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Keeping Flows Separate: Good Management Practices in Novel Urban Water Systems Derived from Error Analyses

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Abstract: This article examines the causes and addresses the prevention of unintended interconnections, particularly cross-connections, in novel urban water systems using the example of Qingdao, where a Resource Recovery Centre for the reuse of greywater and blackwater has been established for 12,000 inhabitants. With respect to cross-connections, this work incorporated both social-scientific and technical error analyses. The social-scientific error analysis systematically focused on the planning, implementation, and operational phases of the project. Organisational shortcomings were identified in four areas: (A) Coordination and consensus between the commissioned design institutes, (B) information in tenders, expertise, and awareness, (C) ownership by investors, and (D) time management. Based on empirical evidence, this article derives and discusses (eight) recommendations for good management, integrating technical and organisational measures aimed at preventing cross-connections. The pursuit of such measures is appropriate in order to prevent most types of misconnections—not just for the case under discussion, but for other novel urban water systems as well.

Keywords: source separation; misconnections; quality assurance; dual supply; greywater; novel urban water system

1. Introduction

Water resources in the People's Republic of China are limited, with some regions experiencing severe water shortages. Existing resources need to be handled carefully and efficiently. Among the supply and discharge management approaches, water reuse is politically very salient and is now enforced by law cf. [1]. The implementation of a reuse strategy will pose major challenges for urban water management in future cf. [2]. Various approaches, including source separation for water supply and wastewater discharge, facilitate more flexible supply and more efficient treatment. In recent discourses, the strategies to separate sources for reuse are framed as making a resilient contribution to protecting the sponge base in sponge city infrastructure approaches cf. [3–5]. The most basic example of source separated water supply and discharge is greywater and its equivalent service water. Water originally used for showering, hand washing, or washing machines can be reprocessed for toilet flushing and other residential service water purposes. Even blackwater can be reprocessed for street cleaning, car washing, or irrigation in landscape management. There is a high level of acceptance among Chinese people for most of these uses [6].

Efficient source separation requires specific piping systems for the different water flows to be kept separate. Cross-connections in particular have to be prevented.

According to [7], a cross-connection is defined as the point in a distribution network where water of undrinkable or at least questionable water quality is connected to a drinking water system. Another type of cross-connection refers to each point in the source separated sewage system where greywater and blackwater can be mixed. The causes of potential cross-connections have not previously been systematically investigated using social-scientific and technical error analysis. Experiences from SEMIZENTRAL, the world's largest source separation system located in Qingdao, allow an interdisciplinary and transdisciplinary analysis of the causes of cross-connections, and an examination of organisational, technical-organisational, and technical ways of preventing them. The City of Qingdao is one of the 30 cities selected for the sponge city program launched by the Ministries of Housing and Rural–Urban Development (MHURUD), Finance (MOF), and Water Resources (MWR) in 2014 cf. [3]. While there has been articulation of the need for future implementations to adhere to principles of precautionary management to prevent (or at least minimise) cross-connections, a management system of this kind has not yet been developed [8]. The aim of this article is to answer the following questions using interdisciplinary and transdisciplinary error analysis of the implementation in Qingdao: (A) In which key situations are cross-connections likely to occur? (B) What are the appropriate technical, organisational-technical, and organisational solutions for addressing cross-connections at an operational level? Based on the results of both error analyses, recommendations for good management practices have been derived and discussed.

2. Case and Methods

2.1. The SEMICENTRAL Approach in Qingdao: A Case of a Source Separating Novel Urban Water System

The fast-growing city of Qingdao requires alternative water resources to keep pace with the rise in its population and its economic growth. Beyond coping more easily with population growth due to an enlargeable technical approach, the project contributes to addressing the environmental concern for better protection of the coastal town's outlying ocean through better wastewater treatment [9]. The World Horticultural Exhibition (WHE) in Qingdao in 2014 provided the opportunity to establish a semi-central water infrastructure based on the principles of source separation for a newly constructed city district, Bijia (cf. Figure 1), with its residential buildings, hotels, and office blocks. The SEMIZENTRAL approach in Qingdao was developed by scientific partners from Germany and China, as well as by practitioners from German industry. At 12,000 population equivalents, this implementation is currently the world's largest design for a novel urban water system [10]. Greywater from showers, handbasins, and washing machines, and blackwater from toilets and kitchen sinks is collected in separate sewer systems. In the resource recovery centre (RRC), greywater is treated to become service water for toilet flushing, while blackwater is processed into water for irrigation and street cleaning [5,11]. The integration of organic waste (i.e., food waste from restaurants/canteens) in the anaerobic sludge treatment increases biogas production, allows almost energy self-sufficient operation of the RRC [9].

During the construction and implementation phase, a public company set up on behalf of the municipality of Qingdao City was responsible for investment and for commissioning the RRC, while the scientific and technical staff on the Sino-German SEMIZENTRAL project team advised on the RRC's initial operational phase. Scientific support and monitoring of the implementation were assigned to the German part of the research network, funded by Germany's Federal Ministry of Education and Research (BMBF). The first trial runs of the RRC started in 2014. During this phase, the public company established for the RRC's construction and implementation still bore responsibility. It was only in 2017, at the end of the experimental phase, that the RRC was handed over to a municipal utility. Owing to time pressures in particular, the original schedule for construction, commissioning, and operation had to be abandoned.

