Flood proof wells

Guidelines for the design and operation of water abstraction wells in areas at risk of flooding

Flood proof wells

Guidelines for the design and operation of water abstraction wells in areas at risk of flooding

COLOPHON

Title
Flood proof wells. Guidelines for the design and operation of water abstraction wells in areas at risk of flooding

Report number
PREPARED 2011.007

Deliverable number
Del. 5.2.1

Authors
Femke Rambags, MSc., dr. Klaasjan J. Raat, Inke Leunk, BSc., and dr. Gerard A. van den Berg (KWR)

Quality Assurance
Prof. dr. Pieter J. Stuyfzand (KWR), dr. Lars J. Hem (Sintef)

Document history

Version	Team member	Status	Date update	Comments
v1	Femke Rambags	Draft	23-Dec-2010	
v2	Klaasjan Raat	Draft	25-Feb-2011	updated draft
v3	Klaasjan Raat	Draft	15-Mar-2011	quality checked by Pieter J. Stuyfzand (KWR)
v4	Femke Rambags	Final Draft	21-April-2011	quality checked by Lars J. Hem (SINTEF)
Final	Klaasjan Raat	Final	13-May-2011	

This report is: PU

Preface

This document provides guidance for the design and operation of water wells in areas at risk of flooding, and is intended to be used by water suppliers to guarantee the supply of safe and sufficient water during flood events. This document builds upon the knowhow and practical experiences of water suppliers in the Netherlands and Germany. The authors thank the following persons, who contributed to this report by attending a brainstorm session on November 23, 2010, by providing examples and/or by commenting on drafts of the report:

- Pieter Dammers (Dunea, the Netherlands)
- Thomas Grischek (University of Applied Sciences Dresden, Germany)
- Maria Juhàsz-Holterman (WML, the Netherlands)
- Wim Kessels (WML, the Netherlands)
- Ate Oosterhof (Vitens, the Netherlands)
- Carl van Rosmalen (Brabant Water, the Netherlands)
- Harrie Timmer (Oasen, the Netherlands)
- Theo Vlaar (Waterbedrijf Groningen, the Netherlands)
- Pieter Stuyfzand (KWR Watercycle Research Institute, the Netherlands)
- Lars J. Hem (SINTEF, Norway)

Summary

River floods are the most common natural disaster in Europe, and flood damage is expected to increase in the next decades. Water well fields are among the assets at risk, and flooding of wells may obstruct the supply of safe and sufficient water in affected areas. Most important risks are microbiological infection of the raw water and interruption of the power supply. There are several pathways through which flood water may mix with the production water, either directly via leakage through the infrastructure, or indirectly after infiltration of flood water into underlying aquifers. All these routes should be considered in a risk analysis.

To safeguard the water supply during floods, the design of water wells should be adjusted. In addition, it is essential to have clear management procedures before, during and after floods. These should be drafted in a contingency plan, providing clear instructions on how and when to act, for all persons and institutions involved. With a clear contingency plan and the appropriate technical design, water supply can be assured during floods. Many of the technical measures are relatively easy to implement, such that with little cost investment existing well fields can be made flood proof already.

Guidelines for well design		
	Location	**Preventive and corrective actions**
Site selection	The potential for contamination is enhanced under certain site conditions: • Wells in phreatic aquifers • Wells located in depressions • Wells located near unsealed abandoned wells	• Construction of dikes around the production site and pumping station • Elevation of the well head and/or pumping station • Sealing of abandoned wells • Removal of potential sources of contaminants from the well site
	Preventive measures and corrective action	
Well design, above ground	Contamination of flooded wells can be prevented by a proper design and construction of the well. Exterior design: • ensure that the well head is watertight. Of special concern are the access door, air vent and openings for cables and pipelines • prevent possible uplift of the well head (well chamber) due to buoyancy forces during a flood • let surrounding soil or cement surface slope away from the well • protect well head from vandalism and other damage Interior design: • install a warning system, alarming when water has entered the well head • seal the well head with watertight bolts. Screen the air vent • prevent short-circuiting of flood water by sealing the observation wells (piezometers)	

	• use high quality materials when constructing an observation well
Well design, below ground	Infiltrating flood water may enter the production well via several below ground short-circuit routes. • Seal the uppermost section of the annulus (borehole) with a cement grout or bentonite clay • Clay seals should be installed in the annulus where a well penetrates a confining (clay) layer. Condition of clay seals can be checked using borehole geophysics • Select appropriate materials for the well casing, using knowledge of the water chemistry. Check the condition (joints, cracks, holes) of the well casing regularly, with camera inspections.
Power supply	Without energy, no water. • Inside the well head, make electrical connections and switches watertight • Position electrical transformers in flood-free locations, like mounds • Emergency energy supply should be available

Management procedures	
Prior to floods	• Regular visual inspection of each well: - Well head: signs of vandalism or damage - Warning systems: still operative - Observation wells, air vents: seals, cracks, leaks • Check condition of well casing and annular seals • Water quality samples must be taken periodically and stored in a database for reference (i.e. conductivity, turbidity and pH)
Flood warning and contingency plan	• Flood warning systems should be in operation. Ensure good communication between authorities operating the warning system and water suppliers. • A contingency plan must be set-up, comprising all personal roles and responsibilities and measures with regard to: - safety of employees - alerting all relevant agencies - coordinating emergency support - protection of infrastructure and utilities - availability of transport and access to the terrain - adjustment of operating procedures
Operation during flood	• Maintain water pressure in the distribution network at all times, to prevent flood water from infiltrating the pipelines. Run production wells continuously and at constant discharge • Adjust the operation of the well field, e.g. shut down selected (shallow) wells, intensify water quality monitoring, et cetera. • Add a disinfection step to the water treatment, to ensure microbiological safety . Check the disinfection efficiency at short intervals.

Management procedures	
Flood follow-up action	• Visually inspect the well condition (well head, exterior and interior), restore protection of the well (fences, vegetation), remove sludge and debris from the well site. • Follow the appropriate procedures to recommission each of the water production wells. • Restore the water quality in pipelines by flushing with good quality water • Pipelines and wells should not be released to service until physical, chemical and microbiological water quality parameters have met pre-established criteria.

Contents

1 Introduction

River floods are the most common natural disaster in Europe. Between 1998 and 2004, Europe suffered over 100 major damaging floods and since 1998 floods in Europe have caused some 700 deaths, the evacuation of about half a million people and at least €25 billion in insured economic losses (http://ec.europa.eu/environment/water/flood_risk/index.htm). Several extreme flood events have struck Europe in recent years, such as the Elbe flood in 2002, the UK floods in 2007 and the Central European floods in May, June and August 2010. There is no proof that these extreme floods are a direct consequence of climate change; yet it is expected that, due to climate change, the chances of flooding will increase in many regions of Europe. Flood damage is expected to rise across of western, central and eastern Europe, as well as in Italy and northern parts of Spain. Meanwhile, some north-eastern parts will become less flood-prone (EEA, 2008).

In 2007, the European Commission issued Directive 2007/60/EC on the assessment and management of flood risks. This Directive requires Member States to assess which water courses and coast lines are at risk from flooding, to map the potential flood extent assets and humans at risk in these areas, and to take adequate and coordinated measures to reduce this flood risk. One of the assets at risk is the infrastructure, including infrastructure related to water supply, such as water abstraction wells, treatment plants and the distribution network. Damage to these will obstruct the public water supply in affected areas, both during and after floods.

In European countries, 30-95% of the drinking water is prepared from abstracted groundwater, including river bank infiltrated water (RBF) and artificially recharged surface water. Many well fields are located in river basins, as indicated by the estimated 1-35% share of RBF in national drinking water productions of the various countries. Being close to the river, RBF well fields are at risk of flooding, as indicated by recent examples from the Netherlands (1998, flooding of the Hunze River, Figure 1.1) and Germany (2002, Elbe Flood). Damage to the wells, such as to the electrical system, is one of the direct risks of flooding, but of more concern are indirect effects, especially the contamination of well and underlying aquifer. Under normal conditions, groundwater is of good chemical and microbiological quality, and only mild treatment is required to produce safe drinking water. When flooded, short-circuiting may lead to infiltration of polluted river water into the well and as treatment facilities are often not designed to cope with these or any pollutants, this introduces a risk for human health.

