Distribution System Contamination Prevention Fall 2014

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Abstract

Contamination of treated water in the distribution system has the potential to negate the improvements to water quality provided by an AguaClara plant. Intermittent distribution systems may create the conditions for the mechanisms which cause this contamination to occur. The most likely mechanisms of distribution system contamination are pipeline intrusion, cross contamination and inadequate household storage. Through proper operator training, effective regulation and installation of secure storage facilities and backflow prevention valves, these mechanisms can be prevented and safe water delivered to all AguaClara households.

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1. Introduction

Contamination of treated water in the distribution system has the potential to negate the improvements to water quality provided by an AguaClara plant. In practice, most common pathways of contamination can be avoided by proper operation and regulation of drinking water systems; however, under conditions of high topographic variability and intermittent supply, current AguaClara systems may be at risk of distribution system contamination even with proper system management. This semester, our team has investigated the potential mechanisms that may cause this contamination and proposed solutions to mitigate them.

In a developed country with a properly maintained infrastructure, distribution system contamination should not present a threat to drinking water quality. Adequate household plumbing and a distribution system that maintains constant high pressure are responsible for preventing most mechanisms of contamination. In many developing countries, however, distribution systems do not provide a continuous water supply; rather, water is delivered intermittently, and the pressure in the distribution system is lowered between delivery periods. Recent studies have provided evidence for recontamination in these systems, but the exact mechanisms are not well understood. We hypothesise that cross-contamination from contaminated storage containers and pipeline intrusion are the most likely cause of this contamination.

2. Literature Review

In order to adequately assess the risks and causes of distribution system contamination, we first analyzed existing literature. In this review, information was gathered on problems associated with intermittent water supply and on the physical mechanisms thought to cause contamination in distribution systems.

2.1 Intermittent Supply

Intermittent supply has been shown to cause damage to distribution system infrastructures. The frequent changes in flow caused by the shutdown and startup of an intermittent system have the potential to cause large pressure transients in the system if it is operated incorrectly. Pressure transients, or waves of energy that move through a pipeline, cause temporary localized periods of high and low pressure. These transients can severely damage pipe systems causing higher concentrations of leaks and potentially creating conditions for contaminant intrusion into pipelines (Charalambous 2011).

Recent studies have shown that recontamination to be an acute problem in certain intermittent distribution systems. One study examines water quality from household taps from two water sources in the twin cities of Hubli-Dharwad in Karnataka India; one intermittent and the other continuous. In Hubli-Dharwad, surface is drawn from the Renukasagar Reservoir fed by the Malaprabha River and the rain-fed Neersager lake. The water is treated in the Amminbhavi and Kanvihonnapur water treatment plants (WTP) through aeration, coagulation and flocculation with alum, clarification, rapid sand filtration, and chlorination with Cl_2 gas. Both intermittent and continuous zones received its water from the same treatment plants, but different storage reservoirs. The study found evidence of contamination in the intermittent system that did not exist in the continuous supply system.

Specifically, the study found elevated levels of bacteria when pressure in the intermittent system dropped below 10 psi. Periodic contamination resulted in pipes with pressures between 10 and 17 psi and no significant contamination was observed in systems that maintained a pressure of 17 psi or greater. Furthermore, higher levels of contamination resulted during the rainy season than in dry seasons in intermittent systems than continuous systems (Kumpel & Nelson 2013). Many of the contaminants related to recontamination in distribution systems are listed in Ercumen et al. (2013).

In another study by Kumpel & Nelson, using the same supply system, the avenues of contamination in intermittent water supply was investigated. Postulates from this study include the potential of intrusion through infrastructure deficiencies and household storage. Pressure surges were noted as a cause of transient low pressure in the system. The drops in pressure were strongly correlated with the concentration of contamination in the drinking water. Kumpel concludes that this relationship is likely evidence of intrusion caused by transient pressure (Kumpel & Nelson 2014).

