Stress Test Report

of the water recovery system

in the Blue Diversion Toilet

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Content

Summary

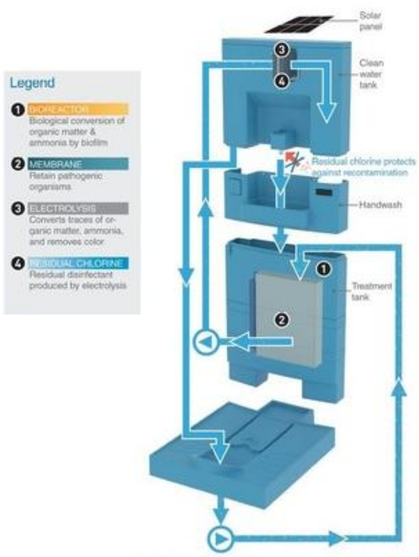
The on-site water recovery system must provide hygienically safe and appealing water at all times. Since there will be times of high and low toilet usages the amount of urine and feces that pollute the water will vary. The tests investigated the operation of the recovery system under stress. The focus was on the first treatment step Bambi. Our experience from phase 1 showed that aeration is an important feature to achieve a sufficient degradation of organics and ammonium. The stress test was executed to investigate the effect of a varying extent of aeration and varying toilet usage, i.e. variations in the load of organics (mostly from feces) and ammonia (mainly from urine). The following table summarizes the performed stress tests with lab working models. It can be concluded that the water recovery system is quite robust against temporary changes in load. A short-term increase in organic loading and color intensity does not compromise the hygienic quality of the water . However, long-term conditions of low oxygen should be avoided, as this results in decreased capacity (flux) and long recovery times.

Table 1: Overview of the performed Bambi stress tests. Recovery time refers to the time until the normal conditions of permeate quality and flux are reached again

Stress test (chronologic)	Description	Results	Recovery time [d]
LOW USAGE	70% less toilet visits for 4 days; i.e. reduced load and turnover	Decrease of COD and NH_4-N; no change in flux	no neg. effects
PARTY	4 times higher load (feces, urine and soap) for 1 day	Increase of COD, NH_4-N and color intensity; no change in flux	6
DIARRHEA	4 times higher load (feces, urine and soap) for 3 days	Increase of COD, NH_4-N and color intensity; decrease of flux and oxygen	11
BATTERY PROBLEMS	No aeration and no electrolysis during night for 2 nights in a row	Increase of COD, NH_4-N and color intensity; decrease of oxygen and flux	6
NO AERATION, e.g. broken pump	No aeration for 3 days	Increase of COD, NH4-N and color intensity; decrease of oxygen and flux	20

Introduction

The on-site water recovery system in the Blue Diversion Toilet must provide hygienically safe water at all times. Therefore, the water recovery system has four barriers: (1) the membrane bioreactor (Bambi) to degrade organic substances and ammonia, (2) the gravity-driven ultrafiltration membrane to retain pathogenic organisms, (3) the electrolysis unit for polishing the water in order to remove the slightly yellow color of the recovered water and (4) the residual chlorine to prevent the regrowth of pathogens. The electricity required by the electrolysis unit and the aeration of Bambi is provided by a solar panel that is mounted on the toilet superstructure.



The water recovery technology inside the toilet

The toilet usage is likely to have high and low peaks (e.g. parties, diarrhea incidents in the family,…) and thus the amount of the urine and the feces that pollute the water will vary. We investigated if this has an impact on the quality (COD, color intensity, ammonia) and the quantity of the recovered water.

Bambi (1) has an important role in the water recovery because it is directly affected by the varying amount of urine (ammonia loading) and feces (organic loading) that end up in the used wash water. Our experience from phase 1 showed that the operation of Bambi requires aeration to achieve sufficient degradation of organics and ammonium. This degradation is important for an unproblematic operation of the subsequent polishing step (3). The reason is because organics and ammonium react with the produced chlorine which would then be missing for residual disinfection (4). Therefore, the five stress tests focused mainly on Bambi (1) including the membrane (2). We investigated in how far a varying extent of aeration and varying loads of organics (mostly from feces) and ammonia (mainly from urine) impairs the operation of Bambi. The stress tests delivered results regarding the quality (COD, color intensity, ammonia) and quantity (flux, permeability or capacity of the system) of the recovered water and allows to define adequate measures.

