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Impact of Water Source Management Practices in Residential Areas on Sewer Networks – A Review

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Abstract Prolonged drought which is occurred everywhere around the world has caused water shortages, leading many countries to consider more sustainable practices which are called Source Management Practices (SMPs) to ensure water availability for the future. SMPs include the practices of water use reduction, potable water substitution and wastewater volume reduction such as water demand management, rainwater harvesting, greywater recycling and sewer mining. Besides the well known advantages from SMPs, however they also contribute to the alteration of wastewater characteristics which finally affecting the process in downstream infrastructure such as sewerage networks. Several studies have shown that the implementation of SMPs decreases the wastewater flow, whilst increasing its strength. High strength wastewater can cause sewer problems such as sewer blockage, odour and corrosion. Yet, not all SMPs and their impact on existing sewer networks have been investigated. Therefore, this study reviews some examples of four common SMPs, the wastewater characteristics and the physical and biochemical transformation processes in sewer and the problems that might caused by them and at last, the potential impacts of those SMPs on wastewater characteristics and sewer networks are discussed. This paper provides sewer system managers with an overview of potential impacts on the sewer network due to the implementation of some SMPs. Potential research opportunities for the impact of SMPs on existing sewers are also identified.

Keywords Blockages; Corrosion; Odour; Sewer networks; Source Management Practices; Water quality; Wastewater quality

INTRODUCTION

Water reduction, reusing and recycling has been initiated within last 10 year as the impact of prolonged drought and also for anticipating the impact of global climate change. Substituting and saving potable water locally (near their source of production/discharge) are preferred because it considers being more environmental friendly compare to a new centralized desalination treatment plant. Source Management Practices (SMPs) is a term that refers to the sustainable practices where they are managed locally and potable water demand is minimized for drinking water and kitchen purposes, in other hand the remaining water demand is met by other sources such as rainwater and treated greywater. SMPs can be implemented in urban residential and non residential sectors, either at single or in neighbourhood/cluster scale; but their uptake depends on the cost, the extent of rebates and incentives offered in local regulations and the ease of operation. However, SMPs in residential areas are more likely to be encouraged, since residential areas are the main contributor (nearly 60%) of urban wastewater (Butler et al. 1995; Radcliffe 2004).

The major advantages of local potable water use reduction and reuse/recycling such as saving potable water, minimizing the cost of water supply network expansion and cross connection, reducing the environmental impact of discharged wastewater to the environment as well as infrastructure saving for the sewerage system have been widely acknowledged (Radcliffe 2010). While reducing the water use and substituting some part of water demand by alternative sources are considered to give positive impacts, however, many stakeholders admit that some barriers and negative impacts to the adoption of SMPs might present. Therefore need a holistic assessment from economic, social-politic and environmental aspect to produce a robust adoption of SMPs.

This review paper describes the motivation for implementing SMPs and discusses four common examples of SMPs, namely, water demand management, greywater recycling, rainwater harvesting and sewer mining. Brief discussion of the impact of each of these SMPs on sewer network is presented, however the impact due to the combinations of these practices are not covered in this paper. This paper also reviews the current residential wastewater characteristics and attempts to present the 'most likely' wastewater characteristics from selected SMPs as well as highlights possible implications on the sewer networks. Potential research opportunities for for the impact of SMPs on existing sewer pipes are also identified.

SOURCE MANAGEMENT PRACTICES

Water Demand Management

Water demand management (WDM) is an intervention in water use to reduce the water consumption through single or mix of financial, structural and operational, and socio-political arrangements (Australian Government 2005; Tate 1990). Financial arrangements of WDM comprise of rebates for installing water efficient appliances and fines, penalties, and higher water prices for using water excessively. Moreover, it is strengthened by structural/operational and socio-political strategies which including the reduction in losses due to leaks and implementation of water use restriction as well as regulations. The average daily residential water use varies from country to country, for example in the U.S.A and Canada it is around 350 L/cap/day; in European countries (Italy, Sweden and France), it has reduced to 250-150 L/cap/day; Middle East countries (Israel and Jordan), it is around 150 L/cap/day while in Australia, around 180 – 100 L/cap/day. Managing water consumption by these water demand management (WDM) strategies has proven to be successful, particularly in reducing water consumption in residential areas (Howe & Goemans 2002; Kenney et al. 2008). The implementation of these arrangements has successfully reduced the water consumption by around 22% - 40% in many countries such as Australia, France, Canada and Jordan. To save more water, many water end use studies in Australia nowadays has moved their focus into highest water demand management which means that all the water appliances within the household use the most water efficient appliances. The significant water use reduction is achieved (up to 40%) when implemented the highest water demand management. Table 1 is obtained from Sharma et al. (2009) that shows the water supply scenarios under three conditions, they are usual, improved and highest WDM. Usual WDM refers to the condition where the water use is not managed which shows the past practice. Improved WDM adopt the Victorian Government's White Paper in 2004 which recommended to use water efficient appliances within the household. Highest WDM adopts the figure of usual water demand management (WDM), but using the most water efficient appliances within the household

Table 1. The scenarios of residential water consumption in Water Demand Management (Sharma et al. 2009)

	Usual WDM (L/cap/day)	Improved WDM (L/cap/day)	Highest WDM (L/cap/day)
Toilet	23	23	15
Laundry	37	26	16
Kitchen	16	16	14
Bathroom	89	65	52
TOTAL	**165**	**130**	**97**

Greywater Recycling

Greywater is defined as wastewater from domestic applications other than the toilet. Greywater includes wastewater from bathroom/shower, washing machine and also the taps. Sometimes, wastewater from kitchen is also included in the greywater, but this has less preference since the wastewater from kitchen is more polluted. Greywater recycling refers to the condition when the wastewater is treated and used for indoor (e.g., toilet, washing machine etc.) and/or outdoor (e.g., gardening, car wash, etc.) purposes. Countries that are pioneering the greywater re-use and recycling are, U.S.A, Australia and Japan. Rebates are often offered to encourage the uptake of greywater systems, the amount varying from one country to another. For example, U.S.A offers up to $3000 for establishment of greywater reuse systems while in Australia, the government provides rebates of $500 as part of purchasing and installing greywater systems (Australian Government 2010; Chung & White 2009). In Japan, no incentive or rebate is offered, but the residents choose to install the greywater reuse systems due to high water price. The capacity for using greywater reuse systems in Japan is smaller as compared to U.S.A and Australia, since they only use the reclaimed water for toilet flushing (Chung & White 2009). In Spain, local regulations are making greywater reuse obligatory (Domenech & Sauri 2010). The greywater characteristics has been investigated by several studies, and summarized by Eriksson et al. (2002). Regarding the organic characterisation of greywater, the study by Hocaoglu et al. (2010) shows that greywater has relatively high readily biodegradable organic matter and contains more soluble COD compared to blackwater that has more particulate COD.

