

**CRANFIELD UNIVERSITY**

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**THE RELATIONSHIP BETWEEN UVT AND TURBIDITY,  
WITH RESPECT TO THE DISINFECTION OF SURFACE WATERS**

**SCHOOL OF APPLIED SCIENCE**

**MSc THESIS**

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**The relationship between UVT and turbidity,  
with respect to the disinfection of surface waters**

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## ABSTRACT

UV transmittance (UVT) is a parameter very closely related to the efficiency of any UV processes. Firstly a theoretical model of UVT proposed by Gregory (2006) was assessed and secondly an experimental approach was undertaken to find out any relationship between turbidity and UVT.

UVT calculations were made for a range of particle diameter from 100nm to 5 $\mu$ m and to assess the impact of particle characteristics (particle size, particle number concentration and refractive index) on UVT. The theoretical model showed that the most important parameter affecting UVT was particle size and this was attenuated when the refractive index of the particle was small. The sensitivity of turbidity measurement required to show a 1% variation in UVT for UVT (for UVT above 90%) was calculated to be 0.01NTU which is below the level of sensitivity of most commercial system.

Experiments with made solution containing one pollutant showed that turbidity is linearly related to the UVT (turbidity range between 0.14-5 NTU), but for real and non commercial water compositions UVT cannot be estimated using turbidity measurement. The nature of turbidity cannot be directly related to the particle characteristics which are particle size, chemical composition and hence absorbance and scattering coefficient.

Finally from comparison between experimental results and theoretical calculation of UVT it appears that difference in UVT prediction (given values from 0% to 100% of UVT whereas measurement are between 90-99%) was mainly due to an error in theoretical determination of particle number concentration measurement. As an improvement of the theoretical model it was proposed to calculate the particle

number concentration from 4 size particle fractionated solutions and then these solutions were diluted and UVT calculations and measurement were performed. Difference between predicted and measured UVT was still too important (but lower than 4%) to get a good correlation and use the theoretical model as a tool to predict UVT.

## **ACKNOWLEDGEMENTS**

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## NOMENCLATURE

A: Absorbance (units/cm)

C: cross section area ( $m^2$ )

c: pollutant concentration ( $mg.L^{-1}$ )

d: particle diameter (m)

$I_0$ : intensity of the incident beam

I: intensity of the incident beam at a distance L in a medium

L: distance in the medium (m)

m: refractive index

N: particle number concentration ( $particle.mL^{-1}$ )

NTU: nephelometric turbidity unit

$\emptyset$ : diameter (m)

Q: scattering coefficient ( $m^{-1}$ )

UVT: UV transmittance (%)

$\alpha$ : molar absorption coefficient ( $Mol.^{-1} cm^{-1}$ )

$\Delta$ NTU: difference in turbidity

$\epsilon$ : extinction coefficient ( $m^2.mol^{-1}$ )

$\lambda$ : wavelength of the incident beam



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# 1. Introduction

## *The emergence of the UV*

UV processes are used in both water (Tobin et al., 1983) and wastewater treatment (Qualls et al., 1989) primarily for disinfection and more recently for the removal of organic compounds by oxidation (Wang et al., 2000). UV is becoming a more prevalent treatment option for potable water especially in relation to the inactivation of *Cryptosporidium* but also in the reduction of micro-pollutants such as pesticides. Efficiency of UV disinfection was first demonstrated on activated sludge effluent being discharge to shellfish water (Roeber and Hoot, 1975). UV disinfection was first introduced to a wider audience in North America by the publication in 1979 of an American National Symposium on Water Disinfection (Venosa, 1979) and the first full scale UV disinfection process with a wastewater flow of around 10MLD was installed in 1982 by Trojan Technologies Inc. (Kapitain, 1995). By 1991 over 300 UV treatments units had been installed (Gross and Davis, 1991).

## *Principles of the UV treatment*

An overview of the different UV categories is shown below (Figure 1.1). It can be seen how the germicidal wavelengths are in the range from 200nm to 300nm and where a cell will be likely to absorb UV light and consequently be inactivated (Hijnen et al., 2006).

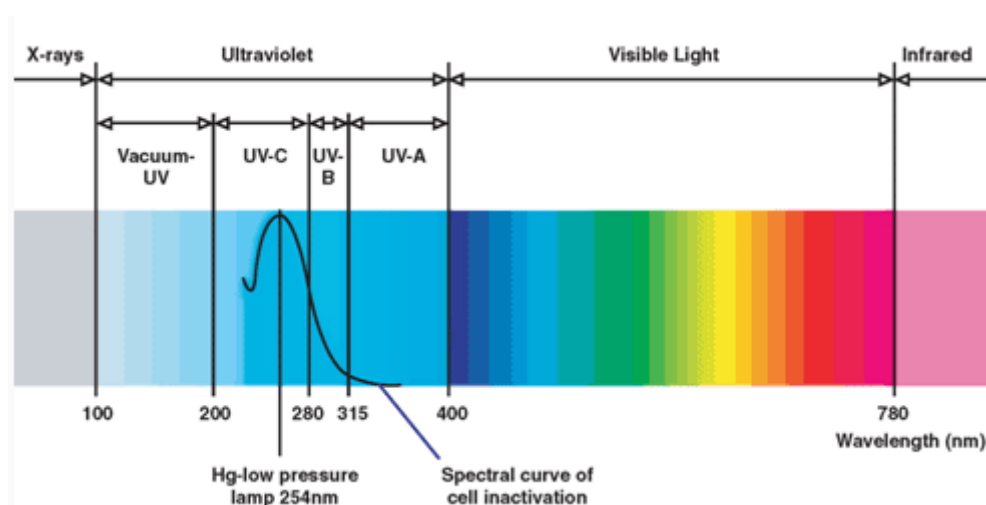


Figure 1.1: UV wavelength spectrum ((Aquabest®, 2007))

UV light is generated by using different types of UV lamp such as Low Pressure mercury vapour lamps, Low-pressure high-output (LPHO) mercury vapour lamps and Medium Pressure mercury vapour lamps, the latest commonly used in water treatment (USEPA, 2006). The required UV dose for disinfection purposes needed to be transmitted to the water is in the range of 30 to 70  $\text{mJ.cm}^{-2}$  (USEPA, 2006). The dose  $D$  of UV light delivered to water measured in Watt second per square meter ( $\text{Ws/m}^2$ ) or Joule per square meter ( $\text{J.m}^{-2}$ ) is a function of the UV intensity  $I$  in Watt per square meter ( $\text{W/m}^2$ ) and the exposure time  $t$  in second (s):

$$D = I.t \text{ (defined by (Yip and Konasewich, 1972))} \quad (1)$$

The exposure time ( $t$ ) corresponds to the hydraulic residence time in the UV reactor which is a function of the flow and the reactor volume. The intensity of the UV light is directly related to the light intensity produced by the UV light and depends mainly on the type of UV lamp, the number and the age of lamp and the applied voltage (USEPA, 2006). An important parameter that drastically affects UV efficiency is the water transmittance (Sommer et al. 1997). Increasing the UV transmittance (UVT) of water will (1) increase UV treatment efficiency and (2) reduce operational cost. Sommer et al. (1997) for example showed that Reduction Equivalent Dose (RED) (Cabaj et al., 1996) corresponding to the UV dose delivered to the water increases from  $540\text{J.m}^{-2}$  for a UVT of 6% to  $940\text{J.m}^{-2}$  for a UVT of 67%. By increasing UVT operational cost can also be reduced as shown below (Table 1.1).

**Table 1.1: Example of power and cost saving by increasing UVT (Malley et al.)**

| Average design flow (MLD) | UVT increase (%) | Power saved (kW/MLD) | Regional power cost (\$/KW-Hour) | Annual Power Cost savings (U.S. dollars) |
|---------------------------|------------------|----------------------|----------------------------------|--|
| 760                       | 2                | 0.3                  | 0.05                             | 105120                                   |
| 1150                      | 1                | 0.2                  | 0.08                             | 126144                                   |
| 380                       | 7                | 1.1                  | 0.1                              | 359160                                   |
| 190                       | 3                | 0.5                  | 0.05                             | 39420                                    |
| 95                        | 5                | 0.8                  | 0.08                             | 50808                                    |
| 1500                      | 8                | 1.2                  | 0.13                             | 2140944                                  |

## 2. Literature review

### 2.1. UV absorbance

UV absorbance of a water sample corresponds to the quantity of light which is absorbed by a medium and in context to this project the more water absorbs, the lower the UV dose and thus the UVT (Harris et al., 1987). According to Beer-Lambert Law (Morowitz, 1950), a monochromatic beam is adsorbed as written in equation (2) and (3):

$$I = I_0 \cdot 10^{-\alpha \cdot C \cdot L} \quad (2)$$

or can be written expressed on the neperian logarithm basis:

$$I = I_0 \cdot \exp(-\varepsilon \cdot C \cdot L) \quad (3)$$

where:

$I$ : Average intensity at distance  $L$  ( $\text{W}/\text{m}^2$ )

$I_0$ : Incident intensity emitted by the lamp ( $\text{W}/\text{m}^2$ )

$\alpha$ : Absorption coefficient ( $\text{m}^2 \cdot \text{mol}^{-1}$ )

$\varepsilon$ : Extinction coefficient ( $\text{m}^2 \cdot \text{mol}^{-1}$ )

$C$ : the concentration of the absorbing compound

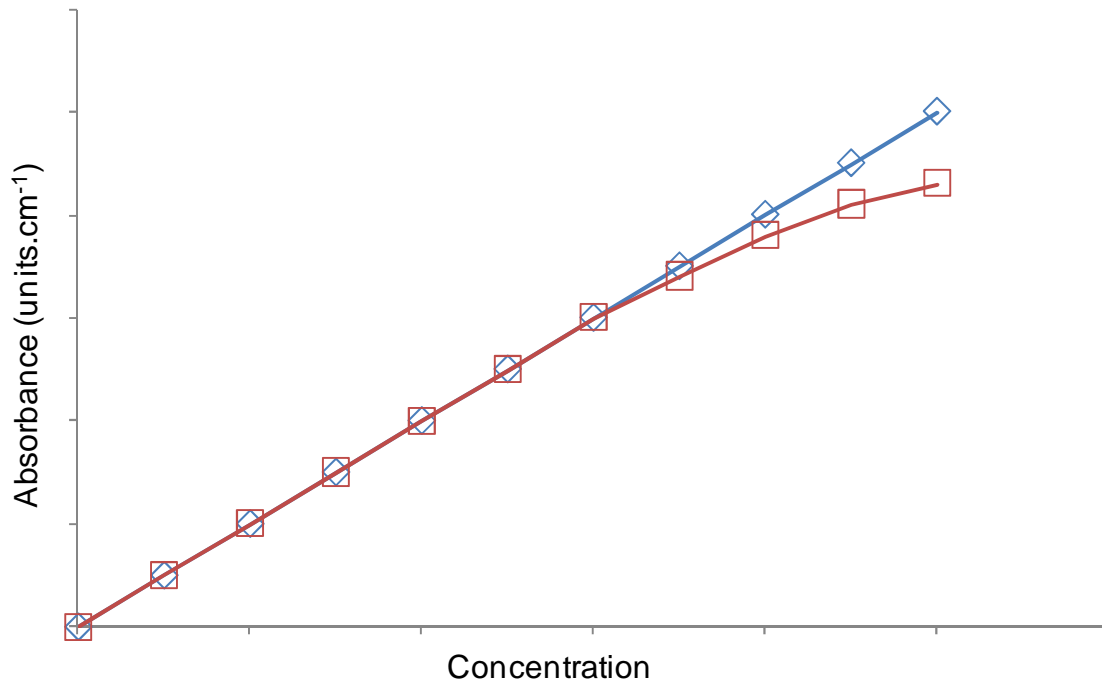
$L$ : Distance in the liquid (m)

Both equations (2) and (3) show that the average intensity of a monochromatic beam passing through the water sample depends on the absorption coefficient and the extinction coefficient respectively and decreases exponentially as the absorbing material concentration increases. The absorbance (no unit) of a medium can be expressed by rearranging equation (3) and is given in equation (4):

$$A = \varepsilon \cdot C \cdot L \quad (4)$$

According to equation (4) it can be seen that the absorbance is a linear function of the absorbing concentration species (Housecroft and Constable, 1997). The linearity

of the Beer-Lambert law is limited by chemical and instrumental factors (Figure 2.1). The main causes of nonlinearity include the deviations in absorption coefficients at high concentrations (>0.01M) due to electrostatic interactions between molecules in close proximity, scattering of light due to particles in the sample, changes in refractive index at high analyte concentration and shifts in chemical equilibrium as a function of concentration (Brian M. Tissue, 1996).



