Review: Suspended Sediments and their interaction in Water Supply Chain Network

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ABSTRACT

There have been several problems caused by sediments which have never been addressed before now in the water supply chain and have therefore been overlooked as not having sizable consequences; however, they actually do and these problems over a period have demanded the attention of sediment in urban water cycle to be given due scrutiny to understand the connection between sediments and the derivative problems in the water supply chain. This review article examines the problems associated with sediments along the water supply chain from the drainage basin, water bodies, treatment plants, water distribution system and end consumers. More so, this review article proposes policies that can be adopted to reduce the influx of sediment in the various stages of the water supply chain.

Keywords: Sediment, Water, Turbidity.

1. INTORDUCTION

Sediments are inorganic particles of earth materials which are yielded through the natural processes of weathering and erosion and are being transported through several media such as runoff (water), wind or even ice as the case may be. The main source of sediments in surface water is the runoff from topsoil surface in the basin after precipitation (Stall, 1972). The presence of sediments in water sources has its merits and demerits such as degradation of water quality and impedance of light in the water body (Bilotta and Brazier, 2008). Sediments are naturally occurring particles which are needed in balancing aquatic ecosystem but also it poses a lot of problems and also contemporary threats linked to sediment in the course of delivering potable water from surface water which is at the upstream of water supply to the treatment plant and water distribution system which are at the middle stream of the water supply and also at the taps where it gets to the end consumers which is the downstream of water supply. Suspended sediment load is sub-grouped into two which are: The wash load and the bed material load. The wash load accounts for the quota of suspended sediment load that easily migrate with discharge without a trace and it is sourced from the runoff from the catchment and it is assumed that the hydraulics and kinematics of flow has no effect on wash load but the characteristics of the catchment; while the bed material suspended load is the quota that found at the bed of the water body in sizable amount (Karna *et al.* 2015). In this review the effects of sediment presence in water in different cardinal stages of water supply will be reported starting from the Upstream of the water supply chain which is the Source water (typically surface water) to the middle-stream of the water supply chain which comprises the treatment plant and the distribution network system and finally the downstream of the water supply chain which is the end user point where the water is being consumed.

2. Water Supply Chain Network

A water supply chain network is beyond just water treatment and water distribution network, it actually spans from the basin to the point of consumption or usage which comprises: drainage basin, water source (whether surface water or groundwater), water treatment facility, water distribution system and the final end consumer.

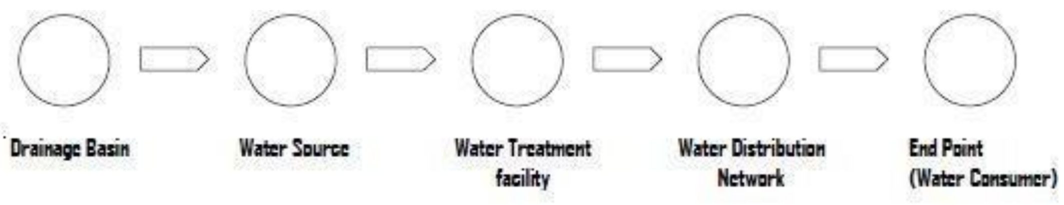

Figure 1: Flow Chart of Water Supply Chain

2.1 Drainage Basin

The drainage basin is a region of land mass that contributes precipitation into a common discharge point such as a river or any other water bodies. It comprises surface water which are sourced from rainfall runoff and streams close by; and also groundwater which underlying the earth surface (Drainage basin, 2004). When analysing a basin, the most prominent factors include the topography, type of soil, climate and the purpose for which the land of the river basin is used for as well as the sub-basins. In terms of climate rainfall and wind play the major role. A typical example is the outlet of the Shejiagou gully in Shanxi Province where 90% of its sediment load lost is due to events of storm in the rainy season (Wang *et al.* 2014).

More so, in the case where the basin has uniformity in its climatic areas as well as its types of soil; then the local topography takes a prevalent role in describing the rate of erosion through its major components which are the length of slope and gradient. Areas with steeper slope and the longer slopes tend to experience more erosion because of instability and shallowness of soils, as well as much higher velocities, volume of runoff. Analysis done in the river Nile basin showed that the area of the basin vulnerable to high soil erosion rate have steep slope, little vegetation cover thus exposed soils, and also experience high rainfall (Abdalla, 2008).

Another factor that affects rate of erosion and influx of sediments in rivers and their basins alike is the soil type; this is typified in soils that contain a high level of less and sand which are known to contribute a voluminous amount of sediments from the basin to the river system as reported in the case of Haihe River Basin where sediment influx from the basin to the river is about 150 million tonnes annually (Liu *et al.* 2008). More so, the land usage of the basin also plays very key roles in sediment yield and subsequent transport by the river. Vegetation in the catchment serves as protection for the soil against rainfall and eventual runoff; it also helps in boosting infiltration and lowering the velocity and general volume of runoff. This is visibly supported in the case of Volga River Basin whereby where there was a massive change in the land use where the land vegetation was drastically reduced during the war and so this caused an increase in sediment yield and soil erosion (Sidorchuk and Golosov, 2003).

