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Gutiérrez, Juan Pablo

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Riverbank filtration in highly turbid rivers

Juan Pablo Gutiérrez Marín

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Juan Pablo GUTIÉRREZ MARÍN

Master of Science in Civil Engineering
University of Puerto Rico

geboren te Cali, Colombia

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Samenstelling promotiecommissie bestaat uit:

Rector Magnificus,	voorzitter
Prof. dr. ir. L.C. Rietveld	Technische Universiteit Delft, promotor
Dr. ir. D. van Halem	Technische Universiteit Delft, copromotor

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Dr. ir. L.D. Sánchez	Universidad del Valle, Colombia
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J.P.GutierrezMarin@tudelft.nl
juan.p.gutierrez@correounivalle.edu.co
juanpaguma@hotmail.com

Table of Contents

List of Figures

List of Tables

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Summary

Samenvatting

Resumen

Summary

Riverbank filtration (RBF) is a surface water filtration method for drinking water through the banks and bed of a river, using extraction wells located near the water body in order to ensure direct aquifer recharge. As the surface water travels through the sediments, contaminants, such as suspended and colloidal solids and pathogenic microorganisms, are removed. Apart from water quality improvement, RBF has the advantage of reducing peak concentrations which commonly pass through a river. RBF has been widely used in Europe, USA and, nowadays, in some Asian countries (e.g., South Korea, India, China).

Latin-American and specifically Colombian river basins, have been suffering a continuous deterioration, leading to high suspended sediment loads being transported by the rivers. The RBF technology has not been proven yet in highly turbid waters, in which the excessive transport of suspended sediments threatens sustainable operation. Clogging of both the riverbed and deeper aquifer may increase flow resistance, reducing water revenues over the course of time.

To assess the feasibility of RBF for highly turbid river waters in Colombia, a combination of field and laboratory research was conducted – both in the Netherlands and Colombia. In Colombia, the studies were done at the Cinara institute's Research and Technology Transfer (R&TT) Station for drinking water and at the Fluid Mechanics lab. The station is located at the Northeast of Cali, Colombia, and was built at the premises of the main water treatment plant of Cali, Puerto Mallarino. In the Netherlands, the laboratory work was done at the Delft University of Technology, running infiltration column experiments at the Sanitary Engineering lab and the flume experiments at the Fluid Mechanics lab.

In addition, an extensive review of the literature was carried out to determine the feasibility of using the RBF for highly turbid sources. Considering the inexistence of the RBF experiences in highly turbid waters, and the unfamiliarity of the technology in Latin-America, the inclusion of the RBF technology in the decision-making process for solving drinking water problems in Colombia made it necessary to compare the technology under the multi-criteria analysis methodology by developing a framework structured for the selection of alternatives based on the investment, operation and maintenance requirements, sludge management, environmental impact, vulnerability issues, current legal aspects and social acceptance. Considering these criteria, it was concluded that the RBF technology is a feasible, and more reliable alternative than other water treatment technologies.

Deep bed and cake clogging, and its renewability are highly linked to the particulate matter characteristics. Therefore, field research in Colombia was executed to characterize the suspended particulate matter of a highly turbid river (Cauca River) to have seasonal information on the composition and particle size distribution, and then to have a starting point

for the development of the laboratory studies. Characterization of the particulate matter in the Cauca River has shown that the total suspended solids concentration did not depend on river flows, but merely on precipitation events in the basin due to the erosion of soils. A high scattering was obtained between total suspended solids concentration and turbidity values, potentially due to the different characteristics contributing to both parameters, such as true color and particle size. Seasonal tracing of particulate matter suspended in the Cauca River showed slight differences in the composition and particle size distribution. A slightly higher content of particles smaller than 2 µm was found during rainy conditions due to changes in vegetation coverage and decomposed organic matter in the runoff. Although the differences seem to be minor, further studies demonstrated a considerable impact of their characteristics on clogging and self-cleansing of the particulate matter and, therefore, in the infiltration capacity recovery.

The renewability of the infiltration capacity due to streambed and aquifer clogging and their opposite self-cleansing because of scouring forces was studied. This analysis was performed with emphasis on the river bottom, where lower velocities are expected in these areas and therefore greater sediment accumulation at higher risk of clogged pores, by using infiltration columns inserted into horizontal tilting flumes. Natural infiltration rate recovery at low shear stresses was possible during simulated riverbank filtration tests with water consisting of a mixture of different sediments. Clay and silt behaved very differently, due to the difference in cohesiveness. Clay was found to produce a persistent sticky cake layer, whereas silt penetrated deeper into the bed, both resulting in a poor recovery of infiltration rate. Altogether it may be concluded that natural recovery of infiltration capacity during RBF of highly turbid waters is expected to occur, as long as the river carries a mixture of suspended sediments and the grains in the streambed are not too coarse (about 0.2-0.8 mm in diameter as tested in this research).

Samenvatting

Riverbank-filtratie (RBF) Riverbank filtration of oeverfiltratie is een oppervlaktewaterfiltratiemethode voor drinkwater door de oevers en bedding van een rivier, met behulp van extractieputten in de buurt van een waterlichaam. Door de putten dichtbij de oever van een waterlichaam te plaatsen wordt gezorgd dat de watervoerende lagen direct worden bijgevuld. Terwijl het oppervlaktewater door de sedimenten sijpelt, worden verontreinigingen, zoals zwevende en colloïdale stoffen en pathogene micro-organismen, verwijderd. Afgezien van de verbetering van de waterkwaliteit heeft RBF het voordeel dat het piekconcentraties van verontreinigingen, die vaak in rivieren voorkomen, afvlakt. RBF wordt veel gebruikt in Europa, de VS en tegenwoordig in sommige Aziatische landen (bijvoorbeeld Zuid-Korea, India, China).

Latijns-Amerikaanse, en specifiek Colombiaanse, stroomgebieden hebben een voortdurende verslechtering ondergaan, wat heeft geleid tot hoge sedimentvrachten in de rivieren. De RBF-technologie is nog niet bewezen in zeer troebele wateren, waarin het overmatige transport van sediment duurzame exploitatie bedreigt. Verstopping van zowel de rivierbedding als dieper gelegen watervoerende laag kan de stromingsweerstand vergroten en de wateropbrengst in de loop van de tijd verminderen.

Om de haalbaarheid van RBF voor sterk troebel rivierwater in Colombia te beoordelen, werd een combinatie van veld- en laboratoriumonderzoek uitgevoerd, zowel in Nederland als in Colombia. In Colombia werden de studies uitgevoerd op het Research and Technology Transfer (R&TT) onderzoeksstation en in het vloeistofmechanica laboratorium van het Cinara Instituut. Het station ligt in het noordoosten van Cali in Colombia, en werd gebouwd op het terrein van de belangrijkste waterzuiveringsinstallatie van Cali, Puerto Mallarino. In Nederland werd het laboratoriumwerk gedaan aan de TU Delft, met filtratiekolommen in het laboratorium voor gezondheidstechniek en de experimenten met goten in het vloeistofmechanica laboratorium.

Daarnaast werd een uitgebreide literatuurstudie uitgevoerd om de haalbaarheid van het gebruik van de RBF voor zeer troebele bronnen te bepalen. Omdat er enerzijds weinig bekend was over de toepassing van RBF in zeer troebele wateren en de technologie anderzijds onbekend is in Latijns-Amerika was het noodzakelijk om een vergelijkingsmodel op te zetten waarin de technologie vergeleken kon worden met andere zuiveringsalternatieven voor de watervoorziening van Colombia. Hiervoor werd aan de hand van de multi-criteria methodiek, op basis van de investerings-, exploitatie- en onderhoudskosten, slibbeheer, milieueffecten, kwetsbaarheidsproblemen, actuele juridische aspecten en sociale acceptatie, aangetoond dat de RBF-technologie een haalbaar en betrouwbaarder alternatief is dan andere waterzuiveringstechnologieën.

Diepe bed- en oppervlakkige verstopping en het herstel daarvan zijn sterk verbonden met de karakteristieken van het getransporteerde sediment. Daarom werd het veldonderzoek in Colombia uitgevoerd om de zwevende deeltjes van een zeer troebele rivier (de Cauca) te karakteriseren, om seizoensgebonden informatie te vergaren over de samenstelling en deeltjesgrootteverdeling en om vervolgens een startpunt te hebben voor het ontwikkelen van de laboratoriumstudies. Karakterisering van de deeltjes in de Cauca heeft aangetoond dat de totale concentratie van zwevende stoffen niet afhankelijk was van het debiet, maar alleen van neerslaggebeurtenissen in het stroomgebied als gevolg van erosie van bodems. Er werd een hoge spreiding geconstateerd tussen de totale concentratie zwevende stof en de troebelheidswaarden, mogelijk als gevolg van de verschillende kenmerken die bijdragen aan beide parameters, zoals ware kleur en deeltjesgrootte. Seizoensgebonden analyses van zwevende stof in de Cauca-rivier vertoonden geringe verschillen in de samenstelling en deeltjesgrootte. Tijdens regenachtige omstandigheden werd een iets hoger gehalte aan deeltjes kleiner dan 2 μm aangetroffen waarschijnlijk als gevolg van veranderingen in vegetatie en afgebroken organisch materiaal in de afvoer. Hoewel de verschillen klein lijken, hebben verdere studies een aanzienlijke invloed van deze kenmerken aangetoond op verstopping en het zelfreinigend vermogen van de bodem en daarmee op het herstel van de infiltratiecapaciteit.

Het herstel van de infiltratiecapaciteit na het dichtslibben van de rivierbedding en watervoerende lagen en de zelfreinigende werking van de schurende kracht van het water werden bestudeerd. Deze analyse werd uitgevoerd met de nadruk op de rivierbodem waar lagere snelheden worden verwacht, en dientengevolge een grotere accumulatie van sedimenten. Hierdoor ontstaat op de bodem een hoger risico op verstopte poriën. Het onderzoek werd gedaan door infiltratiekolommen in horizontale kantelbare kanalen te plaatsen. Herstel van natuurlijke infiltratiesnelheden bij lage afschuifspanningen was mogelijk tijdens gesimuleerde rivieroeverfiltratietests met water dat bestond uit een mengsel van verschillende sedimenten. Hoewel beide grondsoorten een vergelijkbare deeltjesgrootteverdeling hebben, gedroegen klei en slib zich heel anders, vanwege het verschil in cohesie. Klei bleek een persistente plakkerige laag te produceren, terwijl slib dieper in het bed doordrong, beide resulterend in een slecht herstel van de infiltratiesnelheid. Alles bij elkaar kan worden geconcludeerd dat het natuurlijke herstel van infiltratiecapaciteit tijdens RBF van zeer troebel water naar verwachting zal plaatsvinden, zolang de rivier een mengsel van gesuspendeerde sedimenten bevat en de korrels in de stroombedding niet te grof zijn (ongeveer 0.2-0.8 mm in diameter zoals getest in dit onderzoek).

Resumen

La filtración en lecho de río (FLR) es un método de filtración de agua superficial para el agua potable a través de los bancos y el lecho de un río, utilizando pozos de extracción ubicados cerca del cuerpo de agua para garantizar la recarga directa del acuífero. A medida que el agua superficial viaja a través de los sedimentos, se eliminan los contaminantes, como los sólidos suspendidos y coloidales y los microorganismos patógenos. Además de la mejora de la calidad del agua, FLR tiene la ventaja de reducir las concentraciones pico que comúnmente pasan a través de un río. El FLR se ha utilizado ampliamente en Europa, EE. UU. y, actualmente, en algunos países asiáticos (por ejemplo, Corea del Sur, India, China).

Las cuencas hidrográficas latinoamericanas, y específicamente colombianas, han venido sufriendo un continuo deterioro, lo que ha llevado a que los ríos transporten altas cargas de sedimentos en suspensión. La tecnología de FLR aún no se ha probado en aguas muy turbias, en las cuales el transporte excesivo de sedimentos en suspensión amenaza la operación sostenible. La obstrucción tanto del lecho del río como del acuífero más profundo puede aumentar la resistencia al flujo, reduciendo el ingreso del agua a lo largo del tiempo.

Para evaluar la viabilidad de RBF para aguas de río altamente turbias en Colombia, se realizó una combinación de investigación de campo y de laboratorio, tanto en los Países Bajos como en Colombia. En Colombia, los estudios se realizaron en la estación de Investigación y Transferencia de Tecnología (I&TT) del instituto Cinara para agua potable y en el laboratorio de Mecánica de Fluidos. La estación está ubicada en el noreste de Cali, Colombia, y fue construida en las instalaciones de la principal planta de tratamiento de agua de Cali, Puerto Mallarino. En los Países Bajos, el trabajo de laboratorio se realizó en la Universidad Tecnológica de Delft, realizando experimentos en columnas de infiltración en el laboratorio de Ingeniería Sanitaria y los experimentos en canales en el laboratorio de Mecánica de Fluidos.

Además, se llevó a cabo una extensiva revisión de literatura para determinar la viabilidad de utilizar la FLR en fuentes altamente turbias. Considerando la inexistencia de experiencias de FLR en aguas altamente turbias, y la falta de familiaridad de la tecnología en América Latina, la inclusión de la tecnología de FLR en el proceso de toma de decisiones para resolver problemas de agua potable en Colombia hizo necesario comparar la tecnología bajo la metodología de análisis multicriterio mediante el desarrollo de un marco estructurado para la selección de alternativas basadas en los requisitos de inversión, operación y mantenimiento, manejo de lodos, impacto ambiental, cuestiones de vulnerabilidad, aspectos legales actuales y aceptación social. Teniendo en cuenta estos criterios, se concluyó que la tecnología FLR es una alternativa factible y más confiable que otras tecnologías de tratamiento de agua.

La obstrucción del lecho profundo y la obstrucción por torta, y su renovabilidad, están altamente relacionados con las características del material particulado. Por lo tanto, la investigación de campo en Colombia fue ejecutada para caracterizar el material particulado suspendido en un río altamente turbio (río Cauca) para tener información estacional sobre la composición y distribución del tamaño de partícula, y así tener un punto de partida para el desarrollo de los estudios de laboratorio. La caracterización del material particulado del río Cauca ha demostrado que la concentración de sólidos suspendidos totales no depende de los caudales del río, sino simplemente de los eventos de precipitación en la cuenca debido a la erosión de los suelos. Se obtuvo una alta dispersión entre la concentración de sólidos suspendidos totales y los valores de turbiedad, posiblemente debido a las diferentes características que contribuyen a ambos parámetros, como el color verdadero y el tamaño de partícula. El rastreo estacional del material particulado suspendido en el río Cauca mostró pequeñas diferencias en la composición y distribución del tamaño de partícula. Se encontró un contenido ligeramente mayor de partículas menores de 2 µm durante las condiciones de lluvia debido a los cambios en la cobertura de la vegetación y la materia orgánica descompuesta en la escorrentía. Aunque las diferencias parecen ser menores, otros estudios demostraron un impacto considerable de sus características en la obstrucción y capacidad de autolimpieza del material particulado y, por lo tanto, en la recuperación de la capacidad de infiltración.