**Figure 2.1: General trend of Absorbance as a function of absorbing pollutant Concentration (◇ curve representing the theoretical model and □ curve representing typical experimental absorbance measurement)**

Gregory (2006) described another approach of Beer-Lambert's law as a function of the particle number concentration  $N$  and light scattering cross section area  $C$ . The relation of the transmitted light in function of these parameters is given in equation (5):

$$I = I_0 \cdot \exp(-L \sum_i N_i C_i) \quad (5)$$

Gregory (2006) made the assumption that the quantity of absorbed light for a particle is negligible compared to the scattered light. The cross section area is a parameter depending on the particle geometry and refractive index. It represents the area of the particle scattering the light of an incident beam. Cross section area  $C$  ( $m^2$ ) is given in equation (6):

$$C = \frac{Q\pi d^2}{4} \quad (6)$$

where  $d$  is the particle diameter and  $Q$  the scattering coefficient

The scattering coefficient expresses the light attenuation caused by scattering the incident beam during its passage through a medium. The scattering coefficient written in equation (7) is usually expressed in units of reciprocal distance ( $m^{-1}$ ):

$$Q = \frac{8}{3} \left( \frac{\pi d}{\lambda} \right)^4 \left( \frac{m^2 - 1}{m^2 + 2} \right)^2 \quad (7)$$

where  $m$  is the refractive index of a given particle and  $\lambda$  the wavelength of the incident beam

Given that the fraction of scattered light is equal to the transmitted light fraction  $\left( \frac{I}{I_0} \right)$  subtracted to the total emitted light fraction (equal to 1) and by rearranging equation (5), (6) and (7) the fraction of scattered light and the UVT (%) are given in equation (8) and (9) respectively:

$$\%_{Scattered} = 1 - \exp \left( - \frac{8}{12} \frac{NL\pi^5 d^6}{\lambda^4} \left( \frac{m^2 - 1}{m^2 + 2} \right)^2 \right) \quad (8)$$

$$UVT = 100 \times \exp \left( - \frac{8}{12} \frac{NL\pi^5 d^6}{\lambda^4} \left( \frac{m^2 - 1}{m^2 + 2} \right)^2 \right) \quad (9)$$

Equations (8) and (9) are straightforward methods of quantifying the UVT or  $\%_{scattered}$  in function of the particle size, particle number concentration and refractive index at a

given wavelength. Particle size is affected by an exponent 6 indicating that importance of this parameter has much more influence on the UVT than particle refractive index which is affected by an exponent 2 and particle number concentration. Example of refractive index for different particle is given below (Table 2.1).

**Table 2.1: Refractive index of different compounds (Malvern Mastersizer software)**

| Compound                     | Refractive index |
|------------------------------|------------------|
| Aluminium hydroxide          | 1.50 - 1.56      |
| Calcite (CaCO <sub>3</sub> ) | 1.486 - 1.740    |
| Glass                        | 1.48 -1.802      |
| Iron oxide (III)             | 2.94 - 3.22      |
| Kaolin                       | 1.533 - 1.570    |
| Magnesite                    | 1.700 - 1.563    |
| Quartz                       | 1.544 – 1.553    |
| Titanium dioxide             | 2.493 - 2.554    |
| Water (liquid)               | 1.33             |

## 2.2. UV Transmittance

Water quality can be ranked in function of its UVT value as shown in Table 2.2.

**Table 2.2: Water quality and associated UV measurement (DeMers and Renner, 1992)**

| Source water quality | Absorbance (units/cm) | Transmittance (%) |
|----------------------|-----------------------|-------------------|
| Excellent            | 0.022                 | 95%               |
| Good                 | 0.071                 | 85%               |
| Fair                 | 0.125                 | 75%               |



UVT is written in equation (10) and is expressed as a function of the incident intensity and the average intensity at the distance  $L$  in the medium:

$$UVT = \frac{I}{I_0} \quad (10)$$

By substituting the UVT (in %) in the Beer-Lambert law, UVT is calculated as a function of the absorption coefficient according to equation (11) :

$$UVT = 100 \cdot \exp(-\alpha_{254} \cdot L) \quad (11)$$

where  $\alpha_{254}$  is the absorbance of the pollutant at 254nm and  $L$  the path length through the medium

From equation (11), it can be seen that the transmittance declines exponentially with the distance in the medium and conversely the absorbance increases exponentially. Regarding to the UV disinfection treatment the transmittance decline is also considered as exponential with the increasing concentration of the dissolved substances and suspended solids (Snicer et al., 1998). Examples of absorbance values are given in Table 2.3:

**Table 2.3: UV Absorbance Characteristics of Common Water Treatment Chemicals (USEPA, 2006)**

| Compound                       | Molar Absorption Coefficient<br>( $M^{-1} \text{ cm}^{-1}$ ) | Impact Threshold Concentration <sup>2</sup><br>( $\text{mg.l}^{-1}$ ) |
|--------------------------------|--|---|
| Ozone ( $O_3$ ) (aqueous)      | 3.25   | 0.071   |
| Ferric iron ( $Fe^{3+}$ )      | 4.716  | 0.057   |
| Hypochlorite ( $ClO^-$ )       | 29.5   | 8.4   |
| Hydrogen peroxide ( $H_2O_2$ ) | 18.7   | 8.7   |
| Zinc ( $Zn^{2+}$ )             | 1.7  | 187   |

<sup>2</sup> : Concentration in  $\text{mg.l}^{-1}$  resulting in UVT decrease from 91 % to 90 % ( $A_{254}$  increase from 0.041  $\text{cm}^{-1}$  to 0.046  $\text{cm}^{-1}$ )

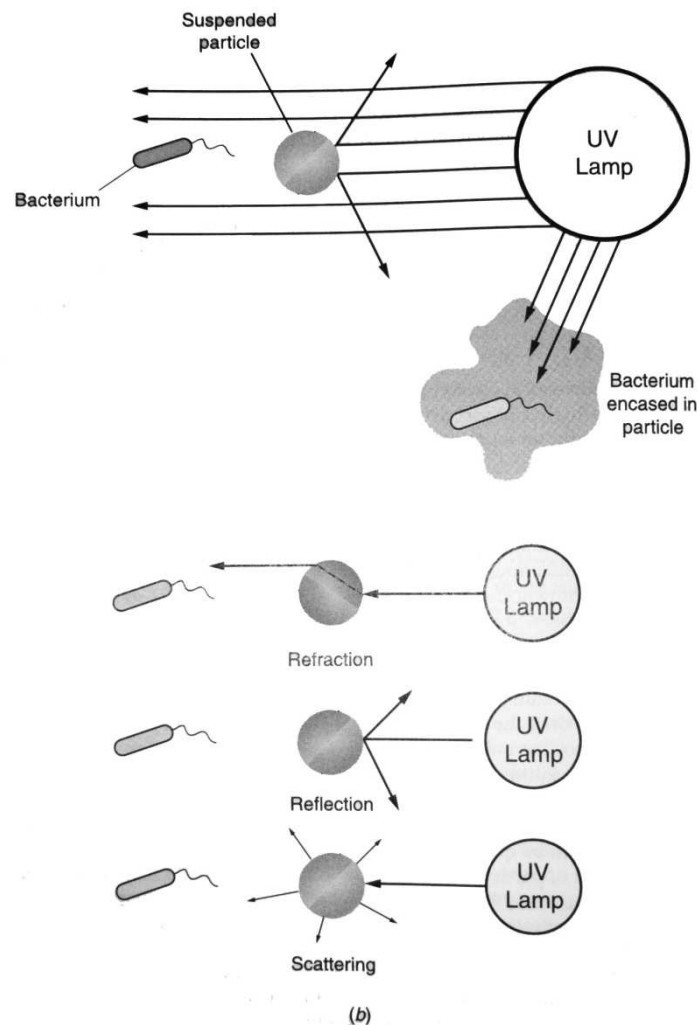
From a water treatment perspective it requires processes upstream of the UV reactors to remove as much of absorbing materials as possible in order to increase the UVT.

A problem remains when measuring the absorbance of a water containing particle. The UV light is deflected away of the spectrophotometer cell due to either scattering or blocking capacity of the particles. Both effects can affect the validity of the absorbance measurement and scattered or blocked light not reaching the cell measurement is considered as attenuated light (Linden and Darby, 1998). Christensen and Linden (2003) reported that the impact of particle on the determination of UV absorbance were underestimated by comparing the result of two absorbance measurement methods using conventional dual beam spectrophotometer and a spectrophotometer equipped with the Integrating Sphere (IS). They reported that for waters filtered at 5, 11 and 40 $\mu$ m and in the turbidity range from 0.046 to 16.2 NTU that UVT was underestimated by between 3 to 9% when using conventional spectrophotometer rather than IS spectrophotometer. They concluded that particles in raw water scatter the light away from the detector in direct mode measurement where IS spectrophotometer can accurately measure absorbance taking into consideration scattered light.

## **2.3. Influence of water quality on UVT**

### **2.3.1. Effect of particle on UV disinfection**

Residual turbidity and suspended solids contained in water have a negative effect on the efficiency of the UV disinfection either by absorbing, scattering or blocking the UV radiations (Qualls et al., 1985). Gregory (2006) made the assumption that most of the light was scattered rather than absorbed and Huber and Frost (1998) shows that scattered light is still available for disinfection but the fact that the path inside the medium is consequently longer leads to a dissipation of the UV dose 2 which is hence reduced or no longer available for disinfection. Shading and shielding phenomenon are also caused by solid particles blocking UV light (USEPA, 1996). The different phenomenon caused by the interaction of a particle and the light are shown in Figure 2.2.



**Figure 2.2: Overview of mechanisms for interferences in disinfection (MWH, 2005)**

Removal of particle leading to a reduction in turbidity increases UV disinfection efficiency as it is believed that residual turbidity (1) provides a matrix to transport microorganisms through or introduce organisms into the system (Lechevallier, 2006), (2) particle from 7 to 10 $\mu\text{m}$  are capable of shielding particle associated organisms from UV light and as result are not destroyed (Ridgway and Olson, 1982; Jolis et al., 2001) or (3) is a nutrient source that can lead to a bacterial activity and water quality degradation (Herson D. S. et al., 1984). Beyond the individual effect of different substances on absorption, in a recent study Mason and Li (2001) reported that rather than an individual species group of compounds were contributing more significantly to UV absorbance.

### 2.3.2. Absorbing organic compounds

Organic compounds such as humic and fluvic acids and pesticides contained in water are all absorbing material. Swift et al. (1992) showed by analysing NMR spectra of humic acid that molecules are made of methyl and methylene groups, saturated carbon, aromatic carbon, carboxyl and carbonyl groups, non aromatic carbon bounded to oxygen. An example of humic acid chemical structure is given in Figure 2.3.

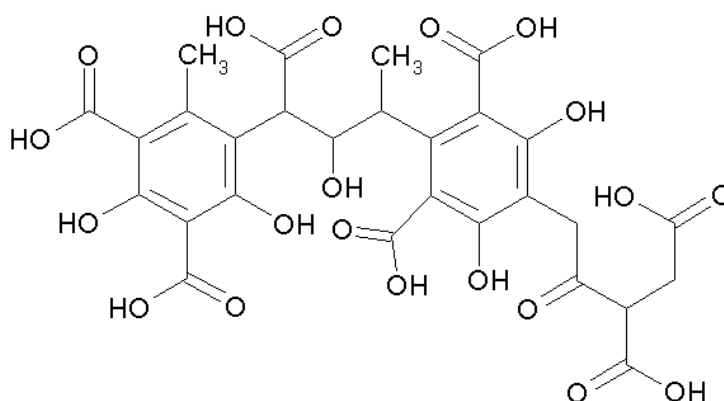


Figure 2.3: Chemical structure of a humic acid

UV absorption principally occurs following the absorption of a photon causing the transition of an electron of a double bond from a low energy level orbital  $\Pi$  to a higher energy level orbital  $\Pi^*$  (Rao, 1975). Qualls et al. (1983) believed that humic substances and related compounds were the major fraction causing UV absorption. Nick et al. (1992) and Tobin et al. (1983) reported that other aromatic containing double bonds as well as pesticide and pharmaceutical were strongly absorbing UV at germicidal wave length. Examples of extinction coefficient of functional organic groups are given in Table 2.4

**Table 2.4: Extinction coefficient of organic functional group (Dean, 1992)**

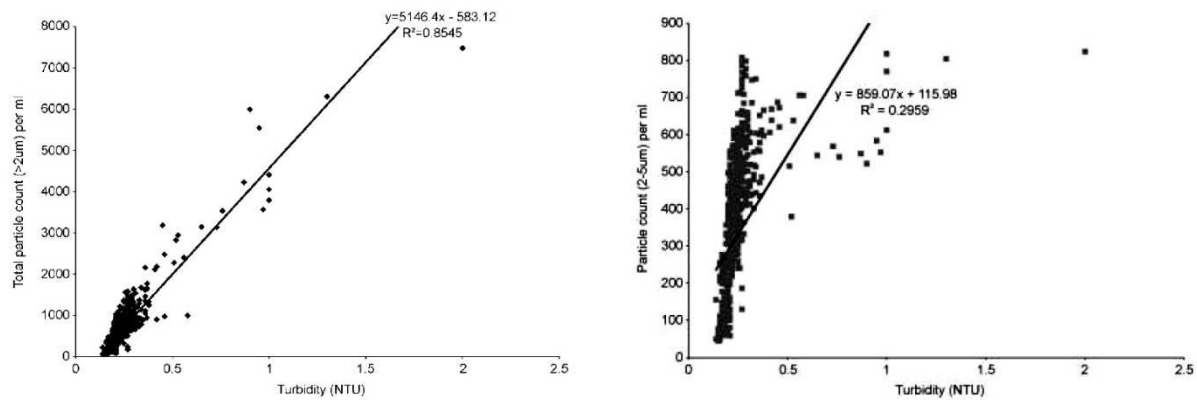
| Chromophore |                      | $\lambda$ (nm) | $\epsilon$ (m <sup>2</sup> .mol <sup>-1</sup> ) |
|-------------|----------------------|----------------|---|
| Aldehyde    | -CHO                 | 210            | strong  |
| carbonyl    | R <sub>2</sub> C=O   | 195            | 1000  |
| carboxyl    | R <sub>2</sub> -COOH | 200-210        | 50-70   |
| ester       | R-COO-R              | 205            | 50  |
| ether       | R-O-R                | 185            | 1000  |
| ethylene    | -C=C-                | 190            | 8000  |
| Azido       | R <sub>2</sub> =N-   | 190            | 5000  |

### 2.3.3. Particle monitoring

Hamilton et al. (2003) reported that three types of particle monitoring are commonly used in water treatment works and have been studied: conventional 90° traditional light scatter (nephelometric) turbidimeters, light obscuration particle counter and a particle index monitor (photometric dispersion analyser). Descriptions of these devices are available in other publications (Hunt, 1993; Kirby et al., 1998; Gregory, 1994); Hargesheimer et al., 1992).

