

D1 - WATER REUSE IN RESIDENTIAL BUILDINGS: HEALTH ISSUES**L. MELO PEIXOTO, O. M. GONÇALVES, L. H. OLIVEIRA****Abstract**

The implementation of water reuse systems is increasing in order to reduce the drinking water demand and increase the supply of water from alternative sources in residential buildings. In order to ensure the safety of users it is necessary to consider the hazards in non-potable water use and the performance requirements concerning quality in the stages of design, implementation, operation and maintenance of non-potable water systems. The aim of this paper is to present a decision-making procedure and a performance evaluation method for water reuse systems in residential buildings based on the principle of Failure Mode Effects Analysis – FMEA. This tool was applied to a residential building with grey water reuse system and the results have indicated that the risk priority number associated with each failure mode helps designers, constructors and managers to make decisions concerning actions to be considered at all stages of non-potable water systems, allowing the choice of level of system performance.

Keywords

Water reuse; greywater; non-potable water; water conservation.

1 Introduction

The implementation of sustainable actions in civil construction has been fostered by sustainability assessment methods proposed by several countries. Regarding water concerns, the following indicators, among others, are defined: water-saving equipment, water submetering systems, non-potable water systems and rainwater management. In Brazil the implementation of building systems that use non-potable water in residential buildings has been growing. In this case, the responsibility for managing the quality and quantity of water is transferred from the utility company to the condominium manager, who is then in charge of meeting the minimum quality standards of non-potable water applied to different uses in the building.

The use of non-potable water in hydraulic building systems when these are inadequately designed and operationalized may result in contamination of potable water and in risks to users' health. For this reason, non-potable water use in residential buildings is an object of concern due to the following factors: few professionals are trained to design,

execute, operate and maintain the system; government organs are not prepared to approve and inspect the implementation and operation of these systems; there is a lack of specific legislation and users do not know the technology.

Even in collective water systems such as in big condominiums, where risk control is better considering there is more specialized management, system failures are not inevitable. An example is the contamination of potable water that occurred in a pilot project for a collective domestic water system to supply 30,000 houses, supported by the Dutch government and presented by Schee (2004). In that case, despite all precautionary measures taken during the design and construction to ensure there would be no threat to public health, some mistakes were made during the construction. In this context, the objectives of this study are:

- to present performance requirements and criteria for the design, execution and maintenance of non-potable water building systems;
- to apply the Failure Mode Effects Analysis (FMEA) tool to assess a non-potable water system implemented in a residential building.

2 Non-potable water system

Non-potable water systems have two sources of water supply, potable and non-potable, and two drainage systems, one for greywater and another for blackwater. It can thus be stated that potable water in a non-potable water system is much more vulnerable to contamination risks than in a conventional potable water system.

The implementation of an alternative system for water distribution and also for the collection of a certain part of the effluents introduces another building system in the traditional model. This new building system is made up of the non-potable water distribution system (NPWS) and the greywater system (GWS).

The greywater system (GWS) collects the effluents from wash basins and showers and transports them to a suitable destination, which may be the treatment plant or the sewage collection network. The non-potable water system (NPWS) carries water from the treatment plant to the point of use of non-potable water, in general the toilets.

Figure 1 illustrates the two systems that compose the non-potable water building system.

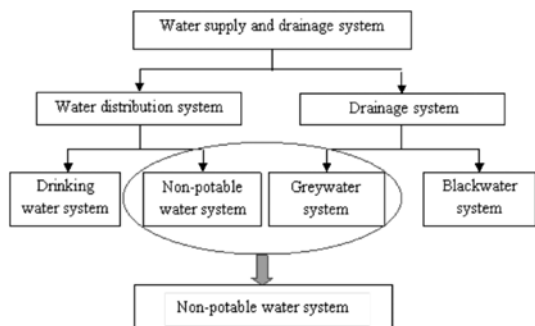


Fig. 1 – Structure do sistema predial de água não potável

2.1 Performance requirements and criteria for non-potable water systems

Contamination risks result from failures in systems that rely on mechanical and electronic components and on human actions, all of which are subject to failures. For the failures to be minimized in non-potable water systems, it is necessary to manage consumption, water quality and risks. For this purpose, it is essential to define performance requirements, of a qualitative nature, and their corresponding criteria, of a quantitative nature.

