Measures to mitigate direct flood risks at riverbank filtration sites with a focus on India

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Abstract: The direct entry of flood water, resultant contamination and damage to groundwater and riverbank filtration (RBF) wells frequently cause the disruption of drinking water production in flood-prone areas worldwide, especially in India and other regions of South and South East Asia influenced by the monsoon. The aim of this paper is to identify critical flood-prone points in the present practice of well construction in India. The focus is on field investigations conducted on wells at the RBF sites in Uttarakhand and at some sites in Germany. Methods to determine whether the annular space of vertical wells and caissons of large-diameter wells are watertight were tested for their practical application in the field in India and Germany. The investigations showed that for a caisson well in poor sanitary condition, flood water can short circuit into the well within 20–45 min along preferential flow paths to a shallow groundwater table. In case of vertical wells chambers in Germany, >300 L of water seeped into the well chamber during a 10-min observation period. The sealing of the annulus between the borehole wall and casing of vertical wells and watertightness measures to well chambers and their covers and well heads to prevent short-circuiting are discussed in context to prevalent practice in India.

Keywords: riverbank filtration, flood, flood-proof well, watertight seal, watertightness test

1. Introduction

Groundwater and riverbank filtration (RBF) wells are potentially at risk of contamination and damage during floods, especially those that are typically located in low-relief and floodplain areas (Ascott et al. 2016; Derx et al. 2013; Hunt et al. 2005; Knappett et al. 2012; Luby et al. 2006, 2008; Oberzill 1956; Rambags et al. 2011; Ray et al. 2002), but also on topographically level bankside areas in submontane and mountainous regions (Sandhu et al. 2013, 2016; Wett et al. 2002). While direct risks of floods include an apparent deterioration of abstracted water quality (turbid water) due to the direct entry of flood water and breakdown of water production due to damage to well infrastructure (e.g. electrical system and pumps), the microbiological contamination to the abstracted raw water is considered the most severe risk to human health (Rambags et al. 2011) that has also been recognized as a health-hazard within the framework of a risk-based management for RBF sites (Bartak et al. 2015). The different transport pathways of flood water into a well depend on the extent of flooding (inundation) of the well field, the location of wells, type of wells (vertical, caisson, horizontal collector), design and construction of well chamber (above / below ground) and the sealing of the annular space between the well casing and borehole wall between ground level and the groundwater table (Bieske et al. 1998; Knappett et al. 2012; Rambags et al. 2011; Sandhu et al. 2013, 2016; Treskatis 2014). These pathways range from the shortest by direct entry (short-circuiting) to longer pathways by infiltration of flood water into the aquifer and its eventual transport to the production well.

Some reported incidences of waterborne disease outbreaks in India that can be directly linked to the drinking water supply, resulted from wastewater, overland runoff due to extreme rainfall and flood water coming into contact with drinking water (Table 1). Thus during monsoon floods and extreme flood events in India, there are multiple pathways to contamination of drinking water between the points of abstraction of raw water, through the treatment process and distribution network to the consumer (Sandhu et al. 2013). However, when considering riverbank filtration (RBF) in the context of a multiple-barrier approach to prevent contamination of drinking water, RBF offers the first important barrier between the source of the water and point of abstraction in terms of a significant removal of pathogens and turbidity in India. Post-flood investigations of groundwater quality at the RBF site in Srinagar (Uttarakhand; "site description"), where it was clearly apparent that flood water had directly entered the aquifer through openings in the well and handpump heads, showed high counts of total coliform and E. coli initially that only decreased after around four to five months of pumping (Table 2). Once the turbidity of the abstracted water from the vertical wells had decreased to <5 NTU (permissible limit in the absence of any other source of water according to IS 10500 2012), the water was disinfected with sodium hypochlorite and supplied for drinking.

Table 1. Some incidences of waterborne disease outbreaks in India directly related to ingestion of contaminated water

Location (state)[reference]	Re-porting period	No. of reported cases	Clinical diagnosis (positive cases of detected pathogens)	Reported cause of outbreak
Lalpur (Gujarat) [a]	12/2010–01/2011	330	Gastroenteritis (+ Vib-rio Cholerae: 19 cases)	Leakages in drinking water supply network
South Dumdum municipality (West Bengal) [b]	02/2007–05/2007	103 (sus-pected)	Typhoid [+Salmonella (enterica) Typhi: 1 of 4 cases were positive]	Intermittent supply of non-chlorinated water in pipe adjacent to open drain connected with sewerage system; faecal contamination of water
Hyderabad (Andhra Pradesh) [c]	03/2005–12/2005	1,611	Hepatitis E Virus (HEV)	Significantly high attack rate where water supply pipes crossed open drains. Crossing water pipelines were repaired &

				attack rates declined.
Baripada (Orissa) [d]	01/2004–03/2004	538	HEV (+Immuno-globulin M antibodies to HEV: 47 out of 48)	Untreated water originating from river supplied (due to strike of waterworks employees)
Gokulpuri (New Delhi) [e]	01/2000–03/2003	141	HEV (41)	Faecal contamination of piped drinking water
Chennai [f]	10/1992	~9,000	Gastroenteritis (+Rotavirus: 7)	Cross-contamination of water in a corroded water distribution system with sewers, and surface run-off during the monsoon from overflowing cesspools

[a] Shah et al. (2012); [b] Bhunia et al. (2009); [c] Sailaja et al. (2009); [d] Swain et al. (2010); [e] Hazam et al. (2010); [f] Jothikumar et al. (1994)

Table 2. Bacteriological indicator counts (in MPN / 100 mL) in wells from direct entry of flood-water at RBF site Srinagar, Uttarakhand, from July (soon after flood / mid-June) to December 2013 (n=1, unless otherwise indicated)

Sample	July (n=2)		September		November		December	
	TC	E. coli	TC	E. coli	TC	E. coli	TC	E. coli
Alaknanda river	11,999	744	9,800	3,000	>112,000	>112,000	5,000	900
vertical well DDP	n.d.	n.d.	12.0	<1.0	2.0	<1.0	n.d.	n.d.
vertical well SF	2,600*	435*	6.3	<1.0	1.0	<1.0	<1.0	<1.0
handpump	1,199*	148*	22.6	<1.0	3.0	<1.0	1.0	<1.0

* median; TC: total coliform; DDP: Deen Dayal Park; SF: Silk Farm; n.d.: not determined