Figure 1.1. Pumping station Onnen (water supply company Groningen, the Netherlands), before (left) and after the 1998 flood (right).

Risks associated with flooding of water wells have been recognized by several water supply companies in Europe, and actions have been taken to reduce these risks. Many of these actions are at the practical level and concern the design, construction and maintenance of water wells. In addition, management procedures have been drafted, providing guidance for the operation of water well fields before, during and after flood events. This knowhow and practical experience is collated in this comprehensive report, providing a guidance document for design and operation of water wells in areas at risk of flooding. The document builds upon existing general guidelines (Wricke et al., 2003; Leunk and Lieverloo, 2007; Makkink et al., 2001), and a brainstorm session held with experts from water supply companies in the Netherlands, on November 23, 2010. Several examples accompany the guidelines, illustrating flood-protective measures that have already been taken by water suppliers in the Netherlands and Germany.

2 Flooding of water well fields: associated risks

This document focuses on flooding of water well fields and what actions to take to safeguard the water supply from these fields. Clearly, other aspects of the water supply chain, such as the treatment facilities and distribution networks, are vulnerable to flooding as well, but these are beyond the scope of this report.

A direct risk of flooding is damage to the well infrastructure, such as the electrical system and pumps, which is often easily noticed by a sudden shutdown of the well. Of more concern are possible indirect effects of flooding, especially contamination and infection of the abstracted raw water. When unnoticed, this may lead to the distribution of contaminated drinking water and subsequent health risks. When noticed, water production wells will be decommissioned and the production capacity of the well field will decrease. In that case, to ensure sufficient water supply, emergency supplies must be accessible or the water production must be taken over by other pumping stations.

Flood water may contain bacteria and viruses from soil, organic debris and sewage systems, along with fertilizers, pesticides, and other chemical contaminants. Microbiological infection of drinking water forms the largest and most direct risk for human health, and direct intrusion of flood water into a well is considered the "worst case" contaminant event. Soil passage provides a barrier against microbial contamination, and a soil residence time of 60-100 days is considered large enough to safeguard microbiological safety of the water (Van der Wielen et al., 2008). Chemical contamination will become a problem when concentrations exceed the maximum allowable values. Problems with chemical parameters depend on the volume of contaminated water entering the well and the concentration of the contaminants in the flood water.

There are several pathways through which flood water may enter a production well (Figure 2.1). The first and most direct pathway is the short-circuiting of flood water into the well through, for instance, the well head or observation wells. The second way is when infiltrating river water enters the well via the annular space between the well casing and the aquifer or via cracks or joints in the well casing. The annular space or gravel pack is often more conductive then the surrounding aquifer, providing a fast flow path. A clay seal built in the annular space should prevent this flow route, but often these seals have not been installed properly. Finally, during a flood, water will infiltrate and may rapidly enter the production aquifer. For shallow, unconfined aquifers this route may be relatively fast, and should be considered in a risk analysis. For confined aquifers, this route is slow and will only lead to deterioration of the water quality at the long term. There are no direct risks associated with this flow path, provided there are no abandoned wells close by.

The aim of this document is to enable safe and sufficient water supply from flooded water well fields. Focus therefore is on the more direct and fast routes of contamination, and not on aquifer contamination in the long run. Technical measures are presented, amongst others, to avoid short-circuiting of river water and to guarantee the power supply to wells. In addition, guidelines for operation of well fields before, during and after floods are provided. Focus of the document is on public wells, operated by professional water suppliers, but many of the guidelines may apply also to private wells.

3 Guidelines for the design of water wells in areas at risk of flooding

The overall objective of a well design is to create a sustainable, efficient well that allows groundwater to move from the aquifer into the well at the desired volume and quality. Guidelines for well design and construction are provided by several text books, including the well-known 'Groundwater and Wells' edited by Sterrett (2007).

Additional guidelines apply when designing and constructing a well in an area at risk of flooding. These additional guidelines are discussed in this chapter. Main purpose of these guidelines is to assure the supply of sufficient and safe raw water from a well field during a flood event.

3.1 Summary

Guidelines for well design		
	Location	**Preventive and corrective actions**
Site selection	The potential for contamination is enhanced under certain site conditions: • Wells in phreatic aquifers • Wells located in depressions • Wells located near unsealed abandoned wells	• Construction of dikes around the production site and pumping station • Elevation of the well head and/or pumping station • Sealing of abandoned wells • Removal of potential sources of contaminants from the well site
	Preventive measures and corrective action	
Well design, above ground	Contamination of flooded wells can be prevented by a proper design and construction of the well. Exterior design: • ensure that the well head is watertight. Of special concern are the access door, air vent and openings for cables and pipelines • prevent possible uplift of the well head (well chamber) due to buoyancy forces during a flood • let surrounding soil or cement surface slope away from the well • protect well head from vandalism and other damage Interior design: • install a warning system, alarming when water has entered the well head • seal the well head with watertight bolts. Screen the air vent • prevent short-circuiting of flood water by sealing the observation wells (piezometers) • use high quality materials when constructing an observation well	
Well design, below ground	Infiltrating flood water may enter the production well via several below ground short-circuit routes. • Seal the uppermost section of the annulus (borehole) with a cement grout or bentonite clay	

	• Clay seals should be installed in the annulus where a well penetrates a confining (clay) layer. Condition of clay seals can be checked using borehole geophysics • Select appropriate materials for the well casing, using knowledge of the water chemistry. Check the condition (joints, cracks, holes) of the well casing regularly, with camera inspections.
Power supply	Without energy, no water. • Inside the well head, make electrical connections and switches watertight • Position electrical transformers in flood-free locations, like mounds • Emergency energy supply should be available

3.2 Guidelines for the design of flood-proof water wells

3.2.1 Water wells: main components

The majority of water abstraction wells in Europe and elsewhere consists of vertical wells. In its most rudimentary form, a well consists of a pvc or steel tube installed in a borehole, with perforations (well screen) at the depth where water is to be abstracted. A modern well, of course, contains many more components, most of which are shown in Figure 3.1.

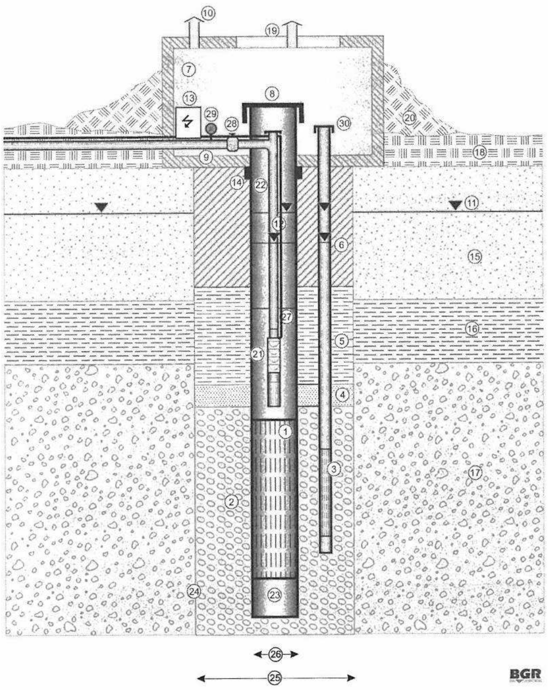


Figure 2.2 Main components of a vertical well: 1 = screen, 2 = filter pack, 3 = piezometer, 4 = sand filter, 5 = annular seal, 6 = annulus filling, 7 = well head, 8 = protective cover, 9 = pipeline, 10 = air vent, 11 = water level of upper aquifer, 12 = water level of lower aquifer, 13 = electrical installations, 14 = foot cementation, 15 = upper aquifer, 16 = aquitard, 17 = lower aquifer (production aquifer), 18 = soil, 19 = access door, 20 = soil backfilling, 21 = riser pipe, 22 = casing, 23 = sump, 24 = borehole wall, 25 = drilling diameter, 26 = well diameter, 27 = electric cable, 28 = backflow preventer valve, 29 = water meter, 30 = protective cap of piezometer.

Figure 3.1 Main components of a vertical well. Illustration courtesy of Bundesanstalt für Geowissenschaften und Rohstoffe (BGR), Hannover, Germany.