Figure 1. Map of the resource recovery centre (RRC) catchment area (settlements and hotel areas with blue borders) and its location in Qingdao.

2.2. Methodological Design

The results presented and discussed here are based on several years' experience of planning and implementation in the SEMIZENTRAL approach. Measurements of the inflow to the RRC cf. [8,12], random sampling in the area, construction plan analysis, limited monitoring tests, and technical inspections of the existing blackwater and greywater sewers, as well as inside the connected buildings in Qingdao, together with expert interviews formed the basis for an interdisciplinary desktop error analysis. Initially, a technical overview of the connection situation was obtained for the RRC's catchment area in Qingdao, followed by a (partial) error analysis in the area of public networks and buildings, in order to identify undesired contaminations. First, hypotheses about causal explanations were addressed. Due to issues with regard to obtaining permission, no review was undertaken of the sewage network situation in the main part of the WHE village.

Complementing the technical error analysis, an attempt was made to investigate the causes of errors using social science methods and identify measures to prevent unwanted connections, mostly by adopting cooperation management [13]. The approach serves as a tool for understanding the procedural dimension of management through structuring processes in planning, implementation, and operation. Moreover, it examines the roles, understandings, and interests of the various actors involved. The aim was to derive possible procedures to prevent the undesirable mixing of flows in the service area by identifying deficient social interactions.

Based on both technical and social analysis, it was possible to determine the specifications and measures that need to be adopted to prevent unwanted connections between flows. There were three possible perspectives for the analysis: The first goes back to a micro level perspective, highlighting the actors' decision-making, and including residents' practices feeding the source separating novel urban water system in Bijia A and C [14]. Moving beyond this micro perspective on individual actions, a second, more general macro perspective addressed issues of regulation or governance cf. [15].

Further on, the relationship between social and technical entities to prevent cross-connections was investigated in a socio-technical vulnerability analysis [11], estimating the impact in a Bayesian belief network. Such networks are statistical multivariate models, which combine a qualitative, graphical representation of a system with a quantitative, probabilistic evaluation of the interactions between the variables of such a system [16]. The data required to model the network were collected in qualitative expert interviews [17]. A total of nine people from research and practice were interviewed who were all dealing with novel water infrastructures and covering different disciplines. The Bayesian belief network was evaluated by using the software Netica.

With regard to the interactions between actors that have proved to be deficient or dysfunctional in the past, an investigation was also carried out to determine the extent to which these interactions could possibly be enhanced. Socially, for example, early and proactive communication about the need for action, transfer of expertise, organisational measures (e.g., avoidance of time pressure, quality management), the introduction of intermediary actors, and other institutional innovations could minimise undesired connections.

This article aims at bundling these perspectives offering a solution-oriented integration on organisational, technical-organisational, and technical approaches to prevent undesired connections. To identify suitable management measures, the potential causes of undesired connections in the phases of planning and implementation are discussed below.

3. Analysis of the Planning and Implementation Process in Qingdao and Identification of Suitable Management Measures

Starting with a broader state of research in the case of Qingdao, this section presents the results of technical and social-scientific error analysis, both of which are based on an interdisciplinary understanding of potential errors (see Section 3.2).

3.1. State of Research in Qingdao

No cross-connections were detected in the dual water supply pipes. For greywater and blackwater, however, the situation was far more complex: Interconnections in their broader sense had to be analysed both as intentional misconnections and unintentional cross-connections. In conventional separate sewer systems, during heavy rainfall for example, interconnections mean that storm water has an impact on the operation of the sewage treatment plant or on the quality of the water received [8]. In addition, incorrect connections in source separation systems have an ongoing impact on the treatment process due to variations in the quantities and qualities of the polluting load. Structurally high concentrations of nutrients could be detected in Qingdao's greywater. According to model calculations, additional N elimination is necessary even if only 3–10% of the connecting lines are mixed up cf. [8]. Incorrectly incentivised misconnections can particularly affect the blackwater stream's flow rate, load, and concentration, as well as its nutrient ratio. The distribution of polluting loads between greywater and blackwater also depends on potential interconnections between greywater and blackwater [12].

As shown by the daily and weekly curves of various suitable parameters (e.g., temperature and chemical oxygen demand) at different points in the district's network, there was no clear pattern in the mixing of different wastewater streams cf. [8,12].

A previously realised socio-empirical household survey demonstrated that only a very small number of operating errors, if any, have so far occurred in households [15]. Everyday behaviour in the households surveyed did not hamper source separation either. Thus, blackwater and greywater systems are generally fed correctly.