Se estudió la renovabilidad de la capacidad de infiltración debido a la obstrucción del lecho y del acuífero y su auto limpieza debido a las fuerzas cortantes. Este análisis se realizó con énfasis en el fondo del río, donde se esperan velocidades más bajas en estas áreas y, por lo tanto, una mayor acumulación de sedimentos con mayor riesgo de obstrucción de poros, mediante el uso de columnas de infiltración insertadas en canales horizontales inclinables. La recuperación de la tasa de infiltración natural a bajos esfuerzos cortantes fue posible durante las pruebas simuladas de filtración en lecho de río con agua conteniendo una mezcla de diferentes sedimentos. La arcilla y el limo se comportaron de manera muy diferente, debido a la diferencia en la cohesión. Se encontró que la arcilla produce una capa de torta adhesiva persistente, mientras que el limo penetró más profundamente en el lecho, resultando en una pobre recuperación de la tasa de infiltración. En conjunto, se puede concluir que se espera que la recuperación natural de la capacidad de infiltración durante FLR de aguas altamente turbias ocurra, siempre que el río lleve una mezcla de sedimentos suspendidos y los granos en el lecho no sean demasiado gruesos (aproximadamente 0.2-0.8 mm de diámetro según lo probado en esta investigación).

Abbreviations and Symbols

Abbreviations

Abbreviation	Description
BF	Bank filtration
Cinara	Instituto de Investigación y Desarrollo en Abastecimiento de Agua, Saneamiento Ambiental y Conservación del Recurso Hídrico
Colciencias	Departamento Administrativo de Ciencia, Tecnología e Innovación
CRC	Corporación Autónoma Regional del Cauca
CVC	Corporación Autónoma Regional del Valle del Cauca
EMCALI	Empresas Municipales de Cali
MCA	Multicriteria analysis
MAVDT	Ministerio de Ambiente, Vivienda y Desarrollo Territorial
O&M	Operation and maintenance
PDA	Plan Departamental del Agua
PSD	Particle size distribution
RBF	Riverbank filtration
SOM	Soil organic matter
SSA	Specific surface area
SSF	Slow sand filtration
TSS	Total suspended sediments
WTP	Water treatment plant

Symbols

Symbol	Parameter	Unit
d_s	Diameter of the particles in the water	µm
d_{50}	Bed particle size	µm
DO	Dissolved oxygen	mg/L
Δh	Head loss	cm
K	Hydraulic conductivity	m/d
q	Specific discharge or bed infiltration rate	m/d
q_o	initial infiltration rate	m/d
n	Porosity	--
S	slope	m/m
τ	Shear stress	N/m^2
τ_b	Bed shear stress	N/m^2
τ_c	Critical shear stress	N/m^2
Φ	Outranking flow	--
$\emptyset_{sed}$	Suspended sediment concentration	mg/L
θ	Shields parameter	--
μ	Dynamic viscosity of the water	Nm/s^2
ρ_w	Fluid density	kg/m^3
ρ_s	Density of the particles in the water	kg/m^3

CHAPTER 1

INTRODUCTION

"When the well is dry, we learn the worth of water"

Benjamin Franklin

1 Introduction

1.1 Implications of high turbidity in surface water on drinking water systems

In rural and some urban areas of Latin-America safe drinking water supply is one of the most serious constraints for sustainable development. Risks in drinking water supply are associated with water quality problems in surface water, since approximately 80% of the water supply in Latin-American countries depend on this water source (Ministerio de Desarrollo de Colombia, 1998). The efficacy of the surface water treatment strongly depends on the variable tropical conditions of the river and poor river basin management. High turbidity levels occur in surface water sources, because of natural and anthropic processes, causing interference in the treatment train and stimulating the transport of contaminants that are attached to the sediments. For instance, in the Cauca River in Colombia turbidity peaks >2,500 NTU are not uncommon, resulting in water intake closures of the water treatment plant (WTP) of Cali city. Turbidity values have been measured to reach as high as 37,700 NTU (Nov, 2017) in the Cauca River, and therefore shutdowns of the Puerto Mallarino WTP are frequently reported (Figure 1.1).

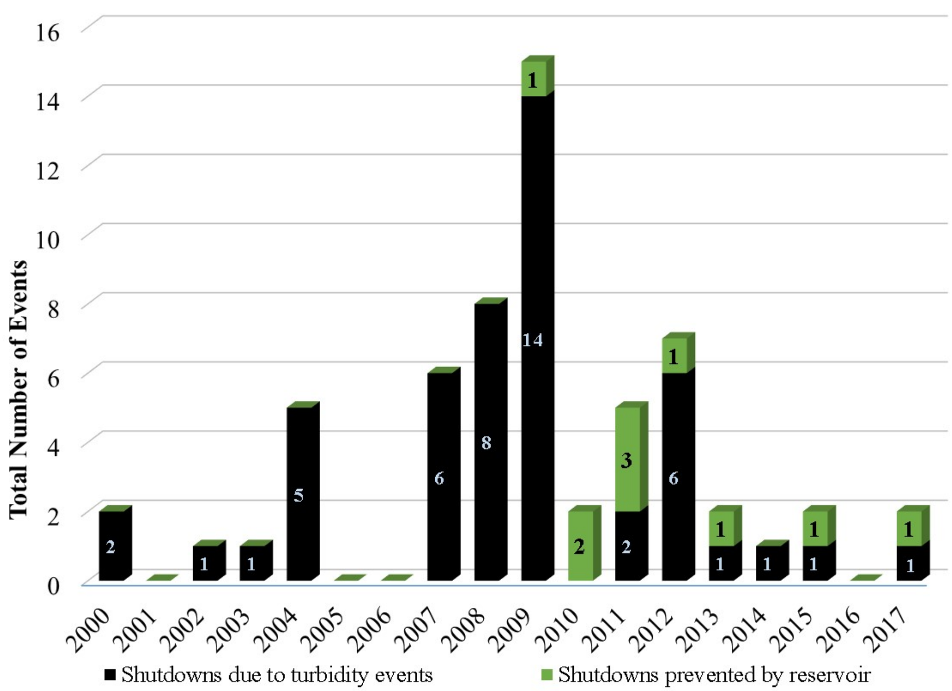

Figure 1.1. Number of high turbidity events in the Cauca River at Puerto Mallarino WTP (2000–2017)
Source: EMCALI, personal communication, February 07, 2018

The suspended solids, which cause turbidity, can be responsible for interference with disinfection and convey disease-causing organisms and compounds (Bourg et al., 1989; Miretzky et al., 2005; Stone and Droppo, 1994; Zhu et al., 2005), leading to increased use of chemicals, and/or increased health risks. If turbidity in the raw water is high, usually the treatment processes, such as coagulation, sedimentation and filtration, must be adjusted, or, in some occasions, it can result in water treatment plant (WTP) shutdowns.

1.2 Riverbank filtration as a pre-treatment for highly turbid surface waters

The technologies for drinking water treatment may be classified into physical, biological and chemical treatment. Physical methods consist of solid-liquid separation techniques, where filtration plays a dominant role. Biological methods rely on the conversion of constituents by micro-organisms. Chemical methods depend on the application of chemicals and chemical interactions with the contaminants. They either assist in the separation of contaminants from water or in the destruction or neutralization of harmful effects associated with the contaminants.

In Table 1.1, a comparative assessment on the removal performance of water quality parameters, production capacity, operation and maintenance requirements, production of sludge and production costs is presented, adapted from Hubbs et al. (2003).

Table 1.1. Comparison of drinking water treatment technologies

Occurrence	RBF	SSF	C	C + Ozone + UV	C + GAC + UV	C + GAC + UV + Membranes
Turbidity removal	++	++	++	++	++	++
Pathogens removal	++	++	+	++	++	++
Nutrients removal	+	0	0	0	++	++
Heavy metals removal	+	0	0	0	++	++
Micro-pollutants removal	+	0	0	0	+	+
Total organic carbon removal	+	++	0	0	++	++
Shock loads and peaks attenuation	++	––	––	––	+	+
Chemicals consumption	++	++	––	––	–	–
Energy consumption	––	++	–	–	–	–

Occurrence	RBF	SSF	C	C + Ozone + UV	C + GAC + UV	C + GAC + UV + Membranes
Operation and maintenance requirements	++	+	−	−	−	−−
Sludge/waste production during water treatment	++	−	−−	−−	−−	−−
Production capacity	++	+	++	++	++	+
Production cost	−	++	−	−	−−	−−
Total	15	11	-4	-3	7	5

C: conventional SSF: slow sand filtration UV: ultraviolet light GAC: Granular activated carbon; "+" means a positive impact and "++" means highly positive impact, whilst a "−" indicates a negative impact and a "−−" means a highly negative impact, and a "0" indicates no impact of the technology on the occurrence or vice versa.
Source: Adapted from Hubbs et al. (2003)

SSF is frequently considered to be mainly suitable for small, moderately large communities, whereas riverbank filtration (RBF) and conventional WTP, consisting of coagulation, sedimentation, rapid sand filtration and chlorination, can be used for small to very large communities. Membrane filtration may be applied up to moderately large communities (Ray and Jain, 2011). As observed in Table 1.1, RBF is suitable for highly contaminated rivers, and supplements advanced treatment systems like the use of conventional treatments extended with technologies such as ozone, ultraviolet light, granular activated carbon, and membrane filtration. RBF has the advantage over the other assessed technologies of dampening shock loads and peaks, which is a need in rivers with extreme variable water qualities such as the Colombian rivers (e.g., Cauca River).

Therefore, in this thesis RBF has been investigated as a promising alternative technology for water abstraction, using the riverbanks as a filter for the pre-treatment of surface water. RBF is widely used in Europe and United States of America (USA), but has so far not been evaluated in highly turbid waters, present in Latin America.

1.3 Experiences using RBF in Europe and USA

The siting and design of RBF systems depend upon river hydrology, hydrogeological conditions, and the aims for water withdrawal (Grischek et al., 2003). Likewise, the quality of any produced filtrate is dependent on existing soil characteristics, and groundwater and river water qualities. The removal of contaminants and sediments is a function of the flow path length (travel time), the thickness of the aquifer and the infiltration area of the river (Grischek et al., 2003; Tufenkji et al., 2002). Furthermore, the water flow to be produced plays an important role when designing the configuration of the RBF system (Hunt et al., 2003). The design of a RBF system is thus site specific and must respond to the water quality in the source and to the goal for selecting the RBF technology.

Riverbed and/or riverbank clogging commonly occurs during water abstraction (Hubbs, 2006a). The degree of the clogging is also site specific, and mainly depends on the sediment load (particle size and concentration), bed configuration and the hydraulics of the river (Schubert, 2006a; Stuyfzand et al., 2006). These three aspects define the deposition, resuspension and erosive processes on the bed (Caldwell, 2006; Hubbs et al., 2007). RBF is preferable used for the surface waters with low concentrations of suspended solids (Grischek et al., 2003; Kuehn and Mueller, 2000). However, there are reports where RBF is also used under higher turbidity conditions (by up to 2,500 NTU) (Benamar et al., 2007; Thakur and Ojha, 2010). Typically, facilities in Europe have been targeted at producing a higher quality filtrate at lower capacities whilst those in the USA produce a lower quality filtrate but with higher production capacities. In Table 1.2 some features of RBF systems in Europe and USA are described.

Table 1.2. RBF systems for drinking water supply in Europe and USA

Localization	Number of wells[a]	Capacity (m^3/s)	Distance to river (m)	Travel time (d)	K (m/s, 10^{-4})[b]	River
Csepel, Budapest, Hungary	>500V	3.7		6 – 14		Danube
Dresden-Tolkewitz, Germany	71V	0.46	80 – 180	25 – 50	10 – 20	Elbe
Düsseldorf, Germany	18H	3.76	50 – 70	10 – 60	40 – 200	Rhine
Mockritz, Germany	74V	1.26				Elbe
Torgau-Ost, Germany	42V	1.74	300	80 – 300	6 – 20	Elbe
Zürich, Switzerland	4H	1.74				Limmat
Maribor, Slovenia	13V	0.75			20 – 40	Drava
Sonoma County, California	6H + 7V	4.92	0 – 75	4.9	2.4 – 4.3	Russian
Cincinnati, Ohio	10V	1.75			8.8 – 15	Great Miami
Columbus, Ohio	4H	1.75				Scioto/Big Walnut
Cedar Rapids, Iowa	2H + 54V	1.49	9 – 245	2 – 17	1.5 – 11	Cedar
Galesburg, Illinois	1H	0.44				Mississippi
Independence, Missouri	1H	0.66				Missouri
Kansas City, Kansas	1H	1.75				Missouri
Boardman, Oregon	2H	1	3 – 18	<1	37	Columbia
Lincoln, Nebraska	2H + 44V	1.53	<30 - >800	<7 – >14	14	Platte
Sacramento, California	1H	0.44				Sacramento
Somersworth, New Hampshire	2H + 1V	0.06	46	<55	4.3	Salmon Falls

Localization	Number of wells[a]	Capacity (m^3/s)	Distance to river (m)	Travel time (d)	K (m/s, 10^{-4})[b]	River
Terre Haute, Indiana	1H + 6V	0.79	24 – 122			Wabash
Louisville, Kentucky	5H	3.19	<30 – 84	2 – 5	6	Ohio

[a] H: horizontal; V: vertical
[b] Hydraulic conductivity of the aquifer material
Source: Grischek et al. (2003); Metge et al. (2010); Ray (2002b); Schalekamp (1984); Weiss et al. (2005)

1.4 Case of Cali, Colombia

In Colombia turbidity and contamination events in rivers have become a vast concern for many environmental authorities and drinking water companies in the last decades (Universidad del Valle and UNESCO-IHE, 2008). Therefore, there is a need for seeking alternative technologies to improve the quality of source water used for water supply.