Rosrud (1980) developed performance requirements for potable water system and for drainage system, but the author does not consider the greywater system nor the non-potable water system, which, although very similar to the conventional system, has its own specificities. Taking into consideration the reliability of the non-potable water system, other requirements besides those of the potable water system should be established in order to guarantee proper system performance. Therefore, performance requirements and criteria have been adapted to the non-potable water system and are presented in Table 1.

The performance approach used in the non-potable water system evidences the complexity of this system. The implementation of this technology requires optimization in non-potable water supply and demand, the use of specific components (pipes, reservoirs etc.), specialized operational services and educational guidance for users. Therefore, the decision to use this system in residential buildings requires special care considering the imminent risk of user contamination in the event of any failure.

Table 1 – Performance requirements and criteria for non-potable water systems

Performance requirements for NPWS (adapted from Rosrud, 1980)	Performance criteria for NPWS based on (EPA (2005), Acta (2005), BSRIA (2006), NSW (2005), NSW (2006) and WRAS (2006))
Avoid contamination of collected greywater in order to guarantee final quality of treated water (non-potable).	Collect greywater separately from blackwater.
The system must ensure that the water delivered at the point of use is of suitable quality to its use.	- Use materials that conserve water quality. - Use in the non-potable water pipe a different material from that in the potable water pipe.
The system must operate safely so as not to harm users' health.	- Periodically monitor non-potable water quality at the outlet of the greywater treatment plant. - Separate pipes carrying fluids of different qualities. - Visually identify components and elements of the non-potable water system. - Color the non-potable water. - Prepare a system operation and maintenance guide. - Inspect the pipes to check the separation from other building systems.

3 Failure Mode Effects Analysis applied to the non-potable water systems

Failure Mode Effects Analysis (FMEA) is used in the development and execution of a new or revised project, process or service (PALADY, 2004). The purpose of this tool is to prevent failures before they reach the user. Broadly speaking, it identifies potential failures, quantifies risks and proposes preventive and corrective measures.

The method is based on defining a hierarchy of risks caused by failures and it varies according to the relevance of the effect of this failure on the system. Its application requires two phases: investigation and failure control. In the case of a non-potable water system, FMEA allows possible failures in the system to be hierarchized and the risk associated with each failure mode to be determined. This helps designers, executors and managers in the decision-making process in all phases of system implementation.

Cheng *et al.* (2008) presented a decision-making and a performance evaluation method for drainage systems within high-rise buildings with good results. Their evaluation tool is mainly based on the principle of Failure Mode Effects Analysis – FMEA.

3.1 Investigation failure

The investigation phase, presented in Table 2, consists in the identification of failures that directly depend on the purpose of the project and on the variables of the performance criteria. Based on these criteria, the mode in which the requirement

may fail is determined and, consequently, its influence on the system is identified. The investigation phase is concluded in the identification of the failure causes

Table 2 – Application of FMEA in the investigation phase

Purpose	Failure mode	Failure causes	Failure effect
Purpose of project – performance requirements to be met.	How the project fails to fulfill its purpose. E.g.: cross-connection, etc.	Reasons that produce the failure mode. E.g.: assembly error, etc.	Consequence of the failure mode. E.g.: potable water contamination.

Table 3 presents the indicators considered in risk assessment, calculated for each potential cause of failure and based on the quantitative assessment of the indicators: severity, occurrence and detection. The risk priority number (R) is obtained based on these indicators. Besides quantifying risks, FMEA presents essential and corrective actions that aim to prevent and correct the occurrence of failures, thus increasing system reliability.

Table 3 – Indicators considered in the control phase of the FMEA tool

Severity (S)	Occurrence (O)	Detection (D)	Risk (R)
Gravity of the effect of the failure mode.	Frequency of the failure mode.	Failure identification before delivery and during system operation.	Product obtained from the values assigned to severity, occurrence and detection.

3.2 Failure control

The activities considered in the control phase are the essential and the corrective actions. Essential actions must be implemented in the system before the start of operation so that failures will not occur while it is functioning. Corrective action is implemented to correct specific failures, that is, it does not prevent their occurrence, unlike essential actions.