3.2. Interdisciplinary Understanding of Potential Errors

Owing to structural and case-specific errors, a differentiation between cross-connections and misconnections cf. [15] is important for a more differentiated error analysis and the development of recommendations: Misconnections are defined as the result of deliberate infringements or noncompliance by tenants, investors, or their agents (e.g., discharge of drainage water into the piping network of greywater or blackwater by tenants or investors in order to save individual costs). In contrast, cross-connections are not intended, but are caused by a lack of due care or insufficient knowledge. Interconnections, the sum of misconnections and cross-connections, are possible on different levels (cf. Figure 2):

- In the RRC itself.
- In public networks (transmission pipes and sewers).
- In built areas (houses and surroundings).

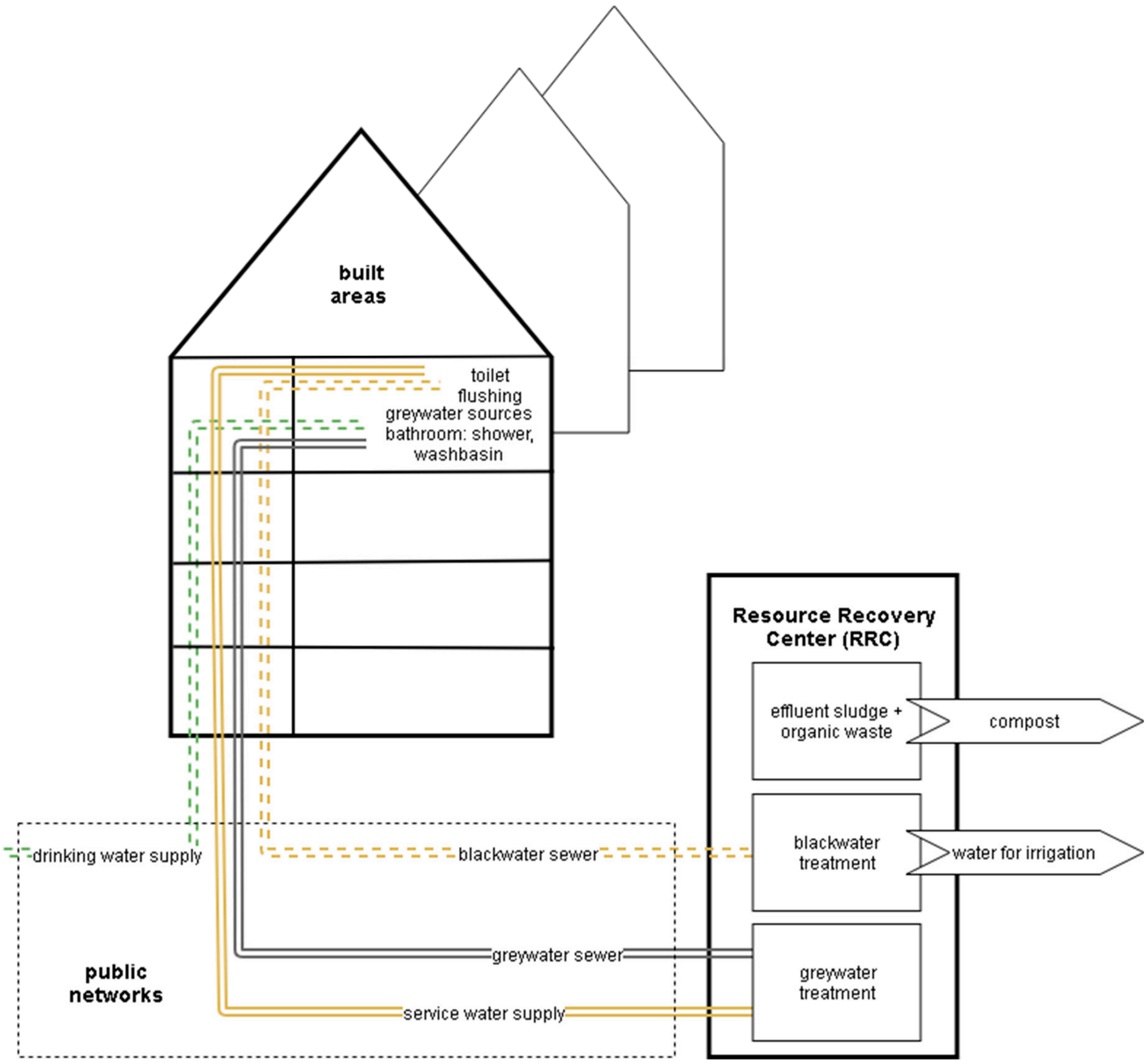

Figure 2. SEMIZENTRAL approach.

It is more likely that both misconnections and cross-connections occur in built areas otherwise unwanted connections between the flows will always be unintended, except in cases of sabotage.

Based on these definitions, the first hypotheses of causal relations between technical errors and organisational issues were derived:

1. Cross-connections have their origin in diverging definitions of greywater and blackwater.

2. Sloppiness in design planning or construction work (e.g., confusion with respect to pipework) lead to interconnections.
3. A lack of interaction between the actors involved and the absence of a common language contribute to interconnections.