Experimental approach

The four lab working models (R1-R4) each consist of a (1) Bambi reactor with a (2) membrane (area 3 m^2) and a (3) clean water tank (CWT) that contains the electrolysis module and where the filtered water (=permeate) is collected. The electrolysis module (WATA module from Antenna) was only inserted to the CWT on May 15th, after the first stress test. From the CWT the water is pumped to the Bambi reactor again. To simulate a toilet visit, a concentrate of feces, urine and soap is added at the same time.

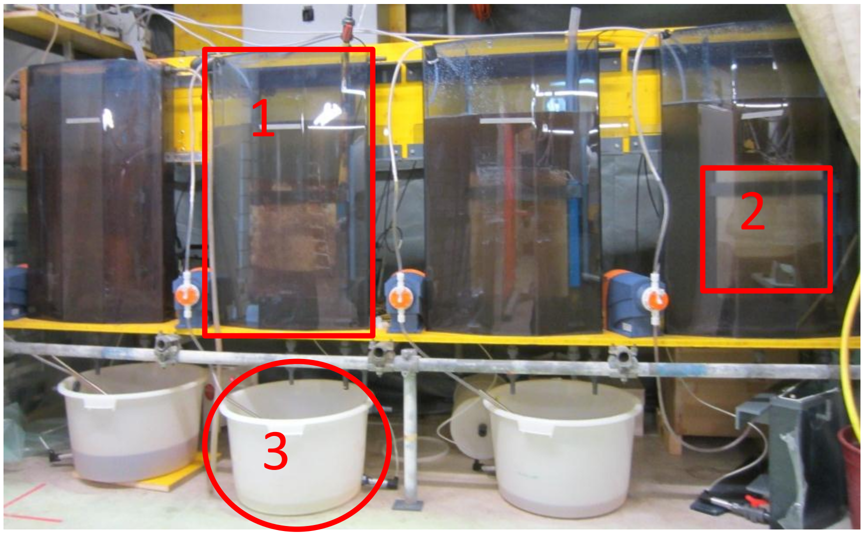


Figure 1: Lab working models at Eawag

Stress tests were conducted with one or two lab working models. The rest of the 4 water recovery systems in the lab were used as reference reactors with the usual operation to compare the results. Usual operation means 50 toilet visits per day (i.e., 5 visits per person) with a water usage of 1.5 L per toilet visit and a recycling rate of 90%. We used two different baseline loadings:

R1 / R2: High loading: 94 g feces, 190 mL urine per day (corresponding to 5 % feces and 2 % urine)
R3 / R4: Low loading: 47 g feces, 95 mL urine per day (corresponding to 2.5 % feces and 1 % urine)

In all stress experiments, the base line loading with soap was 14 g/day.

For practical reasons, the hydraulic loading was kept constant in all stress tests, except for Test 1 (low usage).

The following parameters were measured regularly (once to twice a week) in the treated water (just after the membrane before electrolysis):

- Ammonium (NH_4^+-N)
- Nitrate (NO_3^--N)
- Nitrite (NO_2^--N)
- Chloride (Cl^-)
- Organic matter (as chemical oxygen demand, COD)
- Absorption with the wavelength 436, 525 and 620 nm (indicating the color intensity).

In the biological reactors (Bambi reactors), the following parameters were monitored continuously: flux, oxygen concentration and pH.

Stress test: LOW USAGE

A less frequent use of the toilet, e.g. as expected during work and school days, leads to a lower organic load which provides less feed for the biology in Bambi. Furthermore, there is a low turnover rate of the water, which could lead to odor problems. With this stress test it was examined if the removal efficiency and permeability of Bambi stay on the same level, when the input of organic compounds is low over several days.