3.3 Application of FMEA

In order to use the tool it is necessary to specify and quantify the risk resulting from the failure. The risk (R) is the product of the indicators: failure severity, occurrence and detection, according to equation 1.

(1)

$$\text{Risk (R)} = \text{Severity (S)} \times \text{Occurrence (O)} \times \text{Detection (D)}$$

The values assigned to each indicator vary according to the classification of the failure being analyzed, as presented in Table 4.

Table 4 – Values of the indicators of failure severity, occurrence and detection

Indicator	Assigned value		
	(1)		(1)
Severity (S)	Minimum	Severity (S)	Minimum
Occurrence (O)	Remote	Occurrence (O)	Remote
Detection (D)	Easy	Moderate	Difficult

Quantification of risks allows them to be hierarchized in the system and it thus helps those involved in the design, execution and maintenance phases when choosing the activities to be carried out.

Concerning the water quality requirement, the analysis of potential failures and their effects involves assessing the risks of contamination in the potable and non-potable water distribution systems, considering the minimum quality standards defined for this kind of end use.

The purpose of the non-potable water system project is to maintain the minimum quality necessary to meet the demand without exposing users to health risks. Therefore, the failure effect of this requirement is non-potable water quality that is inferior to what is required. It should be stressed that, in this case, contamination refers to non-compliance with the quality parameters specified for the non-potable water system, which are considerably different from the potability standards for drinking water.

The failure mode is directly related to its cause and effect. Table 5 presents the failure causes and the corresponding effects for the water quality requirement, which are essential factors for the application of FMEA.

Table 5 - Failure causes and effects for the water quality requirement

Failure	Cause	Effect
Water quality	1 Cross-connection between the potable water system and the non-potable water system.	Supply of water of unsuitable quality to points of use such as washbasin, shower, sink etc.
	2 Cross-connection between the greywater collection system and the blackwater collection system.	Inefficient treatment of effluents due to mixture of blackwater and greywater, resulting in the supply of non-potable water of quality that is inferior to the specifications.
	3 Return of non-potable water to the potable water system.	Contamination of potable water and supply of non-potable water to the points of use.
	4 Inexistence of control of non-potable water.	User contamination.

Failure investigation and analysis provide subsidies to determine the specific risk of each failure and this, in the end, results in the global degree of risk for the quality requirement. Partial risks (R) are determined considering the values assigned to the indicators of severity, occurrence and ease of detection for each of the four types of failures.

Table 6 presents the determination of the risk priority number (R) of each failure listed in Table 5, based on the indicators of failure severity, occurrence and detection presented in Table 4. The sum of the different degrees of risk (R) results in the global priority risk number (R_{global}).

Table 6 - Degrees of risk of the four failures and the indicators of partial and total failure of the water quality requirement

Failure effect	Degree of risk
Failure 1 - Supply of water of unsuitable quality to points of use such as washbasin, shower, sink etc.	S = 3 - harm users' health - high severity.
	O = 3 - similar characteristics in the components of different systems favor cross-connection - high occurrence
	D = 3 - similarity in color and odor between non-potable and potable water - difficult detection.
Risk priority	$R_{\text{failure 1}} = (S)3 \times (O)3 \times D(3) = 27$
Failure 2 - Inefficient treatment of effluents due to mixture of blackwater and greywater.	S = 2 - partial and insufficient removal of contaminants - moderate severity.
	O = 3 - similarity between the components of different systems - high occurrence.
	D = 2 - blackwater presents physical characteristics that can be identified (color and solids) - moderate detection.
Risk priority	$R_{\text{failure 2}} = (S)2 \times (O)3 \times (D)2 = 12$
Failure 3 - Contamination of potable water and supply of non-potable water to the points of use.	S = 3 - harm users' health - high severity.
	O = 3 - non-installation of backwater components at the points of cross-connection between the different
	D = 3 - similarity in color and odor between non-potable and potable water - difficult detection.
Risk priority	$R_{\text{failure 3}} = (S)3 \times (O)3 \times D(3) = 27$
Failure 4 - User contamination.	S = 3 - put users' health at risk - high severity.
	O = 3 - absence of monitoring - high occurrence.
	D = 3 - similarity in color and odor between non-potable and potable water - difficult detection.
Risk priority	$R_{\text{failure 4}} = (S)3 \times (O)3 \times D(3) = 27$
Global risk of failure for the water quality requirement	$R_{\text{global}} = (27+12+27+27) = 93$

Determination of the risk priority number (R) contributes to list the control measures needed to avoid the failure. The implementation of actions that reduce the occurrence of failures 1, 3 and 4 is suggested based on the values of the risk priority number (R). According to Table 6, the risk of failures (1), (3) and (4) is equal to 27 and that of failure (2) is equal to 12.