Rainwater Harvesting

Rainwater harvesting (RH) is a sustainable practice that supplies the water with less cost and energy as well as being simple in installation and operation. RH itself refers to the collection and distribution of rainwater from the roof, to be used for indoor and/or outdoor purposes. This practice depends much on the rainfall, water demand, the catchment area and the storage tank size. The implementation of RH has recently boomed in many countries due to uncertain and prolonged drought every where. RH has been known to offer the benefits of potable water saving and in reducing the pollutant load to the drain system (since these pollutants will remain in the tank). Governments have set up the regulations, standards or guidelines for use and installation of rainwater tanks as well as incentive or rebates. In Australia, rebates of up to $500 are given for the installation of a rainwater tank (Australian Government 2010). In Canada and U.S.A, the installation of rainwater tanks is required via local regulations and guidelines for installation and operation of rainwater systems have been developed (Fewkes 2006). In Australia, particularly in New South Wales, the state government created an initiative called BASIX (Building Sustainability Index) to ensure that homes are designed to use less potable water and reduce the greenhouse gas emissions by setting energy and water reduction targets for house and use alternative water sources such as rainwater (NSW Government 2011).

Sewer Mining

Sewer mining is a practice that includes extracting a portion of raw wastewater from an existing sewer to be used as recycled water. The recycled water is usually used for toilet or irrigation purposes (Hadzihalilovic 2009). This practice is not intended for single household applications, but rather to be implemented in collective/cluster scale developments. These systems are often managed by private sector organisations rather than government authorities/ water utilities through some licensing arrangements. A number of sewer mining initiatives are already in place, mostly in Australia (McGhie et al. 2009; Sydney Water 2006) where the recycled water is used for outdoor irrigation, toilet flushing and laundry applications. However, in most instances, these systems are used to provide water for irrigation and non-residential use only.

So far, the adoption of SMPs has been increasing, however, their consequences on downstream infrastructure particularly sewerage system has not been revealed yet. As predicted in some studies, the SMPs could have alter the wastewater volume and content that being discharged to sewerage network. Its alteration definitely will affect physical, biological and chemical processes in downstream infrastructure such as sewerage networks. Alteration in those processes might exacerbate the current condition of solids deposition and biochemical transformations processes in sewerage networks, thus leading to degradation of downstream infrastructure, particularly via blockages, odour and corrosion problem. The next section describes three problems related to existing wastewater systems, namely, blockages, odour and corrosion, and the characteristics of residential wastewater which leads to these problems. Understanding these aspects is essential to study the impact of SMPs on sewer networks, because wastewater characteristics trigger various problems in sewerage systems.

SEWERAGE SYSTEMS

This section first discusses the wastewater transformations in a sewer network that either lead to or reduce these three common problems, followed by a discussion on factors that lead to these problems. Finally, the characteristics of residential wastewater which leads to these problems are also discussed in this section. Understanding these aspects is essential to study the impact of SMPs on sewer networks, because different wastewater characteristics trigger various problems in sewerage systems.

Wastewater Transformation in Sewerage Systems

While transporting wastewater from the point of discharge to the treatment plant, it goes through a transformation process. The wastewater physical and biochemical processes that occur in the pipe create intermediate and end products that either result in benefits or problems for the sewerage system and wastewater treatment plant. Sewer blockages are mostly triggered by physical and chemical processes, whereas odour and corrosion are likely due to biochemical processes. It has been described by the study of Arthur et al. (2008) that the wastewater flow/velocity determines the occurrence of sewer blockages. The wastewater quality also lead to sewer blockages which is outlined in the studies by Crabtree (1989); Mitchener & Torfs (1996); Verbanck et al. (1994); Williams et al. (1989) (see on section *Blockages* for details).

Odour and corrosion occur through the sewer pollutant transformation processes which are classified into four processes; they are (1) sulphide generation, (2) chemical and biological oxidation of sulphide, (3) sulphide emission and (4) sulphide precipitation. The formation of the transformation products depends on a range of factors, including temperature, wastewater flow or residence time in the sewer, type of sewer pipe (pressurized or gravity), the wastewater quality, the sewer structure (i.e., slope) and the nature of the biochemical processes (bulk water, biofilm or sediment) (Almeida et al. 1999a; Nielsen et al. 2008; Nielsen & Hvitved-Jacobsen 1988; Nielsen et al. 1992; Tanaka et al. 2000). The sulphide generation most of the time occurs in biofilm and its equation are presented by Nielsen et al. (2005b) (Equation 1).

$$k_{S(-II)_{ff}} \sqrt{S_F + S_A + X_{S,fast}} \frac{K_{O,H_2S}}{K_{O,H_2S} + S_O} \frac{K_{NO,H_2S}}{K_{NO,H_2S} + S_{NO_3} + S_{NO_2}} \frac{A_f}{V_w} \alpha_{Sff}^{T-20} k_{H,pH} \quad \text{.....................(1)}$$

The equation of chemical and biological oxidation of sulphide in biofilm and bulkwater can be found from study of Nielsen et al. (2005b), Nielsen (2006) and Mourato (2003). The oxidation equations are presented below (Equations 2 – 5).

Biofilm Sulphide Oxidation (Nielsen et al. 2005b)

$$k_{S(-II)Soxb} S_{S(-II)}^{mfb} S_O^{nfb} \frac{A_f}{V_w} \alpha_{Soxb}^{T-20} k_{S(-II),pH} \quad \text{.....................(2)}$$

Bulk water sulphide oxidation (Nielsen et al. 2006)

Aerobic-Biological

$$k_{S(-II)woxb} S_{S(-II)}^{mwb} S_O^{nwb} \alpha_{Soxb}^{T-20} k_{S(-II),pH} \quad \text{.....................(3)}$$

Aerobic-Chemical

$$\frac{k_{H_2Swc} + k_{HS^-wc} \frac{K_{a1}}{0.1^{pH}}}{1 + \frac{K_{a1}}{0.1^{pH}}} S_{S(-II)}^{mwc} S_O^{nwc} \alpha_{Soxc}^{T-20} \quad \text{.....................(4)}$$

Anoxic sulphide oxidation (Mourato et al. 2003)

$$p_{S_n} \frac{S_{H_2S}}{K_{H_2S} + S_{H_2S}} \frac{S_{NO_3-N}}{K_{S,NO3} + S_{NO_3-N}} \alpha_W^{(T-20)} \quad \text{.....................(5)}$$

The sulphide emission equations are described in the study of Nielsen et al. (2005b) and presented below in Equations 6 and 7.