2.2 Household storage

Drinking water samples provided by households, in both continuous and intermittent supply systems, were found to have higher concentrations of indicator bacteria than water analyzed directly from taps. Most households in developing countries studied, even those with continuous supply, store drinking water for long periods, which results in recontamination of their water supply by the time of consumption. Water samples were collected and tested from reservoirs, consumer taps, and drinking water provided by household storage containers, in Hubli-Dharwad, India, over the course of one year. This observation may reduce the benefits of improved water quality in switching to continuous water supply systems (Kumpel & Nelson 2013). According to the World Bank Report from 2006 publicly placed water taps, even clean taps, still do not have a significant impact on improving public health, as the water is often re-contaminated prior to consumption (Cairncross 2006). In order to ensure that treated water makes it to the consumer without contamination, care should be taken in examining each phase the water will go through before being consumed. The ideal solution is to provide consumers with clean and safe drinking water is to distribute water directly to people’s taps or to a closed storage container that is not open to contamination.

2.3 Intrusion

For intrusion into buried pipes to take place in a distribution system, a pathway such as cracked or poorly sealed pipes and a hydraulic gradient need to be present in the system. For this gradient to take place there needs to be lower pressure in the water pipe than in the sewage pipes. Negative pressure in pipes is possible depending on the layout of the distribution system, whether the sewers are clogged or not, or a greater pressure is present in the water table than in the pipe. The contaminants that are being pulled into the piping system due to the negative pressure within the pipes could originate from sewage spills in saturated soils, buried sewer pipe leaks or polluted groundwater (Erikson 2013).

Until recent years, very little effort was spent examining the possibility of intrusion into pipes during periods of low or negative pressure. In the last decade, a few studies have examined the possibility of distribution system contamination through this mechanism. Although there is a general lack of information regarding the intrusion in intermittent water supply systems, research has been conducted on negative pressure transients in continuous supply systems. Even in well maintained systems transients caused by power failures or sudden valve closures can cause brief periods of extremely low or negative pressures (LeChevallier 2004).

A study conducted at Tulane University in 2004, tested a pipe system that was subjected to negative pressure transients to determine if it could cause contaminant intrusion into a pipe network. The study's authors hypothesized that contamination can result if negative pressure transients cause the external water pressure around a pipe system to exceed the pipe's internal pressure. A pilot scale test rig was constructed for the study. The test rig consisted of a 10 hp centrifugal pump attached to a length of 2" PVC piping with the outlet connected into a storage tank. An intrusion element was connected to the PVC pipe to simulate a leaky section of pipe. This element consisted of a ½" ball valve installed below a 4.5' clear observation pipe. During the experiment the ball valve was turned to adjust the pressure and the intrusion element was filled with either water or a chemical tracer. Transients were created in the pipeline by suddenly shutting off the pump or suddenly closing the valve at the end of the pipe. The rig tested various flow conditions with different heads in the intrusion element. Two methods were used to calculate intrusion volumes, a volumetric method and a chemical tracer. Both methods found intrusion into the pipe system, the chemical tracer was found in water that had been flushed all the way through the system (Friedman et al 2004).

Though the Tulane study found that intrusion into a pipe could be caused by transient pressures in the system, the study only examined a circular orifice and did not include a porous medium around the pipe. Two studies, from the University of Sheffield in the UK, used computational fluid dynamics and an experimental test rig to model such conditions. The first study focused on intrusion modeling and the effect of groundwater conditions. It also used computational fluid dynamics to create a computer model of contaminant intrusion into a pipe system in saturated porous media that underwent pressure transients caused by sudden valve closures. The second study, concerning proof of contaminant ingress during transient events, postulated that contaminants would indeed intrude into a pipe system and proposed equations to predict the volume of this intrusion. The model's results suggested a greater dependency on the size of the orifice and that a simple orifice equation will not accurately estimate the intrusion into a pipe. The results also suggested that intrusion can come from locations below the pipeline and proposed a zone of influence as a way of understanding the risk from contaminant intrusion into pipe systems (Collins 2010).