3.2.2 *Site selection*

The location of a well field is determined mainly by the hydrologic and hydrochemical conditions: is sufficient water available in the subsurface, does the permeability of the production aquifer allow water abstraction, and is this water of sufficient quality? In areas at risk of flooding, the potential for microbiological and chemical contamination of water wells is enhanced under certain site conditions.

Phreatic aquifers are directly connected to the soil surface and thus to the (infiltrating) flood water. Travel times of the infiltrating water to the well screen may be too short to guarantee sufficient removal of contaminants, especially in thin and/or highly permeable aquifers (gravels, coarse sands). A travel time of 60 to 100 days is generally considered sufficient to remove viruses and bacteria by soil passage and to safeguard microbiological safety of the water (Van der Wielen et al., 2008). Hydrological calculations should be made to provide insight in the travel times of infiltrating water. Septic tanks, agricultural fields, parking lots, barns and quarries in the vicinity of wells pose an extra risk for contamination.

Wells in local **depressions** (Figure 3.3) are vulnerable for contamination, both in and outside areas at risk of (river) flooding. In flooded areas, the stagnant flood water resides in these depressions over a longer time span, providing ample time for infiltration and/or short-circuiting into a well. Outside river areas, (surface) runoff water may collect in local depression, with risks of well flooding. Similar to river water, runoff water may contain contaminations like viruses (manure, feces) and pesticides.

Figure 3.2 Unsealed abandoned observation well. Photo courtesy of KWR.

Figure 3.3 Water well in a local depression Photo courtesy of KWR.

Abandoned production wells and operative **observation wells** (Figure 3.2) form an open connection between the soil surface and the deeper aquifer. Flood water may thus readily infiltrate into the production aquifer, providing a short pathway to the well screen. Abandoned wells should be properly sealed, preferably by filling the well with a bentonite clay or cement grout. Observation wells that are still in use should be sealed with a protective cap. Water supply company WML, the Netherlands, uses tailor made flexible caps, to ensure that pressure head measurements are not disturbed when the observation well is sealed.

3.2.3 *Preventive measures: mounds and dikes*

The simplest way to prevent damage and contamination is by preventing flooding of a well and other water supply infrastructure. Wells can be installed on top of **artificial mounds or dikes**, with the well head at or above the expected maximum flood level. Figure 3.4 shows a well installed on top of a dike, in perfect fit with the Dutch polder landscape. The example was taken from the production site Onnen, the Netherlands, which is located in an area designated for (controlled) storage of flood water from the nearby Hunze River. Additional information on flood protection at this production site is provided at the end of this chapter.

Figure 3.4. Water production well installed on top of a dike. The dike was newly constructed for this purpose, a flood preventive measure fitting in perfectly in the Dutch polder landscape. Photo courtesy of water supply company Groningen, the Netherlands

Like production wells, other infrastructure such as the treatment plant, should be protected by installation at elevated locations or by surrounding dikes. Of special concern is the energy supply to the well field, including electric transformers, which for the production site Onnen have been placed on mounds as well.

It will not always be possible to place wells on elevations and when placement is possible, there still is the risk of flooding when the flood height exceeds the expected levels. In addition, most of the existing wells in risk areas have their tops (heads) just above ground surface and these wells will be flooded. Other measures to make wells flood-proof are thus still necessary. These are discussed in the following sections.

3.2.4 *Well head design: exterior*

The **well head** (Figure 3.1) is the container (chamber, vault) on top of the actual well, covering the well, pump, observation wells et cetera. First step in preventing flood water to enter the well and mix with the abstracted raw water, is to ensure that water cannot enter the well head. Most vulnerable parts are the access door, the air vent and openings/connections for cables and pipelines:

- Ensure that the **access door** is water tight. Many well heads are equipped with a warning system, which warns when the access door is opened. When the access door is opened unexpectedly, the warning system automatically shuts down the water pump.
- Ensure that the **air vent** opening faces downwards and is automatically sealed when the water level exceeds this opening.
- Ensure that all **openings / connections** for (electricity) **cables**, distribution **pipelines** and the well casing are watertight.

The well head should have a strong **cement base** and cement or steel, watertight walls. During a flood, (upward) buoyancy forces may cause **uplift** of the well head, which should be prevented by anchoring the well head. This can be done by driving tension piles into the ground. Water supply company WML, the Netherlands, has constructed a cement apron which anchors the well head to the ground surface to prevent uplift. The soil or cement surface surrounding the well (Figure 3.1, #20) should slope away from the well head on all sides to prevent water from collecting near the well head.

Wells in well fields which are accessible to the public, livestock or wild life are vulnerable to **vandalism and damage**. Ideally, the well heads should not be accessible, but not always will it be possible to provide protection by for example fences. Visual checks for damage should be carried out regularly, and any damage should be repaired as soon as possible.

3.2.5 *Well head design: interior*

A watertight well head provides the first barrier against flood water entering a water well and mixing with the raw water. A set of additional measures inside the well head provides a second barrier, in case the first barrier fails.

A **warning system** can be installed inside the well head, alarming operators when water has entered the well head. Optionally, the warning system may automatically shut down the water pump.

The **well top** should be properly sealed by a protective, watertight cover (Figure 3.2, #8), using watertight bolts. This also accounts for any other connections of/to the water pipeline. Many wells are equipped with an **air vent** and similar to the air vent of the well head, this vent should be faced downwards and it should automatically seal off when water has entered the well head and rises to the vent. Alternatively, air vents may be removed. Usually there is no problem in keeping the well in operation when the air vent is sealed or absent, though an underpressure may develop in the well top during operation.

Figure 3.5 Well head interior, including the well cover, observation well(s), and electrical system. This well was installed on an artificial mound and thus protected from flooding. Photo courtesy of water supply company Groningen, the Netherlands.

Many wells are equipped with one or several **observation wells** or **piezometers**, which are installed in the gravel pack surrounding the well casing (Figure 3.1, #30). These observation wells form a risk, as they provide a **short-circuit route** to the well screen: flood water may enter an observation well, flow downward, and can enter the water well via the gravel pack. All observation well tops should thus be properly sealed with a watertight protective cap. Note that an observation well can also be the cause of flooding of well heads, when the water pressure in the measured aquifer is above the observation well top. A protective cap provides a remedy here as well or, alternatively, a ball valve faucet can be installed on the observation well.

There is a second, indirect short-circuit route associated with observation wells. An observation well crossing multiple aquifers can connect these when the observation wells are damaged. There is especially a contamination risk when the short-circuit flow is from a shallow (often unprotected) aquifer to a deep, well-protected aquifer. To prevent this type of leakage, use high quality materials when constructing observation wells and check the well for joints or cracks after construction.

Figure 3.6 Flooded well head. The water level is above the well top, but just below the top of the observation wells (piezometers). Protective caps will prevent flood water from entering the observation wells and short-circuiting of this water to the well screen. Photo courtesy of water supply company Brabant Water, the Netherlands.

3.2.6 Well design: below ground

The previous sections predominantly dealt with direct routes via which flood water can enter a well and contaminate the abstracted raw water. During a flood, surface water will slowly infiltrate into the subsurface. This may cause a deterioration of the groundwater quality, especially for unprotected, phreatic aquifers, but in the long run also for deeper, semi-confined aquifers. Chemical water quality is mostly at risk. Microbial contamination is less of a problem when travel times from soil surface to a water well screen exceed the 60-100 days needed to eliminate viruses and bacteria. There are, however, a number of pathways via which infiltrating water may short-circuit to the well screen, introducing a microbiological risk. These pathways and how to eliminate them are discussed in this section.

The **annular space** between the well casing and borehole wall is filled with gravel or coarse sand, preventing sand particles from moving from the aquifer into the well. This so-called gravel pack is often more conductive than the surrounding aquifer, providing a potential fast route for water flow to the filters screen. This can be prevented by taking the following measures.

The uppermost section of the annulus should be sealed with a **cement grout** ("food cementation") or bentonite clay to ensure that no water or contamination can enter the annulus from the surface (Figure 3.1, #14). The depth to which grout must be placed varies by country. Preferably, the food cementation and the surface seal are well connected or form a single unit.