The city of Cali, Colombia was selected as case study, due to its critical surface water quality and its favorable alluvial formations. Cali is the third largest city in Colombia, with a population of approximately 2.5 million. The majority of its drinking water (77%) is abstracted from the Cauca River (Universidad del Valle and UNESCO-IHE, 2008). In recent times, concerns have been expressed about the quality of the water in the Cauca River, which contains high concentrations of pollutants from domestic sewage, industry, as well as from livestock, agricultural and mining activities (Universidad del Valle and UNESCO-IHE, 2008). In addition to these constituents seriously affecting public health, the Cauca River contains extremely high concentrations of suspended solids during winter, reaching turbidity values up to 37,700 NTU (data corresponding to November 08, 2017). Therefore, clogging issues are a concern when considering RBF as a pretreatment.

1.5 Knowledge gaps

The infiltration rate in RBF systems is highly variable dependent on the aquifer characteristics (permeability, porosity and thickness), the temporal hydraulic gradient (river-stage and groundwater elevation) and connectivity between the river and the phreatic aquifer (streambed permeability and streambed thickness) (Hunt et al., 2003). RBF systems worldwide have demonstrated to be susceptible to be clogged during its functioning leading to a decrease in its water production yield (Hubbs, 2006). The connectivity is a function of the streambed particle size, the size of the suspended particulate matter in the water and the scouring of the streambed exerted by the water flow (Benamar et al., 2007; Caldwell, 2006; Stuyfzand et al., 2006; Tufenkji et al., 2002). In this thesis, specific knowledge gaps have been identified related to the performance of a RBF for highly turbid waters. These knowledge gaps are:

- RBF has been widely used in waters with relatively low turbidities (Stuyfzand et al., 2006), but its use in highly turbid waters has been limited to peaks up to 2,500 NTU (Dash et al., 2010; Thakur and Ojha, 2010; Wang, 2003; Weiss et al., 2005).
- The sediment characteristics and seasonal fluctuations of suspended sediment loads have not been assessed in highly turbid rivers in Colombia, such as the Cauca River (CVC and Universidad del Valle, 2004a, 2004b).
- The effect of high concentrations of suspended particulate matter on clogging and streambed thickness has been poorly addressed for RBF sites, where the flow conditions change over the year.
- The self-cleansing capacity of RBF systems is usually assessed in terms of critical shear stress, which depends on riverbed particle characteristics and the shear stress exerted by the river water velocity (Hubbs et al., 2007). However, the infiltration rate renewal capacity due to the characteristics of the streambed / cake layer interaction and flooding events is still missing.

1.6 Aim and research questions

The aim of this thesis is to assess the feasibility of using riverbank filtration in highly turbid rivers in the Latin American context by performing field studies in Colombia, extended with laboratory scale research on clogging, re-suspension, and infiltration capacity renewal.

Specific research questions are:

1. Is RBF a feasible water treatment alternative for highly turbid rivers (>2,500 NTU)?
2. How does RBF relate to other water treatment options in an integrated multiple-criteria framework for the case of Cali city in Colombia, where political, social and stakeholders' interests are involved?
3. What are the seasonal changes in the characteristics of suspended particulate matter and its possible sources in a highly turbid river?
4. What is the infiltration capacity recovery due to the influence of highly turbid waters in a simulated RBF system?

1.7 Thesis outline

This thesis is structured as follows:

Chapter 1. Introduction. This chapter provides the introductory concepts, a brief description of the RBF technology, a problem statement, as well as defining the main research questions of the thesis.

Chapter 2. Riverbank filtration for the treatment of highly turbid rivers. This chapter provides a literature review on RBF, water quality improvements, riverbed and aquifer clogging, self-cleansing capacity, and a discussion on the applicability of the RBF in Colombia.

Chapter 3. Multi-criteria analysis applied to the selection of drinking water sources in developing countries: a case study Cali, Colombia. This chapter gives information about alternatives for safe drinking water in the case of Cali, Colombia, including the construction of an integrated multiple-criteria framework to adequately assess the presented alternatives.

Chapter 4. Particulate matter characterization of Cauca River water in Colombia. This chapter brings information related to the composition of the particulate matter suspended in a highly turbid river, during rainy and dry periods to assess the potential behavior of RBF systems under these conditions.

Chapter 5. Natural recovery of infiltration capacity in simulated bank filtration of highly turbid waters. This chapter assesses the mechanisms involved in infiltration in a simulated riverbank filtration system because of clogging and self-cleansing processes of a streambed by scouring processes during flooding.

Chapter 6. Conclusions and recommendations. This chapter describes the general conclusions and recommendations based on the research questions. In addition, the potential application of riverbank filtration in Cali, Colombia, is described considering the application of this research on the design of a pilot facility for the assessment in a highly turbid river, where the hydrogeological and surface water conditions were evaluated.

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CHAPTER 2

RIVERBANK FILTRATION FOR THE TREATMENT OF HIGHLY TURBID RIVERS

"Water does not resist. Water flows. When you plunge your hand into it, all you feel is a caress. Water is not a solid wall, it will not stop you. But water always goes where it wants to go, and nothing in the end can stand against it. Water is patient. Dripping water wears away a stone. Remember that, my child. Remember you are half water. If you can't go through an obstacle, go around it. Water does"

Margaret Atwood, The Penelopiad

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2 Riverbank filtration for the treatment of highly turbid rivers

2.1 Introduction

Riverbank filtration (RBF) is a water abstraction technology that consists of production wells that extract water some distance away from a surface water body (Figure 2.1). As the production wells pump water from the aquifer, surface water flows underground to recharge it, while the subsurface sediments function as a natural filter that removes several contaminants, producing higher quality water than the raw source water (Schubert, 2003; Sontheimer, 1980; Tyagi et al., 2013). In addition, the naturally present groundwater contributes to the higher water quality extracted from RBF systems, e.g., through attenuation (Kuehn and Mueller, 2000) and the change in redox conditions (Bourg, 1992; Hiscock and Grischek, 2002).

The well configuration in RBF systems can be either vertical or horizontal, offering different benefits. Vertical wells are commonly used for longer residence or travel times to ensure higher removal efficiencies of more mobile contaminants. Horizontal wells are usually applied to obtain higher water flows, but they may be unfavorable for the quality of the water abstracted due to shorter residence times (Hunt et al., 2003; Ray, 2002a).

Many variables influence the performance of RBF systems, including riverbed media composition and the hydraulic connectivity of the aquifer (Hubbs et al., 2007; Hunt et al., 2003; Schubert, 2002). In Europe and the United States, RBF has been widely used because of the favorable hydraulic conditions (Brunke, 1999; Goldschneider et al., 2007; Hubbs et al., 2007; Stuyfzand et al., 2006; Veličković, 2005). In addition, RBF has a demonstrated ability to be an effective water treatment technology for contaminated surface waters (Singh et al., 2010; Thakur and Ojha, 2010).

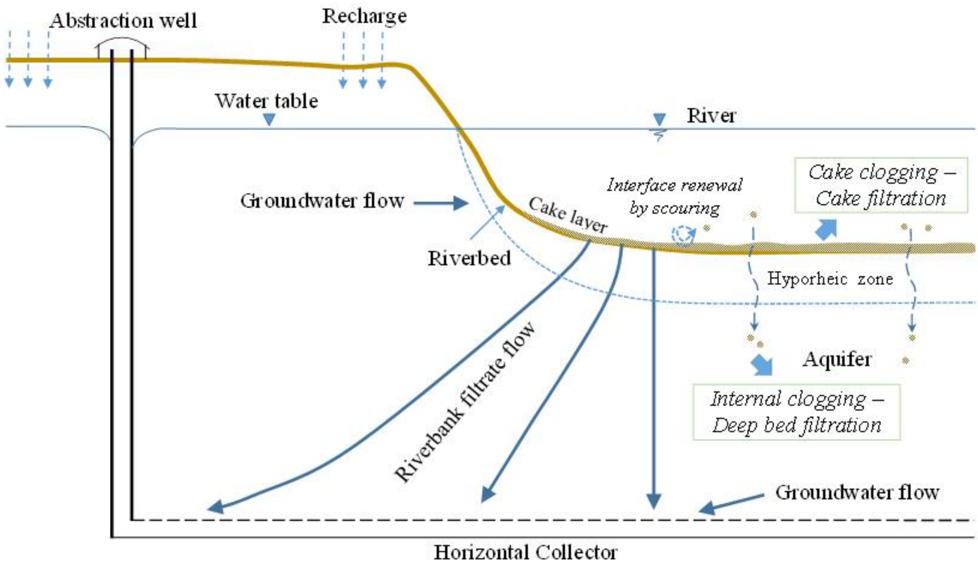

Figure 2.1. A general representation of a horizontal RBF system

A key water quality parameter determining the performance of RBF systems is the concentration of total suspended solids (TSS) contained in the surface water; this is because long-term changes in the composition and concentration of suspended solids can have potential cumulative effects on the clogging of riverbanks and alluvial aquifers. In addition, suspended solids generally act as the primary transport mechanism for emerging organisms and pollutants (Bourg et al., 1989; Miretzky et al., 2005; Stone and Droppo, 1994; Zhu et al., 2005). Turbidity is one of the parameters used to indirectly describe the concentration of suspended solids (EPA, 1999), which can be conveniently measured due to the strong relationship between the two parameters (Susfalk et al., 2008; Wu et al., 2014) and the relatively long analysis time of TSS compared to turbidity analysis (Susfalk et al., 2008).

RBF has the additional advantage of removing or attenuating certain heavy metals (Bourg and Bertin, 1993; Stuyfzand, 1998), pathogens (Dillon et al., 2002; Schijven et al., 2003; Schmidt et al., 2003; Sprenger et al., 2014; Weiss et al., 2005) and nutrients (Krause et al., 2013; Ray, 2002a; Schmidt et al., 2003; Wu et al., 2007). In addition, RBF has demonstrated an ability to decrease mutagenic compounds, including naproxen, gemfibrozil and ibuprofen (Hoppe-Jones et al., 2010; Schubert, 2003), and to remove organic and inorganic micro-pollutants, such as sulfamethoxazole and propranolol (Bertelkamp et al., 2014; Hamann et al., 2016; Schmidt et al., 2003). However, it has also been found that specific micro-pollutants such as carbamazepine and EDTA remain mobile, showing persistent behavior even after 3.6 years of travel time (Hamann et al., 2016). The persistence is mainly driven by the very low reactive and sorptive characteristics of these compounds (Scheytt et al., 2006). RBF has also shown the capacity to mitigate shock loads (Mälzer et al., 2003; Schmidt et al., 2003), resulting in a stable abstracted water quality.

Although RBF has been shown to be highly effective in the removal of many contaminants, it must mainly be considered as a pretreatment method that needs to be combined with a certain posttreatment (Cady et al., 2013; Dash et al., 2008; Kuehn and Mueller, 2000; Singh et al., 2010). A balance between the water quality and the production capacity must be considered; greater removal efficiencies are achieved by increasing travel distances, but this can decrease the rate of productivity.

Surface water bodies are the main sources of drinking water for the Colombian communities and make up approximately 80% of the systems (Ministerio de Desarrollo de Colombia, 1998). However, in the last decades, turbidity and contamination events in surface waters have become a serious concern in Colombia in the context of guaranteeing safe drinking water (Gutiérrez et al., 2016a; Universidad del Valle and UNESCO-IHE, 2008). Fast urbanization, the lack of integration between water management and spatial planning and inappropriate land use are identified as the main causes for the progressive deterioration of the surface water (IDEAM, 2015; Universidad del Valle and UNESCO-IHE, 2008; van der Kerk, 2011). Figure 2.2 illustrates the variation in monthly turbidity percentiles in the Cauca River (Cali, Colombia) for the years 2008-2013 (EMCALI, J.C. Escobar, personal communication, 2015). High turbidity events in the Cauca River lead to intake shutdowns in the main water treatment plant (Puerto Mallarino WTP) in the city of Cali, where of up to 37,700 NTU have been found in the pilot study mentioned in Appendix A (10,000 NTU measured by EMCALI, J.C. Escobar, personal communication, 2015, Figure 2.2). The decrease in the dissolved oxygen concentrations in the Cauca River is used as an indicator of high pollution peaks. It typically drops after heavy rainfalls with the increase in organic matter concentrations (CVC and Universidad del Valle, 2004a).

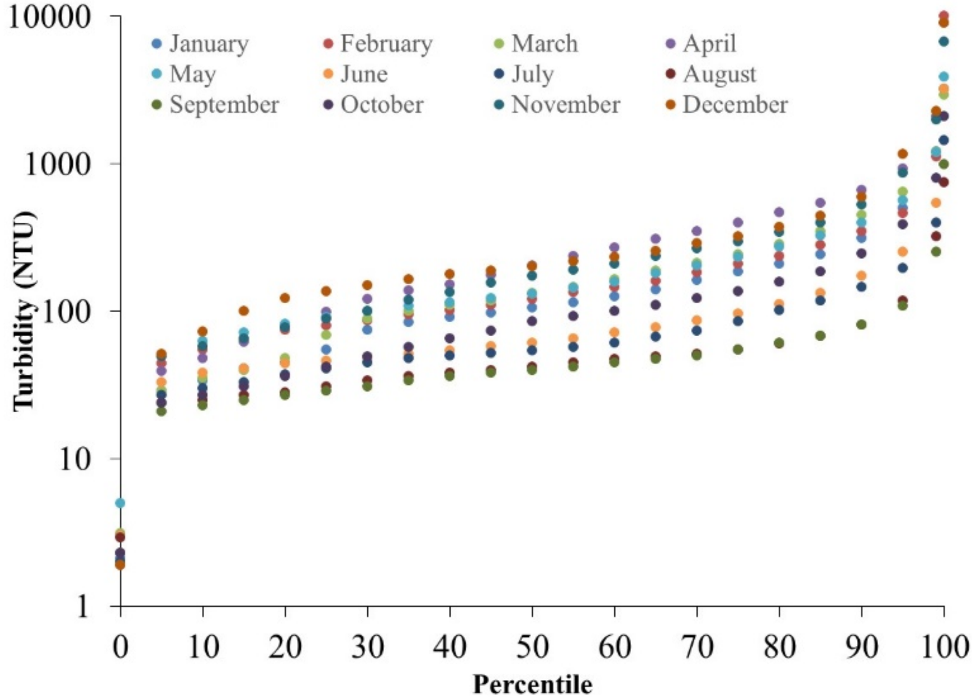

Figure 2.2. Turbidity percentile values in Cauca River, Colombia, during years 2008-2013

The Pacific basins of Colombia have sediment yields between 1,150 and 1,714 t/km^2/year (Restrepo and Kjerfve, 2004), while the Magdalena River in the Magdalena-Cauca basin, which corresponds to the most populated zone in the country, has the highest sediment yield (560 t/km^2/year) of the large rivers in the Caribbean and on Atlantic coasts of South America; this is similar to the yields to those found in the larger basins of southern Asian rivers (Restrepo et al., 2009). In addition, significant loads of heavy metals (up to 122 kg/d Hg; 2,600 kg/d Pb; 3,300 kg/d Cd; 490 kg/d Cr) and nutrients (up to 1,138,000 kg/d N and 769,000 kg/d P) have been found in the sediments of the Magdalena River (IDEAM, 2011).

