her feelings and thoughts while performing the task. Furthermore, the user expressed non-occurring expectations and disappointments as well as aspects of the application which he or she found positive.

After performing the scenario tasks, a *post-test survey* was conducted. This questionnaire included questions on problems, solutions and positive aspects of the tested prototype, and compared the risk management tool to similar products.

The usability test was performed twice, with two different domain experts as test persons. The subjects were both members of the TZW expert team, who were already involved in the requirements elicitation and design process. The first test lasted for 1.5 hours, the second test for around 2.5 hours.

Test results are presented in [15]. In general, the potential usefulness of such a tool was confirmed, but the detailed opinions about the usefulness of the current prototype were ambivalent. The test subjects made many suggestions for improving the tool. A major source of criticism was the fact that the current prototype requires a lot of data input from scratch regarding hazards, events and hazardous events. Hence, for the next round of prototyping, a number of import and export features have been specified. Besides that, many specific issues have bee identified where the users lay loose orientation and overview with respect to GUI design and risk management workflow. This will also lead to many concrete improvements for the next version of the prototype, such as: Clearer distinction between different functional areas of the tool, more clarity regarding automatic versus manually started computation processes, easier handling and better understandability of some tool functionalities, more information for the user during tool usage. Altogether, the users confirmed that the prototype offers all functionalities required for an automation of WSP system assessment; but – in particular when taking into account that this method is already complex by itself – the tool needs to offer much more help and more clarity to really support the user when going through the system assessment procedure.

4.2 Further validations

The tool prototype was also presented to 10-15 people from associated project partners in Peru, coming from (i) Autoridad Nacional del Agua (ANA), Peru's national water authority, (ii) Servicio de Agua Potable y Alcantarillado de Lima (SEDAPAL), a local water supply company, and from (iii) Observatorio, an organization which supports ANA and SEDAPAL by collecting and processing data.

The feedback was positive in general and the test people showed great interest in the developed WSP-risk management tool. Quite a number of improvements was suggested, partly addressing the WSP method in general (for instance: in the catchment of the river Lurin, both surface water *and* groundwater are used for water supply while the employed method currently considers only one kind of raw water source) and partly addressing simple practical aspects (like GUI in Spanish, better education of users, etc.). A more fundamental problem is also related to the method in principle and not so much to the tool prototype: For many regions, no vulnerability data is available. This problem is one area of our ongoing work: To which extent is it possible to derive vulnerability information from satellite data or other available background information?

5 Summary and Outlook

The Web-based tool for WSP risk assessment at the catchment level has been implemented prototypically and was evaluated in depth with two domain experts from TZW, with respect to functionality and to usability. While all required functionality is there or will be there in a further prototype version, many suggestions for usability improvements have been made in order to have a really simple tool that supports the non-trivial workflow of WSP system assessment. Similar comments were produced in a more superficial system evaluation with 10-15 users from Peruvian water managers. Of course, for the creation of an operational solution for daily use, additional aspects must be regarded (e.g., import of legacy data) and the WSP steps not considered in this research work would have to be included.

The benefits for the practice of WSP implementation are obvious: efficiency gains, partial automation of work steps, better documentation, more transparency and documentation of decision procedures, better repeatability of risk management activities, increased homogeneity of the work done by several employees. In the long term, near real-time, reactive risk management can be imagined instead of one-off risk-management activities at discrete times. The automated aggregation of risks and combination with vulnerability and the effects of control measures, would also make possible kind of a decision-support functionality by simulating the effects of alternative control measures for finding the best measures to take.

Another big advantage of the tool is the high degree of configurability. For instance, to make the tool also useful for users without access to high-quality data, the additional implementation of a simplified risk management approach may be reasonable. Vulnerability, for example, could be manually assessed instead of using a dataset. On the contrary, also more complex approaches could be applied. For instance, vulnerability could be considered for each hazard or for particular groups of hazards with similar qualities such as distribution and degradation behavior.

Another practical idea for improving the specified risk management approach could be the implementation of a second risk management cycle. The second cycle would be applied by another person to ensure that no hazards and hazardous events are forgotten, that risks are properly assessed, and that the effectiveness of control measures is not overestimated. Such a two-stage risk management approach could reduce the risk of user-errors in the semi-quantitative risk management.

In the long term, also the system boundaries could be expanded to the entire drinking-water supply chain, considering not only catchments, but also treatment processes, distribution network and consumers. Also, the other components of the WSP approach, namely “assembling a team”, “operational monitoring” and “management and communication” could be included in the tool.

From the scientific point-of-view, also the trade-off between efforts and costs for qualitative, semi-quantitative and qualitative risk-assessment approaches is interesting. In our solution, we follow the semi-quantitative approach. It would be interesting to see whether there are also situations where strictly quantitative methods are necessary and/or possible – offering more automation and maybe better results at the price of high data requirements and complexity. The modular software architecture of our tool is open for all variations.

For the practical application of the presented methods in sustainability research and sustainability projects, the transferability to new local conditions is also important. Water problems often occur in very poor countries. The approach presented here has been developed and is being applied in Germany and in Peru. The applicability in other countries is also of high interest.

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