Wells that abstract water from deeper, confined aquifers penetrate the clay layer overlaying the production aquifer. **Clay seals** should be constructed in the annular space where the confining clay layer is perforated (Figure 3.1, #5), as to restore the protective clay layer. In this way, drainage from the upper aquifer to the lower aquifer is prevented, and any leakage from infiltrated flood water into deeper aquifers is avoided. During construction of water wells, clay seals are not always installed properly. The status of clay seals can be checked using **borehole geophysics** (see example 4 at the end of this chapter), while techniques like grouting are available to repair inappropriate or absent seals.

Figure 3.7 A bentonite clay seal is installed during construction of a new water abstraction well. Photo courtesy of water supply company Brabant Water, the Netherlands.

Over time, joints, cracks or even holes may develop in the **well casing**. Possible causes are, amongst others, corrosion, damages resulting from rehabilitations, or the use of inappropriate materials like, in the past, wood. A leaky casing provides a short-circuit route for infiltrating flood water. The condition of a casing can be checked by **camera inspections** or **geophysics** (for stainless steal wells). When a leak is located, the casing should be repaired or withdrawn and replaced. When constructing a well, select appropriate casing material using knowledge of the water chemistry.

Figure 3.8. A heavily corroded stainless steal casing. The holes provide a short-circuit route for infiltrating flood water. Photo courtesy of water supply company Oasen, the Netherlands.

3.2.7 *Energy supply and electrical systems*

The above sections focused on measures to prevent flood water from entering the water supply system and introducing risks for microbiological (and chemical) contamination of the drinking water. A second prerequisite for safe and continuous water supply during a flood event is a secure energy supply: no water without energy. To prevent breakdown and secure operation of the production site all electric systems should be checked on their ability to operate during a flood event. Flood vulnerable are (i) the electrical system inside the well head, and (ii) energy supply to the wells and well field.

A flooded well can stay in operation as long as the water pump is supplied with energy. Inside the well head, water may cause **electrical short-circuiting** and breakdown of the electrical system. A first barrier is, again, preventing the inflow of flood water into the well head, by ensuring that the well head is watertight (see section 3.2.5). In addition, as a second barrier, ensure that **electrical connections** and **switches** inside the well head are watertight

Often, **electrical transformers** have been installed at well fields. It is difficult and costly to make these transformers watertight. Most effective is to put these on elevated locations, as was done on production site Onnen by water company Groningen, the Netherlands.

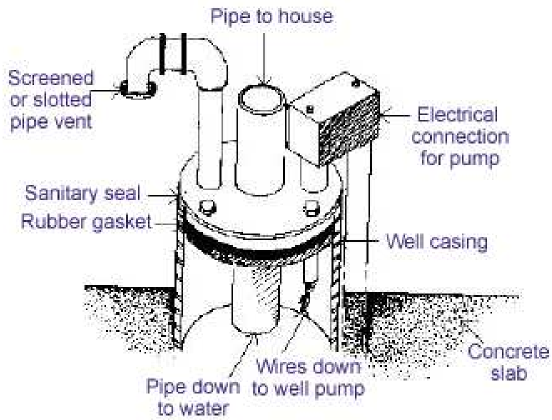


Figure 3.9. Well top, including (non-watertight) electricity wires and connections (left). Schematic of well top, including correct electrical system (right).

For some flood risk areas, energy suppliers do not guarantee the supply of electricity during floods. In this case, when water supply is to be guaranteed, an **emergency power** system should be available. Note that this is a costly measure and that this system should be flood protected as well.

3.3 Examples

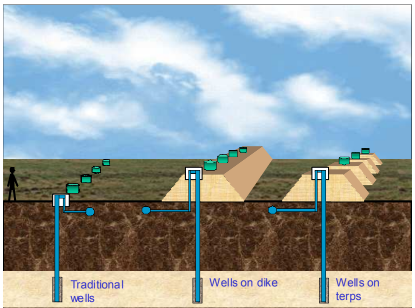
At several well fields in the Netherlands and Germany, technical measures have already been taken to safeguard the water supply from areas at risk of flooding. Water supply company Groningen, the Netherlands, has renovated its well field Onnen such that wells are now above expected flood levels, by putting them on artificial mounds (Example 1). Water supply company Elbaue-Ostharz (Germany) has adapted its well design after lessons learned from the 2002 Elbe flood (Example 2). Oasen water supply (the Netherlands) has recently drafted different scenarios for making its well fields flood proof (Example 3). Floods resulting from extreme local rainfall can already be dealt with by some minor adjustments to the current wells. Floods resulting from (river) dike bursts, however, require many additional investments. In addition to these two examples, in this section information is provided on the flood protection of private wells in the United States (Example 4) and on borehole geophysics, as a technique to check casing and annular seals of water wells (Example 5).

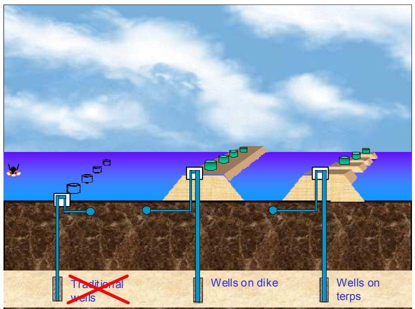
<table>
<tr><th>Example 1</th><th>Preventive measures: wells on mounds</th></tr>
<tr><td>Location</td><td>Onnen, the Netherlands. Water supply company Groningen.</td></tr>
<tr><td>Summary</td><td>Flooding of well is prevented, by putting wells at elevated (artificial) mounds and dikes.</td></tr>
<tr><td>Additional information</td><td>Tamminga, J.K., 2008. Combining flood protection and drinking water production. Presentation at Water and Climate Workshop, IWA, Amsterdam, November 17-18, 2008.</td></tr>
<tr><td>Description</td><td>
Water production site Onnen, the Netherlands, produces about 12Mm³ of drinking water yearly, using up to 55 abstraction wells. Water is abstracted from a deep, confined aquifer that is protected by a thick clay layer. Well screens are located between 50 and 100 m depth.

The well field is located in a polder area, which has been designated for (controlled) storage of flood water from the nearby Hunze River. Controlled flooding of the polder area is foreseen once every 100 years.

To ensure safe and sufficient water supply, the following technical measures were taken in the well field:
- construction of an inlet for controlled flooding;
- flood protection of the purification plant, by construction of a surrounding dike;
- placement of (new) water wells and electrical transformers on artificial mounds and dikes;

In addition, a production scheme was made, defining which wells are shut (the flooded wells) and which wells are kept in operation during flooding. This is shown in the figures below.





Being a controlled storage area, the maximum flood level is known and the height of the mounds and dikes was adopted accordingly. As such, there is no risk of flooding of the elevated wells and intrusion of flood water into the well head.
</td></tr>
</table>

Example 2	**Lessons learned from the 2002 Elbe flood**
Location	Riverbank Filtration Site Torgau-Ost, Germany, Water supply company Fernwasserversorgung Elbaue-Ostharz GmbH.
Summary	New well design after an extreme flood, including watertight covers and connections, monolithic well chamber.
Additional information	Krüger, M., Ende, C., Grischek, T. (2006) Management of river bank filtration in the Elbe River Basin near Torgau, Germany. In: UNESCO IHP-VI Series on Groundwater No. 13, Recharge systems for protecting and enhancing groundwater resources. Proc. Int. Symp. Management of Artificial Recharge, 11.-16.06.2005, Berlin, 49-54.
Description	The waterworks Torgau-Ost, situated south-east of the city of Torgau, has a production capacity of 100,000 m³/day. The 42 production wells are located in an alluvial sand and gravel aquifer with a thickness of 40 to 60 m, covered by a 2 to 5 m thick layer of meadow loam. The meadow loam provides an important protection against pollution and infiltration, for instance during flood events. During a 100-years flood in August 2002, all wells located between the river and the dikes were flooded, some of them by more than 1.5 m. The extreme flood event caused a strong increase in turbidity, organic carbon concentration, and number of microorganisms in the River Elbe water. Raw water was affected by some increase in turbidity and bacteria count, but the quality drinking water was never at risk. At the time of flooding, all monitoring and abstraction wells are equipped with supposedly watertight covers (photo left). However, flood water leaked into several of the well chambers, which had to be cleaned and disinfected afterwards. To ensure safe and sufficient water supply, it was crucial to safeguard the energy supply to the wells. This was done by construction of a sheet pile wall around the electrical connectors and by installing mobile dewatering units (pumps, photo right). Cable connections in the wells were fitted in a plastic dome filled with air, which was effective even during full flooding of the well chamber.   *Well cover at the well field (left). Protection of the energy supply using a sheet pile wall and mobile dewatering units (Photo: Krüger).*

	Since the extreme flooding in 2002, new wells have been equipped by a new generation of covers and a specific well chamber design was created to ensure watertight covers, cables and connections. The air vents can be closed by a butterfly valve. A monolithic well chamber design was chosen to withstand buoyant forces.

