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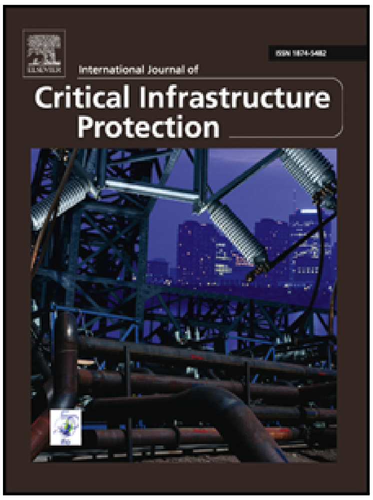

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PII: S1874-5482(17)30187-7
DOI: 10.1016/j.ijcip.2018.04.003
Reference: IJCIP 244

To appear in: *International Journal of Critical Infrastructure Protection*

Received date: 9 November 2017
Revised date: 7 February 2018
Accepted date: 27 April 2018

Please cite this article as: Martin Zimmermann , Martina Winker , Engelbert Schramm , Vulnerability Analysis of Critical Infrastructures in the Case of a Semi-Centralised Water Reuse System in Qingdao, China, *International Journal of Critical Infrastructure Protection* (2018), doi: 10.1016/j.ijcip.2018.04.003

Vulnerability Analysis of Critical Infrastructures in the Case of a Semi-Centralised Water Reuse System in Qingdao, China

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Abstract: Urban centres in newly industrialised countries are experiencing rapid population growth, which poses challenges for infrastructure planning. Semi-centralised water infrastructures have a modular architecture that enables water reuse, and thus they are able to meet these challenges. Since such socio-technical systems represent critical infrastructures, it is appropriate to analyse their vulnerability to internal and external hazards (*e.g.* technical failure, drought) as well as their dependencies on other infrastructures (*e.g.* energy supply). The vulnerability analysis in this paper focuses on the pilot plant of a semi-centralised water infrastructure in Qingdao, China, and uses a newly developed methodology combining expert discussions, questionnaires, a vulnerability assessment heuristic, and cross-impact matrices. The results identified the technical components that were more vulnerable to hazards or the failure of other components. This applied mainly to technical components in the resource recovery centre (RRC). Hazards and system components that have the greatest impact on the vulnerability of other components were also identified. This applied mainly to human failure and the RRC control system. It can be concluded that vulnerability management measures need to focus on the identified hazards and system components. Furthermore, measures to minimise health risks for users should be specifically analysed.

Keywords: blackwater, greywater, socio-technical system, source separation, water infrastructure

INTRODUCTION

Water infrastructures supply drinking and service water and safely dispose of domestic wastewater. A centralised infrastructure design has proven to be appropriate for urban agglomerations in the West for the last 150 years, however urban centres in newly industrialised countries, *e.g.* China, India and Brazil, are experiencing rapid population growth. Moreover, cities in semi-arid regions have to deal with the challenge of water scarcity, which is being exacerbated by climate change. Dealing with these challenges, particularly when they occur simultaneously, requires water infrastructures that are adaptable and flexible [1–3].

Novel water infrastructures are decentralised or semi-centralised in their design, allowing modular architecture and enabling water reuse, and thus exhibiting the characteristics required to deal with the aforementioned challenges [4–10]. The decentralised or semi-centralised configuration facilitates connection with a specified urban district or a restricted number of residential quarters for instance. This means that modular architecture, urban supply and disposal systems are flexible and can be adjusted to rapidly growing (or shrinking) populations [8]. Furthermore, the reuse of water (and heat or other resources for example) contributes to more efficient management of natural resources. By separating wastewater streams of different qualities directly at their source and then treating them accordingly, service water can be produced for a variety of purposes such as toilet flushing and the irrigation of public green spaces.

Conventional water infrastructures can be conceived of as socio-technical systems, *i.e.* technological systems comprising their institutional, administrational and social context [11]. In this regard, it is necessary to transform the conventional socio-technical system in order to realise novel water infrastructures. Furthermore, interdependencies with the system's natural environment have to be taken into account. This might be a complex task given the fact that water supply and disposal systems are viewed as critical infrastructures, *i.e.* they are essential for the functioning of a society and its economy. From this perspective, it is appropriate to analyse the vulnerability of novel infrastructures. In this context, vulnerability is defined as the susceptibility and resilience of the socio-technical system's components in the face of certain hazards. The objective of this paper was therefore to analyse the vulnerability of a specific semi-centralised water infrastructure in Qingdao, China. The main research questions were:

- What hazards do semi-centralised water infrastructures face?
- How vulnerable are specific system components to these hazards?
- How vulnerable are specific system components to the failure of other system components?
- What should risk management measures focus on?

CASE STUDY AND RESEARCH OBJECT

A novel water infrastructure known as Semizentral, serving what is called the WHE village of the Qingdao World Horticulture Exhibition, was built in 2014. The city of Qingdao is located in north-east China and has a population of about 4.7 million living in its urban agglomeration [12]. The capital of the province of ShanDong, the city serves as an economic centre and transport hub, particularly in terms of its seaport. Qingdao is a rapidly growing city with a growth rate of 130,000 new inhabitants per year [12]. The city has struggled for years with water shortages due to drought, but energy-intensive desalination, for instance, is presumably not an alternative solution due to the level of technical sophistication required and high costs [13].