Turbidimeters give an indication on the water clarity whereas particle counting gives information on the particle number and the particle size. Hunt (1993) reported that turbidimeter were able to notice change in turbidity for range of particle upward 0.01 $\mu$ m whereas most of the particle counter can only detect and measure particle with a size >1 $\mu$ m (Gregory, 1994) but are more sensible in changes of large particle size. Doyle (1998) also demonstrated that particle counting provides a better accuracy on the small changes in particle number than turbidimeter and particle size analysis gives much quicker information on the change of water quality as well as a more appreciable sensitivity. Kavanaugh and Trussell (1977) showed that turbidity measurement was particularly insensitive for low particle concentration for a particle size higher than 5 $\mu$ m. Bridgeman et al. (2002) searched for a relationship between turbidity and particle counting in a specific particle size in the range of 2 to 5 $\mu$ m and for particle size greater than 2 $\mu$ m (Figure 2.4) and from weekly data record he reported that no robust relationship between turbidity and particle counting was

identified due to a big variation in linear correlation coefficient (between 0.08 and 0.91).



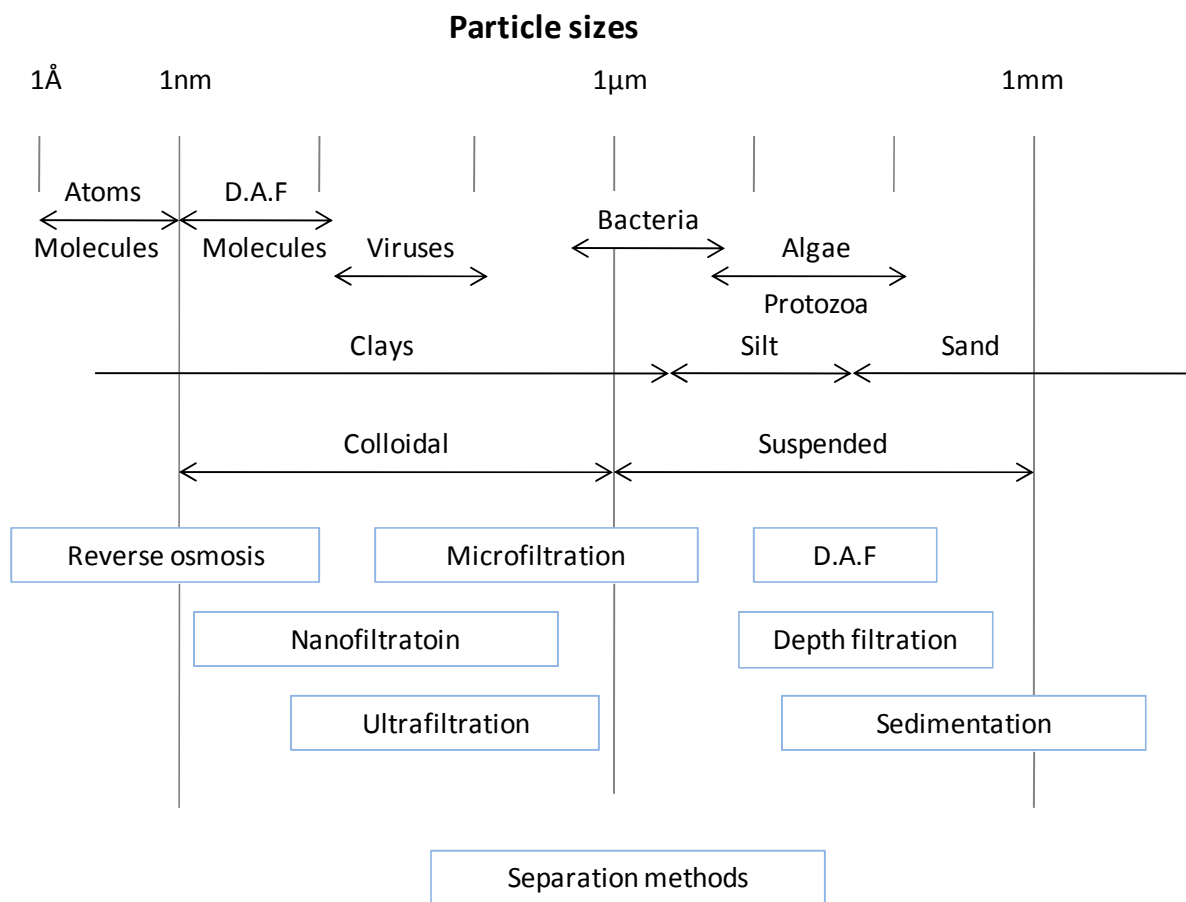
**Figure 2.4: Relationship between combined turbidity (on the left: particle size >2µm; on the right: particle size in the range 2-5µm) (Bridgeman et al., 2002)**

Hall and Croll (1996) clearly showed that no relationship exists between turbidity and particle count and made different comparisons between turbidity and particle counting values recording over a short period of time. Data recorded at the start of a filter run of a pilot scale treating River Thames water showed a variation in turbidity from 0.15 to 0.2NTU whilst particle count was varying between 1500 and 7100 particle per mL. They also reported that an average turbidity of 0.3NTU might be associated to a particle count variation between 500 and 6000 particle per mL. On another hand Hall and Croll (1996) noticed no clear correlation by collecting data from filtered water on two full scale plants and showed that for turbidity of 0.1–0.2 NTU on both sites particle count in the range of particle size of 2-5µm varied between 20 and 250 particles per mL for one plant and between 2000 and 6000 particles per mL for the other plant. Hargesheimer et al. (1992) reported in his study that no relationship between particle count and turbidity were found.

Some other works were done but no convincing relationship between particle count and turbidity was reported (Bishop, 1981; Logsdon et al., 1981; Logsdon et al., 1985; Westerhoff, 1976)

## 2.4. Water composition

Species contained in the water will be responsible of UV absorption as well as particulate and soluble forms of humic and fluvic acid and thus decrease the UVT. Other species will have an impact on the absorbance as other aromatic organics (e.g., phenolic compounds); metals (e.g. iron); and anions (e.g. nitrates and sulphites), (DeMers and Renner, 1992)). Soluble matter in water is known as total dissolved solids (TDS) and is for 90% made of salts and at the concentration of 50 to 1000mg.l<sup>-1</sup> (Gregory, 2006). Insoluble particles which remain suspended are also called total suspended solids (TSS) and are mainly composed of living and dead organisms, inorganics, and organics (including macromolecules) (Gregory, 2006) and are present in a range of concentration of 10-20mg.l<sup>-1</sup>. Particle composition is linked to the seasonal changes and weather condition (e.g. storm, algae bloom) and the size of particle varies from 1mm to 1nm as shown below (Figure 2.5):



**Figure 2.5: Diagram of typical particle in water with range of size and appropriate particle separation processes (D.A.F.: dissolved air floatation) (Gregory, 2006)**

Typical water composition in UK is shown below (Table 2.5) and water typical particle size distribution for two different treatments and untreated water is given in Figure 2.6.

**Table 2.5: Comparison of water qualities (Parsons and Jefferson, 2006)**

| Parameter  | Type of water |        |         |       |
|--|---------------|--------|---------|-------|
|  | Mooreland     | Upland | Lowland | Sea   |
| Colour (Hazen)   | 136           | 128    | 8.25    | -     |
| Turbidity (NTU)  | 1.5           | 5      | 22      | 5     |
| Conductivity ( $\mu\text{S}/\text{cm}^{-1}$ )                  | -             | 70     | 775     | 51000 |
| Dissolved organic matter ( $\text{mg}/\text{l}^{-1}$ )         | 12            | 15     | 5.3     | >1    |
| Algae ( $\text{cell}/\text{ml}^{-1}$ )                         | 0             | -      | -       | -     |
| Bacteria ( $\text{No}/\text{l}^{-1}$ )                         | 0             | -      | -       | -     |
| Total pesticides ( $\mu\text{g}/\text{l}^{-1}$ )               | 0             | 0      | 0.35    | -     |
| Cryptosporidium ( $\text{No}/\text{l}^{-1}$ )                  | 0             | 0      | 0.05    | -     |
| Nitrate ( $\text{mg}/\text{l}^{-1}$ )                          | -             | -      | 4.8     | -     |
| pH   | 6.3           | 6.5    | 8.1     | 7.9   |
| Hardness ( $\text{mg}/\text{l}^{-1}$ as $\text{CaCO}_3^{2-}$ ) | -             | 2      | 353     | 350   |
| Alkalinity ( $\text{mg}/\text{l}^{-1}$ )                       | -             | 20     | 236     | 170   |
| Aluminium ( $\text{mg}/\text{l}^{-1}$ )                        | 0.09          | 0.3    | 0.23    | -     |
| Iron ( $\text{mg}/\text{l}^{-1}$ )                             | 0.42          | 2.4    | 0.3     | -     |
| Manganese ( $\text{mg}/\text{l}^{-1}$ )                        | 0.04          | 0.07   | 0       | -     |

An example of the effects that coagulation/flocculation/sedimentation and filtration process have on particle size distribution is shown below (Figure 2.6). The impact of the turbidity within filter quality guidelines which for a conventional and direct filtration are < 0.3 NTU (USEPA, 2002) and lower has a minimal effect on the UV transmittance and thus UV disinfection (Linden et al., 2002) but consequence of a filter breakthrough could have an adversely effect on UV reactor performance.



Coagulation using ferric salt as coagulant can lead to an increase of iron concentration and hence decrease UVT and as mentioned in Table 2.3 an increase of only  $0.057\text{mg}\cdot\text{l}^{-1}$  as Fe affects UVT.

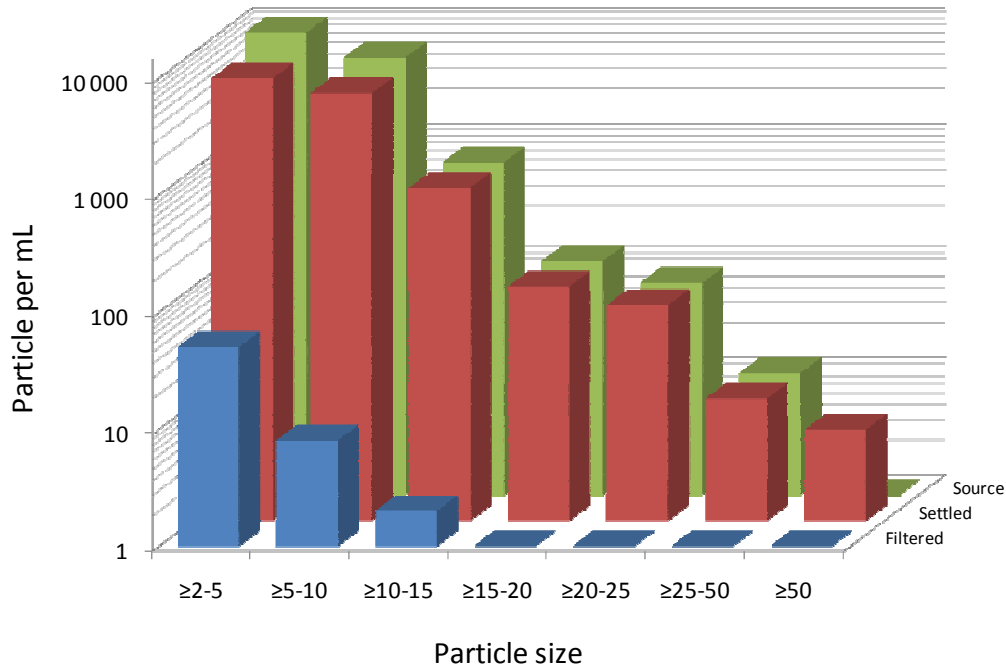


Figure 2.6: Typical particle size distribution in source settled (coagulation, flocculation and sedimentation) and filtered water (Hargsheimer and Lewis, 1995)

## 2.5. Summary

- The Beer-Lambert law can be used to estimate the UVT of water if particle size, particle number concentration (dependent on pollutant concentration and particle size) and refractive index are known. UVT varies with all these three parameters and hence better will lead to high UVTs.
- Light scattered by particle could lead to an incorrect UV absorbance measurement and an underestimation of the UVT. As a consequence UVT underestimation will lead to a UV overdose and hence less efficient process.
- To date no relationships between turbidity and particle counting have been found. Particle counting remains a more sensitive and quicker monitoring to detect

particle size  $>1\mu\text{m}$  and concentration variation but turbidimeter is more sensible for submicron particle change.