3.0 Mechanisms of Contamination

Table 1: Potential Contamination Mechanisms

Mechanisms	Hypothesized Necessary Conditions	Recommended Best Practices
Household Storage: A household's water storage supply can be contaminated if hands, debris, animals or improperly washed utensils are dipped into the storage tank	● Lack of faucets ● Open tank	● Sealed tank with adequate household plumbing
Cross Contamination: Negative pressure transients in pipes or privately attached pumps can suck contaminated water from household storage systems or other connections into the distribution system.	● Intermittent supply ● Submerged outlets ● Connection to contaminated source (ground water, contaminated storage water…) ● Negative internal pipeline pressure	● Float valve in water tanks ● Backflow prevention device ● Prohibition against private pumps ● Proper operator training
Pipeline intrusion: May occur when there is a leak or other type of pathway and the internal pressure of the pipeline drops below external hydrostatic pressure, sucking contaminants into the system.	● Booster pumps attached to system ● Large pressure transients (Pump shutdown, sudden valve closure…) ● High water table ● Contaminated soil profile	● Elevated storage tanks ● Prohibition against private pumps ● Proper operator training ● First flush system in household distribution tanks ● Check valves at household outlets
Bacterial Growth inside the pipeline: Potentially may occur if there was a constant, stagnant volume of water kept inside a pipeline for extended periods of time (unlikely)	● Constant water level ● Stagnant water	● Regularly use distribution system ● Usually, a little excess chlorine is dosed to prevent growth in the distribution lines

3.1 Pipeline Intrusion

One significant danger to drinking water distribution systems is contaminant intrusion into distribution pipelines. Pipeline intrusion occurs when the piezometric head outside a leaky pipeline becomes greater than the piezometric head inside the pipeline. Continuous distribution systems are constantly pressurized, and therefore intrusion is not generally viewed as a significant threat to drinking water quality. In intermittent systems, however, water supply is frequently shut off and the piezometric head inside the pipeline drops to the piezometric head of the lowest open outlet of the system. In flat terrain this is not a concern when no external sources of negative pressure applied to the system. This is because the lowest open outlet will always be at a higher elevation than the water table (see Figure 1). However, if the area has high topographic variability such that the lowest outlet is below the water table at the location of the leak, it is possible for the distribution system to be compromised by pipeline intrusion. External sources of negative internal pressure may also cause the internal piezometric head to drop lower than the external piezometric head. These causes can come from improper system operation, or attempts by citizens to gain more than their share of water from the system.