Considering the poor quality of many Colombian surface waters, there is a need to seek alternative, sustainable treatment solutions with the ability to manage peak pollution events and to guarantee the uninterrupted provision of safe drinking water to the population. RBF has been shown to be effective in the removal of many river water pollutants and can therefore also be of interest for drinking water companies and environmental and public health authorities in Colombia (Hülshoff et al., 2009; Schijven et al., 2003; Schmidt et al., 2003; Schubert, 2003).

The few reported experiences with RBF in highly turbid and contaminated surface waters led to this review to assess the potential of using RBF for the highly turbid waters in Colombia by emphasizing water quality improvement and the influence of clogging by suspended solids.

2.2 Water quality improvement

2.2.1 Mechanisms of water quality improvement in RBF systems

RBF removes contaminants through filtration, sorption of pollutants to soil particles, microbial degradation, chemical precipitation, ion exchange and oxidation and reduction (Schmidt et al., 2003; Schubert, 2003). In the first centimeters of the riverbed, a fine sediment layer is formed, also known as a cake layer. The cake layer is called a schmutzdecke if a highly active biological layer is involved (Hiscock and Grischek, 2002; Unger and Collins, 2006). A certain degree of clogging in the riverbed is preferred since it can be favorable for water quality improvement (Ray and Prommer, 2006) due to the augmentation of traveling times, particulate removal and the richness of the processes occurring in the schmutzdecke (Hiscock and Grischek, 2002; Schmidt et al., 2003; Unger and Collins, 2006). Jüttner (1995) determined that the schmutzdecke and the upper layers were responsible for most of the elimination of volatile organic carbon, and Dizer et al. (2004) concluded that this layer is extremely efficient in eliminating viruses. Maeng et al. (2008) found that 50% of the total dissolved organic matter removal in a simulated RBF system occurred in the first few centimeters of the infiltration surface due to the biological activity in the developed biomass. In the schmutzdecke, the removal of organic matter, pathogens and chemicals occurs through predation, scavenging and metabolic breakdown mechanisms (Haig et al., 2011). A cake layer, mainly composed of organic and/or clay constituents, may also enhance the sorption of pollutants onto its surface (Li et al., 2003).

The interface between the surface water and the groundwater, corresponding to the hyporheic zone (Figure 2.1), plays the most important role in the degradation of contaminants (Doussan et al., 1997; Grischek and Ray, 2009; Maeng et al., 2008; Smith et al., 2009; Stuyfzand, 2011). The hyporheic zone is characterized by redox gradients, the dynamic exchange of oxygen and the presence of organic carbon and microorganisms (Doussan et al., 1997; Febria et al., 2012; Findlay and Sobczak, 2000) that enhance electron transfer, ion exchange and degradation and sorption processes, therefore improving the removal of pollutants (Hiscock and Grischek, 2002; Smith, 2005; Tufenkji et al., 2002). Commonly, microbial activity is high in the early stages of infiltration, depleting the oxygen in the hyporheic zone and producing anoxic or anaerobic conditions (Doussan et al., 1997; Krause et al., 2013).

The flow path between the river and the abstraction well is characterized by lower biological activity and sorption capacity as well as longer retention times and increased mixing (Hiscock and Grischek, 2002; Stuyfzand, 2011). This flow path is therefore of great importance for the removal of poorly degradable pollutants, which require greater distances to be removed or inactivated. In both the hyporheic zone and the flow path, deep bed filtration mechanisms are important.

During deep bed filtration, the particles in suspension to be removed are considerably smaller than the average size of the aquifer pores (Brunke, 1999; Sutherland, 2008; Zamani and Maini, 2009). Therefore, particle separation mainly occurs due to selective straining within the porous media through sedimentation, interception, inertial forces or Brownian motion (Sutherland, 2008). Pathogens are mainly removed from the water through straining, inactivation and attachment to the soil grains (Schijven et al., 2003).

The transformation of nutrients in the subsoil is a function of the exchange rates between the river and hyporheic zone, residence times, dissolved oxygen and biotic processes (Krause et al., 2013; Smith, 2005). The hyporheic zone may have anoxic or anaerobic conditions due to high levels of microbial activity (Doussan et al., 1997; Krause et al., 2013). If the consumption of oxygen exceeds the hydrological oxygen exchange rate, anoxic conditions lead to an oxic-anoxic interface. The reduced and oxidized forms of the nutrients may coexist under such conditions (Duff and Triska, 2000).

The removal of heavy metals from source water during subsurface passage mainly occurs through sorption, precipitation and ion exchange processes, which depend on the content of the inorganic and organic compounds in the aquifer and the contact time (Bourg et al., 1989; Hülshoff et al., 2009). Under aerobic conditions, heavy metal removal is mainly attributed to ion exchange processes at negatively loaded surfaces (Schmidt et al., 2003). The presence of negatively charged surfaces (e.g., clayey and/or organic sediments) and amorphous ferric and aluminum oxides provide exchange sites for binding trace heavy metals (Foster and Charlesworth, 1996; Salomons and Förstner, 1984). As contact time is a critical parameter affecting the fate of most heavy metals, the removal of such compounds by ion exchange processes mainly occurs in the hyporheic zone and the flow path between the river and the abstraction well (Hülshoff et al., 2009; Stuyfzand, 2011). In anoxic aquifers, heavy metals are mainly removed through sorption processes (Schmidt and Brauch, 2008). If the conditions are such that sulfide is formed, the immobilization of heavy metals may occur through sulfide precipitation (Bourg et al., 1989; Salomons and Förstner, 1984).

Micro-pollutants occur in most surface waters that run through heavily polluted regions or large industrial and agricultural areas. The fate of such substances in RBF systems is mainly determined by sorption mechanisms and biological transformations (Schmidt et al., 2003). During absorption, hydrophobic interactions occur between the aliphatic and aromatic groups of micro-pollutants and the membrane cells of the microorganisms. During adsorption, the negatively charged surfaces of the microorganisms and the soil lead to electrostatic interactions of the positively charged micro-pollutants (Luo et al., 2014).

Extensive research in Germany has shown that these compounds may be removed to varying degrees, mainly depending on the properties of each compound (Schmidt et al., 2003). As stated by Schmidt et al. (2004), the biodegradation of organic micro-pollutants is a function of the available organic carbon for energy production. The process of energy production is primarily based on redox reactions. The extent of biodegradation of an organic micro-pollutant is dependent on residence time and favorable redox conditions. Therefore, the elimination rates of certain micro-pollutants vary depending on local geological and hydrochemical conditions and organic loads of surface waters and infiltration zones (Schmidt et al., 2004).

2.2.2 Turbidity removal at RBF sites with highly turbid surface waters

Turbidity removal has been proven to be highly efficient using RBF (Dash et al., 2010, 2008; Ray et al., 2008; Saini et al., 2013; Schubert, 2001; Thakur and Ojha, 2010; Wang, 2003; Wang et al., 2001, 1996; Weiss et al., 2005). Thakur and Ojha (2010) studied the variation in turbidity during the extraction of subsurface water for the supply of drinking water to Haridwar. According to these authors, the river channel (from the Ganga River in Uttrakhand, India) reached turbidity values of up to 2,500 NTU, and turbidity removals between 99 and 99.9% were obtained during RBF. In Table 2.1, more turbidity removal values are presented from RBF sites with highly turbid surface waters.

Table 2.1. Turbidity removal at bank filtration sites with highly turbid raw water sources

Bank filtration site	Pant Dweep Island at Haridwar, India (Dash et al., 2010) (Thakur and Ojha, 2010)	Indiana American Water at Jeffersonville, USA (Weiss et al., 2005)	Indiana American Water at Terre Haute, USA (Weiss et al., 2005)	Missouri American Water at Parkville, USA (Weiss et al., 2005)	Louisville at Kentucky, USA (Wang, 2003)
Distance from source water V: vertical H: horizontal	320 m (V) 108 m (V)	177 m (V) 30 m (V)	24 m (H) 122 m (V)	37 m (V) 37 m (V)	23 (V) 24 (H)
Travel time (d)	420-510 32.5	13-19 3-5	NA	NA	2-5
Source water (maximum turbidity; NTU)	200 2,500	661	1,761	1,521	599
Bank filtration system (maximum turbidity; NTU)	0.6 Not available	1.1 1.5	0.27 0.41	3.8 2.7	±0.8 0.69
Turbidity removal (%)	99.7 ±99.9	99.83 99.77	99.98 99.98	99.75 99.82	±99.8 99.88

Bank filtration site	Pant Dweep Island at Haridwar, India (Dash et al., 2010) (Thakur and Ojha, 2010)	Indiana American Water at Jeffersonville, USA (Weiss et al., 2005)	Indiana American Water at Terre Haute, USA (Weiss et al., 2005)	Missouri American Water at Parkville, USA (Weiss et al., 2005)	Louisville at Kentucky, USA (Wang, 2003)
Aquifer material	Sand, clayey and silty sands	Clay, fine and medium sands, coarse gravels	Medium and fine sands underlain by coarser sand and gravel	Fine to coarse sand, gravel and boulder deposits with intermixed layers of clay and silt overlying consolidated shale and limestone	Sand and gravel with silt and clay

The RBF system configuration (i.e., vertical or horizontal) does not govern the suspended solid removal efficiency, as observed in Table 2.1, since it is not a function of the travel time or the contact time. The texture of the streambed, however, influences the media clogging (Hubbs et al., 2007; Stuyfzand et al., 2006), where external clogging (cake layer formation) enhances the removal capacity of fine sediments contained in the water (Veličković, 2005). The removal efficiency of suspended solids is concentration dependent (Fallah et al., 2012; Thakur and Ojha, 2010); the higher the suspended solid concentration, the faster the cake formation, and therefore the higher the turbidity removal capacity. Although no studies have quantified the role of concentration in entrapment, the critical particle concentration at which the porous media become clogged has been determined to be dependent on the ratio of void size to particle size (Sen and Khilar, 2006). As reported by Sen and Khilar (2006), the critical particle concentration increased from 0.35% to 9% when the ratio of bead size to particle size was increased from 12 to 40. Therefore, the removal efficiency of suspended solids is a function of both the filtering media characteristics (streambed and particle sizes in the aquifer) and the water quality in terms of suspended particle size and concentration.

2.2.3 Pathogen removal with RBF

Schijven et al. (2003) showed the efficiency of RBF for microbial contaminant removal, which depends on flow path length and residence times; the longer the flow path and the residence time, the higher the removal. Bacterial removal larger than 2.5 log has been reported in RBF systems with most of the removal occurring in the first meter of filtration (Wang, 2003). Cady et al. (2013) studied an RBF system in the Kali River and achieving removals of 2.7 log for total coliforms and 3.4 log for *E. coli* (1 log for *E. coli* per 26 m). However, Weiss et al. (2015) found that the total coliform reduction at two sites was 5.5 and 6.1 log on average.

Virus removal up to 5 log was reported by Sprenger et al. (2014) after only 3.8 m of RBF passage (approximately 8 days of residence time), demonstrating that RBF is a suitable technology for rivers in emerging countries with regards to virus removal. Derx et al. (2013) found that flooding events significantly alter the removal efficiency of viruses in RBF systems by increasing the advection and dispersion of the viruses through the aquifer system. The virus concentration in the abstraction wells was found to increase up to eight times due to the decrease in travel times.

Weiss et al. (2005) reported parasite (*Cryptosporidium* and *Giardia*) removal at three RBF facilities, where no parasites were detected in the well waters. Metge et al. (2010) studied the parasite (*Crypstosporidium parvum*) removal efficiency in an RBF system comprised of well-graded, metal-oxide-rich content sediments and found that the main immobilization mechanism was sorption to the metal oxide contents (iron and aluminum).

2.2.4 Nutrient removal with RBF

Doussan et al. (1997) studied the behavior of nitrogen as nitrate, nitrite and ammonium in an RBF system fed by the Seine River. They found a complete removal of nitrate and nitrite, while the ammonium concentrations at the RBF site increased in comparison to the concentration in the river water. Regnery et al. (2015) also found a significant decrease in nitrate concentrations through denitrification. The presence of reducing conditions is commonly found during RBF passage due to the long paths and residence times of the water transported from the river to the RBF abstraction wells. Ammonium concentrations are usually low in surface waters due to the nitrification processes occurring in rivers. However, even low ammonium concentrations can cause an extensive oxygen reduction during infiltration (Doussan et al., 1997). By contrast, Wu et al. (2007) reported a decrease in ammonium concentrations and an increase in nitrate and nitrite concentrations in an unsaturated RBF passage, associated with oxic conditions leading to nitrification processes. They reported removals of nitrogen over 95% through nitrification and denitrification under saturated conditions during the monitoring period. The ammonium concentrations in the river water corresponded to a highly polluted river (16.42 mg/L; Wu et al., 2007).

Phosphorus is generally removed by sorption and precipitation in the form of calcium, iron or aluminum or iron phosphate (Regnery et al., 2015; Schmidt et al., 2003). Phosphorus removal is influenced by the sedimentary structure of the subsoil (Hendricks and White, 2000). Its sorption is linked to the exchange between the river water and the soil matrix (Hülshoff et al., 2009; Smith, 2005). Leader et al. (2008) assessed the sorption dynamics for different materials and found sorption ranging from 66 to 97 mg-P/kg for clean sand and about 515 mg-P/kg for iron-coated sand. As stated by Vohla et al. (2007), the amount of phosphate that can be removed during subsurface passage is limited to the number of sorption sites, leading to a sorption capacity decrease over time and changes in the physicochemical and oxidation conditions. Regnery et al. (2015) found a decrease in the phosphate removal efficiency in an RBF system from 80% during start-up to 40% after 6 years.