➤ Remaining particles decrease UV disinfection efficiency mainly by scattering refracting or blocking light away from the bacteria and viruses. Particles of  $5\mu\text{m}$  and larger can shelter bacteria and viruses from UV radiation.

### **3. Objectives of the study**

UV disinfection efficiency is directly link to UVT. Turbidity of the water affects UVT and a better understanding of the interaction between particles and UV light can possibly lead to find out any relationship between UVT and turbidity and how to improve UV processes efficiency.

The work presented in the paper research will therefore:

- assess the theoretical model developed by Gregory (2006) in order to better understand the behaviour of UVT as a function of the particle properties and estimated the turbidity sensitivity required to detect a small change in UVT for moorland water with UVT higher than 90%,
- estimate the suitability of turbidity measurement as a tool for UVT prediction and
- combine UVT measurements and theoretical model to improve UVT prediction.

## **4. Paper for publication**

## **The relationship between UVT and turbidity, with respect to the disinfection of surface waters**

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### **Abstract**

UV transmittance (UVT) is a parameter very closely related to the efficiency of any UV processes. Firstly a theoretical model of UVT proposed by Gregory (2006) was assessed and secondly an experimental approach was undertaken to find out any relationship between turbidity and UVT.

UVT calculations were made for a range of particle diameter from 100nm to 5 $\mu$ m and to assess the impact of particle characteristics (particle size, particle number concentration and refractive index) on UVT. The theoretical model showed that the most important parameter affecting UVT was particle size and this was attenuated when the refractive index of the particle was small. The sensitivity of turbidity measurement required to show a 1% variation in UVT for UVT (for UVT above 90%) was calculated to be 0.01NTU which is below the level of sensitivity of most commercial system.

Experiments with made solution containing one pollutant showed that turbidity is linearly related to the UVT (turbidity range between 0.14-5 NTU), but for real and non commercial water compositions UVT cannot be estimated using turbidity

measurement. The nature of turbidity cannot be directly related to the particle characteristics which are particle size, chemical composition and hence absorbance and scattering coefficient.

Finally from comparison between experimental results and theoretical calculation of UVT it appears that difference in UVT prediction (given values from 0% to 100% of UVT whereas measurement are between 90-99%) was mainly due to an error in theoretical determination of particle number concentration measurement. As an improvement of the theoretical model it was proposed to calculate the particle number concentration from 4 size particle fractionated solutions and then these solutions were diluted and UVT calculations and measurement were performed. Difference between predicted and measured UVT was still too important (but lower than 4%) to get a good correlation and use the theoretical model as a tool to predict UVT.

**Keywords:** Turbidity, particle counter, Ultraviolet, UV transmittance, UV absorption

## 4.1. Introduction

UV processes are becoming more prevalent treatment options for potable water especially in relation to the inactivation of *Cryptosporidium* but also in the reduction of micro-pollutants such as pesticides (Roeber and Hoot, 1975). The first full scale UV disinfection process with a wastewater flow of around 10MLD was installed in 1982 by Trojan Technologies Inc. (Kapitain, 1995). By 1991 over 300 UV treatments units had been installed (Gross and Davis, 1991).

Germicidal wavelengths in the range of 200-300nm (domain of UV light) are absorbed by cell and chemicals and are consequently inactivated and oxidised respectively (Hijnen et al., 2006). UV light is artificially produced using different type of UV lamp and for potable water disinfection the required UV dose to be transmitted to the water is generally in the range of 30-70 mJ.cm<sup>-2</sup> (USEPA, 2006). The dose (D) of UV light delivered to water in Watt second per square meter (Ws/m<sup>2</sup>) is the product of the UV intensity (I) in Watt per square meter (W/m<sup>2</sup>) and the exposure time (t) in second (s) (Yip and Konasewich, 1972).

The intensity of the UV light is directly related to the light intensity produced by the UV light and depends mainly on the lamp type and condition ((USEPA, 2006). Intensity of UV light transmitted by the UV lamp to the water is a parameter very closely related to UVT (Sommer et al. 1997). Increasing the UV transmittance (UVT) of water will (1) increase UV treatment efficiency and (2) reduce operational cost. Sommer et al. (1997) for example showed that Reduction Equivalent Dose (RED) (Cabaj et al., 1996) corresponding to the UV dose delivered to the water increases from 540J.m<sup>-2</sup> for a UVT of 6% to 940 J.m<sup>-2</sup> for a UVT of 67%. Experiment carried out on wastewater effluent by Mason and Li (2001) showed a UVT increase from 0 to 1.1% with the turbidity decrease from 450 to 20NTU due to successive filtration and

thus a particle size decrease down to 0.22 $\mu\text{m}$ . Gregory (2006) proposed a theoretical model to calculate UVT directly based on the particle properties (diameter, refractive index and particle number concentration) and related to the turbidity. This model will be described and assessed in this paper as well as the relationship between UVT and turbidity.

## **4.2. Material & Methods**

Experimental measurements of UV absorbance at 254nm were carried out using humic acids and kaolin since they are good models of the most likely pollutants present in water. The third pollutant chosen for the study was iron oxide (III) which is a high absorbing chemical and can be either naturally present in water or be a residual from coagulation using iron salt as coagulant. Experimental UVT is calculated from the UV absorbance measurement using Beer-Lambert law as described equation (1) (Masschelein, 2002):

$$\text{UVT}=\exp(-\alpha L) \tag{1}$$

where  $\alpha$  is the UV absorbance at 254nm and L is the path length of the light through the medium.

### **4.2.1. Relationship between UVT and Turbidity**

A series of experiments related to the study of the relationship between UVT and turbidity were carried out using solution prepared from deionised water (5-15M $\Omega\cdot\text{cm}^{-1}$  at 25 $^{\circ}\text{C}$  and TOC<25ppb ) and containing either iron oxide (III) (Sigma Aldrich), humic acid (Sigma Aldrich) or kaolin (Sigma Aldrich). Initial concentrations of these solutions were 5 mg.l<sup>-1</sup> and dilutions were performed after each measurement until

reaching a turbidity and UV absorbance values as low as possible. Turbidity measurement and UV 254nm absorption measurements were performed using a HACH 2100N Turbidimeter and a JENWAY 6505 UV/Vis spectrophotometer respectively.

#### **4.2.2. Impact of the particle size on absorbance**

A series of experiments were undertaken to study the impact of the particle size on UV absorbance at 254nm again using a solution of iron oxide (III) (Sigma Aldrich) at  $1\text{mg.l}^{-1}$  as Fe made with deionised water ( $5\text{-}15\text{M}\Omega\cdot\text{cm}^{-1}$  at  $25^\circ\text{C}$  and  $\text{TOC}<25\text{ppb}$ ). Particle size was measured using size fractionation and 4 fractionated solutions were produced using membranes with pore sizes of 500nm (Millipore LCR Membrane, PTFE, Hydrophilic,  $0.5\ \mu\text{m}$ ,  $\text{Ø}47\text{mm}$ ), 13nm and 1.3nm (Omega<sup>TM</sup> membrane  $\text{Ø}76\text{mm}$  100kDa and 10kDa respectively). Filtration was performed under a 1atm pressure of nitrogen for 13 and 1.3nm membrane pore size. Iron concentration of the 4 solutions were determined by atomic absorption using a Perking Elmer AAnalyst 800 machine and particle size of the filtered and unfiltered samples were determined using Malvern Instruments Zetasizer 3000 which is sensible for submicron particle. The aim of these concentration and particle size analysis is to find out the particle number concentration of each unfiltered and filtered solutions. Dilutions using deionised water ( $5\text{-}15\text{M}\Omega\cdot\text{cm}^{-1}$  at  $25^\circ\text{C}$  and  $\text{TOC}<25\text{ppb}$ ) are made in order to obtain the same particle concentration in each solution to be able to compare UV absorbance measurements at the same particle number concentration.



### 4.3. Results

#### 4.3.1.1 *UV 254nm absorbance and turbidity measurement for different pollutant concentrations*

UVT was calculated from UV absorption measurement at 254nm for all the three pollutants at a range of concentration of 0.05-4 mg.l<sup>-1</sup> (Figure 4.4). Iron oxide absorption remains insignificant for the range of concentration studied whereas it should have an impact on UVT for iron concentration higher than 0.057mg.l<sup>-1</sup> (USEPA, 2006). The impact of kaolin on absorption is seen for concentrations higher than 1mg.l<sup>-1</sup> and the UVT decrease was quite low for the range of concentration studied. Humic acids are seen to have the largest impact on UVT where value of 85% was observed at low concentration of 0.25mg.l<sup>-1</sup>.

Turbidity measurements were performed for different pollutant concentration (Figure 4.5). A linear relationship between turbidity and concentration can be observed for all the three pollutants. Turbidity increases with the increase of concentration but the increase in turbidity is the most sensible for humic acids and is quite similar for kaolin and iron oxide.

#### 4.3.1.2 *Analysis of the iron oxide fractionated solutions*

To allow understanding the relationship between particle size and UVT and to compare the theoretical model and measurements, particle size analysis and iron concentration measurement were performed on fractionated solutions of iron oxide (Table 4.1). As it can be expected iron concentration decreases with the decrease of the membrane pore size which corresponds to a better removal of iron oxide particles and thus a decrease of iron concentration. Particle size analysis of the fractionated sample doesn't fit the particle size expected according to the membrane pore size,

however a decrease of particle size is observed with the decrease of the pore size membrane but the particle sizes are not in the range of dimensions expected, i.e. 500nm, 13nm and 1.3nm for the different fractionation. The particle concentration was calculated using the expected particle size and also the measured particle size (Table 4.1).

#### 4.4. Discussion

##### 4.4.1. Understanding of theoretical model for UVT

It is interesting to better understand the behaviour of UVT variation and how it varies as a function of the particle parameters such as particle diameter  $d$ , particle number concentration  $N$  and refractive index  $m$ . Calculations of UVT are made using equations (12), (13), and (14):

$$I = I_0 \cdot \exp(-L \sum_i N_i C_i) \quad (12)$$

$$C = \frac{Q \pi d^2}{4} \quad (13)$$

where  $L$  is the path length of the light through the medium,  $C$  is the cross section area representing the area of particle receiving light from the beam and  $Q$  the scattering coefficient of the particle

The scattering coefficient expresses the attenuation caused by scattering of the incident beam during its passage through a medium and is given in equation (14):

$$Q = \frac{8}{3} \left( \frac{\pi d}{\lambda} \right)^4 \left( \frac{m^2 - 1}{m^2 + 2} \right)^2 \quad (14)$$

where  $m$  is the refractive index of a given particle and  $\lambda$  the wavelength of the incident beam equal to 254nm for UV light

By rearranging equations (12), (13), and (14), the relationship between the UVT and the particle parameters is as given in equation (15):

$$UVT = 100 \times \exp \left( - \frac{8}{12} \frac{NL\pi^5 d^6}{\lambda^4} \left( \frac{m^2 - 1}{m^2 + 2} \right)^2 \right) \quad (15)$$

Equation (15) shows that UVT is a function of three main particle parameters properties:

- $d$ : particle diameter
- $m$ : scattering coefficient
- $N$ : particle number concentration

A series of calculation were performed by fixing one of these parameters or the UVT and to observe what is the impact on the non fixed parameters. Fixed parameters chosen from literature review include:

- $N = 2120 \text{ particle.ml}^{-1}$  (particle number concentration average calculated low and high values from post filtration measurement (Table 4.3, Hamilton et al., 2003))

- Post filtration range of particle size from 100nm to 5000nm (Parsons and Jefferson, 2006)
- Refractive index of kaolin and iron oxide (III) of 1.53 and 2.93 respectively ((©Malvern Instruments Ltd., 1997))
- Concentration calculations are based on a density of 5242kg.m<sup>3</sup> and 2600kg.m<sup>3</sup> for iron oxide and kaolin respectively ((IPCS INCHEM, 2004; IPCS INCHEM, 1995))
- Chosen concentration for calculation at fixed concentration of 1.10<sup>-8</sup> mg.l<sup>-1</sup>

#### 4.4.1.1 Sensitivity of turbidity required to detect small UVT variation

The variation in turbidity that would equate to a 1% variation of UVT for a solution containing one pollutant has been modelled (Figure 4.1) from equation (12) where Gregory (2006) assumes that the term NC corresponds to the turbidity. N was solved for a given UVT using equation (12). From equation (13) and (14) C was calculated by fixing the particle size diameter d and turbidity variation was thus calculated as shown in equation (16):

$$\Delta NTU = C_i \cdot N_i - C_{i+1} \cdot N_{i+1} \quad (16)$$

where index i is used to represent the value of C and N at UVT i

It can be seen Figure 4.1 that for a change of 1% in UVT to be measured using turbidity for a water of UVT > 90%, a turbidity instrument would need to measure variations close to 0.01 NTU. It can be noticed that particle diameter doesn't affect the turbidity sensitivity because turbidity is calculated from UVT value and according to equation (15) it explains that for a given turbidity particle number concentration

can be either high or low if the particle diameter is small or large respectively. In other words in equation (12) and for a given turbidity the product  $NC$  is constant.