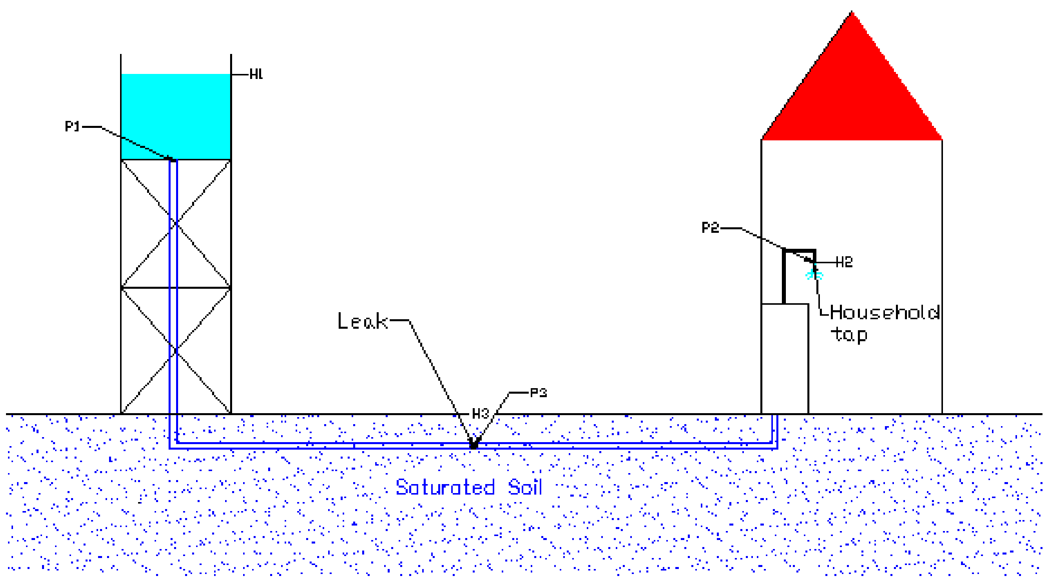

Figure 1: Leak in Flat Terrain

If the household tap shown in Figure 1, is left open when the water system is shut down, the piezometric head inside the pipeline will drop to that of the Household tap, H2. The piezometric head of the water saturating the soil will have a value equal to the height of the water surface, H3. Since H2 is greater than H3, no intrusion will occur.

3.1.1 External Sources of Negative Pressure

There are two potential external sources that may cause negative pressure in the distribution system. The first is the development of large pressure transients that may be generated upon startup and shutdown of the intermittent distribution system. Pressure transients are pressure waves that migrate through a pipe system after a sudden change in the pipeline flow. They can be caused by the sudden closing of a valve or a sudden shutdown of a pump. If operated incorrectly, an intermittent distribution system has the potential to generate these transients at each startup/shutdown cycle. In practice however, proper training of system operators should be able to mitigate most of the risk of this condition occurring. Such training may include teaching operators to close system valves slowly and not shutdown the system suddenly.

The second external source that may cause contaminant intrusion is the installation of private pumps by citizens using the distribution system. These pumps are often used to access the water that is stored in the pipelines after the water has been shut off. They have the potential to create negative pressure conditions in the pipeline and thus induce contaminant intrusion. Through a serious and yet unresolved issue in large cities, this problem may be resolved in small municipalities by effective passage and enforcement of prohibitions on privately owned pumps attached to the distribution system.

3.1.2 Topographic Sources of Negative Pressure

The above mentioned mechanisms of pipeline intrusion, can be prevented through proper operator training and system regulation. However, if a leak occurs in saturated soil above the lowest outlet of the distribution system, contamination may still occur even if operators are properly trained and regulations enforced. If a downstream outlet is left open after an intermittent system is shut off, the pressure in the pipe will normalize to the piezometric head of the system outlet. If the saturated soil should have a water surface above this outlet elevation, then the piezometric head of the water saturating the soil will be greater than that of the outlet, and thus greater than the piezometric head inside the pipe, resulting in pipeline intrusion.

We have determined several scenarios in which the water table may be saturated above the lowest outlet of the pipeline, though all require large changes in elevation throughout the system. First, a restrictive soil layer may cause a perched water table on a hillside that has a higher elevation than a downstream outlet. This scenario can be seen in Figure 1. Second, a prolonged pipeline leak may itself saturate the soil profile. This scenario can be found in Figure 2 .Third, a spill of contaminants in the vicinity of the leak could saturate the soil profile. This scenario can be found in Figure 3.