3.3. Technical Error Analysis of Plans and Pipes

In the catchment area of the RRC in Qingdao, problems arose with the accurate sewer implementation of the different wastewater streams. The technical inspections did not confirm the prevalence of one type of malfunction (e.g., systematic incorrect connection of all kitchens to the greywater system). The analysis of faults using engineering methods, such as the critical assessment of plans or inspection of piped networks, partly revealed evidence of extensive erroneous connections:

(A) The sewage pipelines in buildings in Bijia's two residential areas were correctly designed. According to the plans, kitchen and toilet wastewater was collected by blackwater pipelines, with the remaining wastewater entering the greywater pipelines (information from the construction drawings). Instantaneous sampling of the greywater and blackwater pipelines in one residential building detected that there was no interconnection inside the building. However, random sampling of the transfer points of the two residential areas with the municipal sewage pipes showed that the greywater and blackwater networks outside the buildings in the residential areas had been extensively interconnected.

(B) The building structure of Hotel 1 has three different uses: Three floors have been built for accommodation, three hotel kitchens, one laundry room, several changing rooms and toilets, and there are a further six floors with guest rooms. The connection of the sewage pipelines in the three hotel kitchens with the greywater pipes was both designed and implemented. Other pipelines were correctly designed, but these plans were not implemented: All the pipelines on the three floors housing the hotel kitchens were planned in line with the definitions, but the hotel kitchens had been incorrectly connected to the greywater pipelines.

(C) The connection between the kitchen sink of a large canteen and greywater pipes was designed correctly. There was also no translation error between the design planning and construction phase, so there were no explicit explanations for the occurrence of the interconnection investigated in this building.

(D) Hotel 2 consists of six floors with guest rooms and meeting rooms. All the sewage pipelines on the six floors were correctly designed and constructed (according to information from the construction drawings and personal observations). There is a hotel kitchen on the first floor and, according to the construction drawings, the sewage from the kitchen should be connected to the black water pipeline. Based on the "Code for Design of Building Water Supply" in China [18], sewage from the canteen and the business restaurant should be admitted to the sewer pipe through the rear of the grease remover. Sewage from the hotel kitchen goes through a three-step grease trap, after which the kitchen wastewater flows into the blackwater discharge (proven by the tracing method). Sampling at the junction between the hotel and the municipal sewage pipelines detected that the greywater and blackwater quality was consistent with the design values, meaning that the design and construction of sewage pipelines for Hotel 2 had been implemented correctly.

(E) There is a relatively high groundwater level in the area. Large quantities of drainage or groundwater are presumably continuously being discharged into the greywater system. The key indicator for this assumption was the fact that even at night, unusually high basic flow rates are being registered in the RRC. Intruding groundwater could also be observed in the greywater inlet shaft in front of the RRC.

3.4. Social-Scientific Error Analysis of Management Procedures

The social-scientific analysis produced the following crucial results. Politicians gave a public company the role of the project's financial backer. The company had no previous water management focus and the particularities of novel urban water systems were a new challenge for them. Furthermore, the German project partners did not emphasise the particular attention that needs to be paid to preventing cross-connections.

In China, design planning is (in most cases) carried out by independent design institutes. Various property developers were involved in commissioning the catchment area for the RRC, the public utilities, the office buildings, and the built areas. Each developer chose different design institutes, instead of selecting one body responsible for planning the whole infrastructure altogether (and then commissioning it individually). All the commissioned design institutes implemented the detailed plans for the pipelines to ensure correct connections. However, none of them ever considered the possibility of cross-connections in the public infrastructure or in built areas. Being asked for adapted management approaches in response to the demands of novel urban water systems, at least one of the design institutes was aware of the special features required by source separation. The planners in this design institute pointed out that the different pipes were marked with colour codes and differently dashed lines in the plans, so that with adequate care they could be constructed correctly (green dash = drinking water; yellow dash = blackwater; yellow continuous line = greywater; see Figure 1).

At the start of the construction phase, responsibility was split and highly fragmented between the various property developers. The aforementioned municipal company was the developer for the RRC, whereas the public infrastructure was implemented by the central actor for integrated planning, the Qingdao City Authority. Furthermore, according to the different uses of the buildings as hotels, offices, and apartments, the specific developers were the responsible actors.

Inside the RRC, it was probably easiest to prevent connections incorrectly linking the source separated flows. In principle, no misconnections should be expected here, but cross-connections could occur either due to plans being too ambiguous or to errors during installation (lack of attention, e.g., due to piecework, excessive shifts with fatigued workers, insufficient instruction, and constant workforce rotation). Incorrect piping would be unlikely here. For a brief period, there was a connection between the blackwater and greywater treatment modules via the excess sludge lines, but this was caused by a defective non-return valve.

It is unlikely that at the time of the tendering process it was clear to the construction companies that particular attention needed to be paid to the principle of source separation, resulting in a dual system of water supply and wastewater discharge networks to prevent cross-connections. It can be assumed that the special effort required during construction work was not included when calculating the offers, leading to rising costs later on for the construction companies. One of the ways to reduce costs is simply to ignore these specific requirements, which most likely resulted in cross-connections.