Rea-aeration

$$K_L a_{O_2} 24(S_{OS} - S_O) \text{ where } K_L a_{O_2} = 0.86\left(1 + 0.20 F^2\right)(su)^{3/8} d_m^{-1} \alpha_r^{T-20} \quad \text{.....................(6)}$$

Hydrogen Sulphide (H_2S) Emission

$$K_L a_{S(-II)} 24\left(\gamma S_{S(-II)} - S_{S(-II),eq}\right) \text{ where } K_L a_{S(-II)} / K_L a_{S_o} = 0.86 \quad \text{.....................(7)}$$

The sulphide precipitation potentially reduce odour and corrosion because the sulphide is not released to the sewer atmosphere (Vollertsen et al. 2006). The metals such as iron, copper and zinc are the most important metals for the sulphide precipitation (Nielsen et al. 2005a; Vollertsen et al. 2006). However, the equation for sulphide precipitation due to the metal content is not mentioned in any study since its precipitation is considered to occur instantaneously and depends on the molar ratio between the metal and the sulphide content. The value of molar ratio for the occurrence of metal bound sulphide is still inconclusive. The sulphide precipitation depends on pH and redox conditions.

Organic matter is the most important parameter in the sewer pollutant transformation processes, particularly soluble organic matter (Nielsen & Hvitved-Jacobsen 1988). Besides its solubility, the concentration and the constituent compounds are also an important aspect for the biochemical processes to take place. The highest sulphide production rate was found in domestic wastewater that contain organic compound of lactate, pyruvate and ethanol. Sulphate is also an important parameter as high concentrations of sulphur containing compounds means that the availability of sulphur is not limiting the parameter for sulphide production. Nevertheless, the availability of sulphur containing compounds such as sulphate are sometimes a limiting factor for sulphide production (Nielsen & Hvitved-Jacobsen 1988; Sharma et al. 2008).

Sewer Problems Associated with Wastewater Quantity and Quality

The following subsections discuss the sewer problems that arise due to wastewater quantity and quality variations in sewer network.

Blockages

Sewer blockage is considered to be the number one cause of loss in sewer serviceability (Ashley 2004). The most common causes are build up of fats, oils and greases (FOGs), debris, or other solid deposition, tree root intrusion and sewer line collapse (Arthur et al. 2008; Ashley et al. 2004; Geyer & Lentz 1966; Randrup et al. 2001). Build up of FOGs and solids deposition are likely to be influenced by the wastewater characteristics that enter the sewer network whereas sewer line collapse results from hydraulic and physical factors such as large flows, pipe age as well as pipe condition (Arthur et al. 2008). This review considers blockage problems that are triggered by parameters originating from wastewater characteristics.

FOGs in sewer systems mostly originate from kitchens (food production) and showers (the use of soap) (Keener et al. 2008). FOGs are very slowly digested and degraded by microorganisms (Cammarota & Freire 2006; Wakelin & Forster 1997). High FOGs have an adhesive character and they generally solidify when cooled. The combination of high FOGs and solids in the sewer can create blockage problems (Keener et al. 2008) and some studies also identified that high FOGs alone can lead to sewer blockage problems (Marvin & Medd 2006; Southerland 2002; U.S. E.P.A 2003). According to Keener et al. (2008), the deposit problem due to FOGs does not occur spontaneously after they are discharged to the sewer. Generally, deposits will form between 50 and 200 m downstream of their point of discharge. The same study also revealed that average FOG accumulation rates in sewer pipes were 0.10 cm/day and generally FOG cleaning frequencies in pipes varied from 3 months to 2 years using hydrojet cleaning.

The most widely used technology to reduce the impact of FOGs are pre-treatment systems, such as grease-traps that intercept most FOGs and large particulate solids before they enter sewerage systems. After passing the trap, most of the remaining solids will be in the form of a suspension. The suspended solids in sewage contain soluble organic matter and the remaining FOGs which makes the solids cohesive (Crabtree 1989). Sewer pollutant transformations also contribute to the formation of cohesive solids (Verbanck et al. 1994; Williams et al. 1989). Experimental research by Mitchener & Torfs (1996) and Torfs (1994) showed that the greater the content of cohesive solid in the sewage, the greater is its resistance to erosion. Greater resistance to erosion means that the cohesive solids will not be transported by wastewater flow. To conclude, it is quite obvious that the presence of FOGs, organic matter and solids trigger the occurrence of cohesive solids that can create blockages in sewer pipes.

Odour

It is well known that malodorous compounds in sewerage systems can create nuisance problems and sometimes, threaten public health, if it is released to urban atmospheres. The malodorous compounds can be classified as organic and inorganic compounds. Inorganic gases consist of carbon dioxide (CO_2), ammonia (NH_3), methane (CH_4) and hydrogen sulphide (H_2S), the organic gases (VOCs-Volatile Organic Compounds) consist of products from fermentation such as volatile fatty acids, skatole, indole, ketone, mercaptan, amines, etc (Hwang et al. 1995; Thistlethwayte & Goleb 1972). Not all gases mentioned above contribute to odour problems. CO_2 and NH_3 are gases that are typically released under aerobic or anoxic conditions and are considered odourless (Hvitved-Jacobsen & Vollertsen 2001). NH_3 is considered an odourless gas because it has a high recognition threshold value ($\approx$ 40 ppb) and at typical neutral pH, NH_3 has low tendency to be released from wastewater. Methane (CH_4) gas is also an odourless gas and forms under anaerobic conditions. CH_4 is considered less important since it forms in the absence of sulphate and in typical residential wastewater, sulphate is usually present. The residential wastewater usually has sulphate concentration in range of 40-200mg/L (Araujo et al. 2000).

A study by Hwang et al. (1995) found that the malodorous compounds in sewerage systems are dominated by H_2S and VOCs. H_2S is recognized by its characteristic rotten egg odour and can be detected by the human sense at a concentration level of 0.001 ppm and has sublethal effects (nausea and eye, nose and throat irritation) at 10-50 ppm (A.S.C.E. 1989). The VOC compounds are recognized from many different sense perceptions, for example : dimethyl sulphide and ethyl mercaptan are recognized by their decayed cabbage odour, dymethyl amine by a fishy odour and formaldehyde by the pungent odour (Cheremisinoff 1992). Little information is available about the limit threshold value of each VOC but Hwang et al. (1995) study have indicated that the highest malodorous VOCs are indole and skatole. These two compounds originate from the breakdown of human discharge from the toilet (Alison 2001).