2.2.5 Heavy metal removal with RBF

RBF has been shown to be a suitable technology to remove certain heavy metals (Bordas and Bourg, 2001; Bourg et al., 1989; Bourg and Bertin, 1993; Stuyfzand, 1998), although its ability is site and substance specific. As pointed out by Sontheimer (1980), Schmidt et al. (2003) and Stuyfzand et al. (2006), some RBF systems are able to remove heavy metals, such as chromium, and metalloids, like arsenic, by approximately 90%. This is in accordance with experiences in the use of similar technologies, like sand filtration, also resulting in the removal of heavy metals (Awan et al., 2003; Baig et al., 2003; Schmidt and Stadtwerke, 1977). Schmidt et al. (2003) also found lead and cadmium removals of up to 75% at an RBF site located in Germany with water abstracted from the Rhine River. However, Stuyfzand et al. (2006) found that lead and cadmium concentrations in the abstraction wells increased by over 300% and 30%, respectively, within a 450-day travel time. Bourg et al. (1989) also found that cadmium and zinc were remobilized from sediments, although Bourg and Bertin (1993) still reported zinc removal by river bank sediments.

2.2.6 Micro-pollutant removal with RBF

Hamann et al. (2016) analyzed the fate of 29 micro-pollutant compounds in an RBF system considering a travel time of up to 3.6 years and found the complete removal of 14 compounds (2-naphthalene sulfonate, 2,6-NDS, amidotrizoic acid, AMPA, aniline, bezafibrate, diclofenac, ibuprofen, iohexol, iomeprol, iopromide, ioxitalamic acid, metoprolol and sulfamethoxazole) due to retardation and degradation processes as supported by numerical modeling. In addition, some compounds were partially removed (triglyme, iopamidol, diglyme, 1,3,5-naphthalene trisulfonate and 1,3,6-naphthalene trisulfonate) with removal efficiencies ranging from approximately 60 to 90%, based on the highest concentrations measured in both the Lek River and the observation well (906 m from the river; 3.65 years of travel time). Only 10 compounds were fully persistent during the subsurface passage in the RBF system (1,4-dioxane, 1,5-naphthalene disulfonate (1,5-NDS), 2-amino-1,5-NDS, 3-amino-1,5-NDS, AOX, carbamazepine, EDTA, MTBE, toluene and triphenylphosphine oxide). The authors do not differentiate between biodegradation and sorption where adsorption, ion-pair formation and the complexation of pollutants to the soil may lead to soil pollution (Bradl, 2004).

Bertelkamp et al. (2014) assessed the sorption and biodegradation of 14 organic micro-pollutants (acetaminophen, ibuprofen, ketoprofen, gemfibrozil, trimethoprim, caffeine, propranolol, metoprolol, atrazine, carbamazepine, phenytoin, sulfamethoxazole, hydrochlorothiazide and lincomycin) at laboratory scale and found that most of them (the first eight compounds listed above) were completely biodegraded. However, compounds such as atrazine and sulfamethoxazole were not removed in a 6-month period. Schmidt et al. (2003) found that sulfamethoxazole was primarily removed (20% removal efficiency) under anaerobic conditions (anaerobic aquifer), while only slightly reduced in the RBF system under aerobic conditions. Drewes et al. (2003) examined the fate of selected pharmaceuticals and personal care products during groundwater recharge; the stimulants caffeine, diclofenac, ibuprofen, ketoprofen, naproxen, fenoproxen and gemfibrozil were efficiently removed. However, the antiepileptics carbamazepine and primidone were not removed at all. Organic iodine was only partially removed. The formation of metabolites may be expected during organic micro-pollutant biodegradation; however, this has not been reported.

Schmidt et al. (2004) studied the fate of anthropogenic organic micro-pollutants comprised of aminopolycarboxylates (EDTA, NTA and DTPA), aromatic sulfonates (2-aminonaphthalene-1,5-NDS, 1,3,6-naphthalene trisulfonate, 1,5-NDS, 1- naphthalene sulfonate and 2-naphthalene sulfonate), pharmaceutical compounds (diclofenac, carbamazepine, bezafibrate and sulfamethoxazole), iodinated x-ray contrast media (iomeprol, amidotrizoic acid and iopamidol) and MTBE. Schmidt et al. (2004) found that sulfamethoxazole was primarily removed (20% removal efficiency) under anaerobic conditions (anaerobic aquifer), while only slightly reduced in the RBF system under aerobic conditions. The reduction in EDTA concentrations under aerobic conditions was higher than that achieved under denitrifying and anaerobic redox conditions. In addition, the EDTA concentrations in the filtrated water were higher than those measured in the surface water; the conclusion is that the DTPA was partially biodegraded, leading to the formation of EDTA as a metabolite (Schmidt et al., 2004).

2.3 Clogging and self-cleansing in RBF

2.3.1 Hydraulic conductivity and clogging of the aquifer

RBF systems worldwide have shown a decline in the long-term yield (Caldwell, 2006; Dash et al., 2010; Hubbs, 2006a; Hubbs et al., 2007; Mucha et al., 2006; Schmidt et al., 2003; Schubert, 2006a; Stuyfzand et al., 2006). The production yield of RBF depends on many factors, including the hydraulic conductivity and the degree of contact between the river and the phreatic aquifer (Caldwell, 2006). Temperature affects the production yield seasonally due to changes in water viscosity (Caldwell, 2006; Hubbs, 2006a); however, this parameter is not a concern in tropical countries like Colombia where the temperature in surface water sources remains largely constant throughout the entire year (Lewis Jr., 2008).

Commonly, hydraulic conductivity varies spatially and can be temporally dependent on clogging and interface renewal through scouring. The clogging layer leads to a reduction in the hydraulic conductivity of the streambed and then affects the hydraulic connectivity between the river and the aquifer. This alters the interaction between the surface and the groundwater and therefore may influence the abstraction capacity yield (Brunke, 1999; Packman and MacKay, 2003). Nevertheless, the clogging might be favorable for quality improvement due to longer travel times and greater particulate removal, as discussed previously.

Clogging has been identified as the major contributor to the long-term decay of RBF yield (Hubbs et al., 2007), but there is a lack of understanding of the exact factors that affect clogging (Caldwell, 2006; Hubbs et al., 2007; Schubert, 2006a; Stuyfzand et al., 2006). Hubbs et al. (2007) reported a decrease in the specific capacity of the wells of up to 67% of the initial level in the first 4-year period of operation. Most of the reduction took place within the first year due to riverbed clogging in the vicinity of the well. Clogging is time dependent and is a function of the bed material (Goldschneider et al., 2007; Rehg et al., 2005), the shear forces (Hubbs, 2006b; Schubert, 2006b) scouring out the deposited material on the riverbed (Hubbs, 2006a; Mucha et al., 2006), which are seasonally variable, and the content and composition of the suspended load and the transported bed load material (Bouwer, 2002; Holländer et al., 2005).

Generally, the suspended sediment load carried by the rivers during the rainy season is higher than that found during the dry season (Dunlop et al., 2008; Göransson et al., 2013); however, in regulated river systems, seasonal variations in load do not always follow such a trend (Göransson et al., 2013). Shear forces are also seasonally variable, since these forces are a function of the water level (Hubbs, 2006b). As stated by Regnery et al. (2015), high discharge rates create higher flow velocities and shear stress, which usually results in higher infiltration rates, indicating a lower degree of clogging. By contrast, low discharge rates commonly lead to an increase in pore clogging and then to a lower production yield for an RBF system.

Clogging can be caused by physical, chemical and biological processes, although physical clogging has been found to be the dominant mechanism over the other forms of clogging (Pavelic et al., 2011; Rinck-Pfeiffer et al., 2000). As water flows from the river and through the aquifer to the RBF system, the larger silt particles plug the pore channels to the aquifer in the riverbed and form a less permeable layer together with smaller particles (Grischek and Ray, 2009; Veličković, 2005). Tropical river conditions (temperature and nutrient loads) may be favorable for biological growth onto the riverbed, which might lead to biological clogging (Kim et al., 2010; Platzer and Mauch, 1997; Vandevivere et al., 1995). Rinck-Pfeiffer et al. (2000) reported biological clogging by biomasses and bacterially produced polysaccharides in a simulated aquifer storage and recovery well system; this was related to the high presence of nutrients. Hoffmann and Gunkel (2011) reported severe clogging mainly induced by biological processes in Lake Tegel reaching a depth of at least 10 cm.

As pointed out by Hubbs et al. (2007), medium-coarse sand to fine gravel in the riverbed is desirable, so that little fine sand and silt can penetrate the larger voids in the aquifer; a permanent reduction in the hydraulic conductivity of the aquifer may therefore be avoided.

However, Sakthivadivel and Einstein (1970) stated that if the ratio between the bed particle and the suspended particle is larger than 20, clogging of the bed occurs. Also, experiences from the Netherlands have suggested that riverbeds consisting primarily of gravel (up to 25 cm in size) are at a greater risk of clogging than those consisting primarily of finer-grade materials (Stuyfzand et al., 2006). This is due to the fact that the finer particles will be able to penetrate a greater distance into the gravel riverbed before clogging (Veličković, 2005). Consequently, there is a reduced chance of resuspension or scouring of these particles; the gravel bed acts as a protective shield from flow shear forces, and infiltration rates become permanently impaired (Goldschneider et al., 2007). In sandy and silty riverbeds, the clogging particles cannot penetrate as deeply, and a cake layer will be formed on the riverbed surface (Brunke, 1999; Veličković, 2005). In these instances, flood waves will more easily be able to resuspend and remove the clogging particles, thereby regenerating bed infiltration rates to some degree. Levy et al. (2011) estimated a recovery of the hydraulic conductivity by a factor of 1.5 (from 31% to 47% compared to the hydraulic conductivity of the media before clogging).

Aquifers hydraulically connected to surface waters are susceptible to the long-term accumulation of micro-sized (colloidal) particles (Baveye et al., 1998; Hiscock and Grischek, 2002; Vandevivere et al., 1995), which causes a reduction in the hydraulic conductivity, leading to a reduction in production yield capacity. Hoffmann and Gunkel (2011) reported a decrease in the hydraulic conductivity in a bank filtration system of about two orders of magnitude during the winter period. As stated by Hoffmann and Gunkel (2011), the water temperature decrease only amounted to a change in hydraulic conductivity from $4.8x10^{-4}$ to $3.1x10^{-4}$ m/s. Thus, clogging by micro-sized particles (e.g., particulate organic matter) in combination with atmospheric air intrusion was considered to be the main factor in reducing the hydraulic conductivity. The clogging of the aquifer also depends on the concentration and type of micro-sized particles (Zamani and Maini, 2009). As stated by Okubo and Matsumoto (1983), the concentration should be below 2 mg/L to sustain a high infiltration capacity during long inundation periods. In addition, Jacobsen et al. (1997) reported that particles < 10 µm are absorbed more strongly at the macropore wall due to their relatively large surface charge, while particles > 10 µm are more exposed to hydraulic force.

2.3.2 Interface renewal by scouring

The deposition of sediments carried by river water on the riverbed surface must be balanced by scouring in order for an RBF system to be sustainable. Naturally occurring flow forces may induce sufficient scouring of the riverbed, thereby self-regulating the thickness of the formed cake layer, scouring the bed and restoring its hydraulic conductivity. Scouring is the result of shear stress forces exerted on the riverbed. The extent of scouring is determined by the magnitude of the shear stress and the properties of the riverbed and armor layer deposited onto the riverbed. The shear stress is mainly a function of the fluid velocity and water level at the streambed (Hubbs et al., 2007; Stuyfzand et al., 2006). Shear stress values have been reported to range between 1 and 100 N/m^2 as typical for river streambeds, considering a value of 20 N/m^2 as reasonable for the design of an RBF (Hubbs, 2006b). Schubert (2002) estimated an approximate average shear stress of 10 N/m^2 in the Lower Rhine River region at the Flehe waterworks. Hubbs (2006b) reported a minimum shear stress (during low-flow conditions) of 0.2 N/m^2 and a maximum shear stress of 9.16 N/m^2 (during high-flow conditions) in the Ohio River at Louisville, Kentucky. While flood events may stimulate riverbed renewal by streambed scouring as a result of shear forces, low-flow periods may promote the sedimentation of suspended solids at the riverbed (Levy et al., 2011; Stuyfzand et al., 2006). However, Schubert (2002) stated that flood events might also induce riverbed clogging due to the higher concentration of suspended solids and a higher gradient between the river level and the water table of the aquifer.

The scouring or self-cleansing capacity of RBF systems is commonly assessed in terms of critical shear stress, which depends on riverbed particle characteristics (considering its critical shear stress) and the shear stress exerted by the river water velocity. The viscosity and density of the fluid contribute to shear stress forces (Hubbs et al., 2007), but these properties are expected to be constant in time for tropical rivers (Lewis Jr., 2008). The velocity of the fluid at the streambed is a function of the stream surface slope, water level and resistance to the flow transmitted by the streambed. These parameters vary in time and place, determining the sediment transport capacity on the surface of the streambed (Hubbs et al., 2007).

Erosion and deposition behave dissimilarly for cohesive and non-cohesive sediments (Winterwerp and van Kesteren, 2004). Ahmad et al. (2011) experimentally studied the critical shear stress using sand and different mud mixtures. They found an increase in the critical shear stress by a factor of 1.5 for a mixture with a mud fraction of 50% in comparison to only sand. For non-cohesive sediments, when the bed shear stress is greater than the critical shear stress, erosion and deposition occur simultaneously (Krishnappan, 2007). By contrast, for cohesive sediments, erosion and deposition do not act simultaneously for all shear stress conditions due to the electrochemical and biological processes binding the cohesive particles to the riverbed. Armor layers from the deposition of cohesive materials carried by the rivers will increase their resistance to erosive processes, resulting in higher shear stresses to move the sediments deposited on the riverbed. In addition, the shear stress for the deposition of cohesive sediments is different from the shear stress for erosion (Krishnappan, 2007). As stated by Berlamont et al. (1993), the critical shear stress for deposition is usually in the range of 0.05-0.2 N m^{-2}, while for erosion it is in the range of 0.1-2 N/m^2. Moreover, cohesive sediments consolidate over time when deposited on a bed, altering the critical shear stress for erosion through compaction (Krishnappan and Engel, 1994), while their bulk densities tend to increase as a function of depth and time (Lick, 2008). Jepsen et al. (1997) studied the changes in bulk density as a result of depth and consolidation time in the Detroit River, the Fox River and the Santa Barbara slough. Although different bulk densities were obtained among the locations, the density variation trends were similar. Thus, there was an increase in the bulk density by depths of up to 0.2% cm^{-1} in the river sediments and 0.7% cm^{-1} in the slough sediments. Regarding the consolidation time, it increases up to 0.1% d^{-1} in the river sediments and up to 0.3% d^{-1} in the slough sediments. Therefore, bed age or consolidation time might play an important role in critical shear stress values and erosion rates for deposited cohesive sediments (Droppo and Amos, 2001; Jepsen et al., 1997; Krishnappan and Engel, 1994; Stone et al., 2008; Valentine et al., 2014).