According to technical standards for well construction in some countries (e.g. Germany, USA), the annulus between the well casing and the surrounding aquifer must be sealed layerwise with clay pellets that swell after absorbing moisture to prevent "short circuiting" or the seepage of flood water along the well casing and borehole wall (DVGW 2001; Knappett et al. 2012). Usually such specific clay pellets are commercially available. This provides a barrier to contamination of the well from flood water to some extent. More elaborate technical measures to prevent the direct entry of flood water into wells using watertight well tops and electrical fittings (for cables and connections) and other flood-proofing measures have been established based on experiences of some public water supply companies in western Europe (Rambags et al. 2011; Treskatis 2014). In developing countries, such as in South Asia (e.g. Bangladesh, India), international development programmes (WHO, UNICEF) and national guidelines have recommended the construction of sanitary seals around the base of vertical wells that include the construction of cement or concrete platforms and channels to drain wash water before it seeps into the borehole annulus. However, as the annulus of the borehole is typically filled with soil or sediments obtained during drilling (as observed in Bangladesh, Knappett et al. 2012) or filled up to ground level by filter gravel (as observed by the authors in Uttarakhand in India), the seepage of accumulated surface water (from floods, intense rainfall events or domestic washing activities) along the borehole shaft with resultant microbiological contamination is unlikely to be prevented. This risk can be exacerbated because the cement-concrete used for the sanitary platform-seals tends to shrink upon drying, leading to the formation of cracks / fissures in the platform and development of a gap between the platform and well casing.

To ensure the uninterrupted and safe supply of water from floodprone wells, the water supply organization must be able to ensure that these wells, including their chambers, covers and bases, are watertight against the direct entry of flood water and if necessary to address potential risks and apparent deficits. While some risks are easily visible, e.g. cracks / fissures in the caisson of large-diameter wells and openings in the covers of well casings for power supply cables to the submersible pumps and for water level measurements, other aspects such as the watertightness of well chambers and covers and non-leaky caissons are difficult to determine. Although geophysical (DVGW 2005) and tracer gas (Treskatis 2015) methods can be used to detect short circuit pathways, their application requires trained personnel and elaborate equipment, both of which imply a substantial investment for a water supply organization especially in developing countries. As well construction companies in India usually do not use these methods, there is an absence of service providers for the same in the industry.

The aim of this paper is to identify critical weak points in the present practice of well construction in India through which flood water can directly contaminate wells. The focus is on field investigations conducted on wells at the RBF sites in Uttarakhand, India (Fig. 1). Different methods to determine whether well chambers, their covers and well caissons are watertight were investigated for their feasibility in the laboratory and subsequently tested for their practical application in the field in Germany and India. Techniques to seal the wells beneath the well heads to prevent seepage and designs for watertight well chambers are discussed in context to conditions in India.

