Rainfall and Water Quality

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RAINFALL AND WATER QUALITY

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1. INTRODUCTION

The consideration of rainfalls impact on water management is not new and started with the history of sanitation. At the beginning of the 20th century sewer networks in urban area were designed both for sewage and for stormwater management. In the 70's the impact of urban runoff on water quality was already studied (Pitt et al. 1977) and more recently the question of climate change impacts on water quality was considered with the effect of heavier rainy events. Commonly, categories of rain are defined by their intensity: heavy, moderate and light rain being characterised by the amount of mm of water/hour (respectively 2.5, 2.5 to 7.5, >7.5). According to the duration of a given rainfall, the same intensity can be observed during a period (shower) or a longer one (storm). Consequences of these precipitations can result in so called extreme rain or flood respectively at local or regional scale. As reported by the 2007 IPCC report, it is likely that the frequency of heavy precipitation events has increased over most areas, particularly in Europe and North America, and that available research suggests a significant future increase in heavy rainfall events in many regions. Such phenomena, increasing in frequency and intensity, may have a strong impact on the quality of the waters. Indeed, resulting changes in flow regimes will influence the chemistry, hydromorphology and ecology of water bodies at the environmental level as well as, in urban area, the wastewater quality, the sewage treatment efficiency and the corresponding pollutants load. The effect of rainy events can also reach drinking water production system, impairing the quality of the distributed water (Figure 1)

This chapter aims to make an overview of the impact of rainfall on water quality, by considering, within the water life cycle, chemical, biological and physico-chemical parameters of water quality.

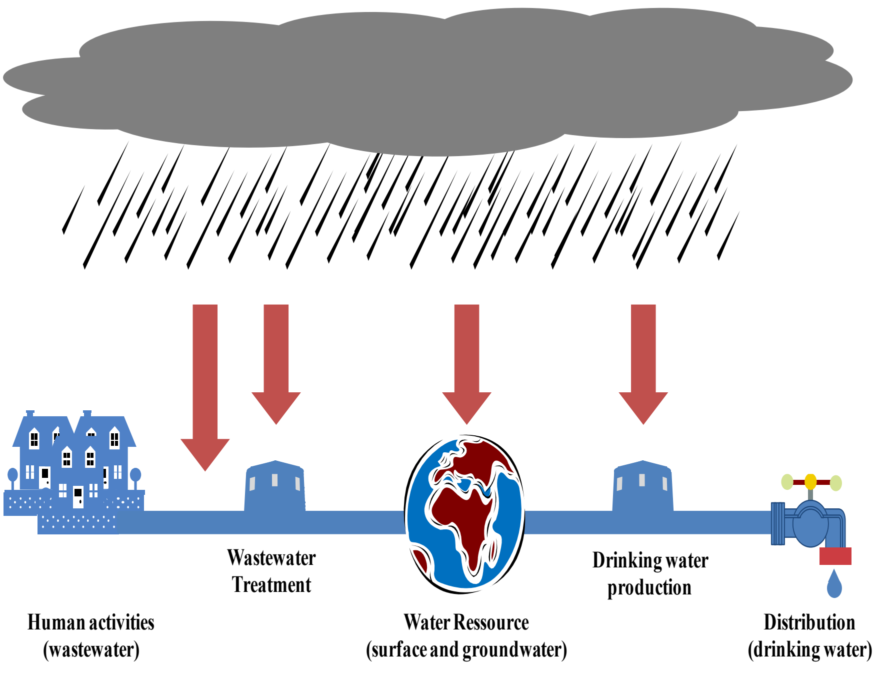

Figure 1. Impact of heavy events on water life cycle.

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2. Water Quality

Water bodies are characterised regarding their chemical and biological status. A number of parameters are used to analyse water quality. European water regulations (Drinking-water Directive (DWD) and the Water Framework Directive (WFD)) have been established, since the end of the 1990s, to ensure public health security for water intended for human consumption by promoting a policy for the management and protection of water resources at European level. More recently, a new preventive risk management approach was initiated by WHO and water suppliers, via the implementation of Water Safety Plans (Bartram et al., 2009), the aim of which is to guarantee the safety of a drinking-water supply through the use of a comprehensive risk assessment and risk management approach. Despite this regulatory framework, numerous water bodies are often of impaired quality and non-compliant with European regulations (Bloech, 2011).