#### *4.4.1.2 Effect of particle parameter changes on UVT for different simulated water conditions*

UVT has been studied as a function of the particle diameter first for a fixed particle number concentration (Figure 4.2a) and secondly for a fixed concentration (Figure 4.2b). One can see on Figure 4.2a that both UVT decreased rapidly for kaolin and iron oxide as the particle size increases over the range of 1500-4000nm and 750-2250nm for each one respectively. Concentration of both pollutant increases logarithmically with an increase in the particle size diameter and for a given particle diameter at fixed  $N$ , it can be seen that kaolin concentration is always lower than iron oxide concentration. This is simply due to the fact that kaolin density is lower than that of iron oxide. The impact of particle size on UVT is more significant for iron oxide than for kaolin which was expected since iron oxide will scatter more UV light than kaolin as it has a higher refractive index (2.93 for iron oxide and 1.53 for kaolin). The UVT decrease is less affected by larger particle when the refractive index is lower, and the slope of the UVT decrease tends to be smaller with the decrease of the refractive index.

For a given concentration of pollutant it can be seen that the UVT decreases with the particle diameter increase (Figure 4.2b). The remarks made in Figure 4.2c for difference in UVT between kaolin and iron oxide are also applicable in this case to explain the difference in UVT values between the two pollutants. Reducing the particle size before UV treatment is proved here to be an efficient solution of UV processes improvement.

Particle number concentration has also been modelled as a function of particle diameter at 95% of UVT for iron oxide and Kaolin. From equation (15) the particle number concentration was also calculated as a function of the particle diameter at 95% of UVT (corresponding to an “excellent” pre-UV process quality water (DeMers and Renner, 1992)) (Figure 4.3). It can be seen that both particle number concentration and pollutant concentration decrease with an increase of the particle diameter and that the range of covered values in Figure 4.3 for the particle number concentration is cubically proportional to the range of the pollutant concentration as expected because pollutant concentration  $c$  is calculated from the particle number concentration according to equation (17):

$$c = N \cdot \frac{\pi d^3}{6} \cdot \rho \quad (17)$$

where  $\rho$  is the pollutant density in  $\text{kg}\cdot\text{m}^{-3}$

As it was already explained for a given UVT and with the increase of the particle diameter corresponding to a turbidity value that the increase of particle number concentration will automatically be balanced by a decrease of pollutant concentration. Obviously the opposite trend is observed for the decrease of the particle diameter i.e. the particle number concentration increases with the decrease of the pollutant concentration to keep turbidity stable and thus UVT.

#### **4.4.2. UVT: experimental measurement**

##### *4.4.2.1 Influence of the pollutant concentration on UVT and turbidity*

The refractive index of kaolin and iron oxide 1.53 and 2.93 respectively, it would have been expected iron oxide to have had a greater impact on UVT but the trend is not followed as it can be seen in Figure 4.4. As shown previously a possible explanation may be the difference in particle diameter between kaolin and iron oxide where the iron oxide particle could be smaller than kaolin particle and causes that difference. Humic acids are not truly a particulate pollutant but a dissolved organic compound and results shows that it has significant impact on UV absorption. Humic acids are largely present in surface moorland water (Goslan et al., 2002) and should not be neglected when a model like the one proposed by Gregory (2006) is used for UV disinfection process design.

Turbidity was also compared with changing pollutant concentration (Figure 4.5). A linear trend was plotted for each pollutant since theoretically a linear relationship between the concentration and the turbidity is expected. The linear function is followed for kaolin and iron oxide but not for humic acids which are not truly particle and the light attenuation is caused mainly by absorption. The model developed by Gregory (2006) can be applied only for particle because the theoretical background lies on the fact that according to equation (15) UVT is calculated assuming that most of the light is scattered and absorption phenomenon is neglected. For a soluble organic pollutant most of the light is absorbed and not scattered. Relatively to the refractive index of kaolin and iron oxide it was expected that iron oxide would be the pollutant impacting the most on turbidity which is confirmed by the result plotted in Figure 4.5.

Even if the range of concentration coped was large enough to notice an exponential trend, results show a linear relationship between turbidity and UVT (Figure 4.6) whereas an exponential relationship was expected according to Gregory's (2006) model. However it is clear that for a given turbidity and if the water composition is unknown the UVT cannot be predicted. For example for turbidity of 0.55NTU the UVT of the solution prepared can either be 85, 99 or 100% for humic acids, kaolin and iron oxide respectively. It proves that for and unknown water composition turbidity cannot give an indication of the UVT.

Particle number concentration  $N$  was calculated using equation (17) but comparison of the expected and measured particle concentration shows too large discrepancy (Table 4.1). Such a difference in values is caused by a poor accuracy in measuring particle size. Initially it was proposed to dilute each sample to obtain different solutions at approximately the same particle number concentration to assess the effect of particle on UVT but due to the large range of particle concentration such dilutions were not feasible. Detection limit of the UV spectrophotometer would have been reached for such high dilution. (from Table 4.1 range of dilution factor are in the range of 1 to  $1.10^8$ ). Despite discrepancy in the results it can be seen that the values for the measured particle number concentration are close to the value of  $2.1.10^6$   $\text{particel.m}^{-3}$  find in other papers (Hamilton et al., 2003).

#### *4.4.2.2 Application of the theoretical model for UVT calculation*

Regarding the very high values of the predicted particle number concentration (Table 4.2) application of the theoretical model using equation (15) had given bad estimation of UVT with values between 0 and 100% (Table 4.1). It shows that a better particle number concentration estimation has to be proposed to optimize UVT



prediction. Online particle counting are not capable of counting and measuring particle size below 1  $\mu\text{m}$  (Hamilton et al., 2003) which would have allowed having an optimal response of UV dose for changes of particle concentration for submicron particle size.

In this last part of the study it was proposed to combine experimental results and theoretical model to determine the particle number concentration with a better accuracy. From measured UVT and expected particle size (values in Table 4.1), particle number concentration was calculated for each initial fractionated solution using equation (15) (Table 4.2). Each fractionated solutions were diluted 2, 4 and 8 times and UVT was measured as well as calculated using particle number concentration previously determined with each initial fractionated solution but divided by the dilution factor. As shown in Table 4.2 this method gives a better estimation of UVT when compared to measured values. It can be seen that the difference between calculated and measured UVT values decreases with the particle size decrease. It is easily explainable by the fact that UVT theoretical model is more affected by the particle size variation than the particle number concentration variation. Even if the difference between measured and predicted UVT is quite small and below 5%, the application of this model for UVT estimation still needs further improvement. An error of just a few percentage of UVT prediction would lead to an inappropriate UV dose calculation when UV processes are designed and thus will fail to meet the requirement in UV disinfection.

#### **4.5. Conclusion and recommendation**

A better understanding of the particle effect was proposed throughout the theoretical model proposed by Gregory (2006). Theoretically a turbidity sensitivity of around 0.01NTU was found to detect a 1% variation of UVT for UVT level higher than 90%. It reveals that the effect of particle size on UVT is less sensible when refractive index is low and shows the importance of removing high refractive particles. Also the impact of large particles was shown to be the most important parameter affecting UVT and reducing particle size can be a way of increasing the UVT. Experimental confirmation could be undertaken by reducing particle size using different ultrasound doses on different solution at same pollutant but difficulties in size measurement will be encountered submicron particle as it was explained earlier.

Even if an improvement of the theoretical model was proposed this remains not enough accurate for UVT estimation. Further investigation should be done to analyse impact of big particle because only scattering effect are considered in the proposed model but for large particle the contribution of UV absorption effect might have a dominant role and explain why the improved model is less accurate for large particle.

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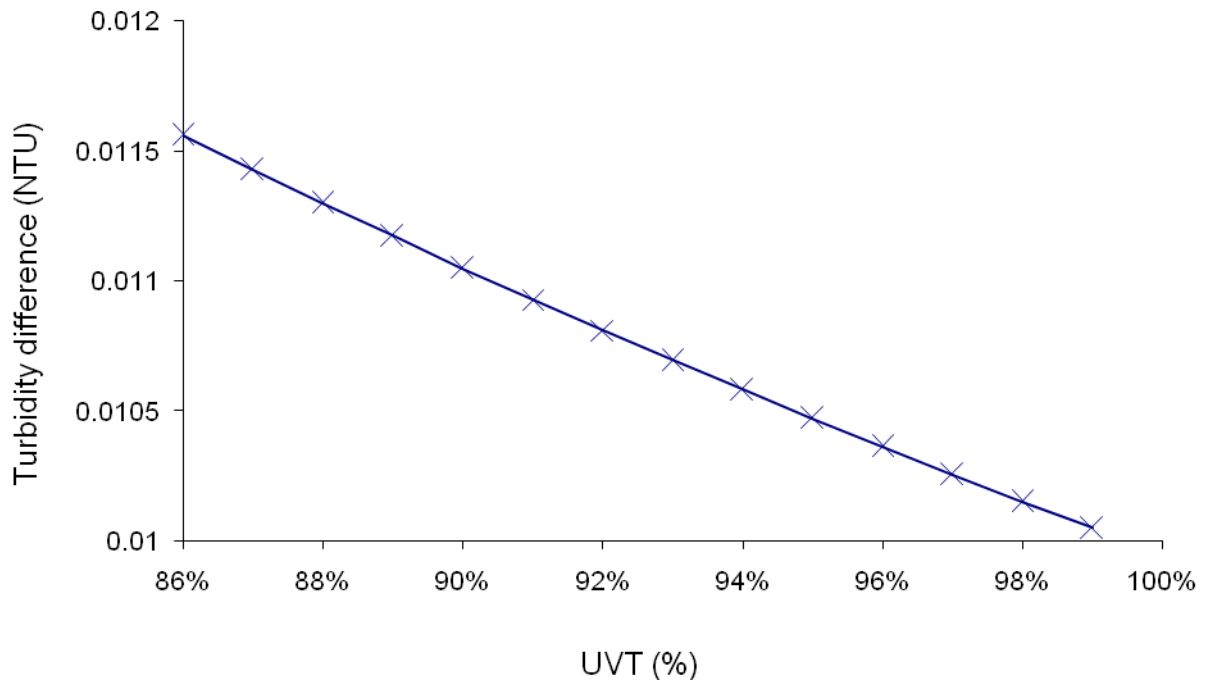
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**Figure captions**