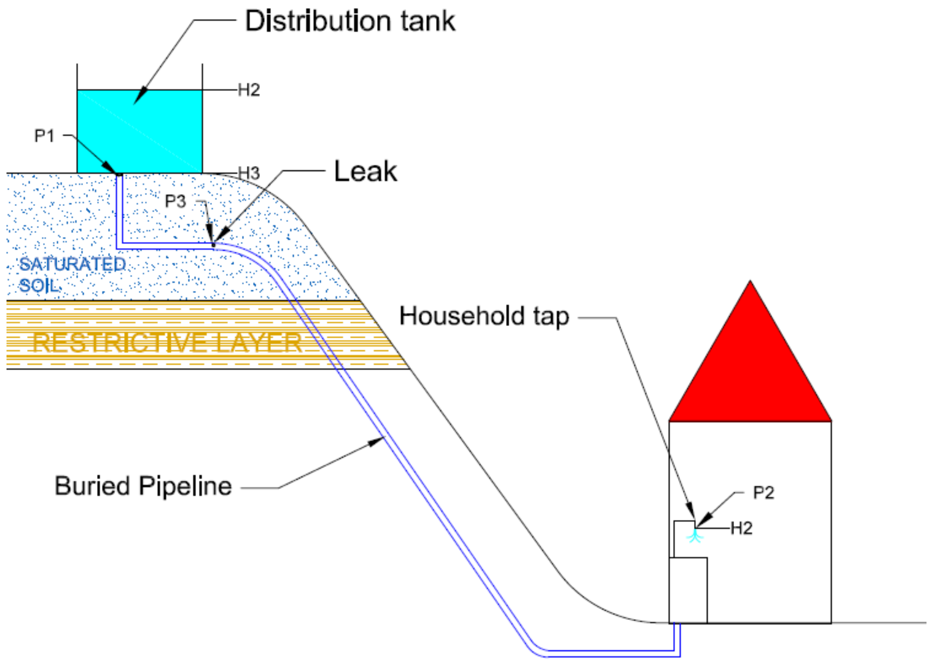

Figure 2: Perched Water Table

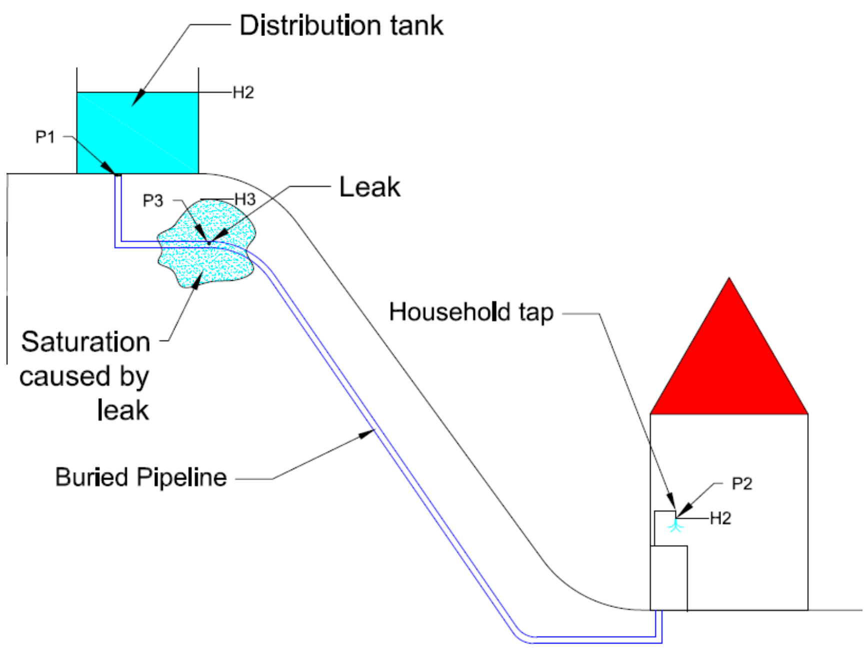

Figure 3: Saturation Due to Leak

If the household taps shown in Figures 2 and 3 are left open when the system is shut down, the piezometric head inside the pipeline will drop to the pressure at the opening, this pressure is equal the elevation of the tap, H2. The piezometric of the water saturating the soil media is equal to the water surface elevation of H3. Since H3>H2, the water will intrude into the pipeline.

Our team has developed three solutions to prevent the intrusion scenarios depicted in Figures 1 and 2. The first solution is to build an elevated storage tank between the slope and the households served. This solution can be found in Figure 4.

When the system depicted in Figure 4 is shut down, the piezometric head inside the pipeline in the section of the leak will drop the piezometric head of the water surface in the elevated tank, H4, rather than the household taps H2. Since H4 will always be greater than the height of the water surface above the leak, H3, the piezometric head inside the pipeline will always remain higher than outside the pipeline, and thus no intrusion is possible.