In general, raw water quality is influenced by both 'natural' and anthropogenic driving forces. The former include spatial and temporal variation in water availability, wildlife, topography, geology, vegetation and the future impact of climate change, particularly with respect to the frequency and severity of droughts or rainfalls. Anthropogenic driving forces come from each of the key sectors that use water (industry, energy production, public water supply and agriculture) and include point sources (e.g. wastewater discharges) and non-point sources (e.g. surface runoff). In general, water quality degradation is directly linked to anthropogenic pressure, and climate change acts as an indirect aggravating factor for these pressures on the environment. In particular, the main determinants of climate change having a direct or indirect impact on water quality are air temperature and extreme water events (flood, drought) (Delpla et al., 2009). Resource availability is linked to these parameters, and it becomes important to consider extreme events in assessing both evolution of water stress and efficiency of the treatment processes (sanitation and sewage treatment).

3. Impact of Rainfall on Urban Water Cycle (From Wastewater to the Environment)

The historical question of rainfall impact on urban water cycle is linked to urban runoff, well studied since the 70's. For instance, Pitt et al. (1977) studied the water-quality effects from urban runoff for a hypothetical city of 100,000 people. Total solids concentration and oxygen consumption were calculated for receiving waters using various storms simulated in the study. and more research on the long-term toxic effects of storm flow were suggested to help solve urban runoff problems.

Cities are becoming increasingly vulnerable to flooding because of rapid urbanization, installation of complex infrastructure and changes in the precipitation patterns caused by anthropogenic climate change (Willems et al; 2012). For more than a century, sewer systems have been constructed at large scale across cities worldwide. These sewer systems could make the cities more vulnerable to extreme rainfall, partly due to the lack of consideration to what occurs when the design criteria are exceeded. Next to this increase in the vulnerability, there is strong evidence that, due to global warming, the probabilities and risk to sewer surcharge and flooding are under discussion. But impacts of climate change on urban drainage are still weakly investigated (Willems et al., 2012).

In AMWA report (2007), the different impacts of climate changes on water suppliers are identified and described as follow:

i. direct impacts resulting from the effects of climate change on water utility functions and operations,
ii. indirect impact resulting from the effects of climate change on the baseline environment in which water utility functions and operations are carried out and
iii. compound impact resulting from the cumulative effect of the direct and indirect impacts which affect the same natural systems or utility systems.

Among the direct impacts, more frequent and intense rainfall events are intended to increase turbidity, sedimentation, risk of direct flood and consequently damage water utility facilities: for example, loss of reservoir capacity storage (shallower, warmer water, increased evaporation and eutrophication and potential conflicts with flood control objectives) with consequences on water treatment (AMWA, 2007). However for urban watercourses, there is often "flashy" hydraulic regimes and poor water quality, making them potential hazards.

Furthermore, the knowledge of impact of intense rainfall events on urban river water discharge and, in particular, fine particle transport is limited (Old et al., 2003). The washed off pollutants such as suspended solids increases the turbidity of the receiving water, thereby reducing the penetration of light, resulting in decreased activity and growth of photosynthetic organisms. Clogging of fish gills has also been attributed to the presence of suspended solids. These ones settle in receiving water pose long-term threats resulting from increased oxygen demand and gradual accumulation of toxic pollutants. Such detrimental effects have made suspended solid concentration one of the pollutant measurement indices (Aryal, 2009).

Moreover, Old et al. (2003) demonstrated that this extremely large and urban flux of fine sediment is likely to have a major downstream impact on water quality in the river.

Brodie and Egodawatta (2011) have shown that suspended particles in stormwater runoff generated from road surfaces loads increase linearly with average rainfall intensity. Above a threshold intensity, there is evidence to suggest a constant or plateau particle load is reached.