2.1.1 Sources of Sediment in an urban area

Sediments are sourced naturally into rivers from basins through activities of deposition of atmospheric dust and erosion of by water runoff. More so, other sources of sediments into rivers are erosion activities in channels, floodplains, resuspension of sediments at the bed of different channels caused by fluctuating conditions of flow. A closer look at sources of sediment due to anthropogenic activities such as construction, road network, industrial operations, mining, etc account for the dominant part of contaminated sediment load with the river basins (Taylor and Owens, 2009).

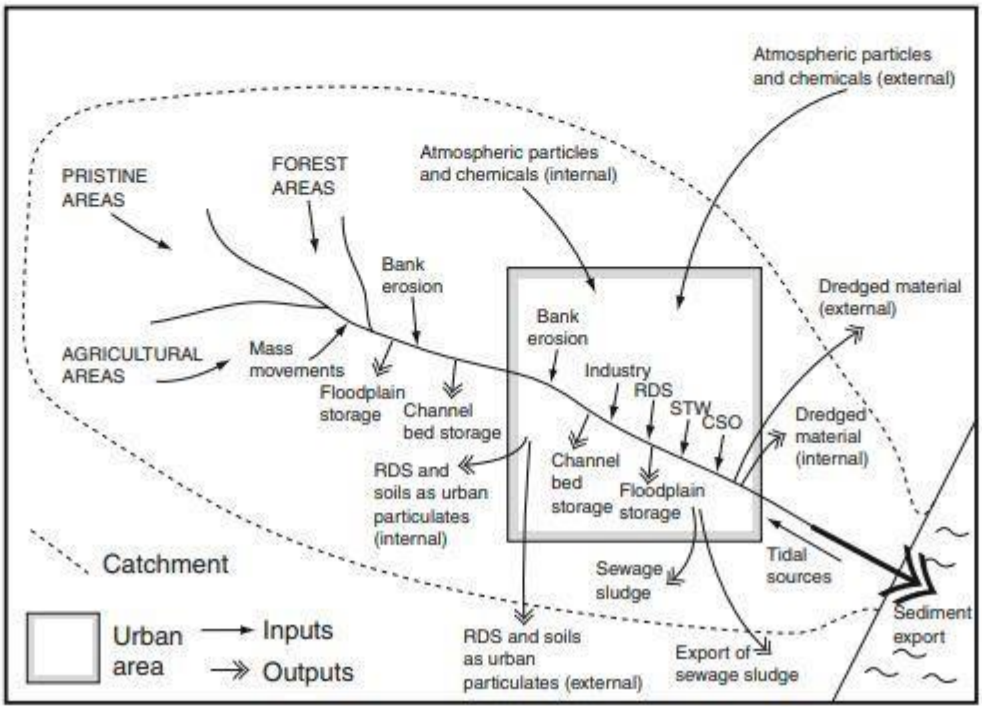

Figure 2: Sources of sediments and pathways in a river basin of an urban region (Taylor and Owen, 2009)

Among prominent sediments that influxes rivers especially in urban basins are the road-deposited sediments (RDS) which are matter overlying street surfaces that have previously been mistaken for dusts. Dusts are matter that fine and are less than 10 μm but then studies of works from the likes of Brinkmann and Tobin (2001); Sutherland (2003) and even Robertson and Taylor (2007) show clearly that sediment from street surfaces have a wide range of sizes. There are a plethora of RDS sources which can be natural or anthropogenic. Some of the natural sources maybe soil materials, deposition of atmospheric matter; while anthropogenic sources comprises materials generated from constructions, emissions, body wear, etc (Lecoanet *et al.* 2003; Thorpe and Harrison, 2008).

Some sediment that been linked with contaminants in a river basin is as shown in the table below.