Generally, fresh wastewater, particularly residential wastewater, produces a musty odour and does not give any odour problem (Water Environment Federation 2008). After entering the sewer, wastewater undergoes a transformation process and potentially forms malodorous compounds when the conditions are anaerobic. Factors that support odour formation are mostly similar to those that encourage the biochemical transformation processes except for pipe material (Hvitved-Jacobsen & Vollertsen 2001). Pipe material is a very important factor for odour generated by H_2S, because if the pipe is made of plastic/PVC, it has slower surface reaction leading to low H_2S adsorption in the surface material. This results in greater accumulation of H_2S gas in the sewer pipe and thus increased odour problems (Nielsen et al. 2008). Odour problems are more frequently found in large intercepting sewers with low slope, downstream of pressurized sewer mains and in pipe sections where high turbulence occurs (Vollertsen et al. 2006)..

Corrosion

Besides causing odour, H_2S is also known as a corrosion-causing compound. Corrosion occurs when the free water surface releases H_2S gas to the atmosphere and it is adsorbed by the moist sewer pipe. The most severe case of corrosion is usually found in the section where high turbulence occurs, at the change from pressurized sewers to gravity sewers and in pumping stations (Aesoy et al. 1997). With respect to the total sulphide concentration, minor corrosion has been found in the wastewater that has sulphide concentration in the range of 0.1-0.5 mg/L. Sulphide concentration higher than 2 mg/L cause severe corrosion in sewerage pipe (Hvitved-Jacobsen et al. 2002). Rehabilitation and restoration of corroded sewer can cost millions in some countries. For example in the U.S.A, the rehabilitation of corroded pipelines are estimated to be $1.91 million/km rehabilitated pipe (Sydney et al. 1996).

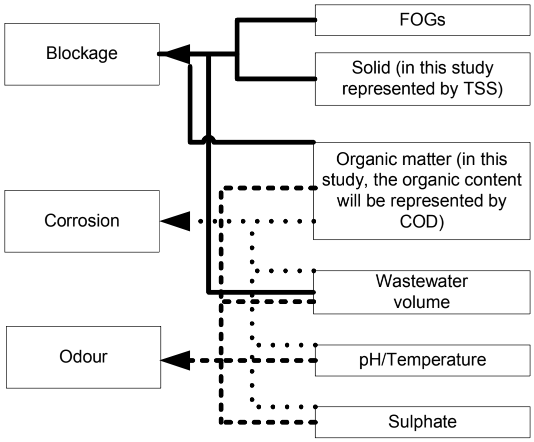
Through biological and chemical oxidation in the moist pipe surface, H_2S is converted to sulphuric acid (H_2SO_4)which corrodes the pipe. The oxidation is triggered by the presence of the corrosion-causing bacteria, humidity, temperature, and pipe age and material. The most common bacteria for biological oxidation are *acidithiobacillus thiooxidans* (Okabe et al. 2007). The rate of biological oxidation is higher than chemical oxidation because the biological oxidation produces readily biodegradable elemental sulphur as its end product, while chemical oxidation's end product is predicted to have slowly biodegradable elemental sulphur (Jensen et al. 2009).

Furthermore, as mentioned earlier, the corrosion-causing process is also determined by the pipe material and age. Likely, corrosion only occurs in concrete or metal pipes because these pipes have faster surface reactions compared to plastic/PVC pipes. Witherspoon et al. (2004) have shown that the corrosion-causing process in corroded concrete sewers occurs faster than in new pipes. This is because the new sewer pipe usually has high alkalinity (with pH ranging from 11-13) and bacteria such as *acidithiobacillus thiooxidans* cannot survive at pH values higher than 7. Generally, aging of concrete sewers results in a decrease of pH to around 6 -7 because aging concrete sewer has adsorbed H_2S which then ultimately is oxidized to H_2SO_4. At pH 6-7, these bacteria colonize the concrete sulphide, further reducing the surface pH to less than 5 which increases the rate of corrosion. These bacteria are very robust since they can survive in H_2S starvation for longer than 6 months (Jensen et al. 2008). This finding is very important for cold areas and other areas where H_2S corrosion is found to be a temporary problem rather than permanent one.

Summary

From the description above, there are several components which determine the occurrence of the three sewer problems associated with wastewater quality and quantity. Figure 1 classifies the parameters which supports the problem of odour and corrosion as well as blockages in sewers. High FOGs, solid and organic content as well as the low wastewater volume are the main factors that increase the blockage problems. Low wastewater volume, high organic and sulphate loads, and high temperature enhance the formation of H_2S gas which leads the problems of odour and corrosion.

Figure 2 presents the wastewater parameters that are able to decrease the release of H_2S and inhibit the generation of H_2S which eventually potential to decrease odour and corrosion problem. Metal content will be bind with sulphide and form a metal sulphide precipitate, therefore, H_2S gas generation will be inhibited. Nitrate/nitrite and dissolved oxygen are electron acceptors in anoxic and aerobic conditions, and also act to inhibit H_2S generation.


Blockage
Corrosion
Odour
FOGs
Solid (in this study represented by TSS)
Organic matter (in this study, the organic content will be represented by COD)
Wastewater volume
pH/Temperature
Sulphate

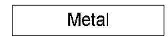

Metal

Table 2. Source of contaminant loads in household appliances

	Toilet		Kitchen sink		Shower		Vanity Unit		Washing Machine		Dishwasher	
	Tap water (%)	**Human input+ products (%)**	**Tap water (%)**	**Human input+ products (%)**	**Tap water (%)**	**Human input+ products (%)**	**Tap water (%)**	**Human input+ products (%)**	**Tap water (%)**	**Human input+ products (%)**	**Tap water (%)**	**Human input+ products (%)**
COD*	0	100	0	100	0	100	0	100	0	100	-	-
Nitrate**	33.87	66.13	1.43	98.57	1.98	98.02	4.92	95.08	8.91	91.09	-	-
Sulphur	4.3	95.7	7.1	92.9	10.5	89.5	5	95	17.6	82.4	43.5	56.5
Iron	20.8	79.2	78.7	21.3	99.99	0.01	2.98	97.02	77.2	22.8	63.8	36.2
Copper	23.4	76.6	40	60	89.74	10.26	8.9	91.1	99.5	0.5	15.5	84.5
Zinc	0.9	99.1	23.9	76.1	58	42	1	99	95.4	4.6	1.3	98.7
TSS***	0.08	99.92	0.27	99.73	0.49	99.51	1.27	98.73	0.86	99.14	-	-
FOGs	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A

*According to Australian Drinking Water Guidelines, there is no organic matter allowed in drinking water.
**Taking an assumption that nitrate content in tap water is following typical concentrations of ADWG (Australian Government, 2004)
***Taking an assumption the tap water has turbidity which is following the minimum value of turbidity at major Australian reticulated supplies turbidity which is 1 NTU. The relationship between turbidity and TSS is taken from the model provided by Packman et al. (1999).