Cheng et al (2009) have studied the impact of four different intensity rainfall (light rain, moderate rain, heavy rain and storm) on water quality of urban combined sewerage system (CSS) in highly urbanized region and the correlations of parameters with both rainfall intensity and runoff graph. Basic parameters and metals concentrations were monitored and shown good relation between them and runoff.

Temporal evolution of microbiological, physical, and chemical quality of stormwater runoff from a stormwater drain was studied by He et al (2010) in an urban residential area in Calgary, Canada. Intensive rainfall events produced highly polluted stormwater runoff when pollutant source limitation did not occur. Inconsistent event-based correlations between total suspended solids (TSS) concentrations and water quality parameters were observed. During storms, the loading of TSS exhibited a flow-dependent nature, whereas microorganism discharge appeared to be governed by a flow-independent mechanism. No strong first-flush effect was observed in either TSS or microorganisms, on average. No correlations of first-flush loads of TSS with rainfall characteristics were identified.

Rainfall events can also play an important role regarding micropollutants load at sewage treatment works (STWs). In general, urban runoff tends to originate from five main categories: transportation (i.e. roads and vehicles), roofing materials, construction activities, vegetation and soil. There may be many variables within a given source, e.g. runoff from roads and associated traffic emissions may contain vehicle lubricants, exhaust emissions, degradation from tyres and brake linings, road maintenance and surface degradation, accidental spillages and road salting in winter. The extent of urban runoff is dependent on levels of contaminants deposited on urban surfaces through wet and dry deposition, the length of the preceding dry spell and the characteristics and size of the urban catchment. Assessing the effects of rainfall STW influent has produced results that suggest that with short rainfall incidences the level of most micropollutants will increase due to ‘first flushing’ events, whereas continuous high levels of rainfall will result in a dilution effect on micropollutant levels (Rowsell et al., 2010).

Another consequence of runoff on water quality may be ecotoxilogical impact linked to the presence of contaminants. Meland et al. (2010), exposed brown trout (Salmo trutta L.) to highway runoff samples during 24 h. The metabolism of the fish through reduced condition factor was affected and the observed effects were likely caused by multiple stressors and not by a single contaminant. A sedimentation pond clearly reduced the toxicity of the highway runoff. But even in the least polluted exposure condition signs of physiological disturbances were evident.

Considering the threats originating from wastewater utilities, the type of wastewater system is of crucial importance. Moreoften a combined wastewater system is prevalent in urban area, with domestic wastewater and storm water runoff from impervious surfaces (streets, roofs etc.) collected in the same sewer system.

During rain events, the wastewater treatment plants as well as the sewer systems have to cope with a high load of combined wastewater that may exceed the systems’ capacity. Thus, certain volumes of wastewater must be stored or discharged. This may be achieved by storm water overflow basins or storm water tanks (SWT), with both retention and treatment functions (Heins, 2009). Combined sewage overflows which were previously designed to directly discharge the exceeding flow tend to be removed from wastewater networks.

In case of heavy rainfall, the wastewater treatment plant temporarily receives low concentrated sewage and high hydraulic loading. Prolonged exposure to storm water conditions will negatively affect all treatment steps by decreasing the residential time and particularly the settling processes (primary and secondary) as well as the biological part of the treatment with activated sludge, and possibly denitrification and phosphorus removal processes. For this last step, it is still not clear whether this is due to inhibition of phosphorous-removing bacteria (PRB) or that the low COD concentrations in the influent are causing the problem. It has been reported that, for example, the deterioration of PRB efficiency regularly occurred at some wastewater treatment plants (WWTPs) after heavy rainfall. The phenomenon was attributed to low plant loading that took place during such events (Brdjanovic et al., 1998).

An observatory of urban pollutants was created in France for the purpose of assessing the dynamic of wastewater and wet weather flow (WWF). The magnitude of WWF pollutant loads characterized by physical-chemical parameters: total suspended solid, DOC, heavy metals (Cu, Zn), polycyclic aromatic hydrocarbons, and their subsequent acute impact on receiving waters have been extensively studied since 1970 (Suarez and Puertas, 2005; Gasperi et al., 2010). Some studies have observed the becoming of specific pollutants concentrations during wet weather flows in wastewater. Gilbert et al.,

(2011) for instance showed that alkylphenols (AP) and polybromodiphenylether (PBDE) concentrations are 1.5 to 5 fold higher under wet weather flows.