Example 3	**Three scenarios for flood proof well fields**
Location	Nieuw-Lekkerland and Kamerik, the Netherlands. Water supply company Oasen
Summary	Different scenarios for making well fields flood proof have been drafted. Floods resulting from extreme local rainfall can already be dealt with by some minor adjustments to the current wells. Floods resulting from (river) dike bursts, however, require many additional investments.
Description	Well fields Nieuw-Lekkerland and Kamerik are located in polder areas, in the vicinity of the rivers Lek and Grecht, respectively. Up to date, these well fields have never been flooded, yet there are two scenarios for possible flooding: - extreme local rain showers (once every 100 years), resulting in worst case floods of 20-30 cm (Nieuw-Lekkerland) and 30-40 cm (Kamerik); - uncontrolled dike bursts along the local rivers (once every 1250 years), resulting in floods of 7 m (Nieuw-Lekkerland) and 2 m (Kamerik). Ideally, during floods both well fields should stay in operation, to ensure sufficient supply of drinking water. Two main risk were identified: (i) microbiological infection of the raw water, and (ii) obstruction of the power supply. Water company Oasen is currently investigating if and how this can be achieved. First, preliminary conclusions are given below. A few minor adjustments are needed to make the current wells flood proof to floods of 40 cm (extreme rain shower). In this scenario, water is allowed to enter the well head, but mixing of this flood water with the raw water is prevented by: – ensuring watertight cover of the well (current standard) – watertight topping of piezometers (to prevent short-circuiting). This includes piezometers in the well as well as those located in the well field – raising the air vent openings to 45 cm above ground surface – raising electrical connections and switches to 45 cm above ground surface – re-ensure that electrical cables are watertight – raising electrical transformers in the well field to 45 cm above ground surface.

	Well field Kamerik can be made flood proof also for the dike burst scenario, by installing new wells and electrical transformers on artificial mounds of 2 m height. Artificial mounds are not an option for well field Nieuw-Lekkerland, where the flood level may reach 7 m above land surface. Making this well field totally flood proof is technically possible, but costly. Measures could include construction of a watertight well head, such that the well stays dry. Or, alternatively, the well head is not made watertight but the well itself is made waterproof by (in addition to the above measures) ensuring that the electrical system is watertight and by removing the air vents. To ensure power supply to this well field, electrical transformers should be placed above expected flood level, for instance on top the pumping station.

Example 4	Protecting (small) private wells
Description	Many home owners in the rural parts of the United States use private wells for the production of their drinking water. Several government authorities provide information on how to protect these private wells from (contamination by) flooding. A leaflet provided by the Federal Emergency Management Agency (FEMA) is presented below.

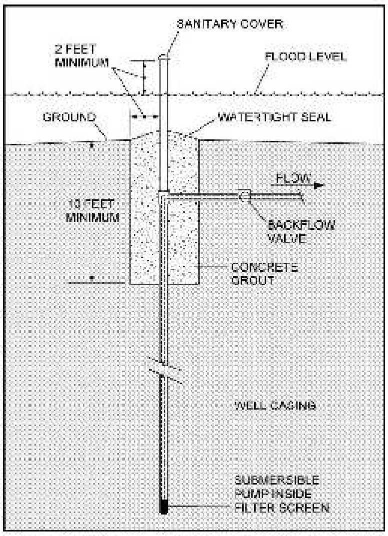
Protect Wells From Contamination by Flooding

FEMA

PROTECTING YOUR PROPERTY FROM FLOODING

Flood waters often carry hazardous and toxic materials, including raw sewage, animal wastes, oil, gasoline, solvents, and chemicals such as pesticides and fertilizer. Flood water that enters a well can contaminate the groundwater and make the well water unsafe to drink or use. The effects may last long after the flood waters have receded.

Proper well construction will help protect your well against contamination. A licensed well-drilling contractor can inspect your well and suggest improvements, such as the following (see figure):



- Extending the well casing at least 2 feet above the highest known flood elevation
- Installing a sanitary seal or cover on the casing
- Curbing the casing at ground level by surrounding it with a watertight seal that is at least 4 inches thick and extends at least 2 feet in all directions
- Placing grout between the casing and the sides of the bore hole to a depth of at least 10 feet
- Installing a backflow valve in the water line
- Protecting electrical controls from flood water
- Drilling a new well on higher ground, above expected flood levels and known sources of pollution

BENEFITS OF UTILIZING THIS MITIGATION STRATEGY

- Helps to prevent contamination of drinking water or water for other uses

TIPS

Keep these points in mind when you improve your well to protect it from flooding:

✓ Many state and local agencies regulate the construction and modification of wells. Check with your local health department or building officials for more information.

✓ Power outages often occur during floods, so you should consider providing a backup power supply to ensure the continued operation of your well. (See fact sheet "Install a Generator for Emergency Power.")

✓ The vulnerability of a well to contamination by flood waters depends partly on the well's age and depth. Wells over 50 years old and less than 50 feet deep are more likely to be contaminated by flood waters.

Protect Wells From Contamination by Flooding April 2008 Page 1 of 2

✓ Do not store potential contaminants within 100 feet of the well. Potential contaminants include fuels, solvents, and dry and liquid chemicals.

✓ Have your water tested annually for the most common contaminants, including coliform bacteria.

ESTIMATED COST

The cost of most improvements to an existing well will vary, depending on the condition of the well. Having a plumber or contractor install a backflow valve in the water line will cost approximately $500. This figure includes the cost of excavation and backfilling. Because geological conditions and groundwater yields vary from site to site, you should contact a local licensed well driller regarding the costs of other well improvements and new wells.

OTHER SOURCES OF INFORMATION

American Water Works Association Standards for Water Wells, AWWA, A100-06, 2006, http://www.awwa.org/Bookstore/productDetail.cfm?ItemNumber=4223.

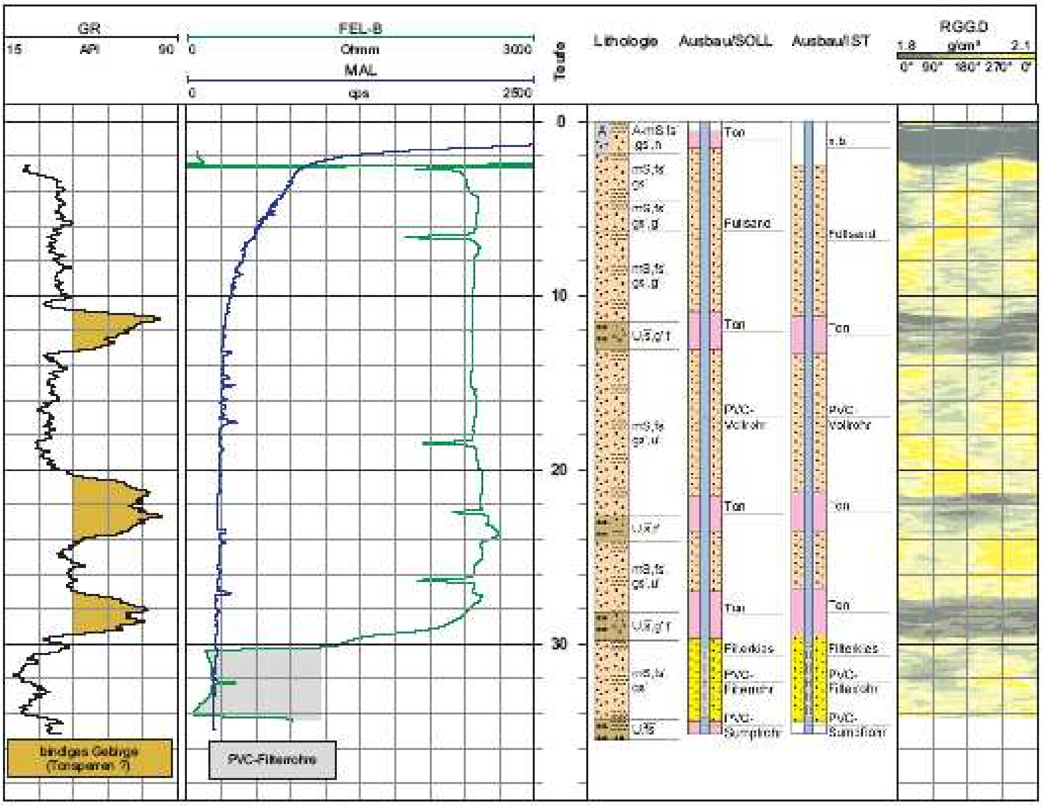
FEMA 348, *Protecting Building Utilities from Flood Damage,* Chapter 3, November 1999, http://www.fema.gov/library/viewRecord.do?id=1750.