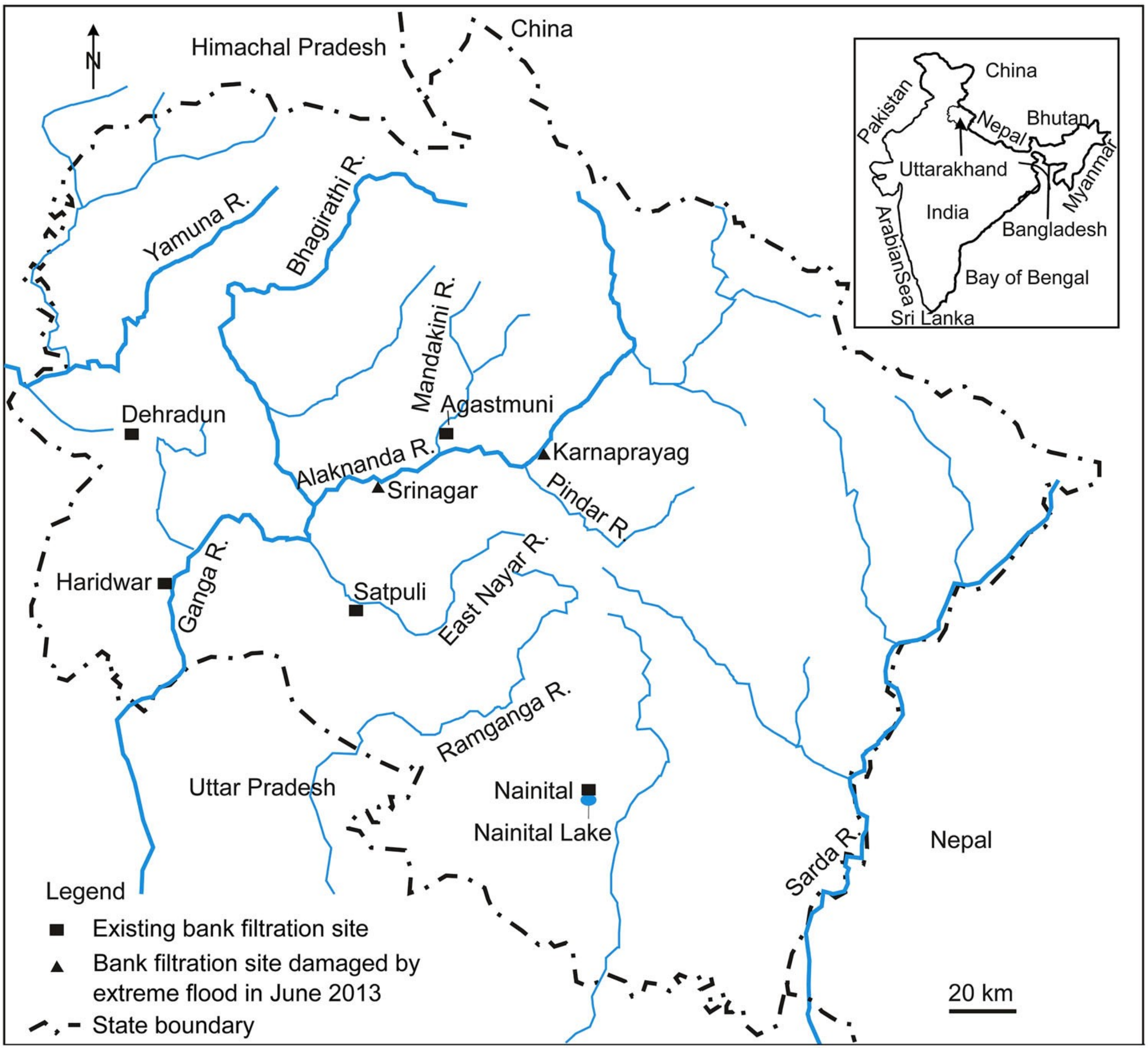

Fig. 1. RBF sites in the state of Uttarakhand, India

2. Site description

The extreme and unprecedented (highest-ever recorded) flood in Uttarakhand from 15–17 June 2013 was characterized by an increase in the Alaknanda River level of >15 m at some RBF sites e.g. Srinagar. Even those RBF sites that were built in 2010 around 7 m above the annual mean flood level and thereby considered sufficiently safe from direct flood-risks, such as Srinagar and Gauchar, were inundated by the Alaknanda River and buried beneath 1.5–3 m thick sand deposits (Sandhu et al. 2016). The severity of damage caused to the RBF sites in terms of disruption of water supply and failure of abstraction equipment (pumps, disinfection apparatus, electricity supply and installations) and the channel widening of the river at the RBF site in Karnaprayag by 20–30 m, was far more serious than just the inundation of the RBF wells by the flood water.

Taking the June 2013 flood as a reference and based on field experience and post-flood damage assessments, it is evident that the most important direct flood-risk is the direct entry of flood water into the well through the critical points listed in Table 3.

Table 3. Summary of direct flood-risks to RBF sites in Uttarakhand and critical points on wells

Direct flood-risk	Haridwar	Srinagar	Gauchar	Karnaprayag
Well design above ground level				
- Absence of well chamber	n/a	x	x	x
- Non-watertight well head or cracks / fissures in caisson	x*	x	x	x
- Absence of concrete base around well head (sanitary seal)	x*	n/a	x	x
- Non-watertight control panel	n/a	x	n/a	x
Well design below ground level				
- Absence of borehole annulus sealing with swelling clay pellets between groundwater table and ground surface	x	x	x	x

x: applicable; x*: applicable for some wells; n/a: not applicable

3. Field investigations

3.1. Investigations of seals around large diameter caisson wells

While the critical points above ground through which flood water can directly enter wells was apparent and identifiable through site audits (Table 3) using specifically designed protocols, the effectiveness of the subsurface sealing could not be easily determined. To check the watertightness of concrete seals placed around the base of large-diameter caisson wells in Haridwar, a salt tracer (NaCl solution) was poured into the ground within 1 m distance from a RBF well caisson (Fig. 2a) with and without a concrete seal (Fig. 2b, 2c). The electrical conductivity (EC) of the abstracted water was measured at regular intervals over a 24 h period.

Fig. 2a. Principle of using a tracer to illustrate the pathway of contamination into a caisson well (e.g. Haridwar) due to seepage of flood water (Sandhu et al. 2016). **b** Caisson well in Haridwar in good sanitary condition, whose base is protected by concrete seal / apron. **c** Well with cracks / fissures in the caisson and the absence of a concrete seal.

3.2. Trial to determine watertight condition of vertical well chamber at RBF site in Germany

Considering that most wells in India do not have well chambers, which on the other hand are common in western Europe, some methods to determine whether well chambers and their covers are watertight were conceived and tested in the laboratory. The application of the methods depends on the construction of the well chamber and cover. For this, impounding (of water) experiments using large-diameter (≥ 1 m) cylinders or rings are practicable on account of easy (and cheap) availability of material (steel) compared to using commercially available water barriers (expensive) or sand sacks (difficult to maneuver when saturated).

Other options to test the watertightness of well chambers are to either depressurize (negative pressure / vacuum) or to pressurize the well chamber (positive pressure) using pumps and using coloured contrasting smoke (e.g. generated from cartridges). For this all openings in the well chambers (drainage and ventilation) have to be sealed and the well chamber has to be covered (e.g. within a tent, which is difficult during windy conditions). Technically more elaborate methods that have industrial applications, may also be considered, such as a mixture of hydrogen (5%) and nitrogen (95%) gas (Treskatis 2015). A non-watertight point in the well chamber is identified when a device (Sensistor Sentrac from the firm Inficon) measures the concentration of the escaping gas out of the well chamber relative to the ambient gas concentration.

During impounding experiments it is important that a minimum amount of impounded water seeps away into the surrounding ground, other than into the well chamber through eventual non-watertight points. Under laboratory conditions, a double-ring cylinder proved most useful (Fig. 3a-c). The water intended to seep into the well is impounded in the inner chamber that is open at the bottom of the double ring cylinder. Commercially available swelling clay is placed beneath the outer ring (Fig. 3b). Upon wetting, the clay swells and seals the annulus between the outer ring and underlying surface. In the outer ring that is sealed at the bottom, the stored water serves as a ballast to press the double ring cylinder onto the underlying surface (Fig. 3c).

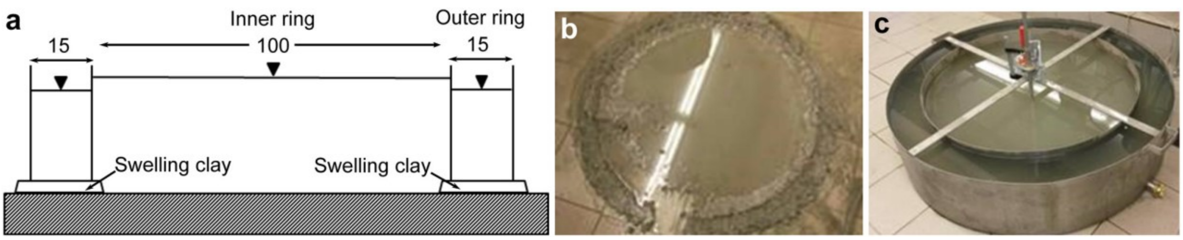

Fig. 3a. Schematic of double ring cylinder (dimensions in cm). **b** Application of swelling clay. **c** Impounded water in inner ring and ballast water in outer ring of cylinder.

Subsequently an impounding experiment was conducted on a RBF well by the Elbe River in Germany (Fig. 4a). However, due to the slightly larger diameter of the cover of the RBF well chamber compared to the diameter of the inner ring of the double ring cylinder used in the laboratory, a single ring cylinder of larger diameter had to be used (Fig. 4b). Groundwater abstracted at a rate of 32.6 L/min was pumped from a nearby monitoring well into the cylinder. The water level in the cylinder was measured with a point gauge (Fig. 4c).