Methods

Only 15 (instead of 50) toilet visits per day (10 people à 5 times) were simulated in two water recovery reactors (R2 and R3) over four days. The input of feces, urine, soap and water, as well as the usage of clean water, was therefore reduced by 70%. Two reactors with normal operation were used as reference.

Results

The COD concentration of the permeate dropped by about 100 mg/L (63%) and the NH_4-N concentration by 25 mg/L (27%) within these four days. The concentration of NO_2-N, NO_3-N and Cl^-, as well as the pH, remained almost the same and the permeate was less colored after the stress test. The O_2 concentration in Bambi increased and the water level in the reactor decreased during the period of lower load. The influence of this stress test on the permeability (flux values corrected by transmembrane pressure) was insignificant.

Interpretation

A lower organic load is no problem for the water recovery unit. The decreasing concentration of nutrients and COD and the increasing oxygen content are actually positive for the quality of the treated water. We did not observe odor problems due to the low turn-over of water.

Please note: In the field test in April 2013, it seemed that a low turn-over of water could lead to odor problems. However, analyses conducted by Firmenich in Geneva showed that the odor was due to degradation products from urine, which was poorly separated from water in the first working model. In the field test we thus had a situation of low water consumption and high loading of urine. In the prototype developed for the next field test in February 2014, the urine/water separation mechanism will be improved by Tribecraft (provided acceleration funding is granted).

Stress test: PARTY

The second scenario tested simulated an increased number of toilet visits over a short time period (e.g. due to festivities). In this experiment it was tested if Bambi can cope with a four times higher load. While the load was increased, the use of clean water remained constant.

Methods

The party stress test was performed with two reactors (R1 and R4) whereas two reference systems ran with normal operation. The diurnal variation of toilet visits was adapted to 200 (instead of 50) toilet visits for one day. At this day the load of urine, feces and soap was four times higher.

Results

An immediate increase of the COD concentration by around 25% was observed in both stress test reactors (see Figure 2, yellow data points). However, the COD returned to the same level as before within 75 hours after the test and the measured peaks during the test were not above the values measured some weeks before (see Figure 2).

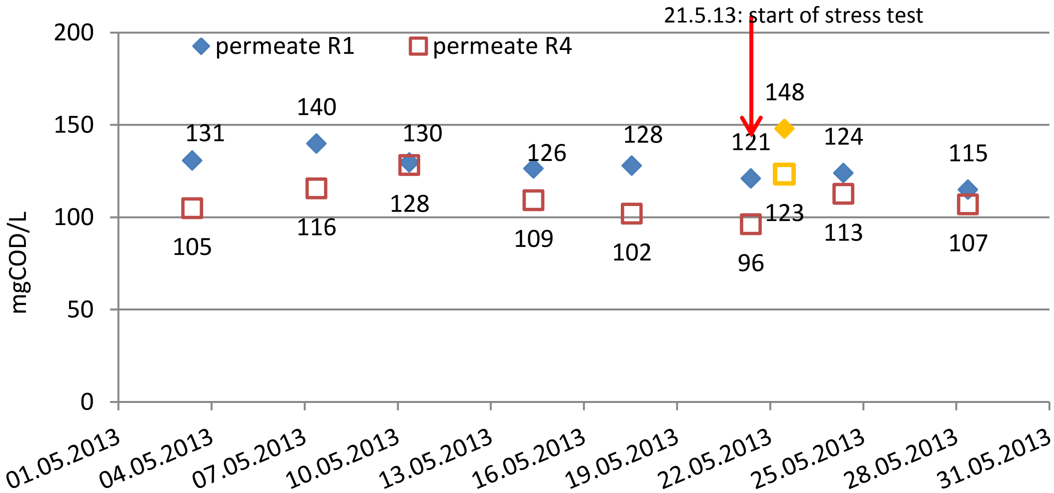


Figure 2: Long-term COD of the two stress test reactors R1 and R4. The yellow data points show the increased COD on the day after the party stress test.