The removal rates of several antiphlogistics and lipid regulating agents was investigated during a rainfall event (Ternes, 1998). The elimination rates of drugs like bezafibrate, diclofenac, naproxen and clofibric acid were significantly reduced on the rainfall day. For bezafibrate a reduced elimination rate (<5%) was observed the last day of the investigation period. These results indicate that the rainfall event may be presumably responsible for the decreased drug elimination rates by the sewage treatment plant probably due to a reduced microbial activity and/or altered sorption and flocculation conditions within this rain period (Ternes, 1998).

4. RAINFALL AND WATER RESOURCE (QUALITY MODIFICATION OF NATURAL WATER)

Water quality depends on stressors among which climate-related parameters such as water temperature and river flows (Murdoch et al., 2000). According to these authors, changes in water quality is related to hydrological factors (e.g. limited dilution of point sources during low river flows, or increased runoff from agricultural area during rainstorms), terrestrial factors (e.g. changes in vegetation and soil structure) and resource-use factors (e.g. increased water use, increased demand for cooling capacity of industrial processes). More recently, bibliographic reviews and case studies (Delpla et al., 2009, Zwolsman and van Bokhoven, 2007, Van Vliet and Zwolsman, 2008) concluded that climate change has a negative impact on water quality. Depending on the season, the same impact (increase of water pollution) may be related to different conditions. During winter rainfall, water and air temperatures are low, river flows generally high and of soil leaching and runoff increase), contrary to summertime where very high air temperature may lead to drought (e.g. Krysanova et al., 2005). Both cases may give a high pollution level either by runoff (heavy rain in winter) or by physical concentration (drought in summer).

According to Bates et al. (2008) and Brunetti et al. (2001), climate change in temperate area will lead to a decrease of the number of rainy days, with however a significant increase of the mean volume for each event. Consequently, the drought and re-humidification cycles for the soils will allow the decomposition and leaching of the organic matter to the surface waters and thus impact water quality as a whole (Evans et al., 2005). Heavy rainfall events could lead to an increase in dissolved organic carbon concentration (Evans et al., 2005 ; Fellman et al., 2009) which is known to play an important role concerning the transport and release of pollutants (Lennartz and Louchart, 2007; Pédrot et al., 2008).

Nutrients concentrations (nitrates, phosphates) and obviously particulate and colloidal suspended matter are directly correlated with rainy events (Prathumratana et al., 2008; Bhat et al., 2007; Drewry et al., 2009) and could consequently exceed water quality regulated limits.

For heavy rainy events leading to an increase of river flows, the major risk is also certainly the transport of pollutants by run-off (such as pesticides and pharmaceuticals). It was often acknowledged that the timing and magnitude of rainfall events are significant on pesticide transport through rapid flow processes (Leonard, 1990, Flury, 1996; Kladivko et al., 2001, McGrath et al., 2010) with in general an increase of pesticide leaching with increasing rainfall amount (Tiktak et al. 2004, Jiang et al., 2012). Pharmaceuticals considered as « emerging substances » are of a special importance because they are not yet regulated. Some studies specifically show the variations of some of these compounds (carbamazepine, monensin, clofibric acid, iopromide, sulfamethoxazole, trimethoprim, flumequine) with flow rates variation during rainfall events (Oppel et al., 2004; Lissemore et al., 2006; Tamtam et al., 2008).

Variations of temperature, pH and water composition occurring during rainfall events could also have an influence on contaminants by impacting their sorption on mineral phases. Moreover, the influence of soils properties has to be taken into account for the leaching behaviour assessment of anthropogenic compounds (Oppel et al., 2004; Yu et al., 2009).

Neal et al (2004), studied the water quality of rainfall and runoff for two catchments of different characteristics. Average water quality concentrations and fluxes vary across the sites, typically by about 30% but stream chemistry is much less variable due to water coming from aquifer sources of high storage. Moreover, the catchments appear to be retain both P and N coming from agricultural practices and sewage inputs to the streams.