Table 1: Some sediment sources with contaminants associated with them to river basins

Material	**Sources**
Sediment (organic and inorganic)	Erosion from rural, agricultural and forested land, channel banks, urban road sediment and construction, STW solids, atmospheric deposition, inputs from tidal areas and coastal zone
Metals and metalloids (Ag, Cd, Cu, Co, Cr, Hg, Ni, Pb, Sb, Sn, Zn, As)	Geology, mining, industry, acid rock drainage, sewage treatment, urban runoff
Nutrients (P, N)	Agricultural and urban runoff, wastewater and sewage treatment
Organic compounds (pesticides, herbicides, hydrocarbons, PCBs, PAHs, dioxins)	Agriculture, industry, sewage, landfill, urban runoff, combustion
Xenobiotica and antibiotics	Sewage treatment works, industry, agriculture
Radionuclides (^{137}Cs, ^{129}I, ^{239}Pu, $^{230\text{Th}}$, ^{99}Tc)	Nuclear power industry, military, geology, agriculture (secondary source)

(Taylor *et al.* 2008)

The bulk of RDS actually are from soil and also build materials (Hopke *et al.*, 1980); these soil materials sourced agricultural lands located at the suburb of the town, parks,etc; and they are responsible for the minerogenic and organic contents of the sediment. Building materials on the other hand are the sources of quartz sand, cement and also concrete to RDS (Taylor and Owens, 2009). However, RDS gets in contact with contaminants majorly through anthropogenic activities, for instance copper and zinc are known to come from vehicular activities such as copper gotten from car body corrosion (Beckwith *et al.*, 1986); whereas, Zinc and Cadmium are gotten from tyre wear (Hopke *et al.*, 1980); the likes of Bromine, Managanese and Chromium are sourced from tyres and brake linings. Detailed analysis of RDS have been done for the purpose of appropriation of elemental source (De Miguel *et al.*, 1997).

More so, the approach of sediment fingerprint was adopted to illustrate the appropriation sources of sediment in urbanised region of the Aire-Calder river basin UK by Carter *et al.* (2003) which showed uncultivated topsoil accounted for (18-33%); on the other hand cultivated topsoil accounted for (20-45%); more so RDS accounted for (19-22%); and sewage input accounted for (14-18%). Furthermore, Yin and Li (2008) utilized a similar method while using ^{7}Be and ^{210}Pb as trace agents which brought about an estimation that 60% of sewer system outlet of suspended sediments in Wuhan City in China was gotten from the drainage system and about 405 from RDS. The findings from this report is in concordance with the report from work of Nelson and Booth (2002) in this regard.