Also the NH_4-N concentration in the reactors 1 and 4 rose within 24 hours by 38mg/l and 8 mg/L (factor 17 and 5 times higher) respectively. The recovery to reference concentrations took less than 6 days for Reactor 1 (with the higher baseline load) and between 6 and 13 days for Reactor 4 (with the lower baseline load). The color intensity also increased immediately, but recovered to pre-test level very quickly (within 2 days). The values did not exceed the normal measurement variation. Neither NO_2-N, NO_3-N nor pH values changed as a result of the stress test and also the flux was not influenced. The measured flux remained within the normal fluctuations (cf. Figure 5). As expected, the oxygen concentration in Bambi decreased with the higher load (with a minimum value of 0.8 mg/L) but rose again within two days.

Interpretation

The experiment shows that a higher load for one day would already be noticeable for the user as the color intensity increased fast. But all the negative influences on the treated water quality adjust again to normal levels within a short time. Festivities with large gatherings of people are quite common but the resulting short increases in loading have only a minor influence on system performance.

Stress test: DIARRHEA

The diarrhea stress test simulates that several users have diarrhea at the same time which leads to a severe organic overloading for some days (for the test 3 days of overloading were conducted). It is assumed that in case of diarrhea also more urine gets into the system which leads to an overloading of ammonium. Higher clean water consumption was not considered during this stress test.

Methods

In one system (R 4) the load of feces, urine and soap was increased four times for three days, simulating 200 toilet visits a day.

Results

The flux decreased during the stress test but recovered within about one week after the test (see Figure 5). It was observed that the permeate smelled more and had a stronger color intensity. Within the three days the COD of the clean water increased by 20-40 mg/l (20-48%). Four days after the stress test it reached the same level as before which was also the case for the color intensity. An NH_4-N peak occurred at day four after the start of the experiment and it took eleven days until it dropped again (see Figure 3). There was no increase of NO_2-N or NO_3-N visible.

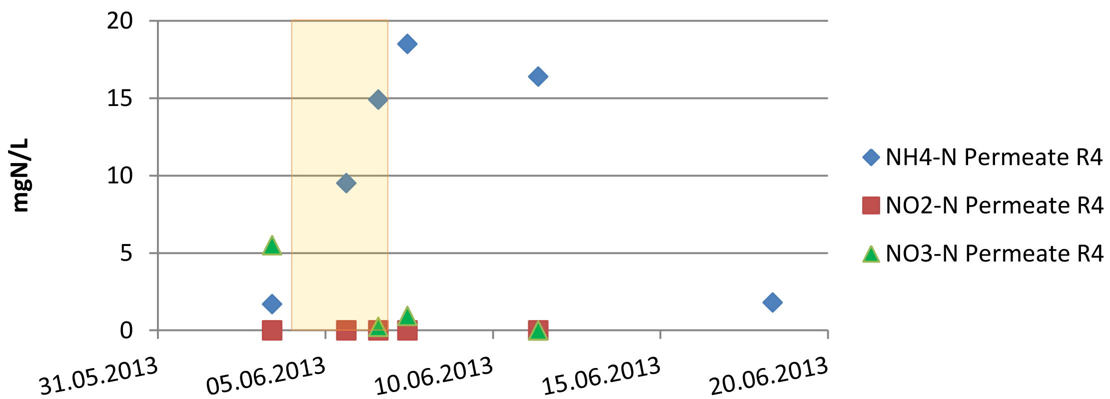


Figure 3: Ammonium, nitrite and nitrate concentrations before, during and after the diarrhea stress test of reactor R4. Increased loading due to diarrhea started on 4.6.13 and lasted until 6.6.13 (indicated by the orange bar).

Both the oxygen concentration and the flux decreased during the stress test and recovered afterwards within a few days. The minimum oxygen concentration measured was 0.4 mg/L.