An idealised version of the above-mentioned pilot plant provided a case study for the vulnerability analysis in this study. Domestic wastewater from 12,000 inhabitants in the service area comprising two residential areas (Bijia A and Bijia C), two hotels, and the WHE office area is collected and treated at a Resource Recovery Centre (RRC) [14]. The core concept of the system is source separation, *i.e.* the separate collection and treatment of partial wastewater flows. Hence it comprises three technical treatment modules: a greywater treatment module, a blackwater treatment module and an energy production module (Fig. 1). The treated greywater is reused as service water for toilet flushing and for an artificial watercourse in a park, while the treated blackwater is reused for irrigation purposes. The combination of service and irrigation water supply, wastewater treatment and organic waste treatment for energy production is resource-efficient and aimed at energy self-sufficiency. Under ideal conditions, drinking water usage can be reduced by 30 to 40 per cent and the energy needs of the RRC met by internal biogas production using organic waste and sewage sludge [15].

The greywater module treats slightly polluted wastewater (*i.e.* greywater) from showers, sinks and washing machines, producing service water that is used for toilet flushing or watering green spaces. Costs, chemicals and energy can be saved since drinking water quality standards do not have to be met for these purposes. Assuming water consumption of 128 litres per person per day, greywater can provide approximately 60 litres per person per day [14], with this value varying depending on the users' behaviour. Greywater is collected separately in the service area and conveyed to the RRC where it is treated with a membrane bioreactor (MBR) [16, 14]. This treatment combines microbial reduction of the contents, sedimentation processes and physical filtration by the membrane. This MBR process is then followed by a chlorine disinfection step to ensure hygienically sound effluent [13].

Blackwater is heavily contaminated wastewater because it contains faecal matter and urine. It is collected and treated separately. After a pre-treatment, which includes mechanical processes such as screens and sieves to hold back the larger contaminants, the blackwater is purified using an MBR constructed similarly to the MBR in the greywater module [14]. The blackwater effluent is then disinfected using chlorine. With these process steps the blackwater module treats wastewater from toilets and produces water that is suitable for irrigating public green spaces.

The energy module produces biogas through anaerobic and thermophilic treatment using organic waste combined with sewage sludge from the greywater and blackwater treatments. Under optimal conditions, the electricity and heat generated covers the RRC's energy requirements [14]. The organic waste comes from the service area's households and hotels, and is collected separately from other waste streams. The substrate is treated anaerobically in a digester, and the biogas produced used by a power plant to produce electricity. Furthermore, the residues from the anaerobic treatment can be used as a soil conditioner after dewatering.

As mentioned above, several assumptions were made for the idealised version of the Semizentral system that differs from the system's actual implementation. This refers first of all to the degree of capacity utilisation. The idealised system operates at full capacity in terms of water usage, wastewater treatment and the energy module. It also implies that service water is used for toilet flushing throughout the service area, *i.e.* in the hotels as well as in the residential and office areas. Currently, only one hotel and an office building use service water for toilet flushing. Furthermore, it was assumed that there is no bypass for diverting wastewater to Qingdao's conventional sewage system in the event of an emergency. Finally, organic waste is supposed to be collected within the service area which is actually not the case.

THEORETICAL BACKGROUND AND METHODOLOGY

Theoretical background

Risk can be expressed as a function of vulnerability and hazard since the extent of damage is closely linked to the vulnerability of the subject of protection, *i.e.* humans or material goods [17–19]. In this context, hazards are the negative consequences of a situation, *e.g.* a process, event, action or inaction, which can potentially cause damage to the subject of protection. In addition, failures during normal operation can also entail undesired effects that cause damage, which is why these kinds of factors also have to be taken into account. In turn, vulnerability generally consists of the three components of exposure, susceptibility and coping capacity (or resilience) [20]. Exposure refers to the fact that subjects of protection are exposed to a hazard in terms of space and time [21]. Susceptibility means that a subject of protection being exposed to a hazard is susceptible to damage [22]. The susceptibility can be high or low depending on the extent to which the subject of protection undergoes functional impairment or irreparable damage. Finally, coping capacity describes the available options and resources to reduce or counteract the negative impacts of a hazard [23, 24]. Thus from the perspective of a critical infrastructure, vulnerability means the failure of the critical infrastructure's functionality due to a hazard that leads to an interruption of its service(s) provided to the population [25].

Method selection

Based on the theoretical considerations on vulnerability, further steps in the vulnerability analysis were taken. In general, a vast number of risk assessment methods for critical infrastructures exist [26, 27] but they either only focus on specific sectors (*e.g.* transport, energy), specific hazards (*e.g.* technical hazards) or do not sufficiently deal with resilience or vulnerability [28–31]. Several frameworks and methods are tailored to conceptualise vulnerability and analyse the vulnerabilities of (critical) infrastructures [22]. In what is known as the BBC framework [32], named after its authors Bogardi, Birkmann and Cardona, vulnerability is understood to be a dynamic and multi-dimensional concept that focuses on social, ecological and economic aspects. It aims to develop interventions (preparedness) to reduce the vulnerability within these three spheres. Turner et al. [33] link the social and natural sciences perspective of vulnerability research in their framework. They have a broader understanding of vulnerability compared to the BBC framework, and consider interactions between society and nature. Holmgren [34] suggests a method to measure vulnerability that uses the statistical analysis of empirical data, mathematical modelling and expert judgements. Baker's [35] assessment method results in a matrix that, dependent on several hazards, shows whether a critical system is vulnerable, not vulnerable or dependent on a scenario. Finally, Krings [36] developed a vulnerability assessment heuristic for municipal infrastructures that consists of concise analytical steps in order to classify the vulnerability of technical components into five classes of vulnerability.