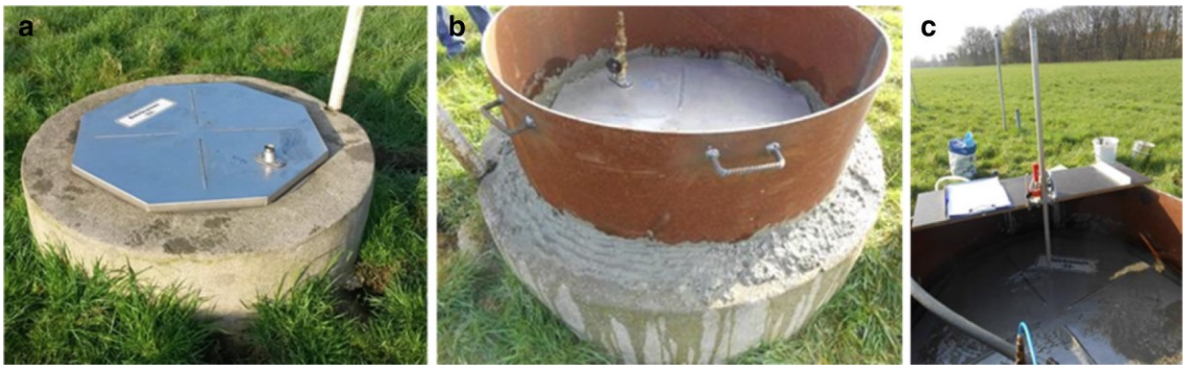

Fig. 4a. RBF well used for field trial in Germany. **b** Cylinder placed atop well chamber and sealed with swelling clay at interface. **c** Water level measurement.

3.3. Trial to determine watertightness of annular sealing of vertical wells at a RBF site in India

To check the watertightness of the sealing of the annular space between the well casing and borehole wall of vertical wells and to identify short-circuiting pathways, the infiltration of a NaCl tracer combined with the determination of the seepage flux was considered. As typically encountered in India, the supply pipe and head of the vertical well were exposed at the RBF site in Uttarakhand (i.e. not enclosed within a well chamber). Thus it was not possible to use the set-up shown in Fig. 4, because any impounded water would have directly entered through visible openings in the well head. Consequently eight PVC pipes with a diameter of 200 mm and a length of 1 m were placed around the well casing and driven to a depth of 0.2 m below ground level (Fig. 5).

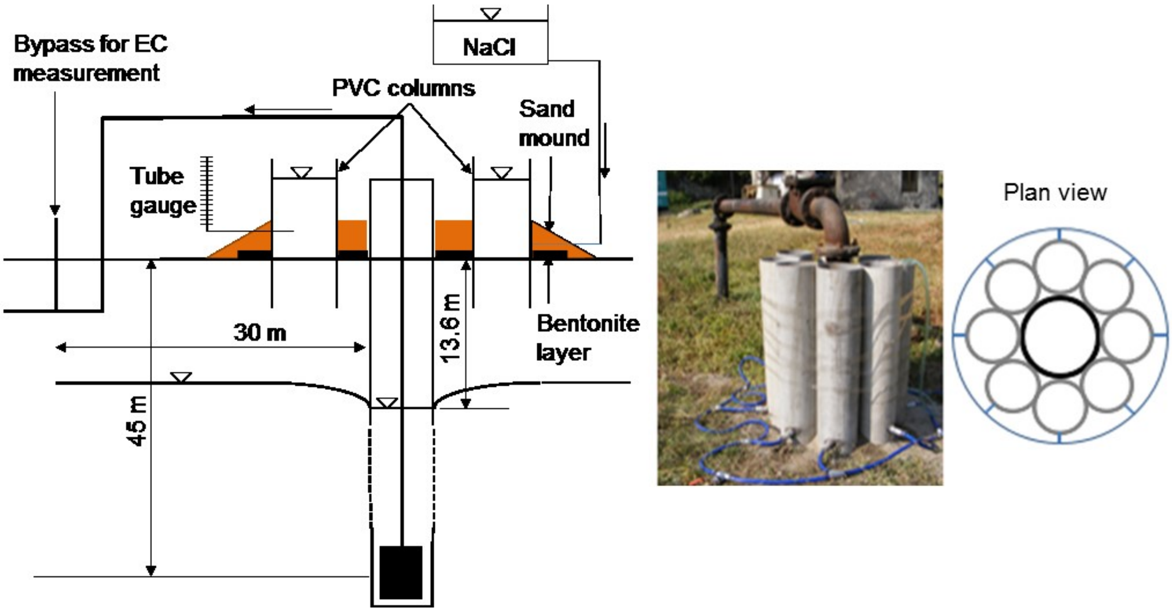

Fig. 5. Set-up for tracer infiltration and determination of seepage flux at a RBF well in India (Handschak & Musche, TU Dresden & HTW Dresden, unpublished figure)

The PVC pipes were interconnected by tubes to ensure an equal water level in each pipe. A flexible tube gauge was used to read the water level in the pipes and to determine the seepage flux. The NaCl tracer was supplied from a 200 L storage tank placed atop a nearby roof. All material for the experiment was purchased at the local market and is easily available in India.

Due to the high infiltration rate and originally unsaturated soil at ground level it was not possible to create an impoundment during the first test. Therefore rubber sheets were placed at the bottom of each column (pipe) to enable the water level to rise. Once impounded, the rubber sheets were suddenly removed and the reading of the water level commenced. However, due to the higher head in the columns, the water seeped upwards through the soil around the columns and spread to the surrounding ground. A sand embankment to increase the weight was insufficient to prevent erosion of the soil. A subsequently placed bentonite layer, weighed down by a mound of sand, was applied around the columns. With this setting no undesired outlet of the tracer solution to the ground was observed. Overall three NaCl tracer infiltrations, each of 200 L, were conducted (Fig. 6), whereby the infiltration rate decreased from 58 L/min/m² on day 1 to 17 L/min/m² on day 2. The EC of the abstracted water was measured on a bypass of the supply pipe at regular intervals over a 72 h period. Additionally the water level and the temperature in the well were recorded to deduce the operating hours of the pump.