Table 7 presents the essential and corrective actions to be implemented in order to reduce failures 1, 3 and 4. Essential actions refer to those conducted in the design, operation and maintenance phases in order to prevent future failures. Corrective actions, on the other hand, refer to interventions in the system in operation in order to correct failures that have already occurred.

Table 7 - Essential and corrective actions to maintain the water quality requirement

Failure	Essential action	Corrective action
1, 3 and 4	a. Use component materials with different characteristics, so that interchangeability is made impossible. b. Color the non-potable water. c. Visually identify components of the NPWS. d. Carry out tests to verify total separation of system components and elements. e. Visually identify system components before execution. f. Use valves that prevent the return of non-potable water to the potable water system. g. Guarantee atmospheric separation (air gap) at the points of interface between the different systems. h. Keep minimum distances between the pipes of different systems and avoid points of intersection between the pipes. i. Conduct regular maintenance of system components and equipment. j. Record changes that occur during the operation of the systems and of the building (as-built drawings). k. Implement a quality guarantee system for system assembly, operation and maintenance that defines the responsibilities of managers and technicians. l. Prepare manuals with the recommended practices for system operation and maintenance. m. Permanently monitor potable and non-potable water quality. n. Promote an environmental education program to users of hydraulic building systems to inform them of the risks they are subject to in the event of cross-connection.	a. Interrupt the operation of the non-potable water system; b. Identify the points of cross-connection between the systems; c. Separate the different systems; d. Implement a water quality control system; e. Implement the essential actions.

3.4 Hierarchy of essential actions for the water quality requirement

Essential actions are hierarchized according to the degree of importance, as presented in Table 8. It should be stressed that some of the project control actions of the non-potable water system are classified as more important in order to guarantee greater safety to users' health.

Table 8 – Classification of the degrees of importance (DI) of essential actions

DI*	Intensity
1	Less important
2	Important
3	More important
4	Much more important
5	Absolutely more important

Besides the degree of importance associated with each essential action, the phase indicators are taken into account – that is, the values assigned to the design, execution/operation and maintenance phases. It is proposed that the design phase should be more important than the execution/operation and maintenance steps. The implementation of the hierarchical degree of importance requires the system to be carefully executed according to the design and it should have specialized monitoring to prevent changes during system installation and operation.

Considering these premises, phase indicators with values 9, 6 and 1 are used for the activities in the design, execution/operation and maintenance phases, respectively. Hence, the value of the action in the requirement is the product of the degree of importance of each essential action multiplied by the phase indicator, related to the system steps, according to equation 2.

(2)

Value of the action = Degree of importance x Phase indicator

Table 9 presents the values of each essential action of the water quality requirement, according to equation 2. The values of the actions presented in Table 9 result from multiplying the degree of importance in Table 8 by the phase indicator: design, execution and maintenance.

Table 9 – Values of the essential actions in the design (D), execution (E), operation (O) and maintenance (M) phases of the water quality requirement

Essential actions	Phase	DI*	Phase indicator**	Value of action
• Install valves that prevent the return of non-potable water or consider atmospheric separation between the potable and non-potable water systems.	D	5	9	45
• Use materials and components with different characteristics, so that interchangeability is made impossible.	D	4	9	36
• Keep positive pressure in the potable water system.	D	3	9	27
DESIGN PHASE TOTAL = 108				
• Train staff.	E	3	6	18
• Visually identify system components before execution.	E	3	6	18
• Hire specialized staff to operate the treatment plant.	O	5	6	30
EXECUTION/OPERATION PHASE TOTAL = 66				
• Record in a building maintenance log book the changes/renovations to the pipes and attest the inexistence of cross-connection.	M	3	1	3
• Color the treated effluent every day.	M	3	1	3
• Promote an environmental education program to users of the building and of the hydraulic building systems.	M	3	1	3
• Annually paint the pipes.	M	2	1	2
• Monthly test the pipes to verify cross-connection.	M	3	1	3
• Carry out tests to verify total separation of the components and elements of the systems.	M	2	1	2
• Carry out monthly inspections to detect leaks.	M	2	1	2
• Permanently monitor potable and non-potable water quality.	M	5	1	5
MAINTENANCE PHASE TOTAL = 23				