All the frameworks or methods presented, except for Baker's [35], have the tripartite conception of vulnerability in common. However, they differ in the scale and scope of their application. To select an adequate procedure for the requirements of the present case study, it should be noted that the focus of this vulnerability analysis was on a specific critical infrastructure including its components, and thus on a regional and local level. Furthermore, the analysis was designed in a qualitative and partially semi-quantitative way due to data availability, not in order to determine occurrence probabilities or threshold values. Therefore, it appeared highly appropriate and promising to combine Krings' assessment heuristics and Baker's vulnerability matrix in order to deal with a multitude of socio-technical components and hazard scenarios. In addition, this combination of methods enables the integration into broader risk assessment approaches (*e.g.* [37]) if necessary.

Definition of system components and hazards

It is important to define the technical components, hazards and system boundaries before explaining in detail the exact assessment procedure used. The spatial scope was determined by the socio-technical system of the water infrastructure, namely the service area, its pipelines and the RRC. The system therefore included the effects of user numbers, user behaviour, personnel responsible for its operation, maintenance and repairs, but also people causing vandalism and sabotage. The temporal scope was limited by the occurrence of hazards and immediate back-up for the potential failure of technical components. This restriction only applies since in the long term, virtually all functional failures can be compensated for.

The analysed system was broken down into reasonable functional technical units in consultation with experts working on the RRC's design, implementation and operation. These technical components can be roughly divided into three groups: components within residential and office buildings and hotels, pipelines in public spaces (*e.g.* sewer lines, service water pipes) and the RRC. A total of 44 components (Table 1) were identified.

Table 1: List of system components (GW: greywater; BW: blackwater; SW: service water; IW: irrigation water)

Area	Type of water	Technical component
Hotels	GW	Connections (*e.g.* showers, sinks, washing machines)
		Pipes
	BW	Toilet connections
		Pipes
	SW	Toilet connections
		Pipes
Residential and office areas	GW	Connections (*e.g.* showers, sinks, washing machines)
		Pipes
	BW	Toilet connections
		Pipes
	SW	Toilet connections
		Pipes
Water body	SW/IW	Outlet
Green spaces	IW	Connection
Sewers and pipelines	GW	Free-flow sewers
		Pressure sewers
		Pumping station
		Reservoir
	BW	Free-flow sewers
		Pressure sewers
		Pumping station
		Reservoir
	SW	Pipelines
		Reservoir
	IW	Pipelines
		Reservoir
RRC (Resource Recovery Centre)	All	Control system
	GW treatment	Pre-storage
		Strainer
		MBR: aeration/biological pre-treatment
		MBR: filtration (incl. backwashing tank)
		Disinfection
	BW treatment	Pre-storage
		Mech. pre-treatment (sand trap, rack, primary treatment, strainer)
		MBR: aeration/biological pre-treatment
		MBR: filtration (incl. backwashing tank)
		(Activated carbon filter, not in use)
		Disinfection

	SW distribution	Reservoir
		Pump
	Energy module	Waste pre-treatment
		Sludge and food waste treatment (fouling, drainage)
		Process water treatment
		Gas utilisation

In addition to this, relevant hazards were discussed and defined in a workshop with the above-mentioned experts working on the design, implementation and operation of the pilot plant. It should be stressed that the concept of hazards used in this study not only comprised negative consequences of exceptional situations, but also failures during normal operation and their undesired effects. The discussions were initially based on hazard scenarios proposed by the authors. The group of experts comprised 15 scientists (*i.e.* civil engineers and architects) and practitioners from engineering and consulting companies. In order to prioritise the hazard scenarios, the experts were also surveyed (n=33) by means of questionnaires. In this context, the priority of a hazard describes its relevance from the experts' point of view, *i.e.* the attention that should be paid to a hazard during the operation of the water infrastructure and consequently its influence on the final vulnerability assessment. Thus priority does not necessarily represent a hazard's occurrence probability. A scale from 1 (low priority of a hazard) to 3 (high priority) was chosen.

Vulnerability analysis

In the first phase of the vulnerability analysis, the identified socio-technical components were classified into five vulnerability classes [36] and depending on the identified hazard scenarios. The vulnerability classes range from I to V and are defined as follows [36]:

I: no exposure of the technical component regarding a hazard

II: technical component is exposed to a hazard but its functionality is not impaired

III: hazard causes the failure of the technical component but it can be completely replaced

IV: hazard causes the failure of the technical component but it can be partially replaced

V: hazard causes the failure of the technical component and it cannot be replaced.