Table 3. Ranking of household appliances based on its contribution to the selected wastewater parameters

Reviewed parameters	Ranking (with 1 being highest and 6 being lowest rank)						References
	1	**2**	**3**	**4**	**5**	**6**	
Waste water Vol.	Shower	Wash. machine	Taps	Toilet	Diswasher	-	(Beal et al. 2011; Willis et al. 2009)
COD	Toilet	Wash. machine	Kitchen sink	Shower	Vanity unit	-	(Almeida et al. 1999b)
Nitrate	Kitchen sink	Shower	Kitchen sink	Vanity unit	Wash. machine	-	(Almeida et al. 1999b)
Sulphur	Toilet	Wash. machine	Shower	Kitchen sink	Vanity unit	Dishwasher	(Tjandraatmadja et al. 2009)
Iron	Toilet	Wash. machine	Shower	Kitchen sink	Vanity unit	Dishwasher	(Tjandraatmadja et al. 2009)
Copper	Wash. machine	Toilet	Vanity Unit	Dishwasher	Shower	Kitchen sink	(Tjandraatmadja et al. 2009)
Zinc	Toilet	Vanity unit	Dishwasher	Shower	Kitchen sink	-	(Tjandraatmadja et al. 2009)
TSS	Toilet	Kitchen sink	Shower	Vanity unit	Wash. machine	-	(Almeida et al. 1999b)
FOGs	Kitchen	Shower	-	-	-	-	(Keener et al. 2008)

IMPACTS OF SMPs ON WASTEWATER CHARACTERISTICS

Wastewater Characteristics from SMPs

Some studies have attempted to predict what will be the wastewater characteristics from SMPs (DeZellar & Maier 1980; Parkinson et al. 2005). Many of these studies discuss common parameters such as wastewater volume and organic, solid and nitrogen contents. Table 4 presents the wastewater characteristics of reviewed parameters from selected SMPs taken from various studies. This clearly indicates that there are some significant changes in the wastewater characteristics from SMPs compared to current practices.

The following sub-sections describe the change in wastewater characteristics due to the selected four SMPs.

Highest Water Demand Management

The use of water saving appliances within households has become a normal practice, particularly in water stressed areas. Therefore, this study focuses on implementation of highest water demand management practices, such as those which occur when all the household appliances are of the highest rating. A study conducted by Sharma et al. (2009) considered developments at two areas in Australia and different water saving alternatives including highest water demand management in residential, commercial, industrial and community precincts. Assuming that highest water demand management was implemented in residential areas, a total saving of 97 litres/capita/day or 43% per capita water demand was predicted. The laundry and bathroom were responsible for the greatest indoor water savings, which matches with the study conducted by Tjandraatmadja et al. (2009), DeZellar & Maier (1980) and Parkinson et al. (2005). DeZellar & Maier (1980) also emphasized that the reduction of water leads to a reduction of wastewater flow and subsequently increases the wastewater strength.

DeZellar & Maier (1980) estimated that reductions of 30-55% in water use caused wastewater flow reductions of 15 to 16%. As wastewater flow decreased the concentration of BOD and TSS generally increased (25-40%), however their loads remained nearly the same. Though their research did not focus on nitrogen, sulphur or phosphate loads, the grab samples taken in their study indicated that nitrogen, sulphur and phosphate concentrations increased while loadings remain constant. Parkinson et al. (2005) confirmed that due to the use of water saving appliances (from 9L flush toilet to 6 L and 4/2 L dual flush toilet), the concentration of TSS, BOD, COD and Ammonium N increased by 10% for a change from a 9L to 6 L flush toilet, and by 24% for a change from a 9L flush toilet to 4/2L dual flush toilet.

Greywater Recycling

The residential appliances that produce greywater are bath, shower, washbasin, washing machine, kitchen sink and dishwasher. However, the highly polluted wastewater from the kitchen and the relatively low volumes makes this sources of greywater unsuitable for reuse (Christova-Boal et al. 1996). Use of greywater in these residential appliances will not only reduce the demand on drinking water, but also reduce the quantity of wastewater discharges to the environment. Greywater recycling is usually used for reducing water consumption associated with the toilet and outdoor use. However, in some places, for example in Australia, greywater is treated to Class A water and then re-used in washing machines (New South Wales Government 2008). Christova-Boal et al. (1996) report that if greywater is re-used for toilet and garden, it can save 31% of total water use and reduce 47% of total wastewater. However, the contaminant loads (organic and TSS) would be lowered by around 40% (DeZellar & Maier 1980). Furthermore, if greywater is also re-used for washing machines then the wastewater volume will reduce by 13-16% (Almeida et al. 1999b; Butler et al. 1995).

Parkinson et al. (2005) studied the characteristics of wastewater from domestic households that had greywater re-use as well as a combination of greywater re-use and water saving appliances. The reference condition was set up by using a household with a 9 L flush toilet, which is the existing household practice. In that study, they assumed that all greywater from household appliances were completely re-used, so the sewer discharge was mainly from toilets (excreta, water flushing and urine). For domestic households that implemented only greywater re-use, the concentration of TSS, BOD, COD and Ammonium N increased by 23%. For households that implemented the combination of greywater re-use and water saving appliances (7.5 L flush toilet), the concentration of TSS, BOD, COD and ammonium increased by 42%. As far as the authors are aware, there has not been a study till now regarding sulphur compounds in wastewater originating from a system that includes greywater re-use thus far.

The soluble COD contributes the readily biodegradable substrate to sewer transformation process. Therefore, the practice of greywater recycling will significantly affect the sewer transformation processes because the amount of soluble COD will decrease.

Rainwater Harvesting

The water collected from rainwater tanks is usually used for garden irrigation, toilet, laundry, shower and bath purposes (Victorian Government 2006). This technology has been reported to saving up to 60% of the main water supply (Villarreal & Dixon 2005) depending on the storage size. Recent studies by Kim et al. (2007) and Najia & Lustig (2006) have identified that organic, total nitrogen and total phosphorus concentrations in rain water are small, ranging from 76-345 mg/L, 1.33-2.0 mg/L and 0.087-0.13 mg/L respectively. However, rainwater contributes significantly to the metal content in wastewater, especially lead. Type of roof, gutter and tank material and its condition, as well as the background air pollution is suspected to contribute to the metal content in wastewater (Foerster 1999; Magyar et al. 2008; Yaziz et al. 1989). The sulphate content of rainwater is also a potential issue because sulphate (SO_4^{2-}) is one of the most common anions occurring in rainfall, especially in air masses encountered in metropolitan areas. D'Innocenzio & Ottaviani (1988) analyzed sulphate concentrations of rainwater in the urban zones of Rome (Italy), and stated that monthly variation in sulphate concentration varied from 3-27 mg/L. Coombes et al. (2002) in Australia revealed that the sulphate concentration in the rainfall collected from roofs was 1.79-14.50 mg/L and that collected from rainwater tanks was 1.7-5.3 mg/L. The concentration variation depended on rainfall intensity.