Interpretation

The impacts of this stress test are the same as for the stress test 'Party' but as the high load remained longer, it also took longer to reach the normal level of NH_4-N, COD and color again. Unlike for the party stress, the flux was also effected but did not take as long as the permeate quality to recover. Diarrhea is frequent in informal settlements of the South and the decrease of perceived water quality in periods where hand washing is of uttermost importance could be critical. At the same time, we expect the Blue Diversion Toilet to lead to a decrease in diarrhea incidents. In a transition period (where this positive effect has not yet occurred), higher capacities for aeration and/or electrolysis should be made possible (see also Conclusion below).

Stress test: BATTERY PROBLEMS

In case of a problem with the battery, energy cannot be stored and is only available if there is solar radiation. This means that aeration and electrolysis are only possible during day time. As it possibly takes a couple of days until the battery is repaired or replaced, the stress test was conducted during 2 days.

Methods

The aeration of the membrane reactor and the electrolysis in the clean water tank were only switched on during seven hours per day. The stress test was implemented for two days within Reactor R4.

Results

During the time without electricity, the oxygen concentration in Bambi dropped close to zero (cf. Figure 4). In the aerated period it did not reach the same concentration of oxygen as when the reactor is aerated permanently (4 instead of 5 mg/L). After these two days the aeration was again applied continuously which resulted in a quick recovery of the dissolved O_2 concentration in Bambi. This stress test resulted in a decrease of the flux by about 30%, but the flux recovered to normal values after 6 days. The COD doubled whereas the ammonium reached a five times higher concentration in the clean water. Both parameters returned to normal within four days. Also the absorption (color) increased and recovered within four days. There was no significant change of the other ion concentrations (NO_2-N, NO_3-N) and the pH did not change either.

Interpretation

As expected, a lack of aeration and electrolysis during 17 hours per day lead to a strong deterioration of water quality. The color response is an important message to the users that there is a technical problem, which must be solved. It is important that the business model will be based on a service contract where the users can apply for a repair without extra costs. The rapid improvement of water quality upon reparation is good news, but the service protocol must include the emptying of the clean water tank into Bambi to further accelerate the process. With the hydraulic system planned for the next prototype, this will be easier than in the first working model.

Stress test: NO AERATION

The situation may occur where the aeration completely fails over some days. For example if the air pump breaks down, the solar panel gets stolen or there is not enough energy because of cloudy weather. This can result in anaerobic phases in Bambi.

Methods

During three days the aeration of one lab working model (R4) was turned off.

Results

The oxygen concentration in Bambi dropped close to zero, as expected (see Figure 4). However, it improved on the first day when the aeration was switched on again. As a result of no aeration the flux decreased drastically and it took around 3 weeks to fully recover to the level before the stress test (cf. Figure 5). Similar to the previous stress test, the COD and NH_4-N increased and reached a 5 and >10 times higher concentration, respectively. However, both concentrations fell to normal within 4 days.

NO_2-N and NO_3-N remained close to zero. The clean water was more colored until day three after the experiment.