Furthermore, the interrelation of the building project with the start of the WHE expo in 2014 added considerable time pressure for the entire construction process because the offices, hotels, and staff housing had to be completed in time for the exhibition opening. This was exacerbated by construction not starting on time, meaning that the building work had to be completed within six months. These time pressures resulted in sloppiness during the construction process.

The plans developed by the responsible design institutes contained the necessary information to implement correct connections. However, a lack of workforce skills or training on site can hinder correct implementation and the prevention of cross-connections.

3.5. Integrated Results of the Technical and Social-Scientific Error Analysis

The systematic error analysis identified four main causes for the streams being mixed:

- Lack of coordination, shared terminology, and consensus in the selection process of design institutes.

- Lack of information in tenders, expertise, and awareness.
- Lack of ownership by investors.
- Lack of appropriate time management.

Principles of good management to address these shortcomings are expounded in section four. An evaluation of the impact of the various measures to reduce interconnections by means of a Bayesian belief network indicated which (combination of) measures are relatively more effective and should therefore be preferred cf. [17]. Figure 3 shows the structure of the network and the actors, measures, and targets taken into consideration.

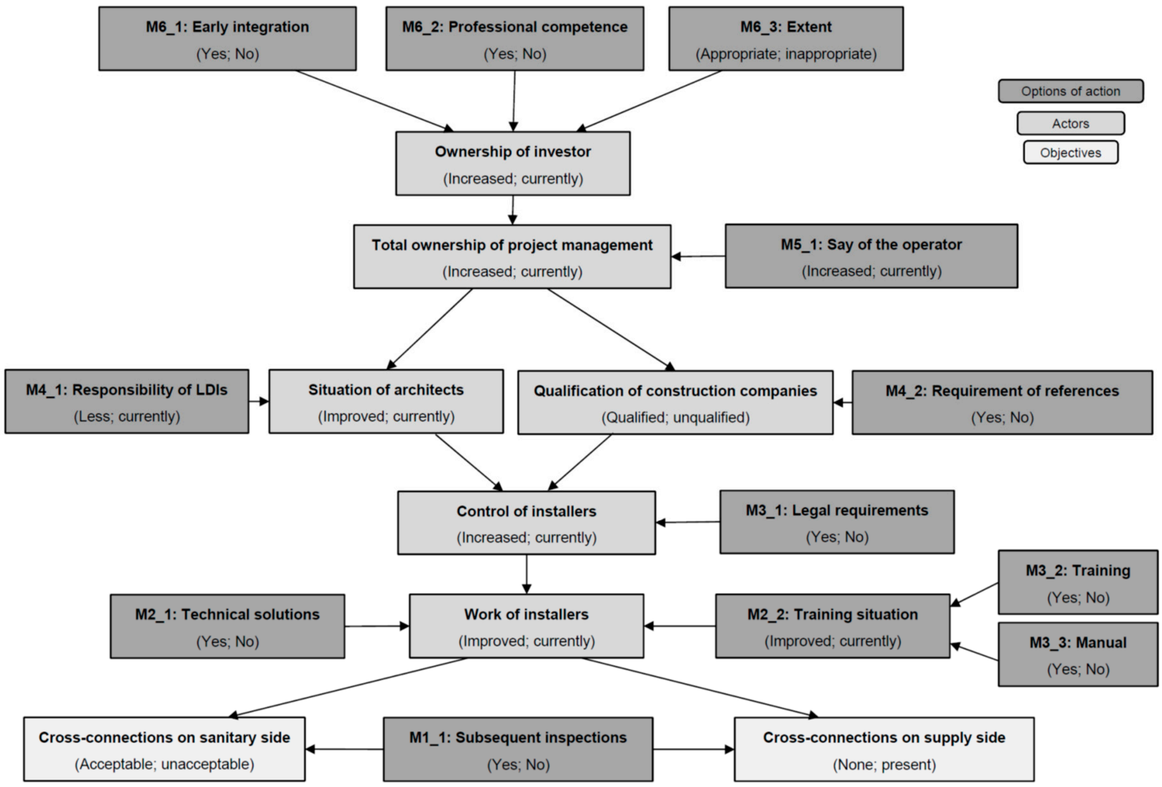

Figure 3. Bayesian belief network of actors, measures, and targets regarding cross-connections in semi-centralized water infrastructures.

The Bayesian belief network allowed the verification of various measures with regard to their effectiveness in reducing cross-connections. Either individual measures or a bundle of measures was examined with regard to their effectiveness. The resulting probability values for the target variables then provided information on the probability that cross-connections would occur within an acceptable range (sanitary side) or not at all (supply side).

An effectiveness of 100% corresponds to the effectiveness of the implementation of all measures taken into account. In order of effectiveness, these measures include:

- Follow-up inspections (e.g., documentation, flaps for maintenance, monitoring of pipelines/sewers) (71.7%);
- Technical solutions (e.g., colour codes, permanent marking of pipes) (61.4%);
- Training courses and manuals for plumbers/workers (59.7%);
- Improved skills in the construction company and responsibility of the local design institute, including a change in legal requirements (55.6%);
- A change in legal requirements (e.g., new standards or laws on misconnections) (53.9%);
- Improved involvement of the operator (52.7%);

- Greater ownership by the investor, including early involvement, technical competence, size of the corporation (52.4%).