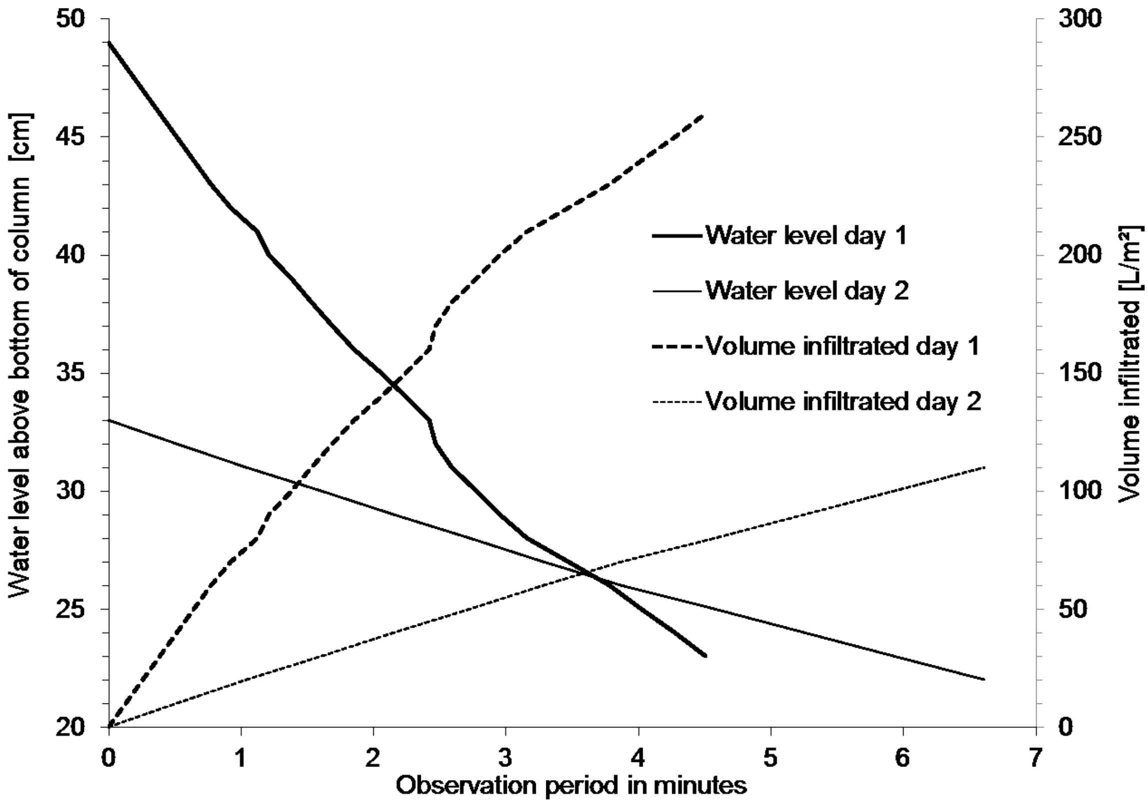

Fig. 6. Infiltration of water around the perimeter of a RBF vertical well casing in India (Handschak and Musche, TU Dresden and HTW Dresden, unpublished data)

4. Results

4.1. Travel time of flood water by direct entry into large-diameter caisson wells

Before the NaCl tracer test on a caisson well without a concrete seal in Haridwar, the pumped water had an ambient EC of 201 µS/cm. As a result of the infiltration of a total volume of ~0.48 m³ of tracer solution (125 g/L NaCl) at the well, having an EC of ~180 mS/cm, the EC of the pumped water increased to a maximum of 488 µS/cm. 50 % of the peak EC value was observed within a very short time of 20 min (Fig. 7). The relatively quick breakthrough of the tracer emphasizes the high risk of contamination not only from direct flood water entry, but also from seepage of grey water from anthropogenic domestic activities taking place near the well (e.g. bathing, washing and defecation).

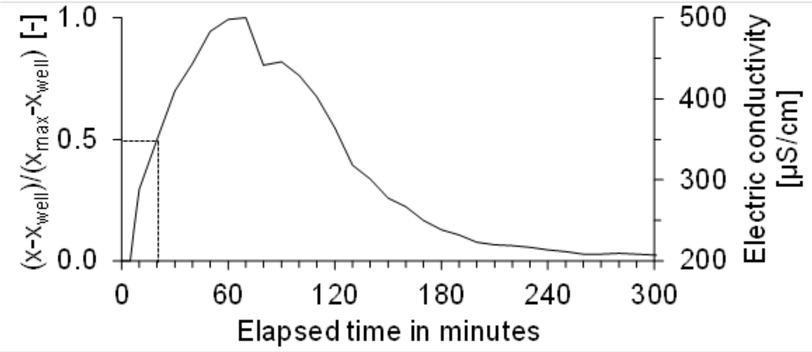

Fig. 7. Breakthrough of 50 % of tracer into a RBF well was measured after 20 min (t_{50}) (x = EC of pumped water from well; x_{max} = maximum EC of pumped water; x_{well} = ambient EC of well water)

Similar experiments were conducted on other caisson wells without a concrete seal in Haridwar. However, taking one example for the latter experiments, a marginal but steady increase in EC of 12–18 µS/cm from the ambient value was observed for the well after ~3 h since the start of the application of the tracer. A peak of 489 µS/cm was attained in pumped water around 1 h later (~4 h since tracer application). An explanation for the low increase in EC could be the dilution of a small amount of tracer used with the significant volume of water stored within the caisson. In this case only around 0.02 m^3 of tracer solution having an EC of 112 mS/cm to a total volume of pumped water of ~500 m^3 having a natural EC of about 477 µS/cm would result in an increase in EC by about 12 µS/cm if the mixing happens over a period of around 4.5 h.

For wells with a concrete seal (e.g. Fig. 2b), the arrival of the tracer was not recorded within the 24 h observation period. Thus it may be concluded that for a caisson well, without a concrete seal and in poor sanitary condition, water that accumulates on the ground surface within 1 m of the caisson as runoff from an intense rainfall event, floods or bathing and washing, can come into contact with the groundwater and eventually flow into the well within 5 h. Furthermore, the seepage of flood or wastewater from anthropogenic activities at the well along preferential flow paths (such as the outer wall of the caisson) and shallow depth to the groundwater table, can result in even shorter travel times of 20–45 min to enter the well.