Some studies on coastal water quality impacts of rainfall like Coulliette et al. (2008) have shown the effect of non-point source contamination linked to stormwater. Fecal coliforms concentrations increased with rainfall intensity but higher than expected values existed during conditions of negligible rainfall (< 0.25 cm), indicating a possible reservoir population in the sediment.

Liu et al (2010), worked on the occurrence and distribution of three typical endocrine-disrupting chemicals (EDCs), nonylphenol mixture (NPs), bisphenol A (BPA), and 17-ethynilestrdiol (EE2), in the coastal water, suspended solid, and sediment. With the increasing rainfall, the concentrations of target EDCs decreased in water and sediment and increased in suspended solid.

The genotoxic impact on fish of heavy rainfall following herbicide application has been investigated by Polard et al. (2011). For three hydrological conditions (basal flow, winter flood, and spring flood), chemical analysis of the water samples confirmed the higher contamination of the spring flood water, mainly explained by a peak of metolachlor. Genotoxicity was evaluated on Crucian carp and exposure to spring flood water resulted in the highest damage induction. Further experiments on pesticides mixture adde on water flood revealed a mutagenic impact of water contamination during the spring flood, emphasizing the need to consider these transient events in water quality monitoring programs

Concerning pathogens, floods frequently lead to a faecal contamination of surface and deep waters and also to waterborne diseases (Beaudeau et al., 2010). As an example, very elevated levels of bacteria E. Coli (2000 – 7000 CFU/mL) have been measured downstream Milwaukee river basin after rainfall events (Patz et al., 2008). Curriero et al., (2001) have shown that half of the waterborne diseases outbreaks in United States during the second half of the 20th century followed a period of extreme rainfall (defined as the excess of the 90th percentile based on 50-year distribution).

Finally changes in rainfalls patterns and temperature could also have an effect on blooms occurrence of cyanobacteria. Intense rainfalls could interrupt bloom development in a water body by flushing and mixing at the event scale but increase the nutrient load and the rate of eutrophication which favour cyanobacteria at a longer time scale (Reichwaldt and Ghadouani, 2011).

5. Impact on Drinking Water Production

Rainfalls events could lead to elevated levels of turbidity and organic matter in river waters which in turn could cause a decline in treatment performance. Mineral particles leaching could lead to high concentrations in natural waters, having a direct impact on coagulant demand during water treatment (Shin et al., 2008) and on Disinfection By-Products (DBPs) formation. However, this decrease in efficiency could be also due to a combination of a change in the nature and increased concentrations of Natural Organic Matter (NOM) and lower water temperatures in the natural water (Hurst et al., 2004). This could explain why seasonal differences have a significant impact on process robustness which is independent of the raw water turbidity. Moreover, in the distribution system, the highest spatial variation in Trihalomethans concentration (from 2 to 4 times) is measured for elevated water temperatures (>18°C) typically during the summer season, whereas this variation is small for water temperature lower than 15°C during the spring or fall seasons (Rodriguez and Serodes, 2001).

Although very few studies reported the relationship between algae and DBPs precursors, some authors pointed out the algal contribution to some DPBs formation such as Haloacetic Acids (Chen and Zhang, 2008).

Heavy rainfall and associated floods could flush biological contaminants into waterways and aquifers, for example with combined sewer systems overflowing and agricultural lands leaching. Greater water flow contributes to increase the pathogen load and the penetration speed of pathogens into resource waters and the drinking-water supply (Unc and Goss, 2003). A significant number of waterborne disease outbreaks have involved the transport of bacteria, viruses, or small parasites into water systems or well-heads during an heavy rainfall event (Auld et al., 2004; Thomas et al., 2006). As an example, heavy rainfalls contributed to the Milwaukee (United States) outbreak of Cryptosporidium in 1993 (54 deaths, 403000 cases) and the Walkerton (Canada) E. Coli O157:H7 outbreak in 2000 (7 deaths, 4300 cases). Monitoring the change of the biological charge with adequate and rapid tools is very important to ensure maximum efficiency of the treatment and protection of the population after rainfall events. This is of primary importance regarding the fact that routine monitoring programs mainly use techniques that are time consuming and not allow a representative picture of the wide range of biological contaminants that could be present in water.