Since it is apparent that cross-connections can only be detected and prevented by integrating organisational and technical measures, the derived recommendations emphasise proactive communication of the need for action, capacity development, avoidance of time pressure, and quality control measures (cf. Section 4).

3.6. Recommendations: Principles of Good Management

The social-scientific analysis allowed the identification of appropriate management practices to prevent cross-connections in public networks and buildings. The management strategy combines technical and organisational measures to ensure cross-connections are prevented and monitored, with a focus on short-, medium-, and long-term principles during the phases of planning, implementation, and operation.

3.6.1. Raising Awareness of Novel Water Systems When Selecting Design Institutes

In China, the design planning of urban water networks is carried out by (mostly) independent design institutes. During the design institute pre-selection phase, awareness needs to be raised of the special technical requirements and managerial responsibilities involved in novel urban water systems. Time and money can be saved only by commissioning institutes that already have planning experience of novel urban water systems (e.g., separate drainage of greywater and the separate supply of service water in addition to drinking water) or that are at least aware of the specific features of such systems.

Furthermore, it is advantageous if the same institute is commissioned to design both the public infrastructure and the complementary infrastructure in the building areas. This allows optimal design of the pipeline interfaces between areas built within public responsibility and areas commissioned and developed by non-state initiators.

3.6.2. Information for Responsible Actors

Those actors responsible for awarding contracts/tenders in the sub-items of the construction of pipelines need to be informed as early as possible about the requirements involved in not interconnecting dual networks. The city authorities and private project developers should therefore be asked to emphasise points with regard to handing over responsibility for the technical approach and timescales in their invitations to tender, e.g., by including a separate sub-item in the invitations to tender concerning good management to prevent misconnections. Tenderers need to be aware of the additional efforts required, for example colour coding, the use of different materials and internal quality controls. Applicants should also be asked to attach references to their bid in the invitation to tender (e.g., for quality management).

To ensure greater understanding (including by design institutes, c.f. above), self-explanatory graphical instructions and illustrations should be developed that can be used at an early stage, for example to inform the responsible actors about the innovative features of stream separation and the technical prerequisites (separation of the piping systems). While basic concepts, such as greywater and blackwater, are not clearly defined in Chinese technical norms or standards, an appropriate planning manual should be made available. Planning and construction manuals are being prepared based on the experiences of the SEMIZENTRAL concept. These manuals can also be used for other implementations of source separation systems.

By using different pipe materials for the different (waste)water streams, pre-identifying possible interconnection points and accurately monitoring these points, cross-connections and misconnections in the buildings can be prevented. It is in the interest of the future operator to ensure installers are appropriately trained or to establish tight controls (working conditions, pipe materials, vulnerable areas) to ensure that correct connections are made.

3.6.3. Appropriate Time Management

Heavy time pressure (e.g., an unrealistic construction schedule) must be avoided at all costs otherwise there is a risk that foremen and workers will take steps to "speed up" the process, e.g., by ignoring more complex connection situations and simply linking the various connections to a single drainpipe instead. Insufficient time meant that the different pipes were not marked as such. If the time pressure is too high, it could be a serious reason for opting out of having a source separation system since the required quality cannot be guaranteed.

3.6.4. Capacity-Building of Construction Workers

At the start of construction work, foremen and construction workers on site have to be informed about the most important features of the dual piping system. This includes identifying different pipes with corresponding lines in the design plans, prompt marking of lines (according to colour/material codes) at installation to avoid confusion, and observance of the marking in order to prevent cross-connections. The informative graphic instructions and images already mentioned above ("Information for responsible actors") have to be made available for training courses and planning manuals.

3.6.5. Final Acceptance of Work: Quality Control and Monitoring Prior to Operation

Before finally accepting the tendered work, a "bluewater test" is carried out on behalf of the RRC's operator to confirm that the piping is correctly installed in the area of dual water distribution. For this purpose, inspectors colour the service water with food colouring such as indigo carmine. The operation of flush toilets and all other water connections in the apartments shows whether the connections are correct in the entire network under investigation. At any point in time when major repair and modernisation work has taken place on the buildings, it will be necessary to consider whether a new blue test should be applied to the RRC and selected inspection shafts. Similarly, salt in greywater sewage can be used to check for any incorrect connections with the blackwater system. This monitoring should be carried out sufficiently early so that the companies responsible are obliged to make supplementary improvements in the event of construction defects.

As part of the acceptance of the construction work, inspection shafts and inspection flaps should be checked to verify whether the different pipes/sewers are marked and correctly connected. Appropriate controls should be performed not only at the interfaces between buildings and the public area, but at the interfaces between individual apartments and the building as well.

3.6.6. Ongoing Management During the Operational Phase

During the operational phase, established management processes should be continued for adequate operation of the system. The updating of documentation for new or changed piping in the buildings is particularly important here. Any changes in the lines should be documented by the tradesmen or an inspector. Random checks of the installed system should be conducted by an inspector paid for by the RRC to ensure that changes to the system's design are documented. In the event of noncompliance, a fine should be payable and a compulsory inspection of the whole building undertaken on behalf of the noncompliant actor cf. [15].