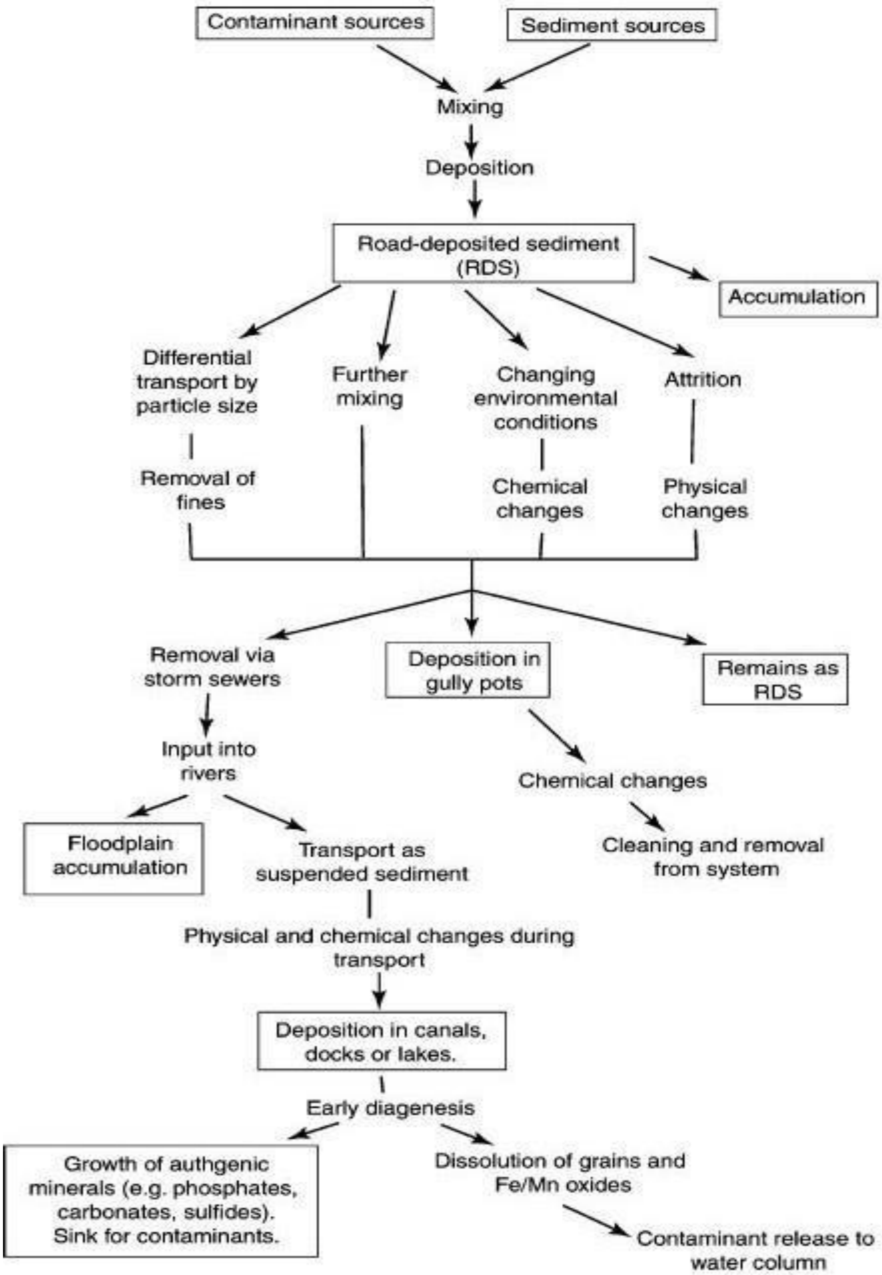

Figure 3: The cascade of urban sediment
(Taylor, 2007)

2.2 Water Source

Sediment is an integral part of the water ecosystem and their associated tributaries; influx of sediment subsequently describes the rate of its deposition in a delta, hence affecting sea level (Giosan *et al.,* 2014). The presence of sediment in a water body like river is quite natural but then this has been worsened by human activities; this natural occurrence of sediment in flow and water body actually brings equilibrium to the system but this is threatened anthropogenic consequence or natural disasters (Karna *et al.,* 2015).

2.2.1 Effects of Sediment influx into reservoirs

Dams which are hydraulic structures constructed for beneficial purposes such as water supply, flood control, etc. But while doing these, they also impede the natural regime of river and cause sediment trappings thereby leading to adverse effects such as reducing reservoir capacities. The sedimentation of reservoirs is a global issue (Vorosmarty *et al.,* 2003). And it globally manifests at a rate of about 0.8% annually, meanwhile this rate is much higher in Asia and Africa (Palmieri *et al.,* 2003). It was estimated that about 45km3 of reservoir capacity is lost annually to sediment influx and to recover such loss in storage will require nothing less than US$13billion annually as well (Palmieri *et al.,* 2003). Reservoirs of surface water are designed to a specific volume whereby a certain volume is taken into consideration known as dead storage in order to cater for sediment influx that pile up over a period of time which is regarded as the economic life of the reservoir. Improper dead storage allocation in design will affect the design life of the hydraulic structure (Kisi, 2010).

Some reservoirs whose capacities have been seriously affected by sediment influx include: Nizamsagar reservoir whose main purpose is water supply has lost about 52% of its storage capacity to sediment (Mohanakrishnan, 2001). Also the Welbedacht Dam in South Africa lost about 50% of its capacity in the first five years of commissioning and now it has lost more than 90% of its storage capacity to sedimentation (IHA, 2017). A projection has been made that in the next 200 to 300 years that majority of reservoirs in Africa would be completely silted (ICOLD BULLETIN, 2009)

Figure 4: View of Welbedacht Dam with so much silt (Sancold, 2018)

2.2.2 Effects of Sediment on aquatic plants

Aquatic plants are not exempted in the adverse effects of sediments in water ecosystem; these sediments are vital for the survival of the animals and plants at the bottom of the aquatic food chain and any alteration in sediment will ultimately affect the entire food chain (Karna, *et al.*, 2015). Aquatic plants such as macrophytes which are at the bottom of the food chain require sediment at the river bed so as to attach their roots to them for germination and survival. When sediments are in suspension they impede light penetration and hence reduce photosynthesis for aquatic plant survival (Van Nieuwenhuyse and LaPerriere, 1986)

2.2.3 Effects of Sediment on some aquatic animals (invertebrates and fishes)

When fine sediments affect aquatic plants such macrophytes, these aquatic plants serve as food for herbivorous invertebrates and these herbivores also serve as food for carnivorous invertebrates along the food chain; so indirectly adverse effects of fine sediments will ultimately affect these invertebrates (Karna *et al.*, 2015). Sediments also have direct effect on these invertebrates contact damage such as scouring and abrasion through the flow of sediment on the body of the invertebrates; this damage can subsequently expose their organs thereby making them vulnerable to larger predators (Wood and Armitage, 1997).

Sediments also have adverse effects on fishes well in terms dispersing a suitable habitat for young fishes. The habitat convenient for young fishes in the spaces between gravel; which sediments while settling fill up those spaces thereby making thereby making the habitat unsuitable for them. Also sediment can also affect fishes in terms of their respiratory organs;

when the water is sediment laden it tends to clog the gills of fishes which may lead to their death in some cases. Since fishes also feed on other organisms along the food chain any effect on aquatic plants which also ultimately affect fishes up in the food chain.