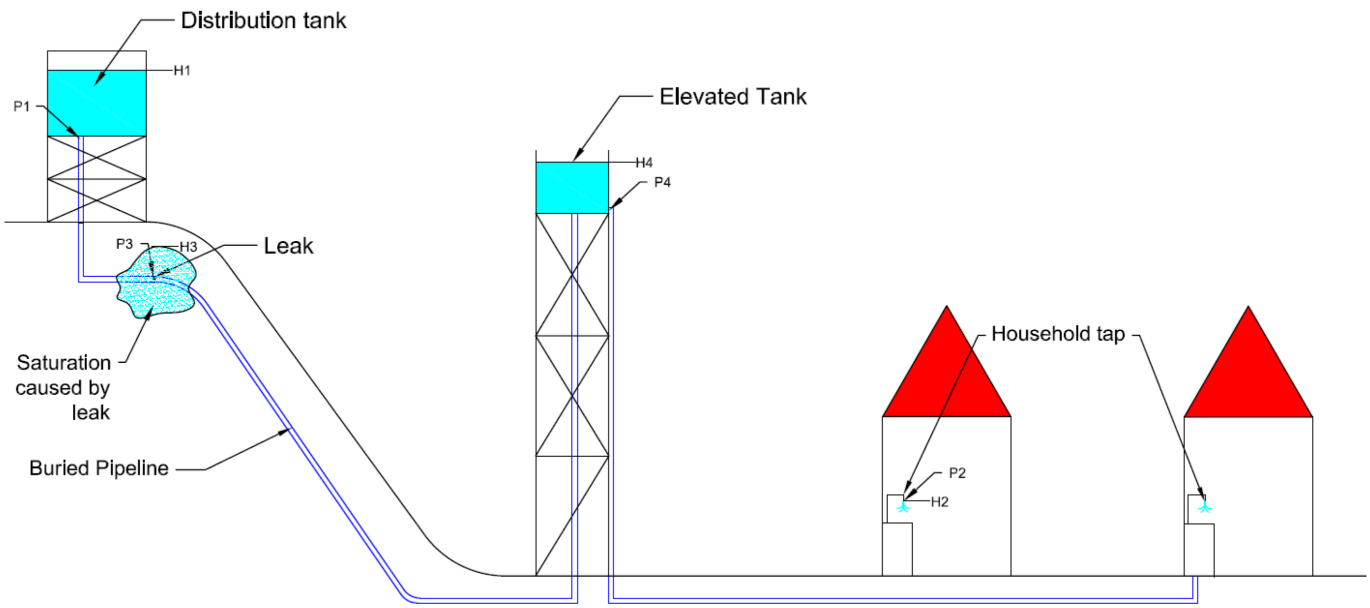

Figure 4: Central Tank Solution

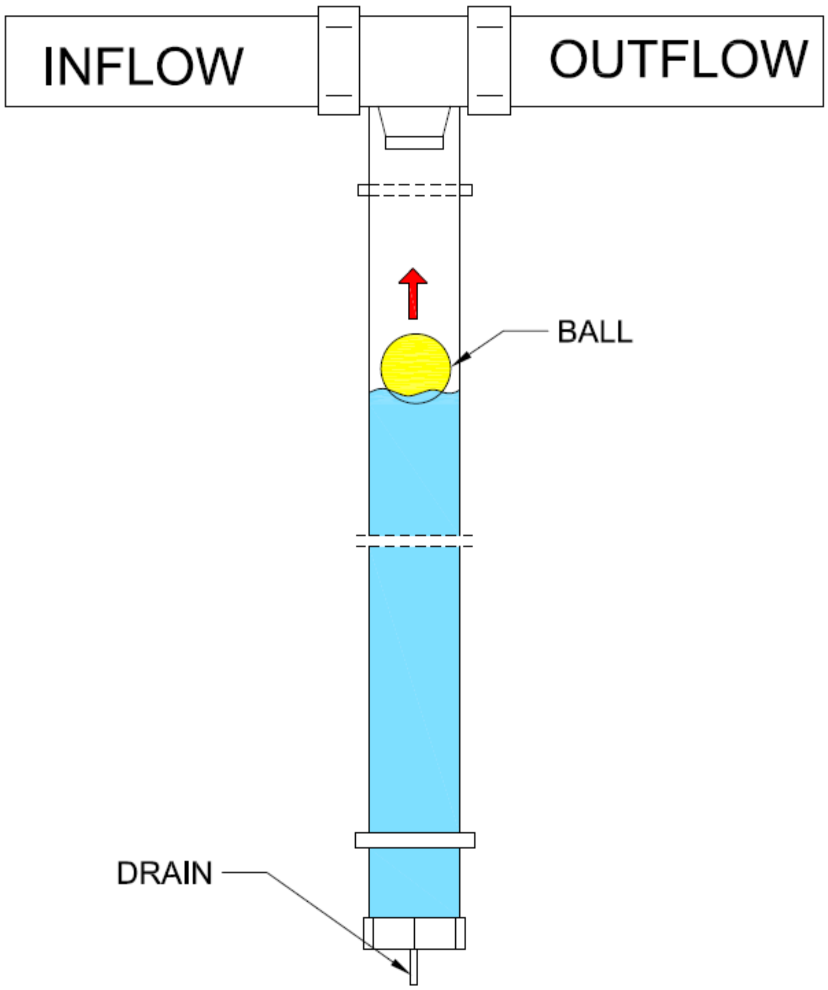

Figure 5: First Flush Valve

As can be observed in Figure 5, when the water starts to enter in the first flush system, it begins to fill the vertical pipe. Inside this vertical pipe there is a floating ball that floats up with the water level as the pipe is being filled. When a the vertical pipe is full, the ball closes the entrance. At this point, the water can no longer enter the vertical pipe, so it continues through the horizontal pipe to the household tap. At the bottom of the system there is a little drainage pipe, that must be opened after each cycle through the system in order to empty the pipe. Though a first flush system may prevent contamination from entering a household, its quantitative benefits are not known. First flush valves also waste a portion of the water being delivered which may be undesirable in areas with scarce water resources.