The classification was conducted according to an heuristic (Fig. 2) proposed by Krings [36]. The resulting vulnerability ratings were recorded in a vulnerability matrix (as undertaken by Baker [35]) in which the rows represent the specific hazards and the columns the different technical components. Starting from a hazard, *e.g.* human failure, the vulnerability of a system component, *e.g.* service water transmission pipelines, is assessed on the basis of the described heuristics. In this case, for example, the service water pipe can be completely damaged by a construction vehicle during construction or maintenance work. This results in an assignment to vulnerability class 5. The procedure is continued with all other hazards and system components in the matrix.

The second phase of the vulnerability analysis focused on the interdependencies of the system components, *i.e.* the vulnerability of technical components due to the failure of other components. Unfortunately Krings [36] does not supply detailed instructions on how to carry out the second phase of the vulnerability analysis, which is why a new method had to be developed and adjusted in the present case. Several methods were eligible in this context, however a cross-impact analysis [38, 39] seemed to be suitable and very promising. In the matrix, the effects of system component failures on the vulnerability of other components could be recorded and assessed using the same vulnerability classifications as in phase one. In order to do so, all 44 technical components (Table 1) were placed along the header row and header column, resulting in a 44 x 44 matrix. For example, a malfunction in the disinfection stage of the greywater treatment module can lead to contamination of the service water reservoir. The latter would thus be assigned to vulnerability class 5. The same procedure is continued with all other system components in the matrix.

Both matrices – the vulnerability matrix and the cross-impact matrix – were evaluated by calculating row sums and column sums based on the fact that each cell's vulnerability class is expressed in numbers from 1 to 5 according to the vulnerability classes from I to V. The row and column sums can be directly used as indicators which is the case with the cross-impact matrix and the "absolute case" of the vulnerability matrix. In the "weighted case", the values representing the vulnerability class were also multiplied by the priority assigned to the hazard by the experts in order to weight vulnerabilities according to the hazards' priority. The matrices used can be described as follows:

$$\begin{pmatrix} a_{11} & \cdots & a_{1j} & \cdots & a_{1n} \\ \vdots & \ddots & \vdots & & \\ a_{i1} & & a_{ij} & & \vdots \\ \vdots & & & \ddots & \\ a_{n1} & & \cdots & & a_{nn} \end{pmatrix}$$

where:
a = vulnerability class of a system component
(weighted case of the vulnerability matrix: *a* = vulnerability class of a system component multiplied by the priority of the corresponding hazard)
i = 1, 2, …, n (rows, *i.e.* either hazards in the vulnerability matrix or system components in the cross-impact matrix)
j = 1, 2, …, n (columns, *i.e.* system components in both the vulnerability matrix and the cross-impact matrix)
n = number of system components or hazards.

The row sum α reflects the comparative impact of a hazard *i* or failure of a system component *i* on the (aggregated) vulnerability of other system components *j*. It is defined as:

$$\alpha_i = \sum_{j=1}^{n} a_{ij}$$

The column sum β reflects the extent to which the (aggregated) vulnerability of a system component *j* is affected by hazards *i* or the failure of other system components *i*. It is defined as:

$$\beta_j = \sum_{i=1}^{n} a_{ij}$$

In the case of the cross-impact matrix, row and column sums were "adjusted", *i.e.* subtracted by *n*-1 to set the lowest sums to zero. Apart from that, composite indicators were formed in the case of the cross-impact matrix to underline results where necessary. The Q-value of a system component is defined as the quotient of row sum and column sum, whereas the P-value of a system component is defined as the product of row sum and column sum.

RESULTS AND DISCUSSION

Hazards and priorities

The list of hazards identified in the expert workshop consisted of 28 elements (Table 2), for instance technological and human failure, heavy rainfall, fire, sabotage and dependency on electricity. The hazards were divided into three groups: internal hazards, external hazards and dependencies (*e.g.* on other infrastructures). The survey of experts resulted in the highest priorities being awarded to technical and human failure, water supply cross connections, a landslide at the RRC and financial dependencies (for details see Table 2). Less priority was assigned to aspects of user behaviour such as misuse by residents, hotel guests or hotel operators, boycott of service water or changing usage patterns. Surprisingly, natural hazards (*e.g.* drought, heavy rainfall, cold or heat wave, lightning strike, tornados) were given the lowest priority.

Table 2: List of hazards and their priorities (priority: 3 = high, 2 = medium, 1 = low)