2.2.4 Effects of Sediment on water quality

Sediments do affect water quality in terms of different parameter such as turbidity which is a measure of clearness of water. Sediments reduce the optical properties of water by dispersing light penetration in water and hence having great influence on turbidity. Apart from turbidity, for the drinking requirements, the maximum amount of sediment in drinking water is 10ppm (Karna *et al.*, 2015).

Sediments have also been reputed to be the source of transporting some contaminants such as Persistent Organic Pollutants (POPs) notably Perfluorinated chemicals (PFCs) which include: perflurooctane sulfonate (PFOS) and Perfluorooctanoate (PFOA) (Lasier *et al.*, 2011). These PFCs have a very slow decomposition rate, persist in the environment and also do biomagnify along the foodchain which is responsible to an increasing amount of them found in the bloodstream animals and humans (Giesy and Kannan, 2002).

Sediments are also known to contribute immensely to Natural organic matter (NOM) to surface water (Sobieszczyk *et al.*, 2015); and this NOM is a mixture of a variety of organic compounds that are complex commonly found in natural waters (Matilainen *et al.*, 2010) and this NOM are estimated in terms of any of these parameters which are: total organic carbon (TOC), dissolved organic carbon (DOC), UV_{254} measurement. This NOM ultimately react with disinfectant in treated water to form different types of disinfection by-products (DBPs) in drinking water (Yee *et.*, 2009). These different DBPs are known to pose serious health risks such as cancer (Ibrahim and Abdul Aziz, 2014).

2.3 Water Treatment facility

This treatment for the removal of sediment in a water treatment facility is done through the process called Sedimentation which is a process in the physical unit of water treatment that utilizes the concept of gravity for the removal of suspended solids in water (O'Melia, 1998). This sedimentation process is carried out in a chamber called Sedimentation tank or Clarifier; the geometry of this settling tanks can either be rectangular or circular and the shapes of the tank determines the philosophy of the sedimentation process. For a rectangular tank, the designed is done such that the inlet zone where the influent enters the tank is at one extreme end while the outlet zone where desilted water leaves the tank is exits the tank after the sedimentation process has taken place is at the opposite extreme. This rectangular tank utilizes the technique of settling by controlling the flow of water into the settling tank and ensuring the velocity of the influent doesn't exceed the settling velocity of the particles so that when the flowing water get to the outlet zone, most of the particles would have settled at the sludge zone of the settling tank. On the other hand, for the circular tanks, the design is quite different from the rectangular tank with the inlet pipe being situated at the bottom adjacent to the pipe for sludge removal while the pipe for extracting the treated water situated near the surface of the tank. The figure below shows a view of both the circular tank as well as the rectangular tank for primary treatment.

Figure 5a: Circular Clarifier (Al-kizwini, 2015)

Figure 5b: Rectangular Sedimentation tank (Al-kizwini, 2015)

However, for sediments to be removed via settling in the sedimentation process some factors play a major role which are: size and distribution of the particle, temperature as well as viscosity of the water, density and shape of the particles, wind, coagulation and flocculation characteristics of the particles, the charges of the particles (Holmden, 2013).

Sediments and other particles settle in water in various ways which are:

1. Discrete Settling: This settling involves the settling of particles individually without interaction with other particles in the water and they rely strictly on their individual weight to settle. Example is the extraction of sediment and grit in Wastewater treatment plant (WWTP).
2. Flocculant Settling: This is a type of settling that occurs when coagulant is used to aggregate particles as flocs thereby having enough weight as a group to settle out. Example is the extraction of Suspended solids in the sedimentation tank
3. Hindered (Zone) Settling: In this settling, flocs experience a trade off between forces of attraction and repulsion to put particles at fixed positions with respect to one another and so there is enough weight for these flocs in this zone of force field to settle in form of matrix. Example is the biological floc removal in secondary clarifier of the WWTP.
4. Compression Settling: This occurs when the water has a high concentration of particles whereby heavier particles as they settle rests their weights on lighter particles and force them to settle by compressing them as they settle. Example is in the sludge thickening process.

It is seen that most of the sediments are being removed in the discrete settling and this is mainly controlled through the flow and ensuring the velocity of water does not exceed the settling velocity of the sediment or particles of interest through the utilization of Stoke's law. The different settling types are shown in the figure below:

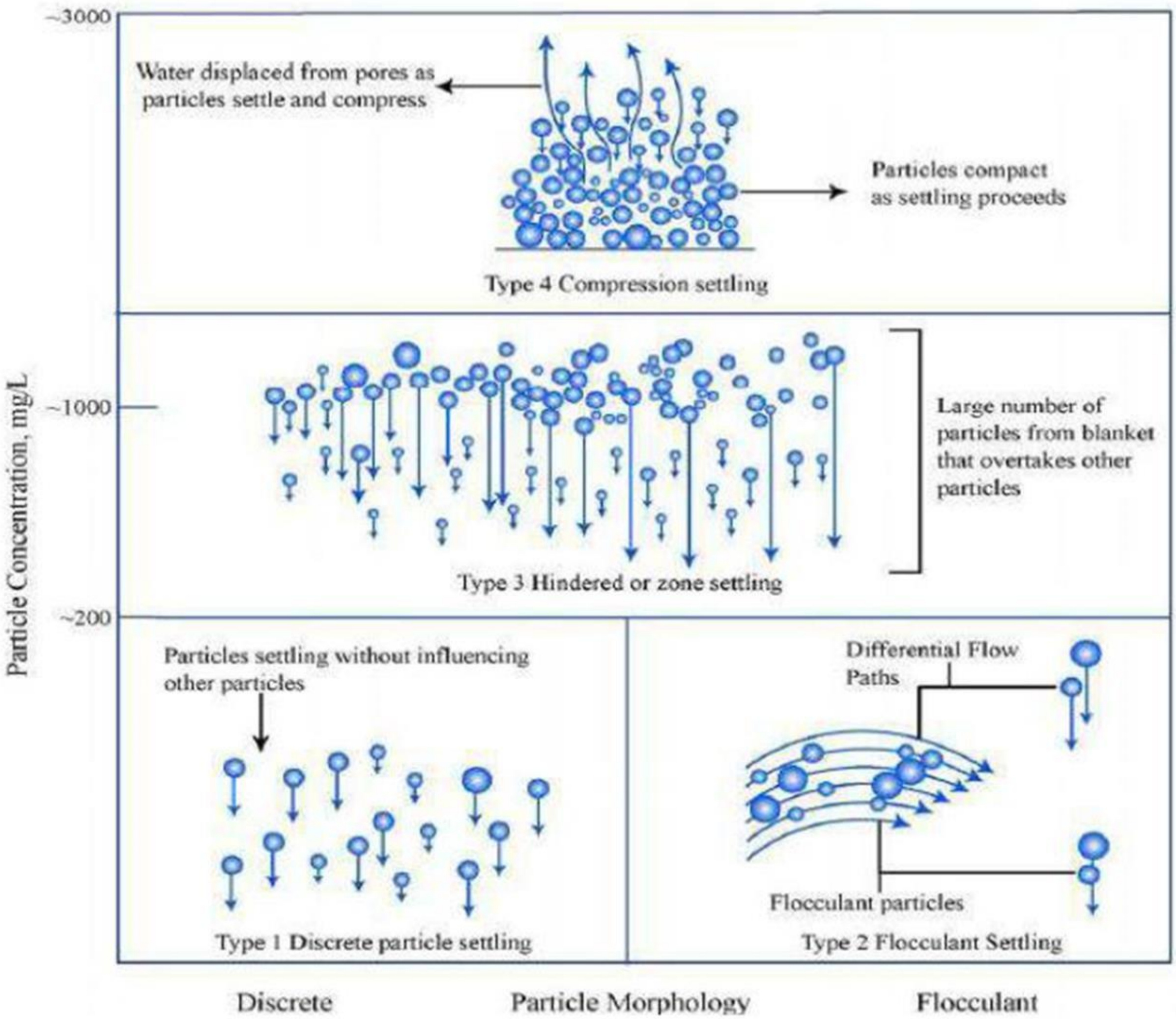

Figure 6: Types of Sedimentation
(Al-kizwini, 2015)

After the sedimentation process, most sediments would have been removed from the water and collected with other unwanted constituents in the water as sludge and this sludge is further treated by thickening, biogas production and dewatering. A close look at the Ghaziabad Water treatment plant in India shows sludge production has fine sand of 60%, silt 24%, clay 16% while other substances such as alumina, ferric oxide, silica and other substances make up for the rest (Ahmad *et al.*, 2016). It showed clearly that sediment make up for the bulk of sludge produced in a treatment plant as seen in the Ghaziabad water treatment plant.

2.4 Water Distribution System

In a drinking water distribution system (DWDS) sediments are known to be present sourcing from various events such as: incomplete extraction of all sediments during water treatment, the corrosion of the inner wall of pipe over time, the removal of biofilms in the pipe during flow as well as the encroachment of soil particles from the surrounding area of the pipe when there is a leak and during repairs (Polychronopolous *et al.,* 2003; Carriere *et al.*, 2005). Some characteristic events that influence water quality deterioration in DWDS are mainly the inflow, storage, production and outflow of particles. As depicted in the figure below.