Install a Generator for Emergency Power, FEMA, April 2008, http://www.fema.gov/plan/prevent/howto/index.shtm.

Wellhead Protection for Private Domestic Wells, A. Tyson, University of Georgia College of Agricultural & Environmental Sciences, 1993, http://www.engr.uga.edu/service/extension/publications/c819-12c.html.

To obtain copies of FEMA documents, call the FEMA Publications Warehouse at 1-800-480-2520 or visit FEMA's Library online at http://www.fema.gov/library.

Example 5	Control of clay seals with borehole geophysics
Description	Borehole geophysics can be used to check the condition of the well casing and clay seals. Especially in Germany, geophysical logs are widely used for these purposes. The example below shows a geophysical log performed to check the position of clay seals. The clay seals are clearly shown in the gamma ray (GR) and 360° gamma-gamma density (RGG.D) logs.
Example courtesy of Bohrlochmessung-Storkow GmbH, Storkow, Germany. http://www.blm-storkow.de	



4 Management procedures

Taking the appropriate technical measures is essential to guarantee safe and continuous water supply in flood affected areas, as discussed in the previous chapter. Equally important is to have good management procedures before, during and after floods. These should include clear instructions on how and when to act, for all persons and institutions involved.

4.1 Summary

Management procedures	
Prior to floods	• Regular visual inspection of each well: - Well head: signs of vandalism or damage - Warning systems: still operative - Observation wells, air vents: seals, cracks, leaks • Check condition of well casing and annular seals • Water quality samples must be taken periodically and stored in a database for reference (i.e. conductivity, turbidity and pH)
Flood warning and contingency plan	• Flood warning systems should be in operation. Ensure good communication between authorities operating the warning system and water suppliers. • A contingency plan must be set-up, comprising all personal roles and responsibilities and measures with regard to: - safety of employees - alerting all relevant agencies - coordinating emergency support - protection of infrastructure and utilities - availability of transport and access to the terrain - adjustment of operating procedures
Operation during flood	• Maintain water pressure in the distribution network at all times, to prevent flood water from infiltrating the pipelines. Run production wells continuously and at constant discharge • Adjust the operation of the well field, e.g. shut down selected (shallow) wells, intensify water quality monitoring, et cetera. • Add a disinfection step to the water treatment, to ensure microbiological safety . Check the disinfection efficiency at short intervals.
Flood follow-up action	• Visually inspect the well condition (well head, exterior and interior), restore protection of the well (fences, vegetation), remove sludge and debris from the well site. • Follow the appropriate procedures to recommission each of the water production wells. • Restore the water quality in pipelines by flushing with good quality water • Pipelines and wells should not be released to service until physical, chemical and microbiological water quality parameters have met pre-established criteria.

4.2 Management procedures

4.2.1 *Prior to floods: regular inspection of water wells*

The previous chapter described various technical measures to be taken in order to safeguard the water supply. After taking these measures, it is important to regularly check if they are still functioning. A **regular visual inspecting** is recommended for (amongst others):

- well head: signs of vandalism or damage to the well head and cement seal;
- warning systems: check if these are still in operation
- observations wells: ensure that they are sealed off with caps;
- air vents: check for signs of cracking or leaking, check if they are sealed off automatically when flooded.

At a less frequent basis, the condition of the well casing and annular space should be checked, for example by camera inspection or (incidentally) by borehole geophysics. These checks could be planned standard following well rehabilitations. Be alert for any changes to the well when activities such as well rehabilitations have taken place. Make sure to perform a visual inspection afterwards.

Mixing of the native water with flood water can be detected from a change in chemical composition of the abstracted raw water. Regular analysis of the raw water quality provides a baseline for a comparison. It is recommended to take samples from each well in a well field periodically, and analyze for a wide range of parameters. Basic parameters like conductivity and pH can be measured online, and are often good indicators for changes in water composition due to intrusion of flood water. Inspection reports and sampling results should be stored in a database so they are available for reference.

Figure 3.1. A water sample is taken from a water production well (left). Electrical conductivity and pH are measured in a water sample (right). Photos courtesy of water supply company Brabant Water, the Netherlands.

4.2.2 *During a flood: warning system and contingency plan*

Flood warning systems are designed to give a forewarning of the likelihood of flooding. Timely information on possible flooding is important for water companies, in order to take immediate and effective actions as to minimize damage and prevent contamination of water wells. Different approaches and warning systems are in operation within the various countries and regions of the EU. Important is the **communication** between authorities operating the warning system and the water suppliers, making sure that water suppliers are informed properly and in time. It is advised to have regular **disaster response trainings**, with all authorities involved.

As soon as a flood warning message is received, a **contingency plan** must be followed. This plan should contain clear management procedures, which enable fast internal notification of and quick response to a flood event. An electronic and paper version must be available to all employees involved. The plan should comprehend all personal roles and responsibilities and should include all measures with regard to:

- safety of employees;
- alerting all relevant agencies and authorities (*e.g.*, nearby pumping stations, fire department et cetera);
- coordinating emergency support;
- protection of infrastructure and utilities (*e.g.*, construction of sandbag dikes);
- removing non-waterproof equipment located in the flood risk area;
- the availability of transport (boats, all-purpose vehicles) and instruction on how to access the terrain;
- adjustment of operating procedures, such as:
    - shutting down selected wells;
    - adjusted operation of water wells to maintain pressure in distribution network (see down);
    - intensive monitoring of raw water quality;
    - additional disinfection of the drinking water

Figure 4.3 Protection by sand bags of a production well (left) and the pumping station (right) in Onnen, the Netherlands. Photos courtesy of water company Groningen, the Netherlands.

4.2.3 *During flood: operation of production wells and additional disinfection*

None of the **pipelines** in a water distribution network are 100% waterproof. While in operation, the water pressure in the pipeline is generally larger than outside the pipeline, and this **overpressure** prevents water from entering the pipeline. Shutdown and isolation procedures, including pump starts and stops, can create transient pressure surges in the distribution system. During these periods of low or negative pressure, (flood) water may infiltrate the pipeline through leakage points, cross connections or faulty seals and joints, thereby introducing potential sources of contamination. A positive pressure should therefore be maintained in the raw water pipeline at all times. This is best attained by running the **production wells** continuously and with a **constant discharge**.

Though beyond the focus of this document, there is an important remark to be made on water treatment. Many production wells abstract water from deep, confined aquifers that contain bacteriological safe water. As such, the **water treatment** scheme for these well fields does not contain a **disinfection** step. Microbiological contamination of the raw water is the largest health risk of water well flooding. It is therefore recommended to add a disinfection step to the water treatment during floods. For facilities where such a disinfection step is already applied, the disinfection efficiency should be checked at short intervals.

4.2.4 After a flood: follow-up actions

Directly after a flood, a careful inspection should be carried out for all production wells in the affected area, both for wells that were kept in operation as well as those that were shut down. A **visual inspection** should include checks on the condition of the well head, protective caps of production well and observations wells, air vents, et cetera. Any damage should be repaired. Also, any protection of the well, such as fences and vegetation, should be restored. Sludge and other river debris should be removed from the well site.