Hazard	Description/Definition	Priority
INTERNAL		
Technical failure (system component)	Failure of a technical component caused by the failure of a sub-component, *e.g.* mechanical wear, short-circuit.	3
Technical failure (building)	Construction deficiencies in the RRC building.	3
Human failure	Incorrect handling or decisions on the operator's part during operation as well as mistakes during repair and maintenance.	3
Extreme user numbers	Extreme water quantities needed and produced, *e.g.* sudden increase or decrease due to holiday seasons or big events.	1
Misuse by residents or hotel guests	Incorrect utilisation routines on the users' part which lead to a high amount of undesirable substances, *e.g.* chemicals, objects, wastes or kitchen grease. This user group includes office workers who mainly differ from residents in quantitative terms.	2
Misuse by hotel operator	Incorrect management on the hotel operator's part, *e.g.* incorrect management of the grease separator, during kitchen construction or equipment replacements.	2
Wastewater cross connections	In-house blackwater pipes are connected by mistake to the system's greywater sewers. The reverse case of greywater effluent entering the blackwater sewers is regarded as less hazardous.	2
Cross connections of supply lines	Service water supply pipes are erroneously confused with drinking water supply pipes.	3
Boycott of service water	Potential users refuse to use service water for various reasons, such as perception of quality, costs or cultural reasons.	1
Changing usage patterns	A trend towards more water-saving and efficient measures leads to a decrease in drinking water and service water needs.	1
Vandalism	Human actions that deliberately lead to the damage and destruction of system components. These actions can be by internal (staff) or external persons.	2
EXTERNAL		
Drought	Drought periods lead to water-saving measures as the need for water increases, e.g. water use restrictions with an increased need for irrigation water. A drought period lasts significantly longer than a heat wave (more than 1 month).	1
Heavy rainfall	Heavy rainfall leads to flooding.	1
Landslide at RRC	A landslide at the RRC can lead to damage and the destruction of the entire centre.	3
Dam break	A dam break leads to interferences and destruction of system components due to water masses and forces.	1
Earthquake	In a severe earthquake, all system and plant components can be damaged on a large scale.	2
Sabotage	Human actions designed to take system components out of operation, e.g. terror or hacking.	2
Fire	Fire leads to the destruction of a single hotel or the RRC, but not the whole residential area.	2
Cold wave	System components are partially exposed to low temperatures, but pipes within buildings or the ground are not exposed.	1
Heat wave	A short period during which the temperature is exceptionally high. Water needs increase but water use restrictions are not expected due to the short time span of a month at most.	1
Lightning strike, tornado	Selective and linear destructions of surface system components.	1
DEPENDENCIES		
Drinking water supply	A breakdown of drinking water supply leads to an enormous decrease in greywater and blackwater quantities, resulting in operational difficulties and breakdowns in system components.	1
Energy	Energy is predominantly needed to operate the system.	2
Delivery of food waste	The supply of food waste is essential for specific parts of the system.	2
Transport connection	Smooth operation depends on regular maintenance and service, making accessibility *via* the transport connection indispensable. If not available, system components will gradually become damaged.	1
Finances	A lack of funds will severely affect maintenance and service. In contrast to the effect of no transport connection, lack of finances will lead to failures at a greater extent.	3
Operating materials	The different processes within the RRC need chemicals such as citric acid, iron chloride as precipitant, acetic acid, hypo chloride and polymers, which might not always be available.	2
Communication/IT	In the event of a breakdown, interdependencies with communication and information technologies lead to the failure of system components.	2

First phase of the vulnerability analysis using the vulnerability matrix

The vulnerability matrix firstly provided insight into the impact of hazards on the vulnerability of system components. This is represented by the row sums of the vulnerability matrix. Hazards with the highest impact are human failure, sabotage (*e.g.* terrorism, hacking), technical failure (system component), technical failure (building), landslide at the RRC and fire (Fig. 3). Two hazards, namely finances and earthquakes, should be viewed as knock-out criteria, *i.e.* their occurrence can potentially lead to the destruction of any system component. Since this does not contribute to differentiating between the vulnerabilities of the system components, they are not considered in subsequent steps of the analysis. It should also be emphasised that certain hazards are specific to the case study in Qingdao, such as a landslide at the RRC and dam breach, which have to be considered when generalising these findings.

Hazards that have the lowest impact on the functionality of system components are cold waves, heavy rainfall, boycotting of service water, heat waves, communication, IT, changing usage patterns, drought and transport connection. This list contains an extraordinary number of natural (or external) hazards and dependencies on other infrastructures. Hence, internal hazards such as human and technical failure seem to increase the vulnerability of system components much more than natural hazards, irrespective of their weight or priority. This reveals the system to be robust against external natural impacts, but the human factor and technical quality are also very important for the system's stable operation.

Potential further steps in the vulnerability analysis should include probabilities of occurrence of hazards and threshold values as soon as there is sufficient experience with the operation of the reuse system. However, these aspects could not be taken into account in the present study.

The differentiation of subareas (*i.e.* service area, sewers and pipelines, RRC) allowed the hazards' impacts to be specified spatially. Some hazards have a clear spatial focus and therefore a higher impact in the subarea concerned. For instance, technical failures (building) and a landslide only endanger the RRC, whereas cross-connections of supply lines have a higher impact on the service area (Supplementary Table A). Furthermore, the service area as well as sewers and pipelines are more prone to natural hazards, especially droughts and heat waves, than the RRC. In the event of droughts, this is due to the risk of blockages in blackwater plumbing and pipelines for instance.

Another key insight provided by the vulnerability matrix is the (weighted) dependency of the vulnerability of system components to hazards (Fig. 4). This is represented by the weighted column sums of the vulnerability matrix. The highest dependency can be observed with the RRC components, in particular the MBR components. In this context, the greywater MBR components' vulnerabilities are slightly more dependent than the blackwater MBR components due to the fact that the greywater MBR is more prone to cross-connections. System components in the service area (residential areas, hotels, offices) have the lowest dependency, while sewers and pipelines have a medium dependency. This is mainly due to the fact that RRC components are only present once in the system, whereas there are many different types of pipelines and connections in the service area. Local hazards have the potential to take single components, such as an MBR, out of operation, whereas it is very unlikely that this will happen to all the components in the service area.