2.4 Discussion about the applicability of RBF in Colombia

It may be concluded that RBF is a technology appropriate for use in the highly turbid and contaminated surface rivers in Colombia (Gutiérrez et al., 2016a) due to its capacity to remove a high variety of pollutants linked to the influence of the highly suspended sediment loads carried by the rivers. As a consequence of the suspended sediments, cake formation on the riverbed and clogging of the aquifer may occur (Caldwell, 2006), contributing to the removal of most dissolved and suspended contaminants (Ray, 2002b). In addition, good water quality can be obtained at the abstraction wells, requiring only a few additional treatment steps for the production of drinking water (Singh et al., 2010; Sprenger et al., 2014; Thakur and Ojha, 2010).

2.4.1 Comparative assessment of water treatment technologies

In Colombia, conventional surface water treatment plants (involving coagulation, flocculation, sedimentation, filtration and chlorination) are currently used to supply drinking water. As stated by Gutiérrez et al. (2016), in Colombian WTPs the operation, maintenance and sludge disposal are the main processes leading to costly water production. The costs are linked to chemical usage, sludge production and its treatment. The following brief comparison of robust drinking water technologies in the removal of turbidity, pathogens and the chemical contaminants discussed in this review is based on the analysis conducted by Hubbs et al. (2003) and Ray and Jain (2011). Slow sand filtration, with pretreatment, is mainly suitable for small- to medium-sized communities, whereas RBF and conventional WTP can be suitable for small to very large communities (Ray and Jain, 2011). RBF is suitable for highly contaminated rivers, and is able to match conventional treatments, including advanced technologies such as ozone, ultraviolet light and granular activated carbon, for pesticide removal. Although using a conventional train with the steps coagulation, sedimentation, filtration, activated carbon filtration and disinfection (O_3, UV, H_2O_2, Cl_2) and an alternative train with the steps RBF, aeration, filtration, activated carbon filtration and disinfection (O_3, UV, H_2O_2, Cl_2) may produce similar water qualities, there are differences in the production costs. The use of RBF leads to savings in chemical dosing, sludge handling and filter backwashing. As reported by Sharma and Amy (2009), the conversion from a conventional WTP to a process including an RBF system may reduce the operational costs by up to 50%. Moreover, the sedimentation step may be skipped, and the advanced removal of pathogens is no longer needed. As reported by Dusseldorp (2013), after anaerobic riverbank filtrate is extracted in a WTP train in the Netherlands, water is pretreated with reverse osmosis prior to the conventional treatment steps of sand filtration, granular-activated carbon and UV disinfection in order to be used in combination with membrane filtration and avoid ultrafiltration and biofouling. RBF has the advantage over the other assessed technologies of dampening shock loads and peaks, which is a need in rivers with extremely variable water qualities, such as the Colombian rivers (e.g., Cauca River; Figure 2.2).

2.4.2 Potential challenges in the application of RBF in conventional surface water treatment plants in Colombia

RBF as an alternative pretreatment step may provide an important reduction in chemical consumption, considerably simplifying the operation of the existing treatment processes. It is expected that employing RBF in communities where the conditions are appropriate for its implementation (e.g., located in an alluvial formation and close to a river) will lead to considerable improvements in source water quality. Mainly, improvements are expected due to the removal of turbidity, pathogens, and to a lesser extent inorganics, organic matter and micro-pollutants. Furthermore, in Colombia, shock loads of pollutants commonly lead to shutdowns of water treatment plants until the peak has passed (Gutiérrez et al., 2016a; Pérez-Vidal et al., 2012). RBF has the potential to mitigate shock loads (Schmidt et al., 2003), thus leading to the prevention of shutdowns of water treatment plants.

During the application of RBF in conventional surface WTPs in Colombia, many of the treatment processes currently employed could be varied or even removed completely, leading to simpler plant operation and control. In the specific case of the Puerto Mallarino WTP in Cali, Colombia, RBF would replace all current pretreatment process steps occurring in the grit chamber, the rapid mix chamber, and the flocculation and settling clarifiers (Gutiérrez et al., 2016a). Chemical doses could be reduced in all remaining processes, but an additional requirement for aeration directly after well extraction may be needed. However, this would only be necessary in the instance that the RBF filtrate had become anaerobic during soil passage. Because of the process changes, a stable inflow quality (turbidity, temperature, pH and electrical conductivity) means that the plant will operate under more stable conditions, thereby increasing plant efficiency and effluent quality. RBF well operation and control are much simpler than the existing treatment steps, which currently require continual adjustment to ensure smooth plant operation according to any changes in raw water quality. Additionally, a complete reduction in the sludge produced by the grit chambers and clarifiers would be achieved.

RBF thus typically results in fewer environmental impacts than conventional surface water treatment. The environmental benefits can mainly be attributed to its considerable reductions in chemical usage and sludge production. Likewise, the elimination of surface water intake structures may have a positive effect on the surrounding aquatic environment. However, the high sediment loads contained in many Colombian rivers may lead to some negative environmental impacts with the use of RBF, mainly associated with changes in vital aquatic habitats caused by riverbed clogging (Kendy and Bredehoeft, 2007).

The suspended sediments responsible for the clogging processes may, on the one hand, be favorable for the improvement of the water quality, mainly due to the strengthening of cake filtration and deep bed filtration processes. On the other hand, the formed cake layer must be balanced by scouring in order for an RBF system to be sustainable. Therefore, clogging and self-cleansing issues must be studied in greater depth to assess the use of RBF technology in highly turbid waters; they may affect the abstraction capacity yield as well as the development of different redox zones for efficient contaminant removal.

Finally, in the design of an RBF system, a balance between the water quality and the production capacity must be sought. Greater removal efficiencies may be achieved with increased travel distances (residence time), yet there is an inevitable trade-off between the ability to supply large flows and the decreased water quality in the abstraction wells. The longer the travel distance, the higher the fraction of groundwater extracted from storage in the aquifer; therefore, the lower the extraction capacity of the system (de Vet et al., 2010). For an RBF system to be sustainable, the infiltration rate must remain high enough throughout the river-aquifer interface in order to provide the water quantity needed, and the residence time of the contaminants must be sufficient to ensure adequate water quality. Nonetheless, even with shorter residence times, the abstracted water will have better characteristics than the raw water, making further treatment steps such as coagulation, flocculation and sedimentation redundant. Therefore, RBF may be considered a feasible option to address water quality changes at a larger scale.

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CHAPTER 3

MULTI-CRITERIA ANALYSIS APPLIED TO THE SELECTION OF DRINKING WATER SOURCES IN CALI, COLOMBIA

"I'm going to sleep well tonight knowing that I made the right decision"

George Ryan

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3 Multi-criteria analysis applied to the selection of drinking water sources in Cali, Colombia

3.1 Introduction

The high variability of water quality in surface water in Colombia, including the level of risk to human health, is threatening its use as a source for drinking water. Colombia is characterized by its abundance in water resources, where its average water yield exceeds six times the average global water yield and three times the Latin American water yield (IDEAM, 2010). However, the availability of water is constrained by the deterioration of its quality. Progressive deterioration of the surface water is mainly caused by rapid urbanization, in combination with a lack of integration between water management and spatial planning. The problem has been exacerbated by inappropriate land use, poor protection of the river basins, wastewater and stormwater discharges from municipalities, discharges from domestic and industrial wastewater treatment plants, and also mining, deforestation processes and improper management (van der Kerk, 2011).

3.1.1 Multi-criteria analysis applied to urban water management

Multi-criteria analysis (MCA) tools have been widely used in decision-making situations to ensure a drinking water supply, in terms of water quantity and quality, where a diverse range of alternatives is available. MCA is a decision-analysis tool for dealing with complex decision-making problems with more than a single criterion and involving a variety of stakeholders. As described by Lai et al. (2008), there are various decision-support methodologies available for MCA, which can be classified as follows: elementary procedures (e.g. conjunctive and disjunctive methods); single synthesizing criterion approaches (e.g. Multi-Attribute Utility Theory (MAUT), Multi-Attribute Value Theory (MAVT), Analytical Hierarchy Process (AHP)); outranking methods (e.g., ELECTRE, PROMETHEE, REGIME, NAIADE); and goal or reference point methods (e.g., Goal Programming (GP) and Compromise Programming (CP)).

The selection of the decision-support methodologies depends on the availability of information and its quality (Lai et al., 2008). Jaber and Mohsen (2001) described the development of a decision-support system for the evaluation and selection of potential non-conventional water supply systems in Jordan using the Analytic Hierarchy Process. Domènech et al. (2013) analyzed the compatibility of non-conventional centralized and decentralized water supply technologies in Spain using a social multi-criteria evaluation.

This chapter focuses on the development of an MCA framework to assess the alternative that best suits the necessities of the city of Cali, Colombia. That framework is based on the drinking water supply problems suffered there and the external constraints involved in the decision-making structure in developing countries such as Colombia.

A review was carried out in order to pinpoint the most pressing drinking water related issues in Cali. Moreover, additional data collection and analysis were conducted to achieve a better understanding of the magnitude of the contamination of the Cauca River, which is used as the main water source for the water supply to Cali. The pre-proposed alternatives were evaluated objectively in order to define the more suitability solutions to meet the future water demand of the city.

3.2 Materials and methods

This study is divided into two parts: (1) impact of water quality on Cali's current drinking water system; and (2) the application of the MCA tool. The methodology used in each part is described as follows:

(1) The impact of water quality on the functioning of the drinking water system for the city of Cali was reduced to the evaluation of the impacts of the current Cauca River water quality on the Puerto Mallarino WTP because, as described above, it represents the most water coverage for the city. This analysis was based on turbidity and dissolved oxygen (DO) because these parameters correspond to the operational thresholds in the WTP. The turbidity indicator is related to extreme sediment loads, and the DO is associated with extreme contamination events. Therefore, when any of the mentioned parameters reaches or surpasses the operational thresholds, the WTP may not treat the entering water due to the uncertainty of contaminants in the source water. Other parameters are monitored at the WTP intake and in a station located 4.5 km upstream from the WTP intake (pH, color and electrical conductivity). However, only turbidity and DO are linked to the operational thresholds.

(2) Multi-criteria decision analysis. An inventory was made of the alternatives as previously proposed by the drinking water company (EMCALI EICE ESP), environmental authorities, consultants and universities. The alternatives studied at a pre-feasibility and feasibility level, that by themselves or in combination comply completely with the water demanded by the city, were compared by applying the MCA tool. The water company has considered the alternatives be included as promising solutions, therefore in this study additional alternatives were not proposed. The water demand for the city is expected to reach 11.9 m^3/s in 2036. The alternatives were evaluated by projecting the costs until year 2036. However, it must be pointed out that the "useful life" is not the same for all alternatives, since some of them will use existing facilities that may require upgrading. A

sensitivity analysis was conducted by applying the MCA under different criteria scenarios.

3.2.1 Study site

Cali is the capital of the Valle del Cauca Department, located in the south-western part of Colombia between the Central Mountain Range and the Pacific Ocean. It is the third most important city in the country, with 560.3 km^2 of municipal area and a population of approximately 2.5 million people. The city has experienced rapid population growth in the past decades due to its geographic location as the principal urban, cultural, and economic centre in south-western Colombia (Universidad del Valle and UNESCO-IHE, 2008).

3.2.2 Drinking water supply system of Cali

The drinking water supply system in Cali is provided by five drinking water treatment plants (WTPs): Puerto Mallarino, Río Cauca, Río Cali, La Reforma and La Rivera (Figure 3.1), having a total capacity of around 12 m^3/s. The distribution system consists of 2,820 km of pipelines having diameters between 75 and 1,400 mm, 41 water storage tanks and 16 pumping stations (PDA, 2008; Pérez-Vidal et al., 2012). The distribution network is divided into four sectors: High network, Low network, Reforma network and Pance network. In addition, there are four deep wells located in the Aguablanca District: Orquídeas, Naranjos, Guaduales, and Desepaz (Figure 3.1). The wells, which had a total capacity of 0.6 m^3/s (0.15 m^3/s each), previously delivered water to a portion of the Low network (normally supplied by Puerto Mallarino and Río Cauca WTPs) during droughts. However, the deep wells are no longer in use.

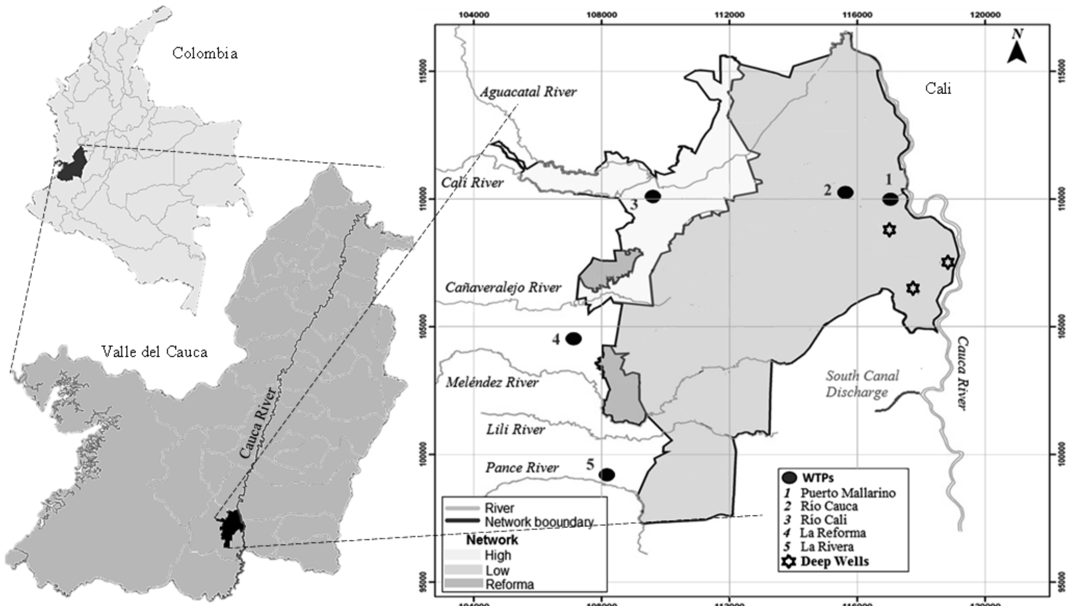

Figure 3.1. Location of WTPs in the city of Cali, Colombia

Puerto Mallarino and Río Cauca WTPs mainly supply the Low network. However, during drought periods these WTPs partially support the High and Reforma networks as well (Figure 3.1 and Table 3.1.). Surface water from the Cauca River is extracted and treated directly by both WTPs. The water quality and quantity from the Cauca, Cali and Meléndez rivers are variable (PDA, 2008; Universidad del Valle and UNESCO-IHE, 2008). Therefore, when there is a shortage of water at any WTP, Puerto Mallarino and Río Cauca WTPs must compensate for these deficits (Table 3.1.). La Rivera WTP extracts its water from the Pance River, which has good water quality in terms of its physical, chemical and microbiological parameters and is in agreement with Decree 1594/84 (Colombian regulation for water use and residual liquids).