Before taking the water wells into production and switching to 'standard' operation (e.g. without additional disinfection), the **wells** should be **re-commissioned**. Most important is the check of the microbiological and chemical water quality. Most water companies have there own procedures for re-commissioning; the following procedure serves as an example:

- following a flood event, pump each well for several consecutive hours and discharge the water (i.e. do not use it)
- stop pumping and analyse the raw water quality of each well after 12 hours of standstill. Typical parameters to analyse are organic micro-pullutants and microbiological parameters like colony count, E.coli, sulphite reducing clostridia (SSRC), intestinal enterococci, and bacteriophages.
- When water quality standards are met, the well is recommissioned and can be taken into operation.
- When water quality standards are not met, the well should remain inoperative. A follow-up procedure must be determined.

To avoid infection from one well to another, it is advised to keep surrounding wells inoperative until water quality standards in the tested well are met. However, it is realized that in practice this is not always possible. Alternatively, an infected well should be pumped continuously, and the abstracted water should be disposed (i.e. not used for drinking water production).

Flood water may have infiltrated into pipelines during standstills. To restore water quality in the pipelines, they should be flushed, using source water of undisputed microbiological (and chemical) quality. Pipelines should not be taken into service until physical, chemical and microbiological water quality parameters meet the pre-established standards. Deviating water qualities could indicate intrusion of contaminated flood water.

4.3 Example of a contingency plan

Well field Roosteren of water supply company WML, the Netherlands, is located near the river Meuse. Being a rain fed river, water levels vary considerably, introducing several risks for the water supply. These include flooding of the well field, as occurred in 2002, 2003 and 2011, and increased riverbank infiltration and reduced groundwater travel times from river to wells. This short-circuit flow of river water may cause an infection of shallow production wells at Roosteren.

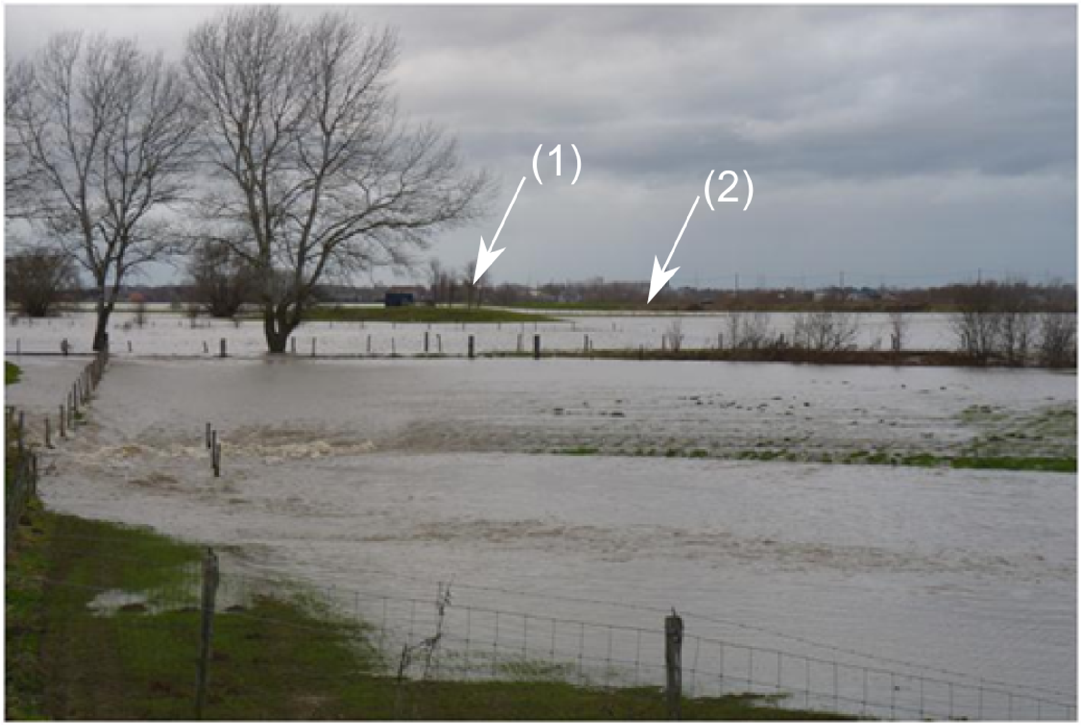


Figure 4.4. Well field Roosteren during the January 2011 flood of the Meuse river. Arrows point to (1) a well installed at an artificial mound, and (2) the levee of the Meuse river.Photo courtesy of water supply company WML, the Netherlands.

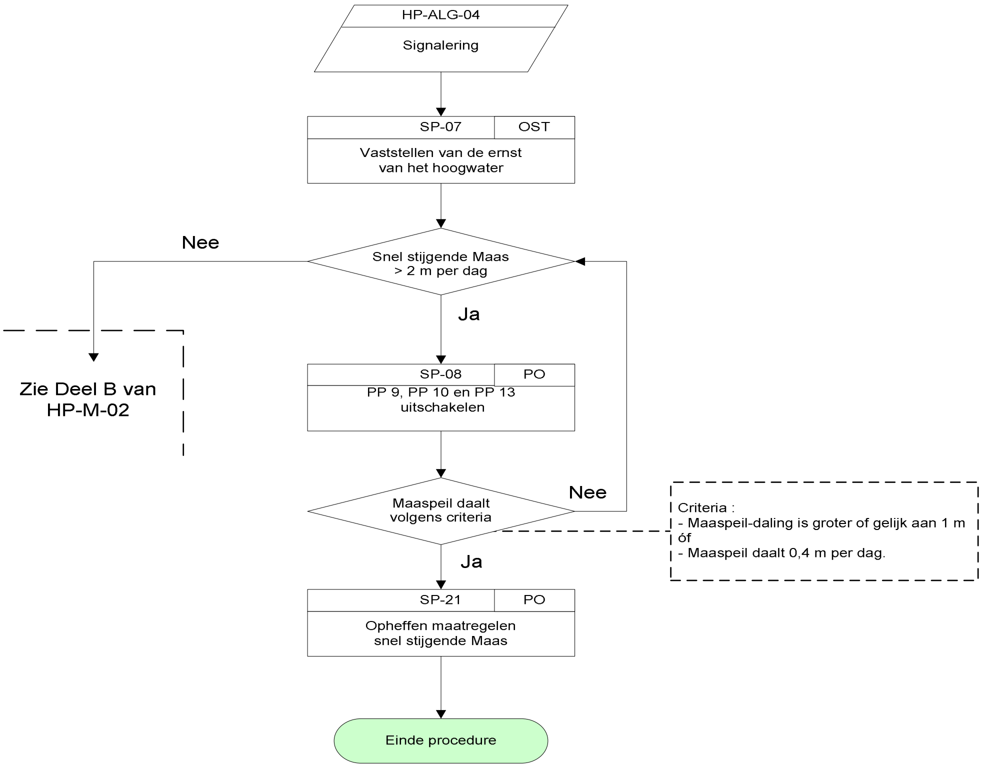
Several technical measures were taken to make the well field flood proof, like installing wells on artificial mounds (Fig. 4.4) and by ensuring that well heads are watertight. Still, as a precaution measure, during a flood many of the shallow wells are taken out of production, including those that are located close to the river and those that are flooded. WML has drafted a detailed contingency plan (WML, 2010), telling exactly what actions to take at which moment. The steering factor is the river water level, which determines the risk level and thus the type of actions required. A summary of the contingency plan (WML, 2010) is provided below.

Example 1	**Contingency plan Roosteren**
Location	Well field Roosteren, the Netherlands. Water supply company WML.
Description	*Main procedure* - fast increase of river water level (>2 m day^{-1}) → shut down shallow wells that are close to the river (and that abstract riverbank filtrated water). - river water level >26.5 m.a.s.l. → shut down well PP13; lower production of the shallow wells PP9-12; install extra UV-disinfection unit. - river water level >27.5 m.a.s.l. → shut down all shallow wells in the vicinity of the river (PP9-13). Production is limited to well PP14, several deep wells, and a radial collector well. - river water level >28.4 m.a.s.l. → shut down PP14; the radial collector well and the deep wells are kept in operation, under strict control of water quality. - flooding of radial collector well → well is taken out of production, unless calamities at other well fields require water supply from Roosteren. In that case, the radial collector well is kept in production, while an additional UV disinfection unit is installed and the drinking is chlorinated. Wells are shut down automatically at the specified river levels. Several sub-procedures and a communication plan accompany the main procedure. Sub-procedures include actions to be taken in the terrain, like sealing of observation wells (to prevent short-circuiting), installing additional bolts (to ensure that the well heads are sealed), removal of devices from the field, remove livestock et cetera. In addition, procedures have been drafted for taking production wells into operation again, when flood levels have decreased. The communication plan includes semi-online access to river level data and forecasts. A flow chart (in Dutch, see down) provides a route through all procedures

Observation wells, equipped with pressure sensors (left). Wells are sealed with flexible caps during flood events (right), to ensure continuous pressure head measurements.