* DI corresponds to the degree of importance of each essential action in the system, ranging from 1 to 5, according to Table 8.

** Values established for the design phase (9), execution/operation phase (6) and maintenance phase (1).

Based on Table 9 it is possible to hierarchize the control activities for the non-potable water building system, thus supporting system designers, executors and operators in the decision-making regarding the activities to be carried out. The implementation of the activities listed in Table 7 minimizes the possibility of failure and, as a result, maximizes the performance of the non-potable water system. Non-implementation of any of the actions increases the likelihood of failure and the exposure of users to contamination risks.

4 Application of FMEA in a residential building

This section presents an assessment of the water quality requirement and its corresponding performance criteria for the GWS and NPWS of a residential building with the application of the Failure Mode Effects Analysis (FMEA) tool. The building has 24 stories and six apartments per floor, totaling 144 apartments. The non-potable water system feeds only the toilets.

Firstly the application of essential actions, presented in Table 7, was verified for the quality requirement. Some actions, such as identification of the pipes and coloring of the non-potable water, were not fully considered due to the following reasons:

- the only painted pipes are located in the basement, and they do not correspond to all the installed piping system. It is thus not possible to guarantee the absence of failure for this requirement. For this reason, a 30% value represents the quantity of pipes in the basement in relation to the other locations.
- non-potable water is pigmented only once a month, during the cross-connection test. The value was estimated at 10%, considering that the pigment would remain in the water for a maximum period of three days.

The essential actions implemented in the building are assigned values from 100% of compliance to 0% in the case of those that have not been implemented. These values, considered for the corresponding actions, are justified according to the analysis of each subsystem of greywater collection and of non-potable water distribution. Table 10 presents the degree of compliance with the essential actions in the building to eliminate failures 1, 2 and 3, presented in Table 6.

Table 10 – Degree of compliance with the essential actions in the building for the water quality requirement

Essential actions	Degree of compliance with the action
• Use materials with different characteristics, so that interchangeability is made impossible.	0
• Color the non-potable water.	10
• Implement a visual code of the system.	30
• Identify the system before execution.	0
• Test the system to verify the separation of the pipes.	100
• Inform the population of the risks of cross-connection.	0
• Regularly inspect the executed system.	0
• Register in a log book the changes and renovations to attest the separation of the pipes.	0
• Use valves that prevent the return of non-potable water in the potable water system or use atmospheric separation.	100
• Maintain positive pressure in the potable water system.	100
• Carry out regular inspections to detect leaks.	100
• Design systems to comply with the minimum separation between pipes, so that in the event of leaks, the discarded effluent will not jeopardize the safety of the other system.	0
• Regularly monitor treated water quality.	100

Table 10 allows the conclusion that not all essential actions that have been proposed were applied. Therefore, the possibility of system failures should be considered.

The risk priority number, presented in Table 6, is considered high for failures 1, 3 and 4. It should be noticed that the occurrence of these failures has a direct impact on the users' health. In the building under analysis, failure 4, whose essential action is permanent monitoring of water quality, has 100% of compliance (Table 10). Therefore, this failure, which has a risk priority number of 27 (Table 6), may be dismissed.

The essential actions to avoid failures in the compliance with the water quality requirement were not fully implemented in the building and this may be regarded as a serious problem, considering that any flaw or oversight jeopardizes system performance and puts users' health at risk.

4.1 Analysis of essential actions for the water quality requirement in the building

This section presents an assessment of the compliance with the essential actions proposed in the building under analysis. Table 11 shows the essential actions and their corresponding design, execution/operation and maintenance phases. The values assigned to each action and the value of the action in the building are also listed in this table. Based on these values it is possible to obtain the action compliance index in relation to the proposal.