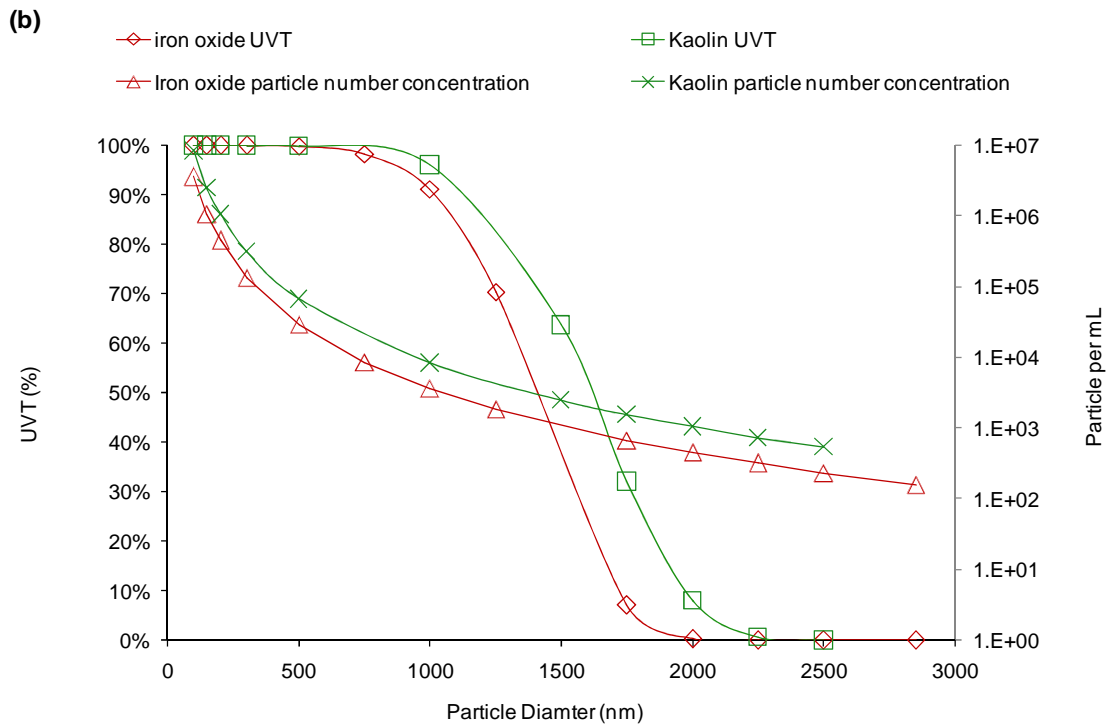
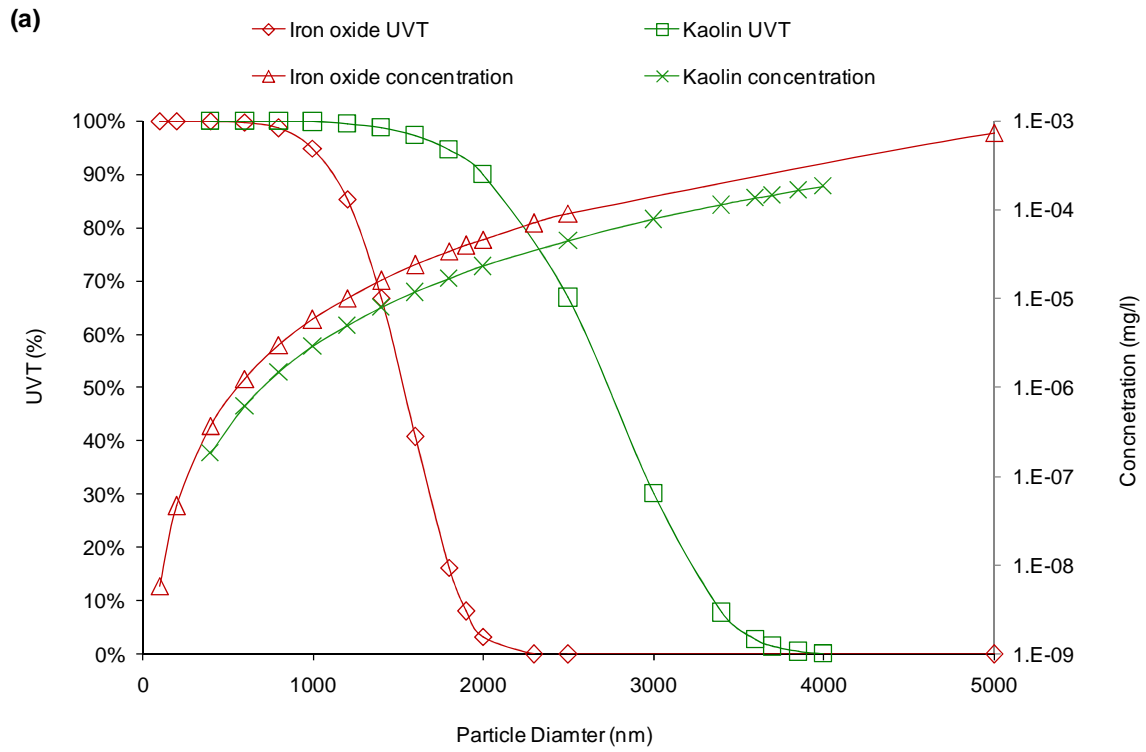
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**Figure 4.1: Variation in turbidity difference for small UVT change**



**Figure 4.2: UVT in function of particle diameter for iron oxide and kaolin: (a) for N fixed and (b) for fixed concentration**



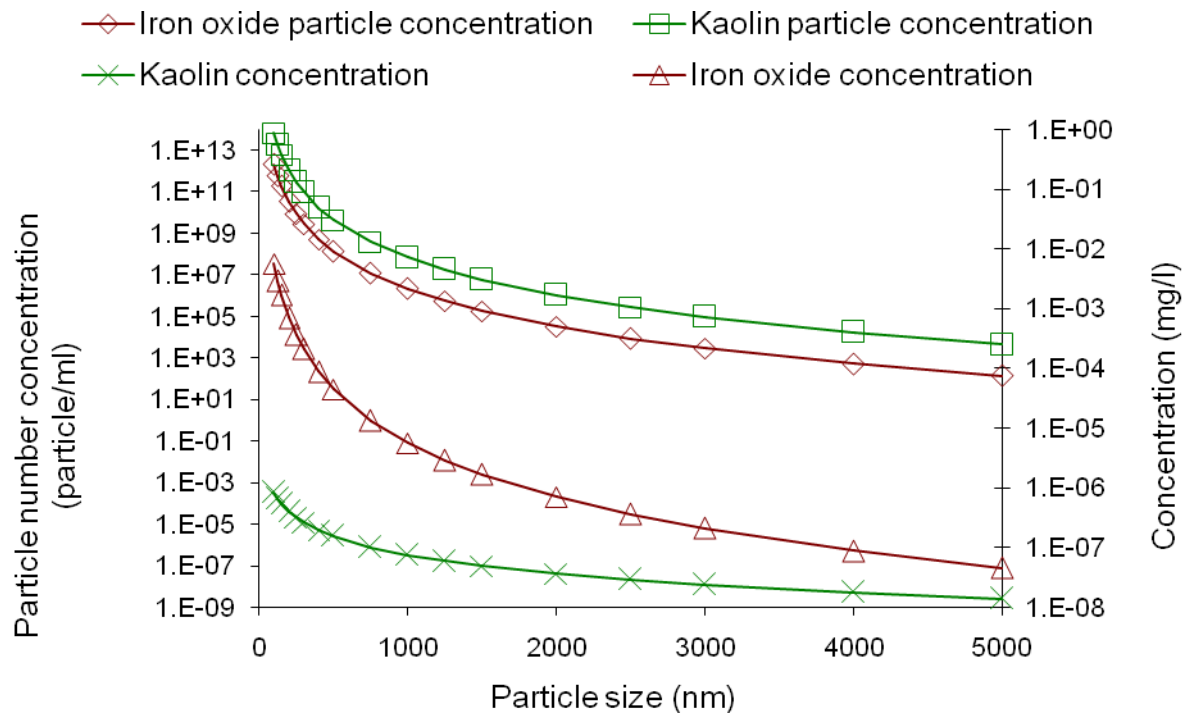


Figure 4.3: Particle number and pollutant concentration in function of the particle diameter at 95% UVT

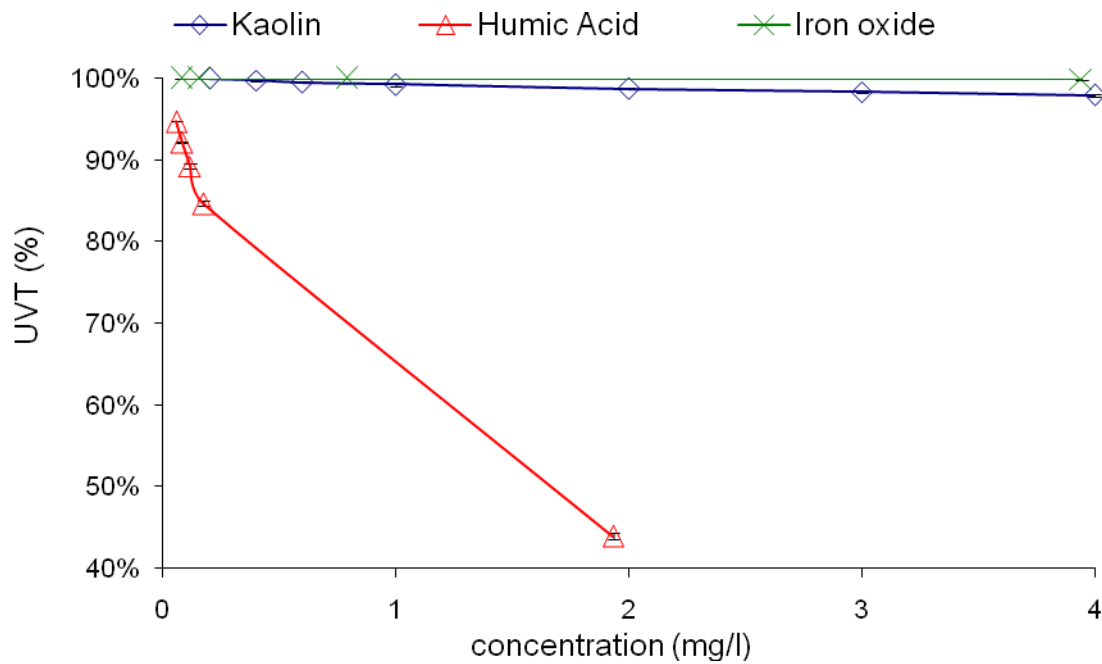


Figure 4.4: UVT in function of the concentration

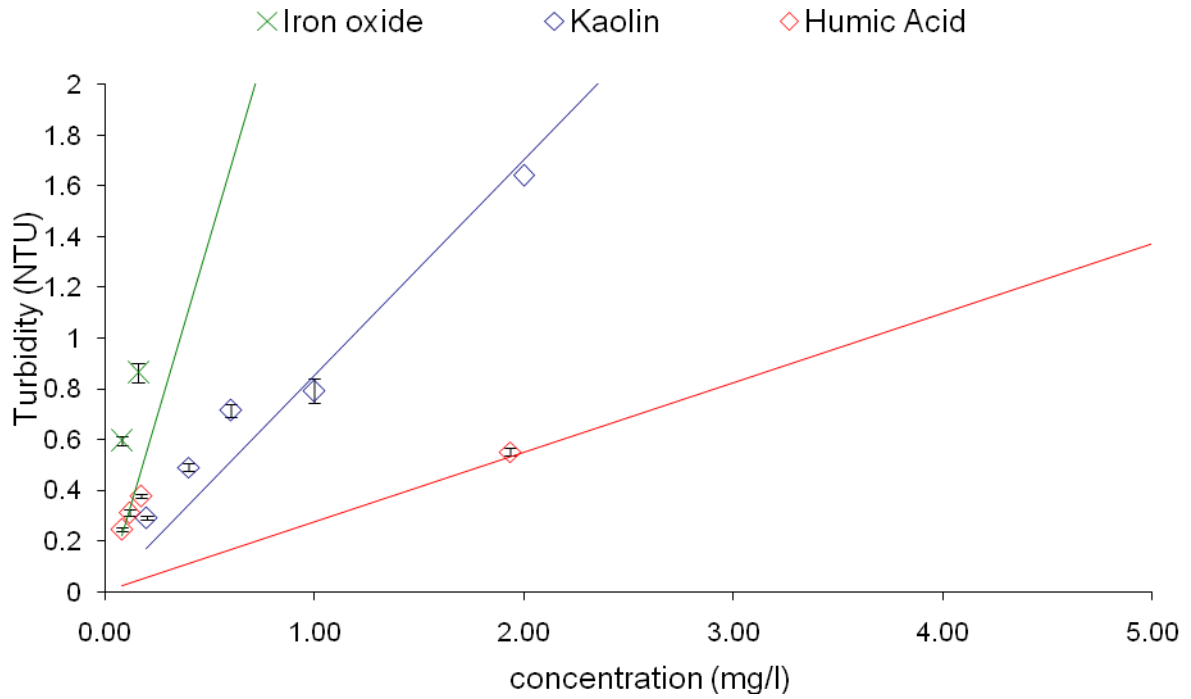


Figure 4.5: Turbidity in function of the concentration

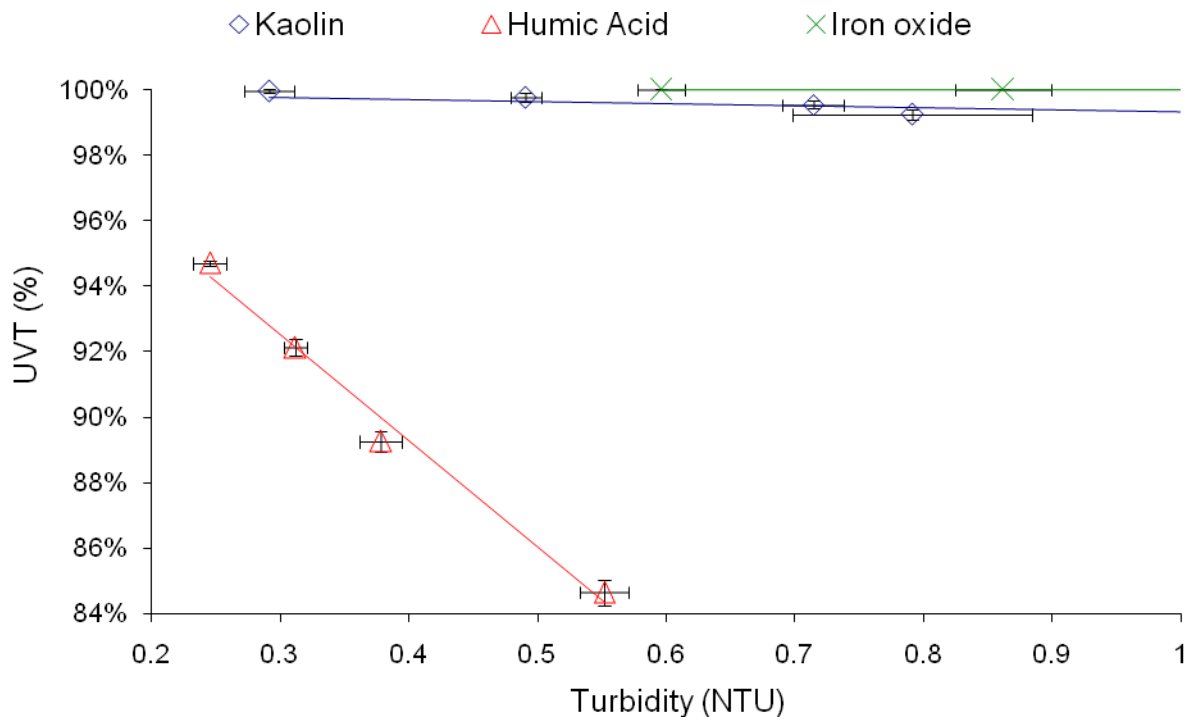


Figure 4.6: UVT in function of the turbidity

**Table 4.1: Measured and calculated fractionated solution composition**

|  | Fe <sub>2</sub> O <sub>3</sub><br>unfiltered | Fe <sub>2</sub> O <sub>3</sub> 0,5µm | Fe <sub>2</sub> O <sub>3</sub> 100K |
|--|--|--------------------------------------|-------------------------------------|
| Predicted particle size (nm)   | ≈5000  | ≈500                                 | ≈13                                 |
| Measured particle size (nm)  | 4833,8                                       | 6816                                 | 5387,5                              |
| Iron concentration (mg.l <sup>-1</sup> )                               | 6,06   | 6,41                                 | 1,08                                |
| <b>Predicted particle concentration<br/>(particle.ml<sup>-1</sup>)</b> | <b>1,77E+07</b>                              | <b>1,87E+10</b>                      | <b>1,79E+14</b>                     |
| <b>Measured particle concentration<br/>(particle.ml<sup>-1</sup>)</b>  | <b>1,95E+07</b>                              | <b>7,38E+06</b>                      | <b>2,52E+06</b>                     |
| Measured UVT   | 90.36%                                       | 84.42%                               | 94.66%                              |
| Calculated UVT   | <b>0%</b>                                    | <b>86,48%</b>                        | <b>100%</b>                         |