The main recent studies dealing with the occurrence and fate of micropollutants with respect to drinking water treatment are related to pharmaceuticals. Actually, the majority of studies on pharmaceuticals focused on wastewater treatment, for which the insuficient removal efficiency may affect the quality of water resources downstream a treated effluent discharge. Although they are partially removed, residual quantities may remain in treated water and contaminate drinking water resources (Al-Ahmad et al., 1999; Hernando et al., 2006). Actually, more than 20 substances (parent compound and residues) have been found in drinking water (Mompelat et al., 2009).

The efficiency of pharmaceuticals removal varies with treatment processes and also with temperature and weather (Choi et al., 2008). For instance, diclofenac showed largely different elimination rates whose range, comprised between 17% (Heberer et al., 2002), 69% (Ternes et al., 1998), and 100% (Thomas and Foster, 2004) depends on these two last parameters. Pharmaceuticals removal could only be achieved with advanced processes as ozonation, activated carbon adsorption, membrane filtration (Ternes et al., 2002) or UV treatment (Canonica et al., 2008). Finally, only some lipophilic pesticides are removed adequately in conventional physico-chemical drinking water treatment processes, such as flocculation, sedimentation, filtration, or lime softening (Baldauf, 2006).

Concerning natural micropollutants, mainly represented by cyanotoxins, chlorination, micro/ultra-filtration and especially ozonation are the most effective water treatment procedures in destroying cyanobacteria and in removing microcystins (Hitzfeld et al., 2000). Lots of studies concerning removal of cyanobacterial toxins from water showed that the effectiveness of the oxidation process is not only dependant on the reactant concentration, but also on temperature, pH, ionic composition (Rositano et al., 1998; Shawwa and Smith, 2001) and NOM concentration (Al Momani et al., 2008). Moreover, some studies tried to improve by-products identification and toxicity assessment for cyanotoxins (Rodriguez et al., 2007; Mérel et al., 2009). Although DBPs formation has largely not been investigated, the few studies conducted have concluded to a decrease in cyanotoxins toxicity (microcystin, cylindrospermopsin, saxitoxin) after chlorination (Mérel et al., 2010).

Extreme weather events could affect the efficiency of drinking water treatment processes, leading to a possible degradation of quality in distributed drinking water (Sinisi and Aertgeerts, 2010). These concerns are of primary importance for small-scale water suppliers (SSWSs), private, community-based or public, which usually prevail in rural areas. A significant part of the population living in these areas (16 million people in Europe (WHO, 2010) do not have access to improved drinking water resources. This vulnerability of SSWSs is due to an insufficient sanitary protection of resources, agricultural pressures, limited water treatment technologies, relatively greater capital costs of technical installations and larger per unit costs of materials and construction. By considering these existing pressures, and the indirect risks posed by climate change, SSWSs are facing several challenges, including their regulatory environment, administration, management, operation, and their available technical, human and financial resources (Sinisi and Aertgeerts, 2010).

CONCLUSION

Rainfall can be a significant source of variation in water quality. In urban area, depending on its intensity, rainfall can have an effect on utility functions and operation as well as water discharge due to runoff (road, roof, …). The relation between water quality and runoff is in particular well known since the 70’s as an increase of turbidity, sedimentation, transport of more or less fine particles and pollutants (conventional and/or emerging). The main outcomes were the improvement of sewer and rainstorm networks design with in situ settling systems for TSS removal and flow storage. More recently the effect of rainfall on soil erosion has been also highlighted, in particular the suspended solid exportation and increase of nutrient in surface water.

Water resource is also stressed by rainfall. Changes in water quality rely in particular to hydrological, terrestrial and resource-use factors as well as climate. Climate changes are more and more studied with consequences on micropollutants transportation and cyanobacteria crisis

One important point of the relation between water quality and rainfall is the evolution of transient effect (in particular toxicity and ecotoxicity) and the effect on sanitary water.

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