4.2. Direct entry of flood water into well chambers of vertical wells

The impounding experiment began with the commencement of pumping of water into the cylinder. Initially the water level rose to a point just above the well head cover. But thereafter it was observed that despite a constant inflow of 32.6 L/min, the water level steadily decreased and could not be maintained constant. Accordingly for an observed decrease in the impounded water level of 9 mm after a 10 min period and with a total volume of 326 L pumped into the cylinder during this period, a total outflow of 334 L was calculated (Fig. 8). The additional 8.2 L of water that flowed out were contributed from the initial storage in the cylinder. During the experiment no outflow of water was noticed from the clay seal around the cylinder. Thus the heavy mass of the cylinder coupled with the swelling clay had apparently created an effective seal between the cylinder and well head. Hence it can be concluded that 334 L of water seeped into the well chamber during a 10 min observation period.

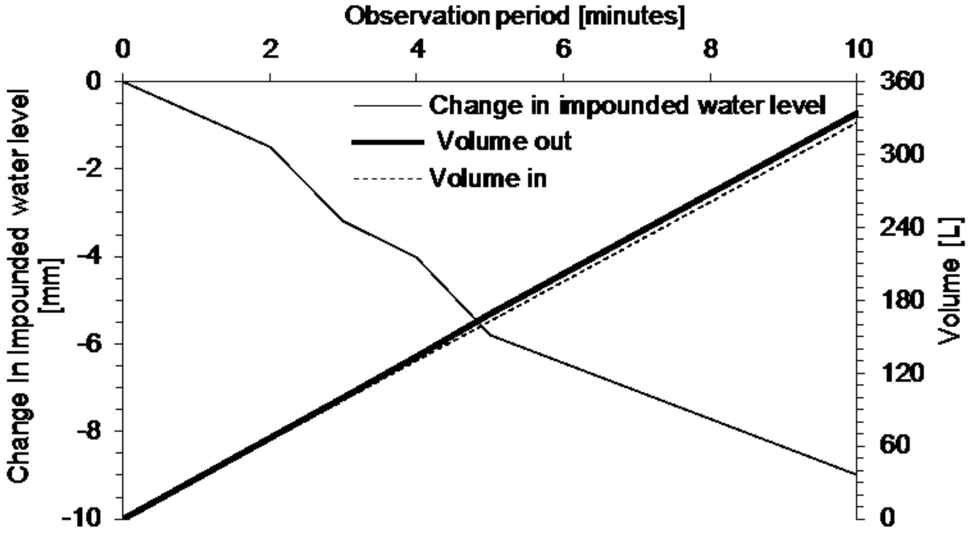

Fig. 8. Seepage of water into well chamber during impounding experiment

After conclusion of the experiment and removal of the apparatus, the well cover was opened and inspected for non-watertight points through which the impounded water seeped into the chamber. The rubber ring that is intended to provide a seal between the well cover and the rim or frame of the cover had a visible gap and did not fully encompass the rim. Furthermore gaps were visible between the rim and the well head and in the area where the ladder is mounted to the chamber. Subsequently, with the intention to conduct a pressurization experiment to observe if smoke generated from cartridges placed inside the closed well chamber escapes, it was observed that smoke escaped even without the need to pressurize the chamber.

4.3. Seepage of flood water through annular space into a vertical well at a RBF site in India

The infiltration of the NaCl tracer ("Trial to determine watertightness of annular sealing of vertical wells at a RBF site in India") to determine short-circuiting through the annular space between the well casing and borehole wall appear to be inconclusive if the EC of the abstracted well water is considered because no significant increase in the EC was recorded. Data from water level loggers installed in the production well showed that during the 72 h period, the well was nearly continuously in operation except for 1 h per day when the well was shut down as part of its routine operational schedule. However, due to the relatively high hydraulic conductivity (3×10^{-4} m/s; determined by a pumping test in 2015), low drawdown (1 m) and corresponding low gradient, the tracer could have drifted past the well and not been captured by it. Or the tracer may not have reached the groundwater table during this period. These conclusions are substantiated by the fact that the water level in the well was not too shallow (13.6 m below ground level during operation) and the well is quite deep (50 m). The exact filter-screen length and depth were not available. Nevertheless, it can be concluded that there is no immediate risk from surface water contamination, at least during an intensive rainfall even or sporadic washing / bathing activities immediately next to the well.

5. Discussion

5.1. Improved sealing of well annulus

As already mentioned in literature and demonstrated in previous sections, the need to maintain caissons (large-diameter wells) and well heads (vertical wells) in good technical and sanitary condition (cracks / fissures should be immediately repaired) and to appropriately seal the well base is imperative. It must be noted that in the present practice of constructing wells in India, the annulus in the borehole around the casing in between the groundwater table and ground surface is not always sealed with swelling clay, although this is recommended (Bieske et al. 1998; RDSO 2014). The on-site presence of the authors during the construction of vertical wells at some RBF sites in Uttarakhand provided useful insights concerning the subsurface sealing of the annulus of the borehole between the filter section and ground surface. In practice and contrary to theory, the well construction company often filled the annulus up to nearly the ground surface with filter gravel. Unlike Bangladesh, where the practice is to fill the annulus with the subsurface material obtained during borehole drilling and thus provides a “short circuit” for flood water and wastewater from domestic activities at the well (Knappett et al. 2012), the use of filter gravel will exacerbate the short circuit by causing greater seepage and further shortening the time for flood water to reach the groundwater table. A review of available well construction data and comparison with the German Standard (DVGW 2001) showed that there is potential to improve the sealing of the annulus.

For the improved sealing, the annulus should ideally be sealed using commercially available swelling clay pellets at critical points such as at the ground surface and at the depth of the groundwater table (Fig. 9). The available bentonite in India attains stability of form and against erosion and can be used for sealing. The sealing at the groundwater table should, as far as possible, remain moist year-round. It is necessary to take the lowest pre-monsoon (deepest) groundwater table into consideration so that the lower most clay pellets are in continuous contact with the groundwater table and thus the continuous swelling is sustained. If this is not the case, then drying of the pellets will result in shrinkage leading to the formation of cracks in the clay and the creation of a gap between the clay seal and the casing pipe of the well and eventually also with the borehole wall. This gap will result in preferential flow path for water to short circuit. In case a greater depth has to be sealed that would require large quantities of clay pellets (cost factor), then the total depth over which the clay seal is to be installed may be broken into an upper and lower sealing segment with a sand segment in between (Fig. 9). The installation of a finer counter filter gravel pack (1–2 mm) between the overlying sealing of annulus and the underlying main filter gravel packs (2–3.1 mm and 3.1–5.6 mm) will prevent the clay from subsiding into the pores of the coarser filter grains, especially since the main gravel pack is expected to subside during well operation.