The most effective solution to the problem of pipeline intrusion caused by elevation differences may in fact be the simplest. In order for piezometric head in the pipeline to drop below the piezometric head of the groundwater, downstream taps must be left open when the intermittent water system is shut off. A simple solution to the problem therefore, is to install check valves which automatically close all household outlets when the distribution system is shut off. These valves could then be calibrated to close at a pressure higher than the highest possible pressure at the site of a potential leak, meaning that the internal piezometric head could never drop below that pressure, and therefore intrusion could never occur. A diagram of a typical version of such a valve can be found in Figure 6.

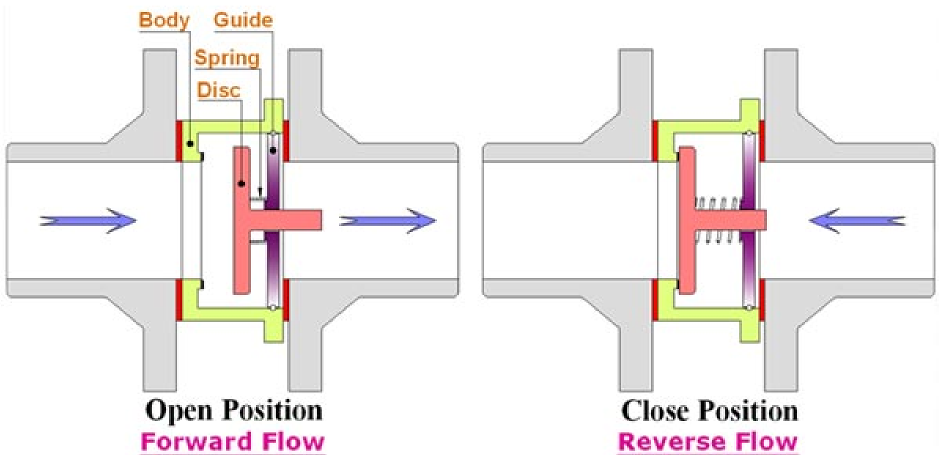

Figure 6: Generic Check Valve
(http://www.nivzvalves.com/disc_check_valve.htm)