Table 3.1. Overall description of the water supply system of Cali

WTP	Surface water source					Treatment capacity (m^3/s)	Mean production (m^3/s)	Network supplied	Coverage (%)
	River	Q_{min} (m^3/s)	Q_{max} (m^3/s)	Q_{mean} (m^3/s)	Water Quality				
Puerto Mallarino	Cauca	48	1260	258.75	Poor	6.6	4.03	Low	56
Río Cauca						2.5	1.53	Low	21
Río Cali	Cali	0.2	193.0	3.80	Good	1.8	1.29	High	17.1
La Reforma	Meléndez	0.3	19	0.82	Poor	1.0	0.37	Reforma	5.7
La Rivera	Pance	0.1	21	1.5	Good	0.034	0.014	Pance	0.2

Puerto Mallarino and Río Cauca WTPs cover 77% of the city and occasionally the coverage reaches more than 80% of the city: when water flows in Meléndez, when the Cali rivers are too low, and when the Río Cali and La Reforma WTPs are not able to produce a sufficient water flow. Cali thus relies heavily on the Cauca River as its main source of potable water.

Puerto Mallarino WTP

The WTP Puerto Mallarino is located on the western bank of the Cauca River, in the northeastern part of the city (Figure 3.1). The plant currently uses a complete train comprising (Figure 3.2): (a) a lateral intake; (b) raw water pumping station with six pumps; (c) powdered activated carbon (PAC) dosing in injection lines; (d) two grit chambers with four containers each; (e) two rapid mixing chambers where chlorine (pre-chlorination step) and coagulant (liquid $FeCl_3$) are added; (f) four compact circular sludge blanket and solid contact reactors where flocculation and settling occur; (g) intermediate chlorination; (h) 24 declining-rate rapid filters (sand and anthracite); (i) pH conditioning where $Ca(OH)_2$ is added; (j) chlorine disinfection in a 24,000 m^3 contact tank; (k) a drinking water pumping station with nine pumps to the distribution network; and, (l) an 80,000 m^3 clarified water reservoir.

At the end of 2009, the clarified water reservoir was put into operation to deal with turbidity and contamination events. The reservoir stores clarified water, which is the water coming from the compact circular sludge blanket and solids contact reactors. This allows the mixing of raw water and water from the reservoir during high turbidity peak events (turbidity > 2,500 NTU) and avoids the intake of raw water during contamination events (using only water from the reservoir when DO is in the raw water < 2.5 mg/L).

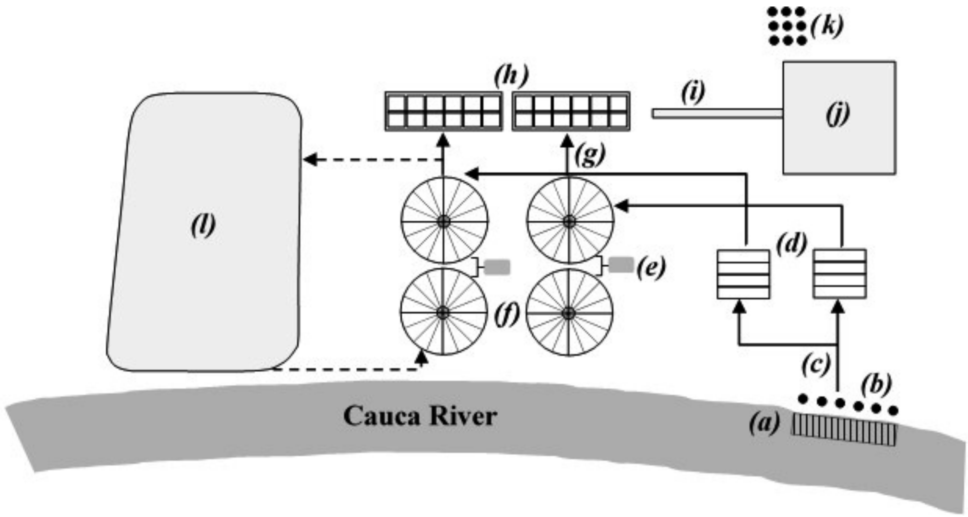

Figure 3.2. Puerto Mallarino WTP operation units: (a) intake, (b) raw water pumping station, (c) PAC dosing, (d) grit chambers, (e) mixing chambers, (f) clarifiers, (g) intermediate chlorination, (h) filtration, (i) pH conditioning, (j) chlorine disinfection, (k) treated water pumping station, (l) clarified water reservoir

<u>Río Cauca WTP</u>

The Río Cauca WTP accounts for approximately 21% of the city's water demand (PDA, 2008; Universidad del Valle and UNESCO-IHE, 2008). According to PDA (2008) the WTP currently uses a complete train with solids contact reactors comprised of: a lateral intake; 2 km of pipeline to the WTP; activated carbon dosing in an injection line; one grit removal chamber; one raw water pumping station with six pumps; one distribution chamber to reactors; six reactors for rapid mixing where chlorine (pre-chlorination step) and coagulant (mineral polymer of aluminium) are added and where flocculation and particle settling processes occur; 32 rapid sand filters (only sand) at a constant rate and constant head; chlorine disinfection in a contact tank; pH conditioning where $Ca(OH)_2$ is added; two chlorine contact tanks; and a drinking water pumping station with five pumps to the distribution network. Its intake is located at a few meters downstream of the intake of Puerto Mallarino WTP.

3.2.3 MCA framework structured for selection of alternatives

MCA was used to evaluate alternative solutions for covering future water demands in Cali based on selected criteria. The selection of these criteria was made by comparing similar frameworks on urban water management (Balkema et al., 2002; Domènech et al., 2013); however, specific issues regarding the problems of this case study, such as current legal and social acceptance, were included. Therefore, the following criteria were selected: investment, O&M requirements, sludge management, environmental impact, vulnerability issues, current legal aspects and social acceptance. A preliminary framework was given to a group of six professionals with senior experience in the water supply sector and from different institutions (universities, environmental authorities and independent consultants) in Cali. The group was asked to review the framework and to evaluate each criterion separately, which resulted in a weighting factor according to the given situation. The final criteria selection and weighting was realized as objectively as possible, in agreement with the concept given by the group of professionals who individually provided input. The inventory of alternatives was also given to the group, who then graded the criteria individually, according to the resulting framework (Table 3.2).

Table 3.2. Multiple criteria framework to assess the selection of the alternatives

Criteria	Indicator	Description	Weight	Grading[a]
Investment	Investment costs	Initial investment based on the construction of dams, WTPs, wells, reservoirs, adjustment of existing facilities, etc.	10	Quantitative scale –
Operation & maintenance	Raw material	Use of chemicals for water treatment (e.g. activated carbon, chlorine, coagulant, polymer, lime, etc.)	6	Impact[b]
	Energy requirements	Involves consumption of energy during water abstraction, treatment and distribution	6	Impact[b]
	Staff requirements	Requirement of specialized staff and number of employees needed during water abstraction and treatment	4	Impact[b]
	Hydraulic	Comprises washing of reactors and other facilities, backwashing of filters, O&M of conducting structures, purges, etc.	2	Impact[b]
	Electro-mechanical	Maintenance of equipment in terms of electrical, electronic and mechanical features	2	Impact[b]
Sludge management	Sludge production	Sludge/waste production during water treatment	4	Impact[b]
	Sludge treatment and disposal	Treatment needed to transform the sludge/waste produced during water treatment. This considers special sludge (organic matter, micro-pollutants, iron and manganese precipitates, etc.). In addition, treated sludge disposal requirements are considered	6	Impact[b]
Environmental impact	Soil	Comprises alteration of soil structure, subsidence phenomena, soil movement, chemical composition, etc.	2	Impact[b]
	Air	Contamination of air during operation. Its effect during construction is also considered with a low weight when grading	0.5	Impact[b]
	Water	Contamination of water during operation. Its effect during construction is also considered with a low weight when grading	2	Impact[b]
	Noise	Noise production during operation. Its effect during construction is also considered with a low weight when grading	0.5	Impact[b]
	Landscape	Landscape modification during construction and operation	2	Impact[b]
	Wildlife	Wildlife migration	3	Impact[b]
Vulnerability	Shock loads	Robustness and flexibility of the system facing shock loads of contaminants	3.5	Impact[b]
	Flood	Robustness and flexibility of the system facing flood events	2	Impact[b]

Criteria	Indicator	Description	Weight	Grading[a]
	Drought	Robustness and flexibility of the system facing drought events	3	Impact[b]
	Terrorism	Robustness and flexibility of the system facing terrorism activities	1	Impact[b]
	Earthquakes	Robustness and flexibility of the system facing earthquake events	0.5	Impact[b]
Legal Aspects	Current Legal Acceptance	Considers the legal procedures in terms of time, ease/difficulty, acceptance by current normalcy	20	Impact[b]
Social Acceptance	Social Acceptance	Contemplates obstacles imposed by society, land negotiations with communities	20	Impact[b]

[a]A qualitative scale was used for all criteria except for the "Investment Costs" criterion which has a quantitative scale using a linear function. In this last case the decision-maker considers that alternatives A and B are completely indifferent as long as the deviation between f(A) and f(B) does not exceed an established indifference threshold (the largest deviation which is considered negligible by the decision-maker)

Table 3.2 displays the framework for the assessment of the alternatives, including the criteria with their respective descriptions, assigned weight and grading scale, which was the result of the professionals' judging. Political and stakeholder interests, especially in developing countries such as Colombia, are key factors in influencing decision-making. Obtaining environmental permits for the execution of major projects such as dams can, therefore, take many years, due in part to bureaucratic procedures and obstacles placed by both legally settled communities and the slums that are frequently located on the banks of rivers and other protected zones (iDMC and NRC, 2011). Hence, the legal and social acceptance criteria (weighting factor 20) became important in the use of the MCA for this case study. Additionally, O&M and sludge disposal are the main processes leading to costly water production in the city of Cali. The costs are linked to chemical usage, sludge production and its treatment, and energy consumption due to pumping actions (Universidad del Valle and UNESCO-IHE, 2008), making O&M of crucial importance to the selection of alternatives for Cali.

Multi-criteria decision analysis, based on the outranking method, was used in order to provide an approach to select a robust and flexible alternative. The PROMETHEE method was used to evaluate the alternatives. PROMETHEE uses the outranking principle to rank options where, as stated by its authors, it is possible to introduce arbitrary numbers for the weights, giving the relative importance of the criteria according to the problem statement. As described by Brans and Mareschal (2005), the preference structure of PROMETHEE is based on pairwise comparisons, where the deviation between the evaluations of the alternatives for a criterion is considered.

In this study, the judgment of alternatives was based on the complete ranking, where the net outranking flow (Φ) was considered, $\Phi = \Phi^{+} - \Phi^{-}$. The net outranking flow is the balance between the positive and the negative outranking flows. The positive outranking flow, Φ^{+}, expresses how an alternative outranks all others, while the negative outranking flow, Φ^{-}, expresses how an alternative is outranked by all others. The net flow is built on clear and simple preference information and relies on comparative statements (Brans and Mareschal, 2005).

This proposed MCA approach may serve as an example of how this analytical and decision-making process can be used for the selection of suitable alternatives for solving the drinking water problem facing the city of Cali.

3.3 Results and Discussion

3.3.1 Impacts of Cauca River water quality on Puerto Mallarino WTP

There are two main reasons for the deterioration of water quality at the Puerto Mallarino WTP intake (Universidad del Valle and UNESCO-IHE, 2008): diffuse and point sources. Diffuse sources are mainly due to the deforestation upstream, cause higher levels of erosion leading to higher turbidity during heavy rainfall events, which is a general problem for the river basin. Point sources originate for example from the South Canal (Figure 3.1) and the Navarro disposal site, which discharge raw sewage and other waste materials into the river and is only 11 km upstream of the Puerto Mallarino WTP. Operation in 1985 of the upstream Salvajina Dam also had a significant impact on the river water quality. This dam was constructed to control floods, dilute contaminants in the water and for hydro-power generation. Because of its operation, the hydraulic characteristics in the river were modified (Ramírez et al., 2010), leading to higher concentrations of suspended solids (EMCALI (1987), cited by Pérez-Vidal et al. (2012)).

The Cauca River contains extremely high turbidity values (up to 37,700 NTU) during the winter months. Contamination events decrease the dissolved oxygen (DO) to levels below 2.5 mg/L, which can indicate a serious risk to human health due to the uncertainty of the types of pollutant substances carried by the river. Water containing high suspended solids concentrations and water with low DO levels cannot be treated with the current treatment system at Puerto Mallarino WTP, resulting in the closure of the treatment plant during these concentrations. Closures leave a large proportion of the population of the city at risk of having no water during these times, with only the 80,000 m^3 emergency reservoir (up to 4-hours supply capacity) available at Puerto Mallarino to bridge these periods.

Turbidity

High turbidity events in the Cauca River lead to the WTP's intake shutdowns, if over a certain threshold (2,500 NTU). An analysis of the raw water intake turbidity data at Puerto Mallarino has yielded the following information related to when turbidity peaks occur, how long they last, and how they are distributed.

High turbidity peaks generally occur during the rainy season when river flows are highest. Figure 3.3 illustrates the annual variations in turbidity for year 2009. Turbidity peaks occur on only a few occasions each year, and they last for periods as long as 10 hours. For most of the year, turbidity values do not fluctuate greatly and 95% of the time they remain below 568 NTU. The average annual turbidity is less than 190 NTU.