**Table 4.2: Comparison between UVT calculated and measured**

| Dilution factor | Iron concentration (µg.L <sup>-1</sup> ) | Particle number concentration (particle.mL <sup>-1</sup> ) | UVT measured | UVT calculated | UVT difference |
|-----------------|--|--|--------------|----------------|----------------|
| Unfiltered      |  |  |              |                |                |
| 2               | 2512.0                                   | 4.3E+08  | 95.1%        | 100.0%         | 4.9%           |
| 4               | 628.0                                    | 4.5E+17  | 97.5%        | 100.0%         | 2.5%           |
| 8               | 78.5                                     | 4.3E+23  | 98.7%        | 100.0%         | 1.3%           |
| 500nm filtered  |  |  |              |                |                |
| 2               | 63.1                                     | 1.2E+02  | 92.0%        | 91.9%          | 0.1%           |
| 4               | 15.8                                     | 3.1E+01  | 95.9%        | 97.9%          | 2.0%           |
| 8               | 2.0                                      | 3.9E+00  | 97.9%        | 99.7%          | 1.8%           |
| 13nm filtered   |  |  |              |                |                |
| 2               | 0.12                                     | 2.2E+17  | 97.3%        | 97.3%          | 0.1%           |
| 4               | 0.03                                     | 5.6E+16  | 98.6%        | 99.3%          | 0.8%           |

Table 4.3: Particle number concentration data from other Paper

| Reference*                               | Sample        | Particle counter/sensor                   | NTU low | NTU high | PSC low | PSC high |
|--|---------------|---|---------|----------|---------|----------|
| (Gregory, 2006) Fig. 2                   | Post RGF      | Hiac PC-320/Not specified (>2.5 µm)       | 0.11    | 0.2      | 16      | 100      |
| (Beard II and Tanaka, 1977) Fig. 3       | Post RGF      | PMS Liquilaz E20                          | 0.3     | 1.2      | 600     | 5300     |
| (Bourgine et al., 1998) Table 3          | Post RGF      | Unspecified LO counter                    | 0.04    | 0.05     | 400     | 4200     |
| (Chipps et al., 1995) Table 3            | Post filter   | Hiac Royco 9064/HRLD-150 (LO, >1 µm)      | 0.09    | 0.1      | 174     | 413      |
| (Goldgrabe et al., 1993) Table 3         | Post filter   | Hiac Royco 9064/HRLD-150 (LO, >1 µm)      | 0.08    | 0.1      | 82      | 440      |
| (Goldgrabe et al., 1993) Table 3         | Post filter   | Hiac Royco 9064/HRLD-150 (LO, >1 µm)      | 0.09    | 0.11     | 172     | 514      |
| (Goldgrabe et al., 1993) Fig. 1          | Post RGF      | Hiac Versacount                           | 0.1     | 0.5      | 100     | 2500     |
| (Hall,T. 1997) Table 4                   | Post RGF      | Hiac Versacount                           | 0.15    | 0.2      | 1500    | 4300     |
| (Hall,T. 1997) Table 4                   | Post RGF      | Hiac Versacount                           | 0.2     | 0.4      | 7100    | 15000    |
| (Hall and Croll 1997) Fig. 8             | Groundwater   | PMS Liquilaz E20                          | 0.36    | 0.69     | 1385    | 3886     |
| (Hamilton et al., 2000) Fig. 6.1         | Post RGF      | PMS Liquilaz E20                          | 0.05    | 0.15     | 12      | 490      |
| (Hargesheimer,E.E. 1995) Fig. 6.1        | Surface water | PMS Liquilaz E20                          | 0.6     | 7.4      | 7800    | 30000    |
| (Hargesheimer and Lewis, 1995) Fig. 3.10 | Post RGF      | Model 4100/346B (FALS, >0.7 µm)           | 0.08    | 0.12     | 600     | 2100     |
| (Hargesheimer,E.E. 1992) Fig. 8.11       | Post RGF      | CMH-150 sensor (>2.5 µm)                  | 0.08    | 0.98     | 40      | 440      |
| (Hargesheimer,E.E. 1992) Fig. 8.15       | Post RGF      | HRLD-150 sensor (LO, >1 µm)               | 0.04    | 1.5      | 250     | 9000     |
| (Hargesheimer,E.E. 1992) Fig. 8.15       | Post GAC      | HRLD-150 sensor (LO, >1 µm)               | 0.07    | 1.3      | 750     | 12000    |
| (Hargesheimer et al., 1992) Fig. 7       | Post RGF      | Hach 1900 WPC                             | 0.075   | 0.082    | 8       | 9        |
| (Johnson et al., 2000) Fig. 10           | Post RGF      | Hiac Model 320                            | 0.18    | 0.36     | 20      | 1000     |
| (Kavanaugh et al., 1980) Fig. 3          | Post RGF      | Unspecified electrical resistance counter | 0.1     | 0.25     | 50      | 550      |
| (Keay, 1995) Fig. 2                      | Post RGF      | Hiac Royco 4100/346-BCL (FALS)            | 0.1     | 0.3      | 100     | 3000     |
| (Lewis,C.M. 1991) Fig. 2                 | Post RGF      | Hiac Royco 4100/346-BCL (FALS)            | 0.1     | 0.45     | 300     | 8000     |
| (Lewis and Manz, 1991) Fig. 3            | Post RGF      | Not specified                             | 0.09    | 0.21     | 3       | 350      |
| (Murray, 1995)                           | Post RGF      | Not specified                             | 0.1     | 0.16     | 140     | 250      |
| (Peters,J.P. 1999)                       | Post RGF      | Not specified                             | 0.1     | 0.16     | 150     | 200      |
| (Peters, 1999)Table 3                    | Post RGF      | Not specified                             | 0.025   | 0.042    | 9       | 121      |
| (Pizzi and Rogers, 1998) Figs 1.8        | Post RGF      | Not specified                             | 0.025   | 0.026    | 20      | 125      |
| (Saunders et al., 1999)Fig. 7            | Post RGF      | Hiac Model 320                            | 0.11    | 0.36     | 5       | 105      |
| (Tate,Carol H. 1978) Fig. 8              | Post RGF      | Hiac Model 320                            | 0.2     | 0.25     | 10      | 40       |
| (Tate,Carol H. 1978) Fig. 9              | Post RGF      | Hiac Model 320                            | 0.3     | 0.65     | 11      | 50       |
| (Tate and Trussell, 1978)Fig. 5          | Post RGF      | PMS Liquilaz E20                          | 0.2     | 0.36     | 130     | 680      |

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## Appendix 1: Experimental results of UV absorbance and turbidity

**Table 4: Turbidity values at different concentration using Kaolin, Ferric Hydroxide, Iron (III) oxide and Humic acid**

| Kaolin (in mg/l)                               | 1     | 2     | 3     | 4     | 5     | Average | Std dev |
|--|-------|-------|-------|-------|-------|---------|---------|
| 0.2  | 0.267 | 0.312 | 0.286 | 0.283 | 0.31  | 0.2916  | 0.02    |
| 0.4  | 0.503 | 0.495 | 0.483 | 0.5   | 0.474 | 0.491   | 0.01    |
| 0.6  | 0.7   | 0.723 | 0.753 | 0.697 | 0.699 | 0.7144  | 0.02    |
| 1  | 0.928 | 0.804 | 0.787 | 0.77  | 0.668 | 0.7914  | 0.09    |
| 2  | 1.49  | 1.62  | 1.62  | 1.78  | 1.7   | 1.642   | 0.11    |
| 3  | 2.23  | 2.88  | 2.82  | 2.68  | 2.9   | 2.702   | 0.28    |
| 4  | 3.47  | 3.37  | 3.45  | 3.25  | 3.28  | 3.364   | 0.10    |
| 5  | 3.89  | 4.52  | 4.11  | 4.41  | 4.06  | 4.198   | 0.26    |
| Fe(OH) <sub>3</sub> (in mg/l as Fe)            | 1     | 2     | 3     | 4     | 5     | Average | Std dev |
| 0.36   | 0.25  | 0.24  | 0.255 | 0.25  | 0.247 | 0.2484  | 0.01    |
| 0.89   | 0.275 | 0.29  | 0.28  | 0.275 | 0.31  | 0.286   | 0.01    |
| 1.78   | 0.55  | 0.56  | 0.5   | 0.51  | 0.52  | 0.528   | 0.03    |
| 3.56   | 1.16  | 1.1   | 1.1   | 1.18  | 1.06  | 1.12    | 0.05    |
| Fe <sub>2</sub> O <sub>3</sub> (in mg/l as Fe) | 1     | 2     | 3     | 4     | 5     | Average | Std dev |
| 0.08   | 0.59  | 0.61  | 0.58  | 0.62  | 0.58  | 0.596   | 0.02    |
| 0.16   | 0.87  | 0.84  | 0.89  | 0.9   | 0.81  | 0.862   | 0.04    |
| 0.79   | 2.23  | 2.3   | 2.31  | 2.22  | 2.31  | 2.274   | 0.05    |
| 3.94   | 10.8  | 10.7  | 11.3  | 11.2  | 11    | 11      | 0.25    |
| Humic Acid (in mg/l)                           | 1     | 2     | 3     | 4     | 5     | Average | Std dev |
| 5.8  | 1.58  | 1.54  | 1.58  | 1.56  |       | 1.565   | 0.019   |
| 0.17   | 0.56  | 0.54  | 0.57  | 0.53  | 0.56  | 0.552   | 0.016   |
| 0.12   | 0.365 | 0.377 | 0.38  | 0.39  | 0.38  | 0.3784  | 0.009   |
| 0.08   | 0.31  | 0.32  | 0.33  | 0.3   | 0.3   | 0.312   | 0.013   |
| 0.06   | 0.25  | 0.252 | 0.24  | 0.24  |       | 0.2455  | 0.006   |