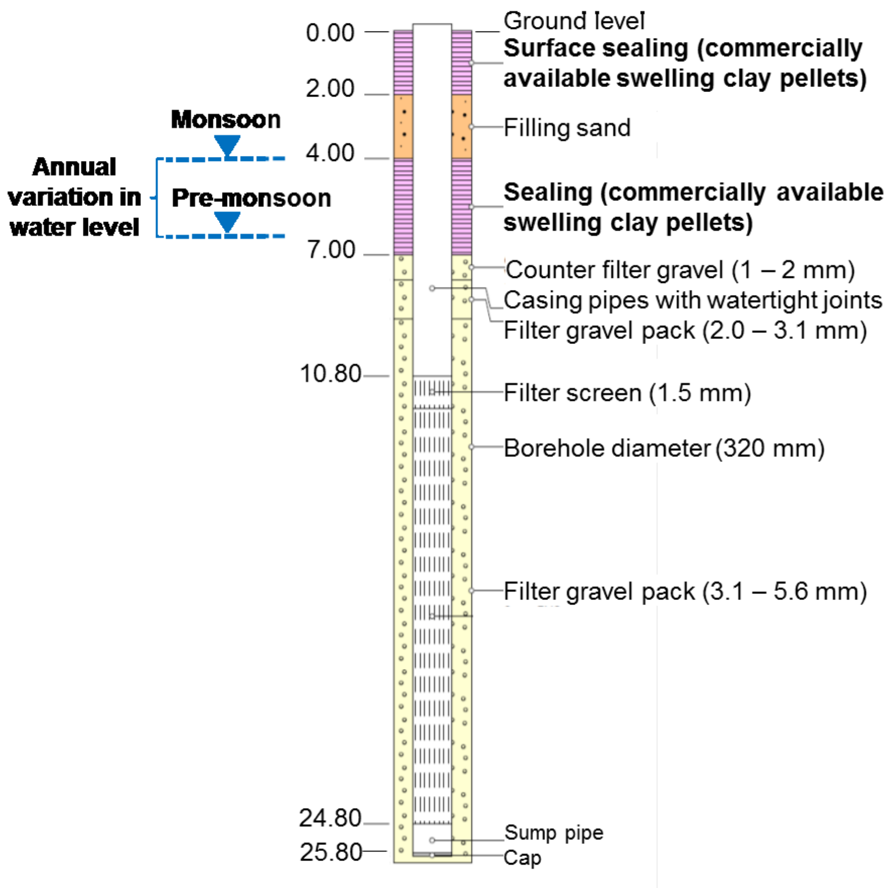

Fig. 9. Proposed sealing of RBF well with sealing of annulus (depth in metres below ground level)

5.2 Watertightness measures for well chambers, well chamber covers and well heads

Safeguarding RBF wells during floods by preventing the direct entry of flood water (short circuiting) and ensuring continuous operation remain critical issues for sustainable drinking water production not only in India but most countries affected by floods during monsoon in South and South-East Asia. While practical measures have been taken by public water supply companies in Germany (e.g. in Görlitz by the Neisse River, in Leipzig by the Mulde River and in Dresden by the Elbe River) and the Netherlands to flood-proof well chambers using watertight elements and other technical measures (Rambags et al. 2011), designs for flood-proof well chambers for RBF sites in India exist only at a conceptual level (Fig. 10).

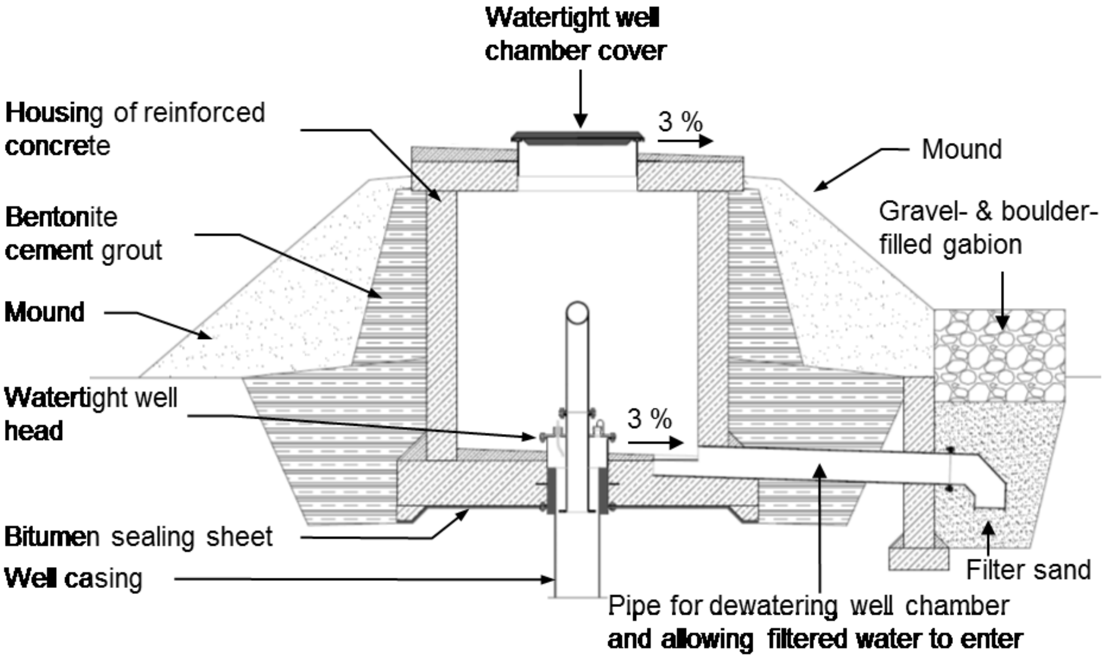

Fig. 10. Conceptual design for a well chamber with a watertight cover and well head

The covers of well chambers and the interface between the individual structural parts of the well chamber also must be watertight. Watertightness of well chamber covers can be ensured by attaching durable rubber seals with a suitable anchoring onto the frames of the covers. The condition of such seals has to be regularly inspected. As demonstrated in the impounding experiment, it is important that the frame of the well chamber cover is also attached in a watertight manner. The cover must fit properly onto the frame and the opening mechanism has to resist the pressure while inundated. In west European countries (e.g. Germany and The Netherlands) such frames and covers are manufactured of stainless steel. Most designs of such covers are patented, the covers and frames are long-lasting, resistant to corrosion and have smooth surfaces enabling a watertight adhesion of the sealing surfaces. There are various covers commercially available and inexpensive sealants or adhesives specifically available for wells in Europe.