Second phase of the vulnerability analysis using the cross-impact matrix

The second phase of the vulnerability analysis was performed with a cross-impact matrix. This was used to analyse the impact of a system component's failure on the vulnerability of other system components which is represented by the row sums of the cross-impact matrix. The control system has the greatest impact by far, followed by blackwater MBR components and greywater and blackwater components in sewers (Fig. 5). Failure in components in the RRC energy module, RRC blackwater components (*i.e.* activated carbon filter, disinfection) as well as greywater and blackwater connections in the service areas (*i.e.* hotels, residential areas, offices) have the least impact on the vulnerability of other system components.

The vulnerability of system components to failures of other system components is represented by the column sums of the cross-impact matrix. The most vulnerable system components are all RRC components except the control system (Fig. 6). The system components least vulnerable to the failure of other system components are those in the RRC control system, all system components in the service areas (*i.e.* hotels, residential areas, offices) and in service and irrigation water discharge and/or connections. This corresponds to the results from the first phase of the vulnerability analysis, with the exception of the RRC control system. Again, the more central and unique components are in relation to the overall system, the higher their vulnerability. However, the RRC control system is not dependent on other system components; it only influences others, which is why it is not at all vulnerable to system failures.

Aside from this, it should be remembered that the system boundaries end at the connection points in the service area, *e.g.* taps where the irrigation water is provided for irrigation purposes. Low vulnerability does not necessarily imply that users or the ecosystem are not affected, *e.g.* by misuse, wrong handling of the irrigation water. The extent to which they are impaired or even endangered needs to be evaluated separately. This is especially the case if the users' health is at stake, for instance in the event of cross-connections of drinking water and service water supply pipelines. Another example would be if untreated wastewater reaches the environment, for instance due to a (partial) system breakdown. The immediate effects might be limited in space and time, but its external effects could be more extensive.

The above-mentioned results (Fig. 6) based on the row and column sums of the cross-impact matrix could be confirmed by using Q-values, *i.e.* the quotient of row and column sum. The higher a system component's Q-value, the greater its impact on other system components' vulnerabilities. This applies in particular to all greywater and blackwater pipeline components (Supplementary Table B). However the control system has the highest Q-value. The lower a system component's Q-value, the greater its vulnerability to the failure of other system components. It could be confirmed that this applies mainly to components of the RRC.

Apart from this, the P-value (*i.e.* the product of row and column sum) might indicate the criticality of a system component within the system. The higher a system component's P-value, the more critical it is since it does have an impact on other system components' vulnerabilities but its vulnerability is dependent on the failure of other system components. This applies to components of the RRC, in particular the control system and MBR components (Supplementary Table C). The lower a system component's P-value, the less critical it is. Such system components might have a buffering function regarding the vulnerability of the overall system. This applies mainly to system components of the service areas (*i.e.* residential areas, hotels, offices).

Finally, when comparing the column sums of both the vulnerability and the cross-impact matrices, it is possible to conclude whether a system component's vulnerability is more dependent on hazards or the failure of other system components by comparing the discrepancy of system components' ranks (Supplementary Table D). In this regard, the RRC control system is an outstanding system component. Its vulnerability is much more dependent on hazards than on other system components. The same applies to waste pre-treatment. Aside from this, there are system components that are much more dependent on the failure of other system components than on hazards. This applies to RRC service water storage, irrigation water pipelines and greywater storage within the transport system. Vulnerability and risk management should take this into account to improve corresponding measures.

Conclusions

Semi-centralised water infrastructures, such as the one analysed in this paper, are characterised by greater resource efficiency and higher flexibility compared to centralised water infrastructures. This can make them an appropriate solution for the requirements of rapidly growing megacities in semi-arid regions. The analysis of the idealised Semizentral system in Qingdao showed which components of the infrastructure are vulnerable to hazards and the failure of other components. This applied mainly to the components of the RRC in general since they are much more dependent on other system components, which can often be redundant. Furthermore, the analysis identified the hazards (*i.e.* human failure, sabotage, technical failure, landslide at the RRC, fire) and system components (*i.e.* RRC control system, blackwater MBR components, greywater and blackwater components in sewers) that had the greatest impact on the vulnerability of other components.

The socio-technical vulnerability of semi-centralised water infrastructures has not previously been investigated in other studies. This makes the results of this paper important for the planning, operation and maintenance of future replications of semi-centralised systems. In particular, risk and vulnerability management has to focus on the identified system components to minimise their vulnerability. Concerning the vulnerability assessment procedure, Krings' existing methodology [36] could be considerably further developed by a second analysis phase, which had not been elaborated yet.

The analysis has so far focused on the socio-technical system. Nevertheless, certain impacts and causes lie outside of the chosen system boundaries. Users of the system (inhabitants, officers, hotel guests, service and management) have a considerable impact on its overall functioning, which is why they were taken into account in the analysis, and their acceptance of the service water supplied is a key factor in its sustainable management. However, impacts such as drinking and service water cross connections cannot be grasped directly by the applied vulnerability concept. Measures to minimise health risks in particular should therefore be specifically analysed. In terms of impacts on the ecosystem that fall outside of the system boundaries, a social-ecological analysis can help interpret the interdependencies between the environment and society as well as, for instance, cascading risks, as suggested by Völker et al. [40].