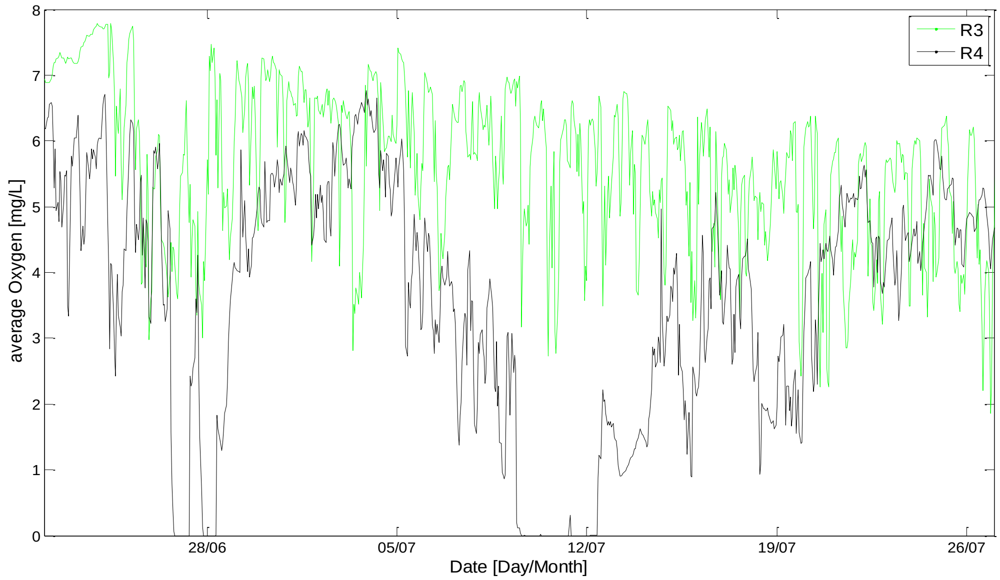


Figure 4: Hourly average oxygen concentration of R3 (control) and R4 during the period of the stress tests 'battery problems' (26.-38.6.13) and 'no aeration' (9-12.7.13).

Interpretation

The results of the experiment clearly shows that a broken air pump is going to have severe negative influence on the water quality. The color of the water intensifies quickly and it will be obvious to the users that something is wrong. Again, the business model with a service contract is a good incitement for the users to immediately report the problem; it would be critical if they had to pay for the repair themselves.

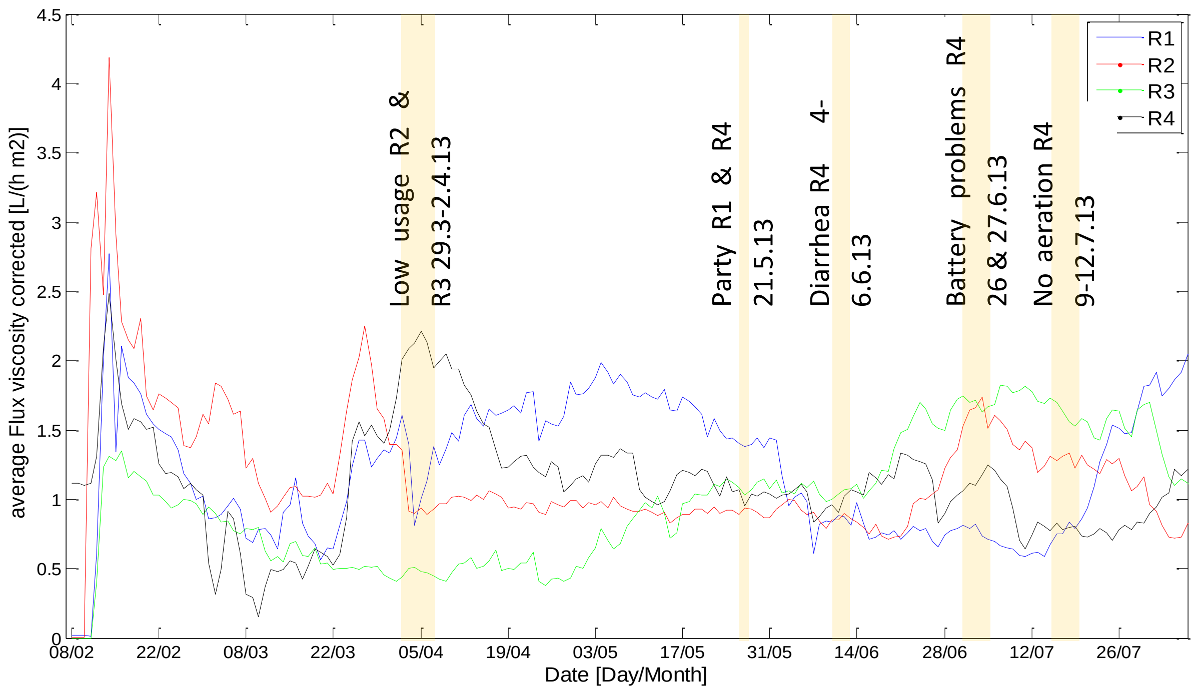


Figure 5: Viscosity corrected daily flux data.