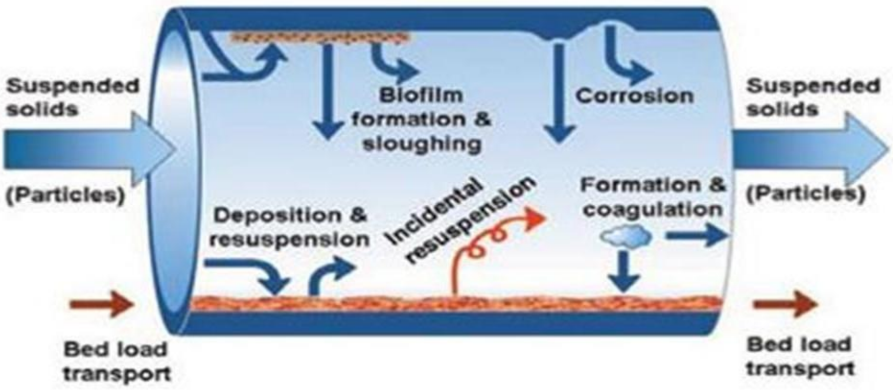

Figure 7: Physical processes resulting in discolouration (Vreeburg, 2007)

The events of inflow as well as outflow of particles in a DWDS comprises:

- Influx of sediment and other particles in the DWDS due to incomplete extraction of solids during water treatment (Gauthier *et al.,* 2003; Kirmeyer, 2000).
- Daily operation causes distortion of particles and then subsequently bringing about conspicuous loading of particles in the system (Kivit, 2006).
- Some particular treatment unit sources particles into treated water and subsequently is responsible for their presence in DWDS such as: powdery activated carbon (Brazos and O'Connor, 1996), more so, the introduction of sand, iron and alum flocs emanating from biofilters (Ahmad and Amirtharajah, 1998).

The combination of processes of biological, chemical and physical events bring about the production of particles in the DWDS as described:

- Gradual agglomeration of small particles to larger flocs leading to precipitation in post water treatment (Lin and Coller, 1997)
- Multiplication of microorganisms especially in biofilms found along the walls of the pipes of the network due to the assimilable organic carbon (AOC) present (Siebel *et al.,* 2008)
- Corrsion and erosion of cement or cast iron pipe chemical constituents (Boxall *et al.,* 2003)

- Monumental resuspension of settled sediments as well as biomass sourced from the pipe and treatment process.

The process of storage of sediments in pipes of the DWDS is a physical process characterized by deposition, dispersion and transportation. The cumulative result of these events leads to the storage of sediments in the DWDS over a period (Verbeek *et al.*, 2009).

The resultant of sediment and other particles in pipes of the DWDS ultimately lead to degradation of the pipe and contributes to the declining quality of water quality as hwon below.

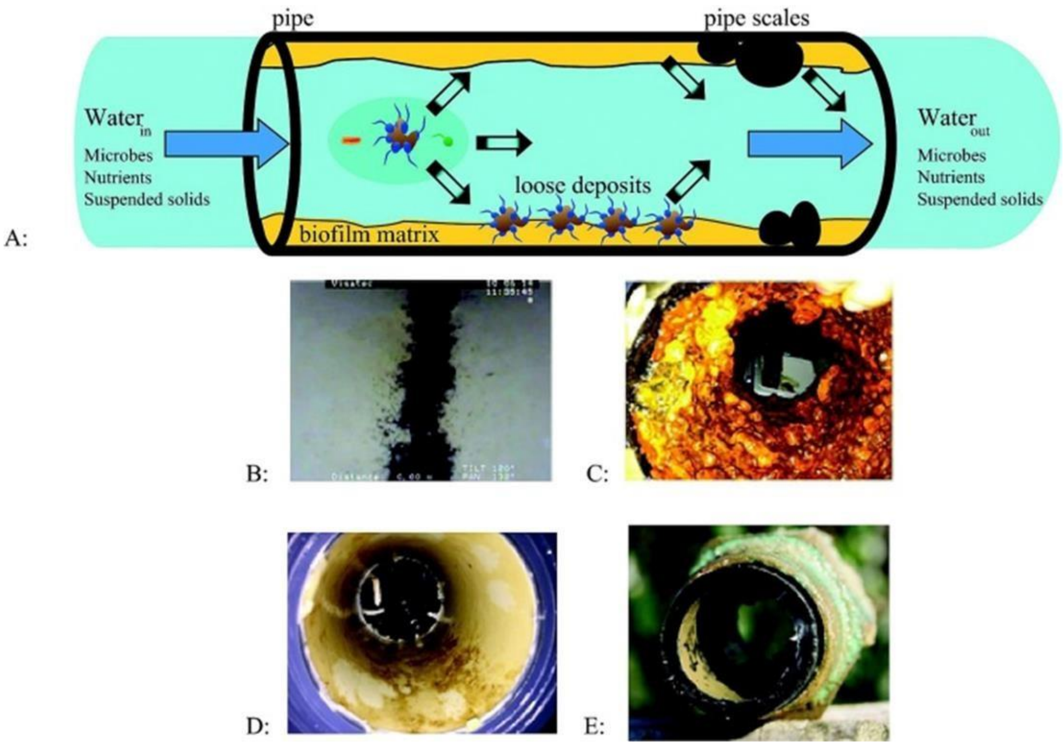

Figure 8: Deterioration of pipe due to particles in the DWDS
(Liu *et al.,* 2017)

2.5 Water from Taps

Water from taps is the end point in the upstream of urban water cycle where water is being consumed and used for various purposes. It is at this point that the quality of water parameters needs to be controlled as this is the most critical aspect of the water supply chain. If there is a compromise of any of the stages which can bring about deterioration of water quality, then it could lead to damaging consequences of public health and even death.