3.2 Cross Contamination

Cross-contamination is a simple, but preventable pathway for distribution system contamination. The most likely form of cross-contamination is backflow from household storage tanks. In order for this condition to occur, three things must happen. First, a negative pressure must be generated in a distribution pipeline. These pressures may be generated by pipeline transients, private pumps or elevation differences as discussed above. Second, the outlet of a distribution system must be submerged, and thus when the pressure goes negative the outlet will suck water into the outlet. Third, the water sucked into the outlet must be contaminated (as described in section 3.2).

This problem can be solved by taking three simple measures. First, proper operator training and prohibitions of pumps should be implemented in order to reduce the risk of negative pipeline pressure. Second, float valves should be installed on all household storage tanks in order to prevent the distribution system outlets from submergence. A schematic of one proposed backflow prevention device can be found in Figure 7 developed by the 2014 AguaClara Village Supply team. The check valves discussed in the preceding chapter may also be used in lieu of the float valves. Third, household tanks should be securely covered in order to reduce the risk of contaminants entering the household supply.

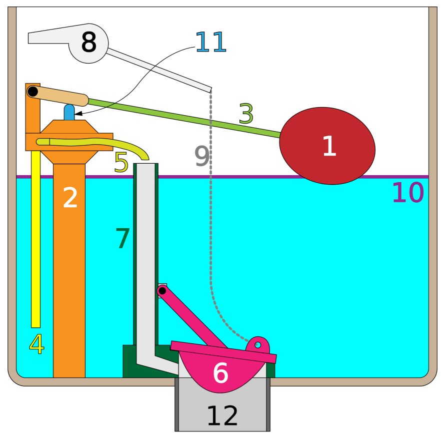

Figure 7: Float Valve
(Figure courtesy of the Village Supply Team)

3.3 Household Storage Contamination

Even if water makes it to a distribution system uncontaminated, all efforts are lost if the water is re-contaminated during household storage. As demonstrated by studies such as (Kumpel & Nelson 2013) and (Cairncross 2006), household storage contamination is a substantial problem that needs to be addressed in order for a community to truly have access to safe water. Though the technical solution to the problem of household storage is quite simple (securely cover the storage contained to assure no contaminants enter) convincing a community to adopt these methods is not always so easy. In order to truly ensure that safe water is brought to households, the community must be educated about the dangers of contamination and convinced of the need for safe water storage.

4. Conclusions

Distribution system contamination represents a significant threat to intermittent drinking water systems in the developing world however, the problem is preventable if the community takes appropriate action. First, all system operators should be adequately trained to shutdown and startup the system without causing pressure transients. Second, all private pumps should be prohibited from being attached to the system. Third, check valves should be placed before all system outlets that lie below large elevation drops. Finally, secure household storage tanks containing float valves should be installed at all household served by the system.

5. Future Work

Though the proposed pathways presented in this paper represent a threat to AguaClara distribution systems, no data has been gathered on whether AguaClara systems are actually being recontaminated during distribution. Future work may include gathering water samples from household taps served by AguaClara, and testing them for contaminants. Priority should be given to those houses that lie below an elevation drop, since they are the ones most vulnerable to contamination through intrusion, but random samples of other taps should also be tested. If distribution system contamination is found to be a problem, more work should be done to identify the cause of the contamination as well as investigate the practicality of installing the solutions presented in this report. Regardless of the detection of contaminants in the distribution system, investigations can be made into the cost and feasibility of installing check valves on all taps at low elevations.

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