Cook et al. (2010) showed that metal content in wastewater from rainwater harvesting was significantly higher compared to areas without rainwater harvesting. Iron and lead were the two metals that had the highest increase of around 300% and 500%, and it was assumed that the rainwater was used to replace the potable water source for laundry and toilet applications.

Sewer Mining

Sewer mining practice is allowed to be conducted as long as there is sufficient wastewater flows in the sewer networks to flush out any solids that may have been deposited during low flow periods. Swamee et al. (1987) have described the approach for estimating minimum flow requirements. The flow is deemed sufficient when minimum sewer operational flow is considered together with the diurnal flow pattern and the existing practice which extract the wastewater either upstream or downstream of the proposed sewer mining connection point. Generally, the sewer mining does not use conventional wastewater treatment plants, but typically a compact, sometimes portable advanced treatment plant. This practice allows the residual from treatment to be discharged back to sewer as long as it does not increase substantially the load in the sewer (Sydney Water 2008). According to Sydney Water (2008), the residual discharge of sewer mining is more likely to contain grit, more concentrated wastewater and some additives from the treatment such as iron, aluminium, sulphate, etc. For example, in Sydney they set the acceptance standard for the concentration of suspended solid in the receiving sewer to 600 mg/L and no grit is allowed to be discharged back to sewer. The residual discharge from sewer mining treatment is classified as trade waste by the water/wastewater retailer. Problems will arise from sewer mining operation if these residuals are discharged back to the sewerage networks. Unfortunately, the setup of regulations was intended only to overcome the solid problem in sewerage network while neglecting the other problems (odour and corrosion) that may arise due to wastewater extraction.

Table 4. Wastewater characteristics of reviewed parameters from SMPs from various studies

	Population (Cap)	W.W volume (m^3/day)	TSS (mg/L)	Organic (mg/L)		Percentage of the increase of Sulphate conc. from the base case	Metal (mg/L)			Reduced nitrogen (mg/L)		Oxidized nitrogen (mg/L)	Total nitrogen (mg/L)	Reference
				BOD	COD		Fe	Cu	Zn	TKN	Ammonium N	Nitrite/ Nitrate		
Existing household practice (Ref)**	86000 (not including the pop. for commercial, industrial & community)	31287.67	140.24*	31.61*	148.43*								7.35*	(Sharma et al. 2005; Sharma et al. 2009)
Rainwater tank, untreated greywater re-use, highest demand management		14854.80	248.35*	86.12*	306.89*								9.77*	
Existing 9 L flush (Ref.)**	21434	2893.59	391	400	751					82	40			(Parkinson et al. 2005)
Reduced 7.5 L flush		2764.99	409	419	786					85	42			
Reduced 6 L flush		2636.38	429	439	825					90	44			
4/2 L flush		2314.87	486	498	934					102	50			
Greywater re-use (9 L flush)		2207.70	509	522	978					106	52			
Greywater re-use (7.5 L flush)		2057.66	549	562	1056					115	57			
Existing household practice (Ref.)**	1694	270.15					0.26	0.12	0.16	41.71				(Cook et al. 2010)
Water demand management		168.76					0.36	0.17	0.19	66.54				
Greywater recycling (direct diversion)		226.32					0.26	0.13	0.16	48.92				
Greywater recycling (treatment & storage)		139.48					0.24	0.09	0.09	75.03				
Rainwater harvesting		269.21					1.13	0.12	0.33	44.33				
Existing practice (Ref.)**	2389500	886504.5	310.07	261										(DeZellar & Maier 1980)
Practice with Water conservation		678618	350.5	338.29		+31%					increase	decrease		

*Some of the wastewater concentration was calculated from their load
** Reference condition

IMPACT OF SMPs ON SEWER PROBLEMS ASSOCIATED WITH WASTEWATER CHARACTERISTICS

This section attempts to analyse the impact of the predicted characteristics from SMPs on sewer pipe networks, as might occur when retrofitting of residences occurs.

Impact on Blockages

As mentioned previously, blockages in sewer pipes are caused by low wastewater volume and high solids, organic matter and FOGs in wastewater. Highest water demand management reduces water consumption as well as wastewater volume (Blanksby 2006). However, Blanksby (2006) stated that this practise might have little impact on solids or pollutant loading and was unlikely to have any serious deleterious impact on branch sewers, but in main trunk sewers with flat pipes, blockage problems might occur. DeZellar & Maier (1980) agree that the practice of water conservation is unlikely to add solid loading to sewers. However, they predict that problems in downstream infrastructure might arise as wastewater flows decrease. A similar conclusion was suggested by Parkinson et al. (2005), who found that reductions of water consumption lead to subsequent wastewater flow reductions, and increases in solid deposition and pollutant concentration, particularly for dry weather flows. Sharma et al. (2009) also indicated that this practice tended to reduce the wastewater volume and increase the pollutant concentration, however, they did not discuss explicitly about the impact on sewer networks. The practice of highest water demand management is able to reduce the water consumption and wastewater production, but the solids load remains constant, however, less wastewater and constant solids load leads to an increase in the solids concentration within the sewerage system. This increase in solids concentration tends to exacerbate blockages in sewer networks. A study conducted by one of the water retailers in Australia (Yarra Valley Water 2011) correlates the water consumption per household with the number of sewer blockages. It is shown in Figure 3 that lower water consumption gives rise to a higher rate of sewer blockages.

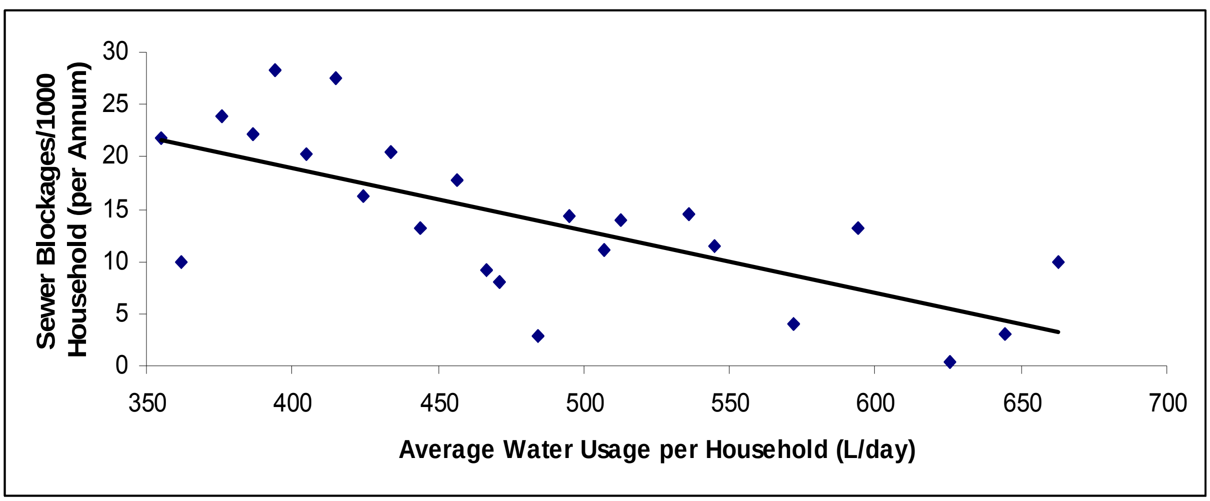


Figure 3. Sewer Blockages vs Water Consumption data (Yarra Valley Water 2011)