Another open question is which of centralised or semi-centralised water infrastructures is more prone to hazards and undesired effects. A comparison of the vulnerabilities of these different system approaches would make their specific strengths and weaknesses evident. Finally, in terms of the methodology, only the direct impacts of the failure of system components on the vulnerability of other components were identified. The vulnerability analysis developed in this paper could be enhanced in order to take longer cause-and-effect chains and feedback loops into account.

ACKNOWLEDGEMENTS

The authors would like to thank all the partners involved in the SEMIZENTRAL project for their collaboration and support. They have contributed to this work with their fruitful discussions and comments. This work was accomplished within the project "SEMIZENTRAL – Resource efficient and flexible supply and disposal infrastructures for rapidly growing cities of the future" (grant number 02WCL1266G), which is funded by the German Federal Ministry of Education and Research (BMBF).

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Figure 1: Scheme of the idealised Semizentral system

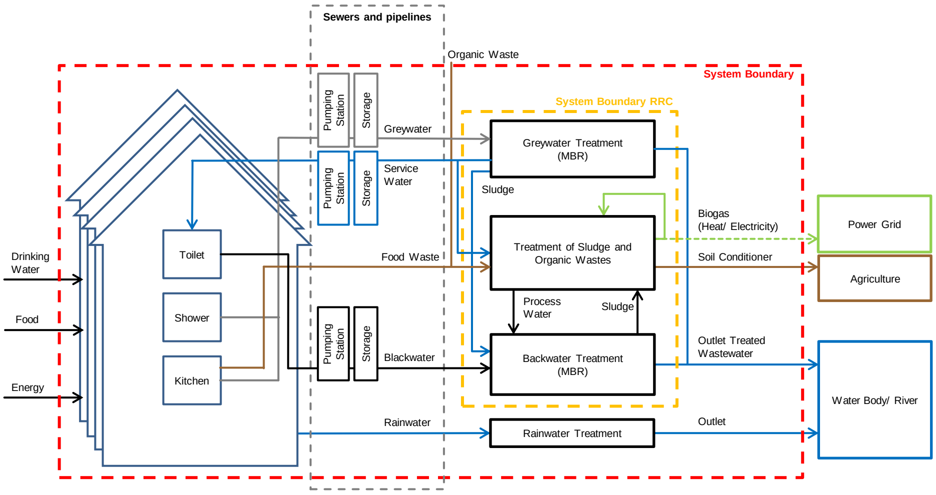

Figure 2: Heuristic for the assignment of vulnerability classes [360]

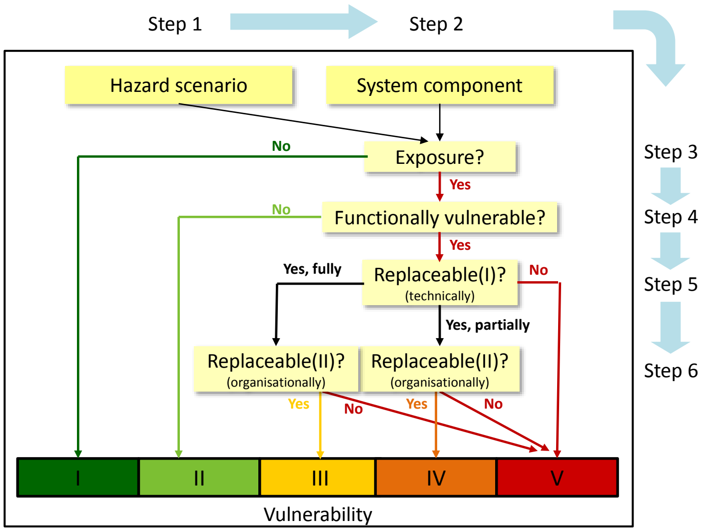

Figure 3: Impact of hazards on the ~~system's~~ vulnerability <u>of system components represented by row sums of the vulnerability matrix. The weighted row sum takes into account the priorities of the hazards,</u> <u>whereas the absolute row sum does not.</u>