**Table 5: UVT absorbance values and calculation of the UVT at different concentration for Kaolin, Ferric Hydroxide, Iron (III) oxide and Humic acid**

| Kaolin (in mg/l)                               | 1     | 2     | 3     | 4     | 5     | Average | Std dev | UVT    | Std dev |
|--|-------|-------|-------|-------|-------|---------|---------|--------|---------|
| 0,2  | 0,003 | 0,002 | 0,002 | 0,002 | 0,001 | 0,0005  | 0,001   | 100,0% | 0,071%  |
| 0,4  | 0,012 | 0,009 | 0,009 | 0,009 | 0,01  | 0,00245 | 0,001   | 99,8%  | 0,130%  |
| 1  | 0,02  | 0,017 | 0,019 | 0,019 | 0,018 | 0,00465 | 0,001   | 99,5%  | 0,113%  |
| 2  | 0,032 | 0,032 | 0,031 | 0,031 | 0,028 | 0,0077  | 0,002   | 99,2%  | 0,163%  |
| 3  | 0,05  | 0,049 | 0,05  | 0,051 | 0,051 | 0,01255 | 0,001   | 98,8%  | 0,083%  |
| 4  | 0,07  | 0,066 | 0,067 | 0,068 | 0,067 | 0,0169  | 0,002   | 98,3%  | 0,149%  |
| 5  | 0,081 | 0,086 | 0,084 | 0,084 | 0,084 | 0,02095 | 0,002   | 97,9%  | 0,175%  |
| Fe(OH) <sub>3</sub> (in mg/l as Fe)            | 1     | 2     | 3     | 4     | 5     | Average | Std dev | UVT    | Std dev |
| 0,36   | 0,066 | 0,061 | 0,068 | 0,064 | 0,065 | 0,0162  | 0,003   | 98,4%  | 0,254%  |
| 0,89   | 0,063 | 0,063 | 0,065 | 0,064 | 0,06  | 0,01575 | 0,002   | 98,4%  | 0,184%  |
| 1,78   | 0,154 | 0,152 | 0,15  | 0,14  | 0,152 | 0,0374  | 0,006   | 96,3%  | 0,533%  |
| 3,56   | 0,312 | 0,325 | 0,32  | 0,329 | 0,34  | 0,0813  | 0,010   | 92,2%  | 0,956%  |
| Fe <sub>2</sub> O <sub>3</sub> (in mg/l as Fe) | 1     | 2     | 3     | 4     | 5     | Average | Std dev | UVT    | Std dev |
| 0,08   | 0     | 0     | 0     | 0     | 0     | 0       | 0,000   | 100,0% | 0,000%  |
| 0,16   | 0     | 0     | 0     | 0     | 0     | 0       | 0,000   | 100,0% | 0,000%  |
| 0,79   | 0     | 0     | 0     | 0     | 0     | 0       | 0,000   | 100,0% | 0,000%  |
| 3,94   | 0,001 | 0,004 | 0,005 | 0,003 | 0,002 | 0,00075 | 0,002   | 99,9%  | 0,158%  |
| Humic Acid (in mg/l)                           | 1     | 2     | 3     | 4     | 5     | Average | Std dev | UVT    | Std dev |
| 5,8  | 1,58  | 1,54  | 1,58  | 1,56  | -     | 1,565   | 0,019   | 20,9%  | 0,397%  |
| 0,17   | 0,162 | 0,168 | 0,169 | 0,168 | -     | 0,167   | 0,003   | 84,6%  | 0,271%  |
| 0,12   | 0,113 | 0,113 | 0,114 | 0,115 | -     | 0,114   | 0,001   | 89,2%  | 0,085%  |
| 0,08   | 0,082 | 0,082 | 0,082 | -     | -     | 0,082   | 0,000   | 92,1%  | 0,000%  |
| 0,06   | 0,053 | 0,057 | 0,055 | 0,053 | -     | 0,055   | 0,002   | 94,7%  | 0,181%  |

## Appendix 2: Results of UV absorbance and iron concentration of the fractionated solutions

**Table 6: Results of UV absorbance and iron concentration of the fractionated solutions**

| Solution          | Iron concentration<br>( $\mu\text{g.l}^{-1}$ as Fe) | UV absorbance |         |         |       | UVT    |       |
|-------------------|---|---------------|---------|---------|-------|--------|-------|
|                   |   | value 1       | value 2 | average | std   | UVT    | error |
| unfiltered        | 5024.06   | 0.406         | 0.405   | 0.406   | 0.07% | 90.36% | 0.16% |
| 500nm             | 126.14  | 0.677         | 0.678   | 0.678   | 0.07% | 84.42% | 0.09% |
| 100KDa            | 2.18  | 0.219         | 0.22    | 0.220   | 0.07% | 94.66% | 0.30% |
| 10KDa             | 0.23  | 0.21          | 0.211   | 0.211   | 0.07% | 94.87% | 0.32% |
| <b>Unfiltered</b> |   |               |         |         |       |        |       |
| undiluted         | 5024.06   | 0.406         | 0.405   | 0.406   | 0.07% | 90.36% | 0.16% |
| 2                 | 2512.03   | 0.201         | 0.201   | 0.201   | 0.00% | 95.10% | 0.00% |
| 4                 | 628.01  | 0.104         | 0.102   | 0.103   | 0.14% | 97.46% | 1.34% |
| 8                 | 78.50   | 0.053         | 0.053   | 0.053   | 0.00% | 98.68% | 0.00% |
| <b>500nm</b>      |   |               |         |         |       |        |       |
| undiluted         | 126.14  | 0.677         | 0.678   | 0.678   | 0.07% | 84.42% | 0.09% |
| 2                 | 63.07   | 0.333         | 0.332   | 0.333   | 0.07% | 92.02% | 0.20% |
| 4                 | 15.77   | 0.17          | 0.168   | 0.169   | 0.14% | 95.86% | 0.80% |
| 8                 | 1.97  | 0.084         | 0.083   | 0.084   | 0.07% | 97.93% | 0.83% |
| <b>100kDa</b>     |   |               |         |         |       |        |       |
| undiluted         | 0.23  | 0.219         | 0.22    | 0.220   | 0.07% | 94.66% | 0.30% |
| 2                 | 0.12  | 0.11          | 0.113   | 0.112   | 0.21% | 97.25% | 1.85% |
| 4                 | 0.03  | 0.058         | 0.058   | 0.058   | 0.00% | 98.56% | 0.00% |

## Appendix 3: Theoretical calculation of UVT

**Table 7: UVT calculation at a fixed concentration ( $1.10^{-8}\text{mg.l}^{-1}$ ) for iron oxide and kaolin**

| Iron oxide |                                   |                       |                    |        |
|------------|-----------------------------------|-----------------------|--------------------|--------|
| d (nm)     | N (particle per $\text{m}^{-3}$ ) | Q ( $\text{m}^{-1}$ ) | C ( $\text{m}^2$ ) | UVT    |
| 100        | 3643379                           | 3.218490047           | 2.53E-14           | 100%   |
| 150        | 1079520                           | 16.29360586           | 2.88E-13           | 100%   |
| 200        | 455422                            | 51.49584075           | 1.62E-12           | 100%   |
| 300        | 134940                            | 260.6976938           | 1.84E-11           | 99.99% |
| 500        | 29147                             | 2011.556279           | 3.95E-10           | 99.86% |
| 750        | 8636                              | 10183.50366           | 4.5E-09            | 98.37% |
| 1000       | 3643                              | 32184.90047           | 2.53E-08           | 91.20% |
| 1250       | 1865                              | 78576.41715           | 9.64E-08           | 70.38% |
| 1750       | 679                               | 301859.1641           | 7.26E-07           | 7.10%  |
| 2000       | 455                               | 514958.4075           | 1.62E-06           | 0.28%  |
| 2250       | 319                               | 824863.7967           | 3.28E-06           | 0.00%  |
| Kaolin     |                                   |                       |                    |        |
| d (nm)     | N (particle per $\text{m}^{-3}$ ) | Q                     | C                  | UVT    |
| 100        | 8450705                           | 0.595479172           | 4.68E-15           | 100%   |
| 150        | 2503913                           | 3.014613307           | 5.33E-14           | 100%   |
| 200        | 1056338                           | 9.527666748           | 2.99E-13           | 100%   |
| 300        | 312989                            | 48.23381291           | 3.41E-12           | 100%   |
| 500        | 67605                             | 372.1744823           | 7.31E-11           | 99.94% |
| 1000       | 8450                              | 5954.791717           | 4.68E-09           | 96.12% |
| 1500       | 2503                              | 30146.13307           | 5.33E-08           | 63.75% |
| 1750       | 1576                              | 55849.43326           | 1.34E-07           | 32.14% |
| 2000       | 1056                              | 95276.66748           | 2.99E-07           | 7.97%  |
| 2250       | 741                               | 152614.7987           | 6.07E-07           | 0.59%  |
| 2500       | 540                               | 232609.0515           | 1.14E-06           | 0.01%  |

**Table 8: UVT calculation at a fixed particle number concentration (N=2120 particle.mL<sup>-1</sup>)**

| Iron oxide |                         |                      |                     |       |
|------------|-------------------------|----------------------|---------------------|-------|
| d (nm)     | c (mg.l <sup>-1</sup> ) | Q (m <sup>-1</sup> ) | C (m <sup>2</sup> ) | UVT   |
| 600        | 1.25567E-06             | 4171.1631            | 1.18E-09            | 100%  |
| 800        | 2.9764E-06              | 13182.93523          | 6.63E-09            | 98.6% |
| 1000       | 5.81328E-06             | 32184.90047          | 2.53E-08            | 94.8% |
| 1200       | 1.00454E-05             | 66738.60961          | 7.55E-08            | 85.2% |
| 1400       | 1.59517E-05             | 123641.5136          | 1.9E-07             | 66.8% |
| 1600       | 2.38112E-05             | 210926.9637          | 4.24E-07            | 40.7% |
| 1800       | 3.39031E-05             | 337864.2111          | 8.6E-07             | 16.2% |
| 1900       | 3.98733E-05             | 419436.8414          | 1.19E-06            | 8.1%  |
| 2000       | 4.65063E-05             | 514958.4075          | 1.62E-06            | 3.3%  |
| 2300       | 7.07302E-05             | 900665.4731          | 3.74E-06            | 0.0%  |
| Kaolin     |                         |                      |                     |       |
| d (nm)     | c (mg.l <sup>-1</sup> ) | Q (m <sup>-1</sup> ) | C (m <sup>2</sup> ) | UVT   |
| 1200       | 4.98244E-06             | 2053.875113          | 2.32E-09            | 100%  |
| 1400       | 7.91192E-06             | 3805.057212          | 5.86E-09            | 98.8% |
| 1600       | 1.18102E-05             | 6491.259617          | 1.31E-08            | 97.3% |
| 1800       | 1.68157E-05             | 10397.74276          | 2.65E-08            | 94.6% |
| 2000       | 2.30668E-05             | 15847.8018           | 4.98E-08            | 90.0% |
| 2500       | 4.50524E-05             | 38690.92236          | 1.9E-07             | 66.9% |
| 3000       | 7.78506E-05             | 80229.49661          | 5.67E-07            | 30.1% |
| 3400       | 0.000113327             | 132362.4254          | 1.2E-06             | 7.8%  |
| 3600       | 0.000134526             | 166363.8842          | 1.69E-06            | 2.8%  |
| 3700       | 0.000146051             | 185633.3254          | 2E-06               | 1.5%  |
| 3850       | 0.000164543             | 217616.5728          | 2.53E-06            | 0.5%  |
| 4000       | 0.000184535             | 253564.8288          | 3.19E-06            | 0.1%  |

**Table 9: Particle number concentration and concentration calculation at 95% of UVT**

| d (nm) | N (particle per m <sup>-3</sup> ) | c (mg.l <sup>-1</sup> ) | Q (m <sup>-1</sup> ) | C (m <sup>2</sup> ) |
|--------|-----------------------------------|-------------------------|----------------------|---------------------|
| 100    | 2.02917E+12                       | 0.005569474             | 3.218490047          | 2.5278E-14          |
| 125    | 5.31935E+11                       | 0.002851571             | 7.857641715          | 9.64278E-14         |
| 150    | 1.78144E+11                       | 0.001650215             | 16.29360586          | 2.87932E-13         |
| 200    | 31705789171                       | 0.000696184             | 51.49584075          | 1.61779E-12         |
| 250    | 8311482396                        | 0.000356446             | 125.7222674          | 6.17138E-12         |
| 300    | 2783498638                        | 0.000206277             | 260.6976938          | 1.84276E-11         |
| 400    | 495402955.8                       | 8.7023E-05              | 823.9334519          | 1.03539E-10         |
| 500    | 129866912.4                       | 4.45558E-05             | 2011.556279          | 3.94968E-10         |
| 750    | 11401210.42                       | 1.32017E-05             | 10183.50366          | 4.49893E-09         |
| 1000   | 2029170.507                       | 5.56947E-06             | 32184.90047          | 2.5278E-08          |
| 1250   | 531934.8734                       | 2.85157E-06             | 78576.41715          | 9.64278E-08         |
| 1500   | 178143.9128                       | 1.65021E-06             | 162936.0586          | 2.87932E-07         |
| 2000   | 31705.78917                       | 6.96184E-07             | 514958.4075          | 1.61779E-06         |
| 2500   | 8311.482396                       | 3.56446E-07             | 1257222.674          | 6.17138E-06         |
| 3000   | 2783.498638                       | 2.06277E-07             | 2606976.938          | 1.84276E-05         |

**Table 10: Turbidity sensitivity calculation for small changes in UVT**

| N (particle per m <sup>-3</sup> ) | UVT    | c (mg. <sup>-1</sup> l) | Turbidity (NTU) | Difference in turbidity NTU |
|-----------------------------------|--------|-------------------------|-----------------|-----------------------------|
| 4.01E+11                          | 99.00% | 6.13E-07                | 1.01E-02        | 1.01E-02                    |
| 8.06E+11                          | 98.00% | 1.23E-06                | 2.02E-02        | 1.02E-02                    |
| 1.22E+12                          | 97.00% | 1.86E-06                | 3.05E-02        | 1.03E-02                    |
| 1.63E+12                          | 96.00% | 2.49E-06                | 4.08E-02        | 1.04E-02                    |
| 2.05E+12                          | 95.00% | 3.13E-06                | 5.13E-02        | 1.05E-02                    |
| 2.47E+12                          | 94.00% | 3.78E-06                | 6.19E-02        | 1.06E-02                    |
| 2.90E+12                          | 93.00% | 4.43E-06                | 7.26E-02        | 1.07E-02                    |
| 3.33E+12                          | 92.00% | 5.09E-06                | 8.34E-02        | 1.08E-02                    |
| 3.76E+12                          | 91.00% | 5.75E-06                | 9.43E-02        | 1.09E-02                    |
| 4.20E+12                          | 90.00% | 6.43E-06                | 1.05E-01        | 1.10E-02                    |

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