Blanksby (2006) stated that greywater recycling reduced the wastewater flow which subsequently exacerbated the sediment problem in sewerage networks. His study did not mention the final use for treated greywater, however, it seems that the study assumed that all treated greywater was totally removed from the main wastewater stream. In that study, the pollutant load originating from the greywater reuse/recycling was not mentioned. However, Blanksby (2006) noted that the extraction of greywater potentially reduced the flushing of sewer. Parkinson et al. (2005) highlighted the impact of greywater re-use on sanitary sewers. In this study, all greywater was reused for outdoor and toilet uses, therefore there was quite a significant reduction in wastewater flows entering the sewerage system whereas TSS and organic (BOD and COD) loading were similar to the reference condition. These characteristics led to increasing pollutant concentrations. Bertrand (2008) identified similar outcomes, where greywater recycling contributed to reductions in wastewater flows but there was no mention of pollutant loads or concentrations. From these studies, it can be concluded that greywater re-use/recycling reduces wastewater flows to sewerage networks while the pollutant load remains approximately the same. Lower flow and constant load increases the pollutant concentration of contaminants in sewerage networks and the residence times, this can be expected to significantly increase problems associated with sedimentation and blockages as can be seen in Figure 3. None of these studies considers a case where the residual from the greywater recycling treatment plant discharges back to sewer network. If the residuals from treatment plant are periodically discharged to the sewer then there may be an increase in the peaks in the contaminant loads in sewerage systems.

According to Blanksby (2006), rainwater harvesting will not have any impact on sewer networks because it will not change the wastewater volume and solids content in sewer network. However, the study from Bertrand (2008) proved that there is an interrelationship between the implementation of rainwater harvesting and wastewater flow reductions for the case of combined sewer networks. As far as the authors are aware, no rainwater harvesting studies have related this practice to sewer blockages.

Increased levels of risks associated with sewer blockages arising from sewer mining operations has been recognized and some anticipative actions have been incorporated into the sewer mining policy to avoid potential blockage problems (Sydney Water 2008), though there has not been any study concerning this aspect so far. However, discharging the treatment residuals to the sewer environment which has less flow due to several extraction points can potentially trigger the blockages, particularly during long dry weather periods.

Impact on Odour & Corrosion

Odour and corrosion problems in sewers greatly depend on the presence of sulphide. In turn, the sulphide production rate is dependent upon the concentrations of sulphate, organic matter and nitrate/dissolved oxygen, as well as other factors such as temperature, flow velocity, and residence time. The implementation of SMPs is suspected to increase the potential for odour and corrosion problems in sewer networks thus exacerbating these problems in sewer networks (Tjandraatmadja et al. 2005). However, detailed studies of the relationship between SMPs and odour and corrosion in sewer networks are not yet available. In this review, the potential impact of SMPs on sewer odour and corrosion is estimated solely based on the wastewater characteristics from SMPs and the sulphide production process in sewers.

Highest water demand management will decrease the wastewater flow and subsequently increase the organic concentration and some other odour and corrosion inducing characteristics in wastewater such as sulphate. Low flow in sewer pipes means longer residence time; moreover, the high organic content in wastewater will accelerate the rate of oxygen consumption leading to anaerobic conditions and subsequently sulphide production. Because of the lower flow from this practice, the concentration of other chemical parameters which are responsible for sulphide production, such as sulphate also increases. The message from above description is clear; the implementation of highest water demand management is likely to have negative implications with respect to odour and corrosion problems in sewers.

The wastewater from greywater recycling potentially contributes to sewer problems in a manner similar to wastewater from highest water demand management. The problems are expected to be more serious if the wastewater from the kitchen is not treated and thus the concentrated waste from greywater treatment is discharged back to the sewer. In dry weather conditions, the production rate of sulphide will be significantly higher, which will accelerate the occurence of odour and corrosion problems. Though the odour and corrosion problems will be greater due to this practice, it is thought that sulphide production will take a slightly longer time because wastewater in the sewer contains more particulate organic matter.

Rainwater harvesting produces different wastewater characteristics compared to the other mentioned practices. Wastewater from rainwater harvesting will have a higher level of metal content than other SMPs. Metal content in the wastewater may react with dissolved sulphide to form metal sulphide precipitates. Therefore, the sulphide will not be released into the sewer atmosphere thus inhibiting odour and corrosion issues. Ferrous (Fe (II)) in wastewater can react with sulphide and precipitate as ferrous sulphide (FeS) according to Equation 8. Ferric (Fe (III)) is able to oxidize sulphide chemically to elemental sulphur and being reduced to Ferrous (Fe(II)) which will subsequently form ferrous sulphide (FeS) (Zhang et al. 2008), as can bee seen in Equation 9.

Ferrous Salts : $Fe^{2+} + HS^{-} \rightarrow FeS \text{ (precipitates)} + H^{+}$ ....(8)
Ferric Salts : $2Fe^{3+} + HS^{-} \rightarrow 2Fe^{2+} + S^{0} + H^{+}$ ....(9)

Typical field applications require 3-5 mg/L as Fe per 0.5-1 mg/L of sulphide to prevent the production of H_2S. It is mainly iron (II) that leads to precipitation of sulphide, but zinc and copper also contribute to metal-sulphide precipitation (Nielsen et al. 2005a; Padival et al. 1995). A study by Cook et al. (2010) showed that among three potential precipitation determining metals (Fe, Zn and Cu), iron (Fe) was the most likely to approach the precipitation requirements (1.13 mg/L). Concentration of metals in wastewater is expected to increase when the wastewater includes a greater amount of the wastewater from rainwater harvesting.. It should be noted that precipitation of sulphide does not suppress odour emission by VOCs.

So far, there are no policies or studies which regulate or that have investigated the impact of sewer mining on odour and corrosion in sewer systems. As mentioned above, the residual discharge from sewer mining contains grit, more concentrated wastewater and some additives from the treatment such as iron, aluminium, sulphate, etc. The high concentration of organics, solids, sulphate and some other parameters which support the sulphide production will trigger odour and corrosion in sewer pipes. However, the high concentration of metal might also be able to eliminate the odour and corrosion problems. Therefore, the impact of sewer mining on odour and corrosion problems is inconclusive and needs more research to investigate its impact on sewer networks.