3.6.7. Capacity-Building of Maintenance Workers

Before undertaking any maintenance at the construction site, plumbers and other maintenance workers should be made familiar with the most important special features of the dual piping system. Brief manuals provide information about identifying the different lines in the building plans or documentation, and the marking of the previously installed and now replaced lines, in order to avoid any confusion or mix-ups. For this purpose, the design work of the respective design institute and the training materials mentioned in 3.6.4. should be used.

3.6.8. Monitoring after Building Expansion or a Modernisation/Renewal Process

If there is redensification in the construction areas (or the houses are modernised), a new blue-water test should be carried out on behalf of the RRC's operator to confirm correct pipe routing between the inspection flaps inside the building (see above). The service water is coloured (for details see Section 3.6.5). Similarly, salt in the greywater pipe can be used to check for any incorrect connections in the blackwater system.

4. Discussion

The large-scale implementation in Qingdao, an extraordinary challenge undertaken by Chinese partners, has allowed an analysis of a source separation system beyond model project scale for the first time. Thus, the principles outlined here are based primarily on the specific circumstances in Qingdao. Although good management practice derived from transdisciplinary social-scientific and technical error analysis cannot be generally valid, the analyses and measures in this paper contribute some initial guidance for the implementation of other novel urban water systems, hence this article's particular focus on information for practitioners, especially when it comes to organisational procedures for planning, implementing, and operating source-separated novel urban water systems. In other locations, the principles of good management should be reviewed carefully, depending on the structural and socio-technical dynamics in organisations and relationships with other entities. The good management practices derived therefore require some adaptation before taking action.

At first glance, the principles aimed at preventing interconnections were addressed at the (designated or already active) operator of the RRC. However, a closer look identified the need for cooperation in good management practices, relying on procedures as well as the quality of relationships. Being embedded in precautionary governance instruments, the RRC's operator should have the necessary legitimacy to coordinate and delegate certain responsibilities among the actors involved see [15]. Based on soft law, this objective can be achieved by voluntary agreements between the key players. In contrast, hard law approaches would suggest enforcing a legal definition of roles. Whichever way is considered more appropriate, obtaining the political support of local authorities is key to there being more source-separated urban water systems, as demonstrated by the process in Quingdao where a strong commitment of the local actors, specifically WHE, was given.

There are interdependencies between the three phases, which were distinguished in the social science error analysis and the optimisation of cooperation management. Therefore, principles that contribute to preventing both cross-connections and misconnections should be introduced as early as possible. Measurements that are appropriate in the phase of operation have retroactive effects on the procedures in the planning and construction phases. The interdependency of planning and operation is evident: If specific inspection flaps allowing monitoring are not included in the system's design, easy monitoring during the operational phase will not be possible. In the analysis of the case in Qingdao, the translation between the logic of project management and the logic of monitoring was a particular challenge because when operations started, the RRC's operator, which had not previously been involved, was assigned its new role. Monitoring during the operational phase is highly relevant at critical moments, such as in cases of modernisation or redensification. Repairing residential installations or earthworks around external pipes should also be included in the monitoring.

In principle, the assumption is that a lack of relevant technical standards does not hamper implementation of a novel urban water system. For example, agreements between actors can clarify the separation of wastewater fractions using classifications of the different streams as greywater or blackwater. The deliberation, negotiation, and communication of definitions are essential for enhanced awareness (see Section 3.5). Non-existent binding (international) standards should not hinder implementation of these systems either. In summary, they offer windows of opportunity for case-specific fault-sensitive experimentation and variation, especially in the context of innovative socio-technical systems. To pave the way for more institutionalised good management practices, the

RRC's operator can also come up with its own definitions and communicate these to the other actors via a building manual cf. [19].

Bridging the different phases, special characteristics of novel urban water systems, such as technical definitions concerning greywater or blackwater, colour coding in plans, the pipe material, and inspection flaps, must be communicated to construction managers in the catchment area as well as to the design institutes through invitations to tender.

"Good management" initially focuses on measures that can be taken by the local actors themselves. The focus of the organisational and technical measures incorporated into management principles is primarily on cross-connections caused by a lack of awareness, time pressure, and insufficient (necessary) attention. The organisational measures focus less on misconnections that are intentional (cf. Table 1).

Table 1. Types of measures to prevent undesired connections of water infrastructures (+: Preventing effect, 0: Neutral effect; own assessment).