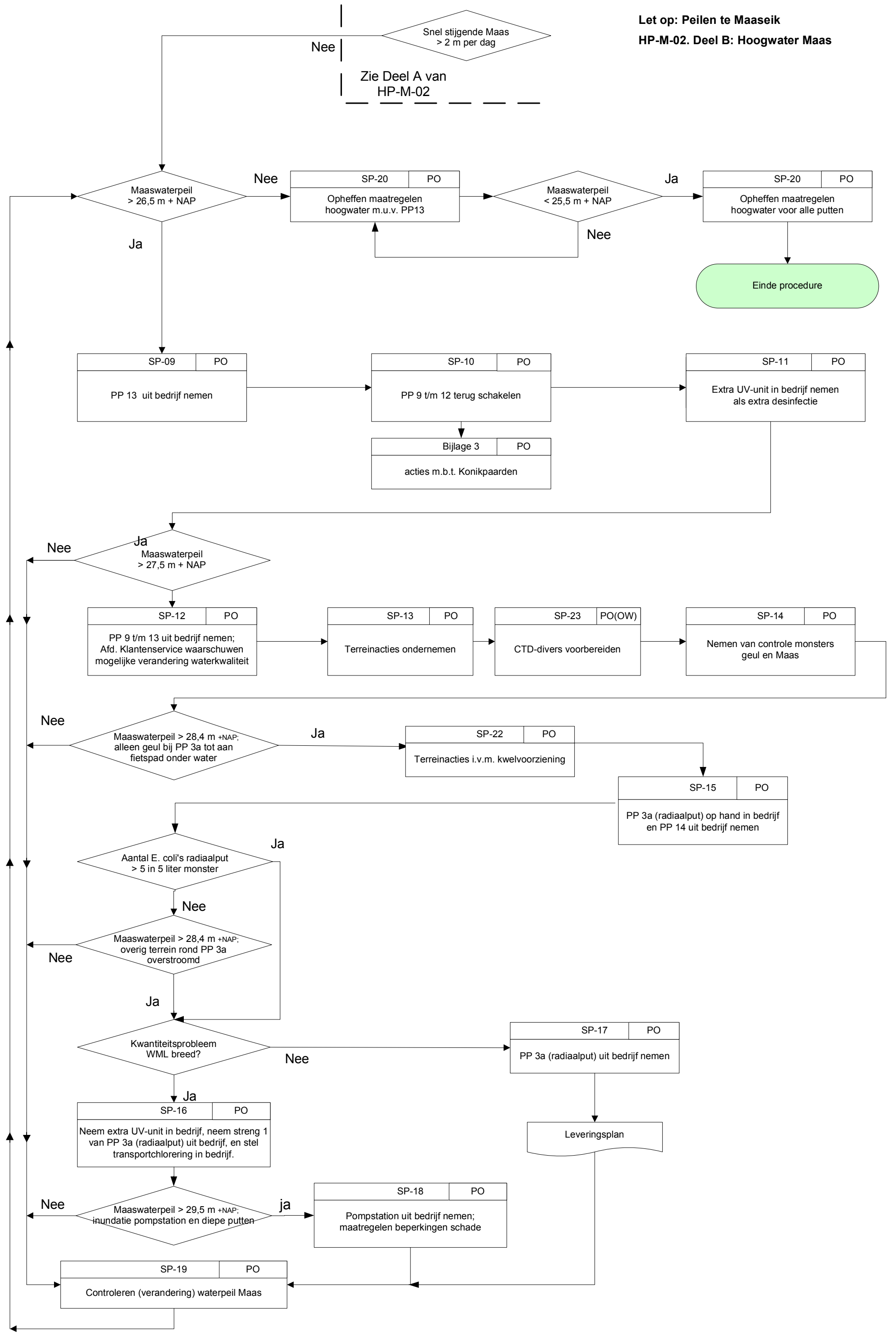
Installatie: Waterproductiebedrijf Roosteren Onderdeel: Hoofdprocedures	Procedure: Hoogwater Maas >26,5 m+NAP en/of Maaspeilstijging >2 m/dag te Maaseik Code: HP-M-02	wml

Let op: Peilen te Maaseik **HP-M-02. Deel A : Snel stijgende Maas**



Datum : 09-12-2010 Revisie : 00-02	Geautoriseerd : Afdelingshoofd OTS Procesbeheerder : Teamcoördinator	Paraaf : Paraaf :	Bladzijde: 3/5

Installatie: Waterproductiebedrijf Roosteren Onderdeel: Hoofdprocedures	Procedure: Hoogwater Maas >26,5 m+NAP en/of Maaspeilstijging >2 m/dag te Maaseik Code: HP-M-02	wml



Datum : 09-12-2010 Revisie : 00-02	Geautoriseerd : Afdelingshoofd OTS Procesbeheerder: Teamcoördinator	Paraaf : Paraaf :	Bladzijde: 4/5

5 Conclusions

River floods are the most common natural disaster in Europe, and flood damage is expected to rise across much of the western, central and eastern parts of the continent. One of the assets at risk of flooding are water well fields, and flooding of these may obstruct the supply of safe and sufficient water in affected areas. Most important risks are microbiological infection of the raw water and interruption of the power supply.

Several technical measures are to be taken, to safeguard the water supply during floods. These include measures to prevent the direct inflow of (contaminated) flood water into the well, but also to prevent indirect routes of contamination, like short-circuiting of flood water into the production aquifer. Many of the technical measures are relatively easy to implement, such that with little cost investment existing well fields can be made flood proof already.

In addition to technical measures, it is essential to have clear management procedures before, during and after floods. These should be drafted in a contingency plan, providing clear instructions on how and when to act, for all persons and institutions involved. With a clear contingency plan and appropriate technical measures, water supply can be assured during floods.

6 References

EEA, 2008. Impacts of Europe's changing climate — 2008 indicator-based assessment. EEA Report No 4/2008.

Krüger, M., Ende, C., Grischek, T. (2006) Management of river bank filtration in the Elbe River Basin near Torgau, Germany. In: UNESCO IHP-VI Series on Groundwater No. 13, Recharge systems for protecting and enhancing groundwater resources. Proc. Int. Symp. Management of Artificial Recharge, 11.-16.06.2005, Berlin, 49-54.

Leunk, I. and Lieverloo, J. H.M (2007) Hygiëne bij winmiddelen. Hygiënecode drinkwater. KWR rapport. BTO 2007.038.

Makkink, H.J., Balemans, M.L.M. & Schrama, E.J. (2001) Kennisdocument Putten(velden) Ontwerp, aanleg en exploitatie van pompputten. KWR rapport. BTO 2000-110(c).

Sterrett, R.J. (ed.), 2007. Groundwater and Wells. Johnson Screens. 812pp.

Tamminga, J.K., 2008. Combining flood protection and drinking water production. Presentation at Water and Climate Workshop, IWA, Amsterdam, November 17-18, 2008.

Van der Wielen, P.W.J.J., W.J.M.K. Senden and G. Medema, 2008. Removal of Bacteriophages MS2 and ΦX174 during transport in a sandy anoxic aquifer. Environ. Sci. Technol. 2008, 42, 4589–4594.

WML, 2010. Operationeel Storing Beheerplan (OSB) Roosteren 2001, herziene versie 2010. WML report 6105B, Waterleiding Maatschappij Limburg, Maastricht, the Netherlands.

Wricke, D. Tränckner and Böhler, E. (2003) Dokumentation von typischen Schäden un Beeinträchtigungen der wasserversorgung durch Hochwasserereignisse, Ableitung von Handlungsempfehlungen" DVGW.