Conclusions

The stress tests show that the water recovery system is quite robust against temporary changes in load. In all scenarios, the influence of the stress test on NO_3-N, NO_2-N and pH was within the experimental variations. The experiments highlighted that higher COD, NH_4-N and color intensity occur during overloading or insufficient aeration. To overcome this problem, one would require a higher chlorine dosage or a more efficient electrolysis. Short-term increase in organic loading and color intensity, however, does not compromise the hygienic quality of the water. Hygienic quality problems in the system can occur during longer systems failures (due to re-growth of pathogens) or if the membrane is mechanically damaged (would lead to turbidity). Long-term conditions of low oxygen should thus be avoided. Furthermore, long-term overloading or technical problems with aeration results in decreased capacity (flux) and long recovery times.

Solutions to short- and long-term failures can be found on different levels:

1) Increased technical robustness. Good and strong air pumps and batteries; overcapacity of electrolysis and solar panels etc. can handle overloading and reduce the probability of technical failure. Obviously, good quality, large-capacity technical devices have a price. Balancing quality and costs is one of the goals of the technical optimization foreseen within the acceleration grant, but only long-time field tests will be able to verify the success of this optimization.

2) Socio-economic measures. Setting the right (financial) incitements for rapid repairs of failing technical parts is an important part of the business model. The chosen model with a service contract is already a basis for a functioning system. However, even if the users are not paying for the repair (and thus inform the company faster about the problem), it must also be in the interest of the firm to solve the problem as soon as possible. Overloading due to parties and diarrhea is a problem of behavior and health status. Understanding that the obvious poor quality regarding color is short-term and per se not critical from a hygiene point of view may be important, especially since both cases are high-risk situations for the spreading of pathogens (it would be highly critical if hand washing was abolished in exactly these situations because of perceived low quality of the water).

3) Short-term technical solutions. For short-term problems of overloading or technical failure, additional dosing of chlorine by the service personal to the clean water tank may be a pragmatic and rapid solution. Due to short travel distances, such measures can easily be taken on-demand, but the exact mode will have to be tested in the field.

The following figure shows a risk matrix of the performed stress tests. One important aim of the Blue Diversion toilet is to improve the hygienic conditions and thus reduce the probability of diarrhea. To reach this goal, it is critical to make sure that people dare to use the water during diarrhea incidents, either through technical means (e.g. intermediate chlorine dosing) or through information ("*short-term* impairment of color is not problematic"). The latter may be problematic since the visual aspects of the water is an important long-term quality criteria. Our aim is to make sure that the probability of technical problems will not be higher than medium (lower than the probability of parties and diarrhea). Obviously, it would be desirable if the probability were low, but only practice will tell whether this is possible.

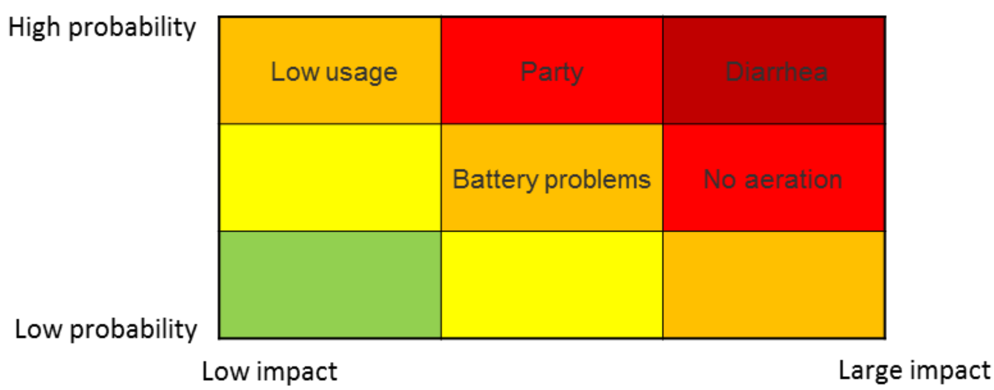


Figure 6: Risk matrix with the probability in the y direction and the seriousness of the impacts in the x direction