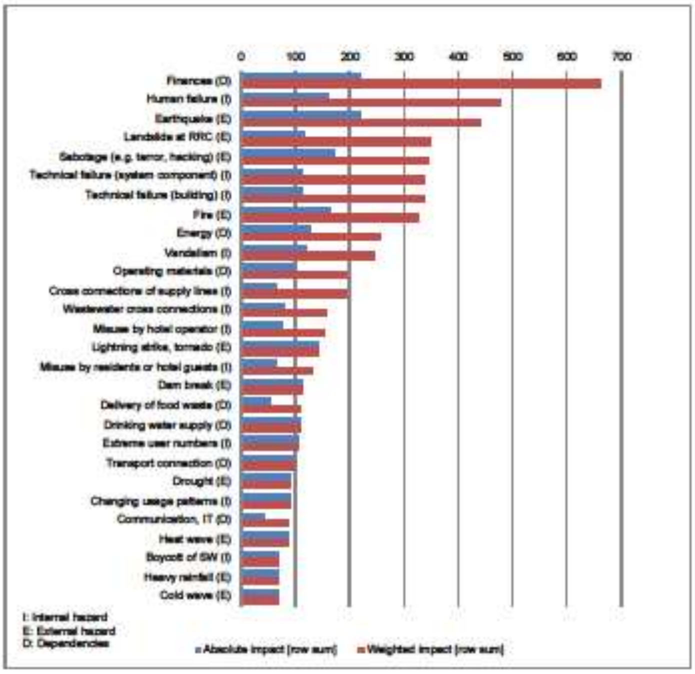

Figure 4: (Weighted) vulnerability of system components to hazards represented by column sums of the vulnerability matrix. The weighted column sum takes into account the priorities of the hazards.

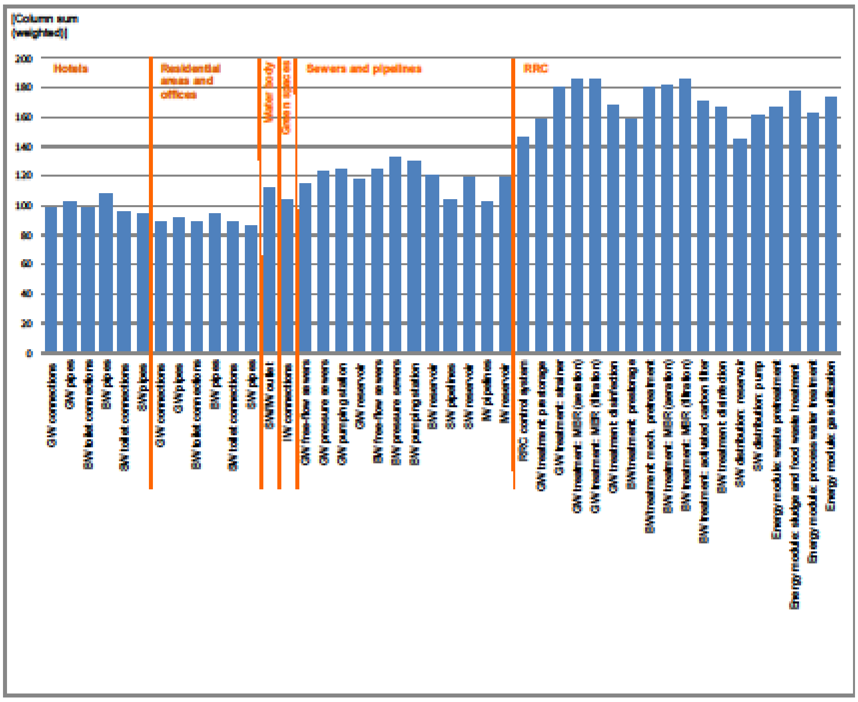

Figure 5: Impact of the failure of system components on the ~~overall system's~~ vulnerability <u>of other system components represented by row sums of the cross-impact matrix.</u>

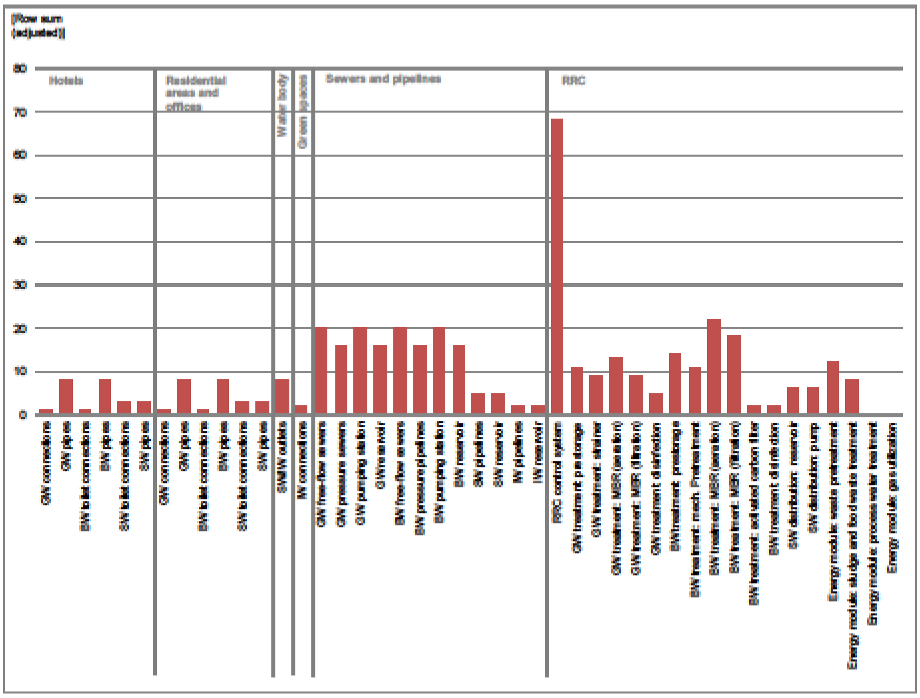

Figure 6: Vulnerability of system components to ~~system~~ failures <u>of other system components represented by column sums of the cross-impact matrix.</u>