Type of Measure	Description	Estimated Effect	
		Cross Connections	Misconnections
Organisational-technical	Colour codes, permanent mark of pipes	+	0
Organisational-technical	Monitoring of lines	+	0
Organisational (-technical)	Commonly shared definitions and system descriptions	+	0
Organisational	Time management	+	0
Organisational	Quality control	+	+
Organisational	Inspector: New independent mediator	+	+
Organisational	Tendering: Early information on new duties	+	0
Organisational	Development of materials and a documentation of the novel water system	+	+
Organisational-institutional	Qualification (i.e., management skills, foremen and workforce) & awareness in construction companies	+	0
Institutional	New norms	+	+
Institutional	Laws regarding misconnections	+	+
Institutional	Public awareness on misconnections	+	+
Institutional	New certifications	+	+
Institutional	Payment for inspectors	+	+
Interorganisational & institutional	Enable deliberation about experiences with novel water systems	+	+
Institutional	Prosecution of misconnections as a criminal offence with fines	0	+
Structural-technical	Different threads	+	+
Structural-technical	Flaps for maintenance, inspection shafts	+	+

It can be expected that principles of good management, which emphasise the avoidance of technical and organisational errors from the outset, will contribute to fewer incorrect connections. However, the social-scientific error analysis pointed out that without complementary structural or institutional measures, enhanced information flows and awareness are not sufficient to prevent the key actors from making incorrect connections. The far-reaching introduction of intermediary actors, such as inspectors, is particularly necessary if large-scale dual supply is to be established (cf. Table 1).

The final acceptance of work and additional monitoring during the phase of operation allows the detection of misconnections (and their extent). If the collective task of water reuse in (source-separating) novel urban water systems is hindered by individual misconduct, that person or organisation should be liable for penalties and costs. Precautionary sewer inspections should be carried out by a local pollution control officer or inspector cf. [15], which incurs additional costs.

The aim should be to identify a solution that distributes costs fairly between public and private actors. Operating costs in a building's infrastructure can potentially prevent large quantities of kitchen wastewater from being connected to blackwater (e.g., if this water has to be pumped a greater distance to the blackwater sewe but flows to greywater with gravitation). Therefore, it is advisable to emphasise to design institutes that pipe-routing solutions should also be as cost-effective as possible in terms of operating costs for the respective (here private) operator.

For the catchment area of the RRC in Qingdao, it cannot be ruled out that larger volumes of erroneous discharges into greywater or blackwater are due to deliberate misconnections. For example, it is possible that large-scale kitchens discharge their wastewater into greywater pipes because it reduces the amount paid for wastewater disposal. Hence, the institutional invention of a pollution control officer should be accompanied by incentives such as fair charges. Awareness of the link between fair charges and the RRC's technical approach indirectly contributes to appropriate behaviour and hence prevents misconnections. As far as possible, by imposing the same charge for greywater and blackwater, the operator of the RRC should ensure that there are no misleading incentives to behave inappropriately.

For various reasons (e.g., issues of acceptance by project developers), domestic use of service water in the catchment area of the RRC in Qingdao was very limited. It was easy to monitor the few domestic service water supplies, which are located in one building: There were no problems with cross-connections between the service water supply and the drinking water. With the limitations discussed above, the documents generated as part of good management practices (e.g., planning manual or training material) can subsequently be used for information purposes and staff training at other locations where SEMIZENTRAL or other source separation approaches are implemented.

5. Outlook

It is clear from other fields that there can be a large number of building defects in construction projects. This has been strikingly demonstrated in a study of building construction in Switzerland [20]. Management approaches combining the technical and organisational measures presented here can be seen as a response to these structural errors, something that can systematically and easily be implemented by every operator of an RRC. More generally, it can be adapted to other source separation systems. Principles of good management have to be incorporated, particularly into the operator's and the constructor's existing management control system. The implementation of the management system minimises operational risks associated with source separation in terms of efficiency losses or healthcare. Practising good management should be perceived as a response to potential objections raised by experts who remain convinced that interconnections are an exclusion criterion for future applications of novel urban water systems such as the RRC in Qingdao. While no incorrect connections can be accepted on the supply side, in wastewater discharge, a certain percentage can be tolerated, even if it reduces efficiency. With the latter, a tolerable percentage of incorrect connections in sewer systems has to be coordinated between the key actors and ultimately approved by the operator who is responsible for the RRC's operational security. Since the percentages of wrongly connected flows are subject to a negotiation process between the key actors, the percentages perceived as tolerable may even differ due to different risk perceptions. Being aware of cross-connections, RRC operators can actively contribute to reducing malfunctions and paving new ways in cross-connection management for wastewater discharge. Nevertheless, beyond the steering capacities of the RRC, good management is absolutely essential, especially if the domestic supply of service water is intended to be a response to regional water shortages.

The experience in Qingdao is based on the first implementation of the SEMIZENTRAL approach. However, the issue being dealt with is independent of the specific socio-technical boundary conditions of this approach: All novel urban water systems are based on the concept of source separation [21].

In future, they will only be implementable on a large scale if unintended stream mixtures can be avoided, or at least reduced to a tolerable extent, by targeted and relatively uncomplicated measures.

In subsequent investigations that can be carried out at the RRC in Qingdao and its service area, it is possible to determine for example the percentage of incorrect connections between greywater and blackwater that result in malfunctions. The more novel urban water systems implemented, the better the empirical evidence of a threshold of interconnections in sewer systems will be. To become an acknowledged norm or standard, a threshold needs to be defined that balances tolerable amounts of faulty connected flows and system reliability.

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