The requirements for waterproofing concrete, where the crack-width is limited by special reinforcement, mixture and processing of the concrete are high. As the authors observed from field investigations and from the experience of well construction companies, a watertight construction of the well chamber and all its interfaces would be difficult to realize. Furthermore the import of watertight well chamber covers could be cost-intensive. According to the manufacturers specifications, the covers and their seals have to be free from even small naturally occurring intrusions / obstructions that need to be carefully removed prior to closure of the well chamber cover.

This is difficult to ensure in the field. Additionally, there is some expansion of the material if temperature changes and this is likely to occur in regions with high temperatures (e.g. India and most parts of South Asia).

Consequently the water supply company focused on trying to make the well head watertight. It is recommended that the well head has to be connected watertight with the well casing pipe (Bieske et al. 1998). The cable inlet for the electricity supply to the submersible pump and opening for water level measurements are sealed with special gaskets suitable for high pressure. The well head should be made of corrosion-resistant steel (e.g. stainless steel, so as to prevent corrosion resulting from condensation of the natural water content in the air within the well chamber). Thus, a durable sealing is achieved, that prevents flood water from entering the borehole annulus and eventually existing short-circuit pathways.

In case the buoyancy created by the rising groundwater level during a flood is greater than the force exerted by the weight of the well chamber, then a controlled and deliberate entry of filtered flood water into the well chamber (Fig. 10; through the dewatering pipe) could serve as a counter force to the buoyancy and prevent an uplift of the well chamber. In this case it is absolutely necessary to ensure a watertight well head. On the other hand, if the weight of the well chamber is greater than the buoyancy but vulnerable equipment is placed within the well chamber and cannot be protected otherwise, then it is necessary to also ensure a watertight well chamber cover. This will at least safeguard against unfiltered water from entering the well.

5.3 Flood-risk management for RBF sites

Risks associated with floods should be included in risk-based management plans for RBF sites, such as in the formation of a WHO water safety plan (WSP) that is specific for each RBF site and which should be implemented prior to more engineered post-treatment options (Bartak et al. 2015; Sandhu et al. 2016). Accordingly, such WSPs address preventive measures to control general pathogen-related risks in the catchment and in the treatment process, as well as monitoring requirements and corrective actions. However, operational experience of Indian water supply organizations has shown that the implementation of preventive measures to control general pathogen-related risks in the treatment process would be more effective than in the catchment because of the influence of a multitude of factors for the latter (e.g. land use, pollution of water sources, population pressure). Apart from monitoring and measurement of disinfection residuals throughout the distribution system, WSPs should include regular sanitary surveys around the well heads, bore holes and well houses, well maintenance, and prohibition of public washing, cattle and defecation in or around the wells.

In practice and at least in Europe, water suppliers can initiate a controlled shut-down of wells (or a series of wells) in case a deterioration of water quality is observed in the abstracted water during floods (increased turbidity, coliforms) and operate other wells that may not be affected by a flood. Water quality deteriorations can be identified centrally at the water works through frequent manual sampling or online monitoring to identify the affected wells. On the other hand in India, if the well head is inundated and usually online monitoring of crucial parameters such as turbidity is not the norm, well heads are not watertight and the power supply to wells may already be disrupted during the flood, the water supply may have to be completely interrupted or switched to emergency measures (e.g. tankers) because contaminated and turbid flood water would have already entered the well through openings for the pump cable and leaky heads. As the aim of the water supplier is to provide drinking water even during floods, the wells could be operated provided the infrastructure is not damaged (power supply, pipes) and as long as the turbidity remains <5 NTU and by increasing the chlorine dosage. But continuous disinfection by conventional methods (e.g. injection of sodium hypochlorite / NaClO), especially in flood-affected areas, is problematic due to storage and supply of disinfectant and functionality of dosage equipment (Sharma et al. 2016). Although wells affected by direct entry of flood water are always cleaned post-flood and before the water is supplied to the consumer, it can take many weeks before coliform counts are considerably lowered (Table 2). Even if shock chlorination is practiced, its effectiveness cannot be guaranteed because a minimum residual chlorine concentration of 0.2 mg/L is unlikely to be achieved continuously as a result of the high chlorine consumption due to the turbid water in the well and surrounding aquifer (which will increase further if the organic content is high).

6. Conclusions

The direct risks from floods to RBF wells, mainly the potential pathways for the direct entry or short-circuiting of flood water into a well, have been discussed in context to information in literature and field experiences of the authors. These direct risks have been verified through field investigations. Nevertheless some potential methods to test the watertightness have been tried under field conditions and are presented in this paper.

The industry in India, supported by applied research, has to play a role in making flood-proof wells. These especially are the fabrication enterprises and suppliers of well construction materials, the well construction company and the water supply organization. India has numerous well construction companies having vast field experience required for constructing high-capacity wells, which are usually demanded by the water supply organisations. From the well constructor's and water supplier's perspective, the contamination of the well through the direct entry of surface water (domestic wastewater, intense rainfall and flood) is addressed by constructing the sanitary seal. While the sanitary sealing of wells, especially the annulus of wells and appropriate protection of well heads (using chambers) is standard practice in most developed countries and also theoretically in South Asian countries, the practice of flood-proof wells with watertight well chamber covers and well heads is rarely followed in developing countries. This paradigm changed for the water supply organization in the state of Uttarakhand after the flood-damage to their RBF sites in 2013. Consequently the water supply organization is motivated to test flood protection measures on a RBF demonstration well within the acknowledged applied research and development projects. The sensitization of water supply practitioners, administrators, researchers and enterprises in India on the need to flood-proof RBF and groundwater wells must be continued through information and education campaigns.

For the construction of flood-proof wells in India, it is necessary to conduct a market survey for the existing availability or future production of well chamber and well head elements and to check how and whether these can be made watertight (e.g. standardized production of concrete shafts or chambers; covers, frames and seals to make the entrance to the chambers watertight; watertight well head components; watertight insulation and housings / chambers for electrical equipment) under various site-specific conditions. In parallel, the presented technologically less intensive but economical methods to determine the watertightness of these well chambers and well heads need to be improved, especially for developing countries.

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