Table 11 - Values of the essential actions for the quality requirement in the design (D), execution (E), operation (O) and maintenance (M) phases of the building

Essential action	Phase	DI*	Phase indicator **	Value of action	Degree of compliance
a. Verify the installation of valves that prevent the return of non-potable water or the existence of atmospheric separation between the potable and non-potable water systems.	D	5	9	45	YES
b. Use materials with different characteristics, so that cross-connection is made impossible.	D	4	9	36	NO
c. Keep positive pressure in the potable water system.	D	3	9	27	YES
Design phase total = 108					(45 +27) = 72
% of compliance with essential actions in the design phase of the building					66%
d. Train staff.	E	3	6	18	NO
e. Identify the pipes before execution.		3	6	18	NO
Execution phase total = 36					(0)
% of compliance with essential actions in the execution phase of the building					0%
f. Hire specialized staff to operate the treatment plant.	O	5	6	30	YES
Operation phase total = 30					(30)
% of compliance with essential actions in the operation phase of the building					100%
g. Record the renovations to the pipes and attest the separation of the pipes.	M	3	1	3	NO
h. Color the treated effluent every day.	M	3	1	3	10%
i. Educate the population, addressing the importance of water quality.	M	3	1	3	NO
j. Annually paint the pipes.	M	2	1	2	NO
k. Monthly test the pipes to attest the separation of the pipes.	M	3	1	3	YES
l. Monthly verify the separation of the pipes.	M	2	1	2	YES
m. Carry out regular inspections to detect leaks.	M	2	1	2	NO
n. Regularly monitor treated water quality.	M	5	1	5	YES
Maintenance phase total = 23					(0,3+3+2+5) = 10,3
% of compliance with essential actions in the maintenance phase of the building					44,8%

*DI corresponds to the degree of importance of each essential action in the system, ranging from 1 to 5, according to Table 11.

** Values established for the design phase (9), execution/operation phase (6) and maintenance phase (1).

In the design phase, there was 66% of compliance with the proposed essential actions. In the execution there was no compliance. In the operation phase, there was 100% of compliance and in the maintenance activities 44.8% of the recommended essential actions were complied with.

As presented, none of the essential actions proposed in the execution activity were implemented. The absence of these actions is considered a serious failure. This was observed in the detection of a cross-connection between the greywater and blackwater collection systems during the execution phase. This fact supports the importance of essential actions to identify failures and improve the quality of the non-potable water system.

5 Final considerations

The use of FMEA contributes to create a hierarchy of probable failures in the system and to determine the risk priority number (R) associated with each failure mode. It also helps designers, executors and managers to make decisions concerning the actions to be carried out in all phases of the implementation of a non-potable water building system by allowing the risks to be assessed. Regarding the non-potable water system analyzed in the residential building, it may be stated that:

- the application of FMEA allowed the identification of failures that occurred in the non-potable water building system, as well as the observation that these failures resulted from non-compliance with the essential actions recommended for each requirement;
- the first failure identified by FMEA in the building was related to the water quality requirement concerning inefficient treatment of greywater. This failure was caused by a cross-connection in the deviations of greywater stacks and blackwater stacks, allowing blackwater to be carried to the greywater treatment plant. This failure occurred due to the similarity between the materials of the pipes, lack of staff training and of inspection of the executed service;
- another failure identified by FMEA was the over-sizing of the greywater treatment plant, which was caused by a mistake in the estimate of non-potable water demand for the toilets.

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7 Presentation of Authors

Luciana Peixoto is Master of Science in Engineering, Escola Politécnica of University of São Paulo.

Orestes Gonçalves is a professor at Department of Construction Engineering of Escola Politécnica of University of São Paulo, where he is the head of the Building Services Research Group.

Lúcia Helena is a professor at Department of Construction Engineering of Escola Politécnica of University of São Paulo, where she teaches and conducts researches on building services.

L. Melo Peixoto (1), O. M. Gonçalves (2), L.H.Oliveira (3)

(1) lu_peixoto@hotmail.com

(2) orestes.goncalves@poli.usp.br

(3) lucia.oliveira@poli.usp.br

(1), (2), (3) Department of Construction Engineering of Escola Politécnica, University of São Paulo, Brazil