KNOWLEDGE GAPS AND RESEARCH OPPORTUNITIES

Use of many types of SMPs are likely to be found in new developments due the greater cost effectiveness of this compared to retrofitting established urban areas (Sharma et al. 2010). In high density urban areas, new development is not anymore preferred; however, these areas have high water consumption and wastewater production. In this case, more research is needed to assess the feasibility of implementing SMPs in existing development.

Studies on the impact of SMPs on sewer networks have focused mainly on the impact of SMPs on blockages, and only few studies quantify their impact. Studies on SMPs have considered greywater recycling/reuse, rainwater harvesting and water demand management (Cook et al. 2010; DeZellar & Maier 1980; Parkinson et al. 2005). But there has been no research on recently developed SMPs such as sewer mining and thus research is required. The impact of SMPs on odour and corrosion has also not been investigated yet. So far, studies have not been able to clearly identify the impact of SMPs on odour and corrosion. In fact, according to literature, the wastewater characteristics from SMPs practice might increase or decrease odour and corrosion problems in sewer networks. The potential impacts of SMPs seem to also be affected by the implementation scale, i.e. whether these practices are being introduced to a single property or to a neighbourhood. Therefore, further research is needed to investigate the impact of SMPs on odour and corrosion.

CONCLUSION

Pressure on current urban water systems is driving a number of practices such as the adoption of alternative water sources and demand management, which are called as Source Management Practices (SMPs). The alternative water sources that are being promoted worldwide include the greywater and wastewater recycling and rainwater harvesting system. Sewer mining is also one of the alternatives which is recommended for established sewered areas. However, the impact of these practices on existing sewer systems has the potential to cause both benefits and problems. This paper attempts to review the potential impacts due to SMPs based on wastewater quality and quantity, and also on the biochemical processes in sewer networks. Based on this review, most SMPs are likely to aggravate the problem of blockages, odor and corrosion in sewers. However, there are SMP such as rainwater harvesting that might be beneficial to sewer. Further research to assess the potential impact that might arise from the implementation of SMPs is required, so that a better sewerage infrastructure design, operation and maintenance plan can be developed, and that implementation of SMPsccan be planned with better understanding of their implications.

NOMENCLATURE

α_w	-- Temperature coefficient in water phase
α_{Sff}	-- Temperature coefficient for sulphide formation
αr	-- Temperature coefficient for reaeration
γ	-- Fraction of dissolved sulphide present as hydrogen sulphide
A_f	-- Biofilm area (m^2)
d_m	-- Hydraulic mean depth (m)
F	-- Froude number, $u/(g\ d_m)$

K_{Sw}	-- Saturation constant for readily biodegradable substrate in water phase ($gCOD/m^3$)
K_{Sf}	-- Saturation constant for readily biodegradable substrate in biofilm ($gCOD/m^3$)
$K_{s,NO3}$	-- Saturation constant for nitrate ($g\ NO_3/m^3$)
$K_{O,H2S}$	-- Saturation constant for inhibiting sulphide formation in the presence of oxygen (gO/m^3)
$K_{NO,\ H2S}$	-- Saturation constant for inhibiting sulphide formation in the presence of nitrate and nitrite (gN/m^3)
K_{SO4}	-- Saturation constant for sulphate (gS/m^3)
K_{a1}	-- First dissociation constant for H_2S
K_{H2S}	-- Saturation constant sulphide oxidation ($g\ S/m^3$)
K_La_{O2}	-- Reaeration coefficient (1/day)
K_{SF}	-- Saturation constant for fast biodegradable elemental sulphur ($g\ S/m^3$)
$K_{O2,SF}$	-- Saturation constant for oxygen in the oxidation of fast biodegradable elemental sulphur (gO_2/m^3)
$k_{1/2}$	-- Half-order rate constant for aerobic growth in biofilm, $gO_2^{0.5}/m^{0.5}/d$
$k_{S(-II)Soxb}$	-- Rate constant for sulfide oxidation by the biofilm ($g\ S/m^2/d$)
$k_{S(-II),pH}$	-- Inhibition factor for pH dependency of biological sulphide oxidation
$k_{S(-II)Woxb}$	-- Sulfide bulk water oxidation rate, biological ($g\ S/m^3/d$)
k_{H2Swc}	-- Rate constant for chemical oxidation of H_2S ($(g\ S/m^3)^{1-mc}/(g\ O_2/m^3)^{nc}/d$)
$k_{HS\text{-}wc}$	-- Rate constant for chemical oxidation of HS^- ($(g\ S/m^3)^{1-mc}/(g\ O_2/m^3)^{nc}/d$)
k_{H2S}	-- Hydrogen sulphide production rate constant ($g\ S/m^2d$)
$k_{S(-II)ff}$	-- Sulphide biofilm formation rate ($1/(g\ O_2)^{0.5}.g\ S/m^{1.5}/d$)
$k_{H,pH}$	-- Inhibition factor for pH dependency of heterotrophic biological processes
mfb	-- Reaction order of biological sulfide oxidation in biofilm with respect to sulphide (0-1)
mwb	-- Reaction order of biological sulfide oxidation in bulk water with respect to sulphide (0-1)
mc	-- Reaction order, S_{H2Stot}
mwc	-- Reaction order of chemical sulphide oxidation in bulk water with respect to sulphide (0-1)
nfb	-- Reaction order of biological sulphide oxidation in biofilm with respect to oxygen oxygen (0-1)
nwb	-- Reaction order of biological sulphide oxidation in bulk water with respect to oxygen (0-1)
nc	-- Reaction order
nwc	-- Reaction order of chemical sulphide oxidation in bulk water with respect to oxygen (0-1)
S_O	-- Concentration of dissolved oxygen (gO_2/m^3)
S_{NO3}	-- Nitrate concentration (gN/m^3)
$S_{S(-II)}$	-- Dissolved sulphide concentration (gS/m^3)
S_{H2S}	-- Hydrogen Sulphide concentration (gS/m^3)
$S_{NO3\text{-}N}$	-- Total nitrate concentration (gN/m^3)
S_{OS}	-- Dissolved oxygen saturation concentration (gO_2/m^3)
$S_{S(-II),eq}$	-- Dissolved sulfide concentration in equilibrium with the gas phase concentration ($g\ S/m^3$)
S_{Sf}	-- Concentration of fast biodegradable elemental sulphur (gS/m^3)
S	-- Slope (m/m)
$S_{(-II)}$	-- Total Sulphide concentration (gS/m^3)
u	-- The mean velocity (m/s)
V_w	-- Bulk water volume, m^3

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