Sediment in drinking water is responsible for poor water aesthetics which is often expressed as turbidity. Potable water should be colourless, odourless, also free from turbidity and microorganisms (Daud *et al.*, 2017). Turbidity is the degree of cloudiness or poor visibility in water. When water is high in turbidity caused by sediments and consumed by humans, such water is known to have a high correlation of microorganisms that caused diseases such as: cramps, headaches, nausea and diarrhea (USEPA, 2017), this is because these diseasecausing microorganism attach themselves to the surface of the sediments and other particles for survival and habitation thereby associating turbidity with these diseases.

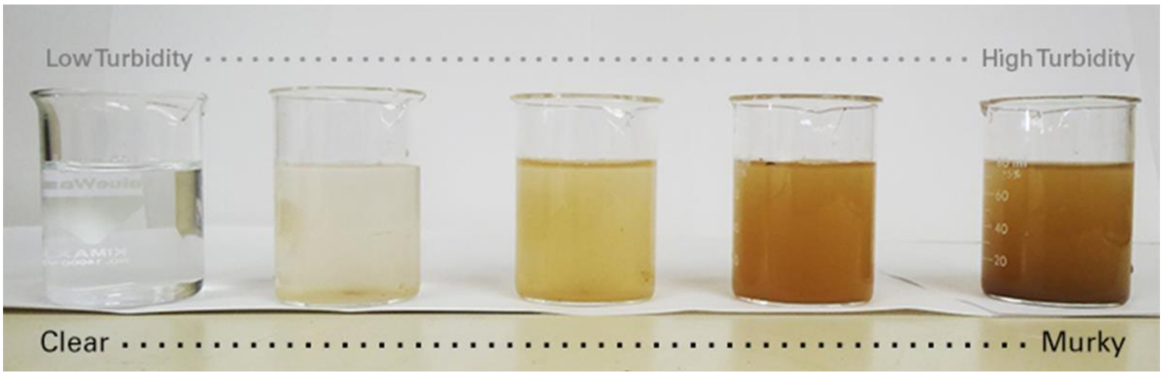

Figure 9: Water samples with different degrees of turbidity
(Village of Chase, 2015)

From the figure above, the water with the lowest turbidity is clear and has the best aesthetics and this decrease until the water sample with the highest turbidity which is murky and apart from not pleasant for visual inspection it is also not fir for consumption.

3. Water Management

The problems associated sediments with drinking water cuts across the several units of water supply chain and it has become imperative to propose some water management practice to help mitigate these problems and these are stated below:

- Encourage the vegetation within the water shed to help intercept and trap a good portion of sediments from being washed into river bodies during runoff
- Maintain a good data management of water bodies to be able to ascertain and make informed management decision of the river or lake and to be able to reliably predict when a problem may occur such as increasing sediment load that may lead to reservoir capacity reduction or flood warning
- Improving units in water treatment facilities such as grits chamber and clarifiers for better efficiency in removal sediments and other suspended particles in water treatment
- Installation of contemporary leakage detection techniques for quick detection in pipes and prompt response to reduces sediment influx in water distribution system.
- Improved maintenance such as regular flushing of the distribution system and prompt replacement of valves, pipes, junctions and other distribution system components that are wearing to arrest water quality compromise
- Regularly test water quality parameters at consumer taps to ensure water quality is optimum and detect problems quickly to avoid public health decline.

4. Conclusion

The problems of sediments in water supply chain deserve adequate attention by all stakeholders as they go beyond just water quality deterioration. Sediments in water causes a lot of problems ranging from reducing reservoir capacity, transporting nutrients which can cause alga bloom, contaminants such as pesticides. They also make up for the highest portion of sludge produced in water treatment thereby increasing resources utilized during water treatment and also increasing sludge production which increasing the cost of disposal in landfills as well. Sediment also cause a lot of problems in Water distribution system by damaging the infrastructure as well as the quality of water transported and ultimately pose a great risk to public health. It is hence of great importance to study this Hydrologic phenomenon in order to maintain good quality of life by controlling sediments in water consumption through the urban water cycle.

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