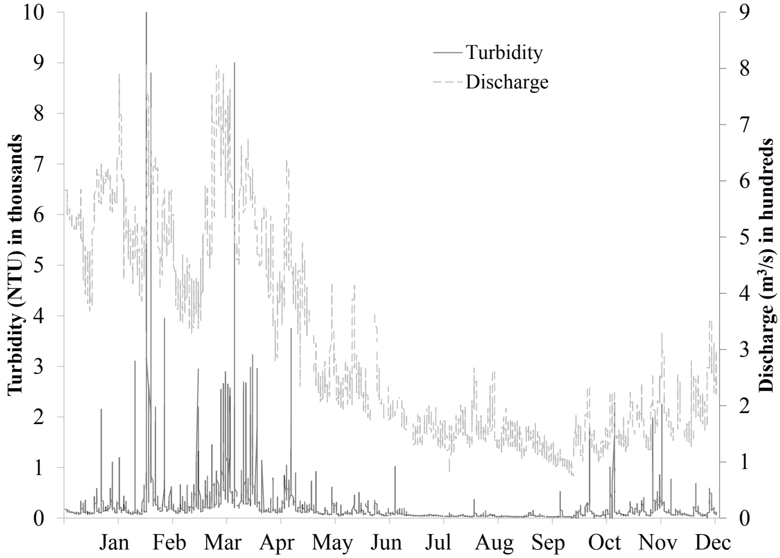

Figure 3.3. Annual variation of turbidity of Cauca River for year 2009

Dissolved oxygen

DO concentrations in the vicinity of Puerto Mallarino typically drop after heavy rainfalls with the increase of organic waste concentrations (CVC and Universidad del Valle, 2004a). The resulting low DO concentrations also lead to WTP intake shutdowns, as it is an indicator of high pollution peaks from mainly domestic, as well as industrial, wastewater. Table 3.3 outlines how often and for how long breaches of the critical 2.5 mg/L DO threshold occurred from 2008 to 2014.

Table 3.3. Univariate analysis of DO (2008–2014)

Year	Average DO (mg/L)	Minimum DO (mg/L)	DO events below threshold	Maximum duration of event (h)
2008	6.13	0.68	18	2
2009	5.37	0.07	20	5
2010	5.86	0.30	22	3
2011	6.44	0.08	19	2
2012	5.26	0.03	36	6

Year	Average DO (mg/L)	Minimum DO (mg/L)	DO events below threshold	Maximum duration of event (h)
2013	5.43	0.04	41	5
2014	5.81	0.01	26	2
Overall	5.76	0.03	182	6

The 80,000 m^3 reservoir can only handle events of poor raw water quality if their duration does not exceed 4 hours. Figure 3.4 shows the shutdown events that occurred between 2000 and 2017 because of turbidity and contamination events, and the effect of the reservoirs in the attenuation of those events since its implementation in 2009 (EMCALI, personal communication, February 09, 2018). Low DO concentration events caused intake shutdowns at Puerto Mallarino more frequently than high turbidity peaks; however, in recent years turbidity events have become more frequent and therefore increasingly significant.

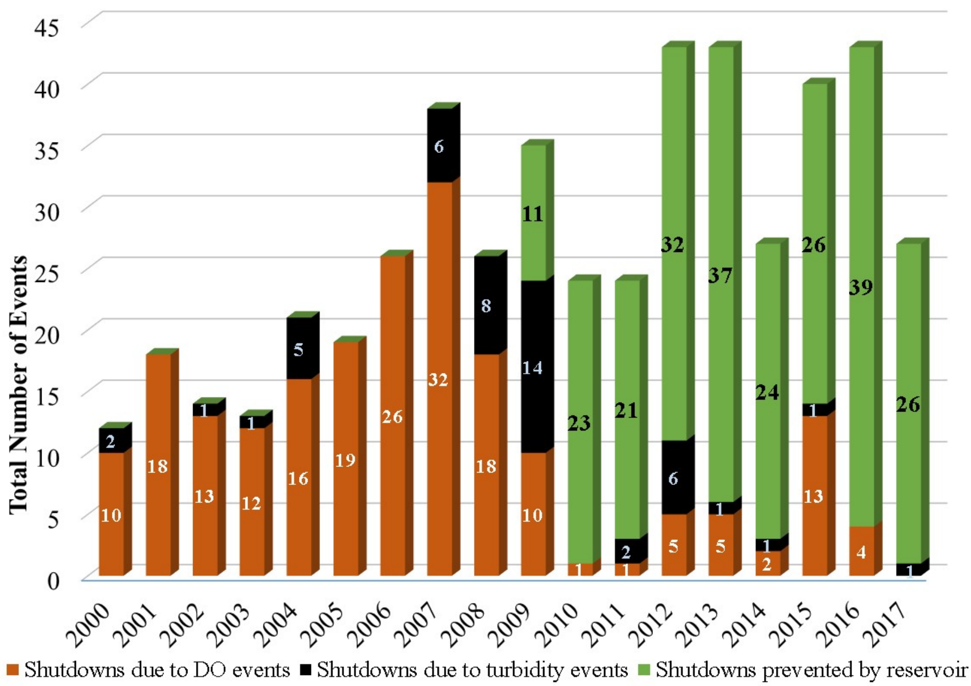

Figure 3.4. WTP shutdown events at Puerto Mallarino WTP (2000–2017)

3.3.2 Alternatives considered for resolving Cali's drinking water supply

EMCALI and CVC have been studying various alternatives at a pre-feasibility and feasibility level in order to improve the city's water supply and thereby eliminating the shutdown incidences and guaranteeing a viable water supply in the present context of increasing demand. The water sources and technologies studied are listed below, in which the alternatives considered for the analysis are denoted with the prefix “A”.

Using surface water sources from the south of the region

The most recent studies were conducted by CVC between 1997 and 1999. They suggested the construction of a WTP at a Pance location which could treat water transferred from basins such as Pance, Cali or Timba through the construction of dams (Figure 3.5). The Timba basin option (Alternative 1, A1) is considered the most promising option in terms of water quantity.

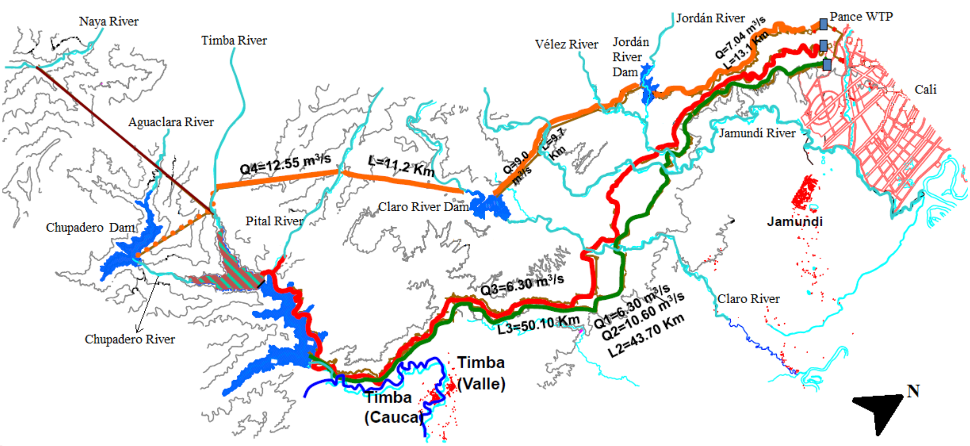

Figure 3.5. Scheme of alternatives at the south of the region

Source: Adapted from (EMCALI, n.d.)

Relocating the Cauca River current intakes of Puerto Mallarino and Río Cauca WTPs further upstream

This alternative proposes to locate the water intake of Puerto Mallarino and Río Cauca WTPs at a point upstream of the current location and to transport the raw water to the Puerto Mallarino WTP where the treatment would take place. The possibility of extracting water at the following three locations has been considered: Salvajina dam, La Balsa and Paso de La Bolsa; all of them are located upstream of the current intake before the South Canal discharge and the discharges from turbid tributary rivers. Likewise, EMCALI has studied the alternative of relocating the intake to the places mentioned above and constructing a WTP in Pance (Figure 3.6). The Paso de La Bolsa point was excluded by EMCALI due to turbidity problems caused by the tributary rivers upstream of this point (mainly from the Palo and Desbaratado rivers). Therefore, the resulting alternatives are: Salvajina dam (Alternative 2, A2) and La Balsa (Alternative 3, A3) delivering to a WTP in Pance; and Salvajina dam

(Alternative 4, A4); and La Balsa (Alternative 5, A5) delivering to the existing WTP in Puerto Mallarino.

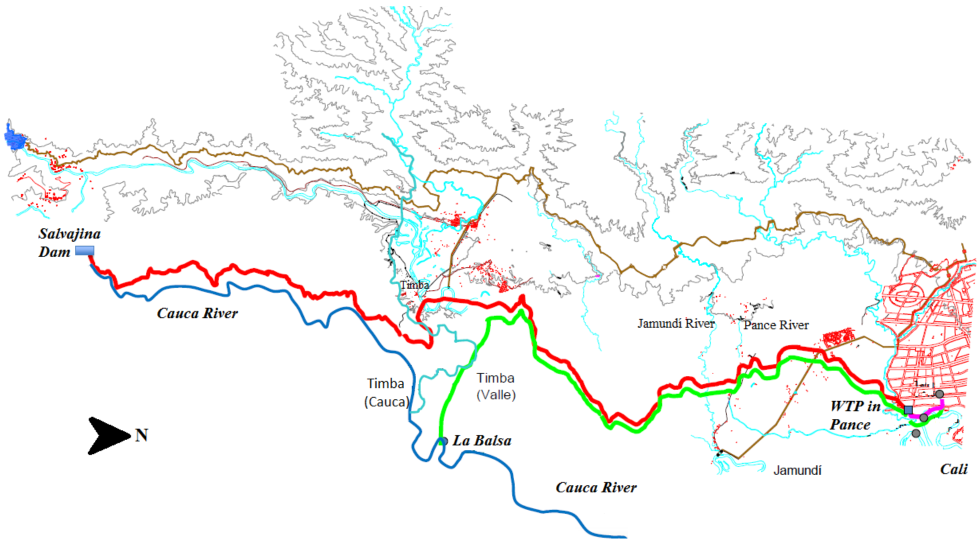

Figure 3.6. Scheme of relocation studies at Cauca River

Source: Adapted from (EMCALI, n.d.)

<u>Using surface water sources from the Cali River basin and Pacific region</u>

The Pichindé River, among others, has been studied to determine whether its capacity is sufficient to supply the Río Cali WTP so as to reduce dependency on the Cauca River. Between 1998 and 1999, an advanced pre-feasibility level study was conducted to determine the possibility of constructing a regulation dam in the Cali River to transfer water to the La Reforma WTP. In 2009, EMCALI evaluated the technical, financial, economic, social and environmental feasibility of constructing a regulation dam in the Cali River (EMCALI, 2009). The study, at feasibility level, was carried out analyzing the availability of water with and without transferring water from the Grande River (Figure 3.7). Therefore, two alternatives emerge from the Cali River basin and the Pacific region: Cali River dam in conjunction with the water transference from the Pichindé River (Alternative 6, A6); and Cali River dam with Pichindé River in conjunction with the water transfer from the Grande River (Alternative 7, A7).

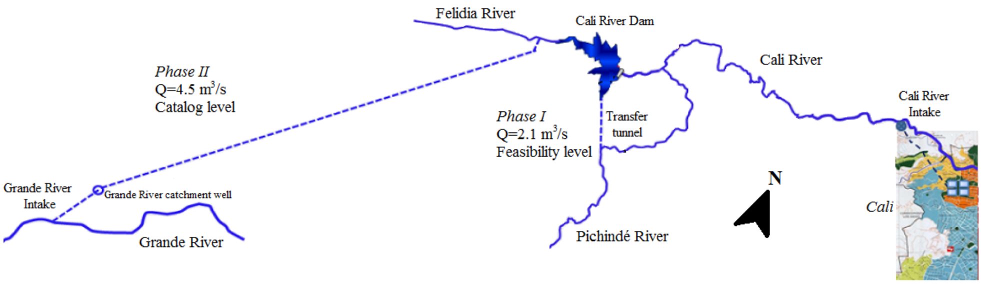

Figure 3.7. Scheme of advanced studies at Cali River basin and Pacific region.
Source: Adapted from (EMCALI, n.d.)

Using deep wells (reinstating deep wells at Aguablanca District – constructing new deep wells up to "El Hormiguero" village)

The rapid development of the District of Aguablanca in the early 1990s led to the construction of four deep wells with a total capacity of 600 L/s as a supply option in this area (Figure 3.1). During the period between May 1992 and February 1993, the national energy crisis required that the wells be used for a few hours a day, leading to intermittent service. Therefore, the population began to store water, which led to the oxidation of iron and manganese commonly present in the groundwater and caused a yellowish color in the water that caused displeasure and rejection among the consumers. This resulted in the suspension of the use of those deep wells for their water supply (PDA, 2008). EMCALI, in 2012, publicly requested the construction of a groundwater treatment system for the removal of iron, manganese, low DO, microorganisms, methane and hydrogen sulfide in order to reinstate the aforementioned wells (Alternative 8, A8) (EMCALI, 2012). A plan has been proposed to supply the extracted and treated water to the Low network. In addition, the construction of 14 more deep wells has been considered to increase water production to 2.5 m^3/s (Alternative 9, A9). The wells would be constructed from the location of the current wells up to "El Hormiguero," a community located approximately 7 km upstream of the South Canal discharge.

Enlarging the storage capacity of the clarified water reservoir

Currently, EMCALI is enlarging the water storage capacity of the reservoir by constructing an additional 100,000 m^3 reservoir (Alternative 10, A10) to increase the bridging period during critical events in the Cauca River. This decision requires an analysis of its impact on water quality, hydraulic performance and water temperature behavior on the current Puerto Mallarino WTP. This last parameter played an important role in the operational aspects since it could generate a mass inversion in water, altering the functioning of the sludge blanket and solid contact reactors of the WTP.

Using indirect abstraction from the Cauca River by riverbank filtration as a pre-treatment stage

Since 2009, riverbank filtration (RBF) (Alternative 11, A11) has been considered an alternative to resolving the water supply problems in the city of Cali, which implies process changes to the existing water treatment scheme in order to help with the variable influent loading conditions. Production wells should extract the water some distance from the water body. As the surface water travels through the sediments, it is expected that many contaminants are being removed (Schubert, 2003). RBF has been used in Europe for more than 100 years (Schubert, 2002; Tufenkji et al., 2002). In the United States, RBF has been used for over half a century (Ray et al., 2002). Other countries that are implementing RBF for drinking water supply are India, China, and South Korea (Ray et al., 2008; Sandhu et al., 2011).

3.3.3 Analysis of alternatives

Currently, the construction of the 100,000 m^3 reservoir and reinstatement of the Aguablanca wells are under execution. Therefore, for the alternatives that involve the use of the reservoir and/or the Aguablanca wells, the investment costs of these facilities were included. In addition, O&M and sludge treatment and disposal costs were considered in the analysis. A few of the alternatives described in this study comply with the water demanded by the city (in terms of water quantity). Only three alternatives can offer the total flow of demanded water:

(A1) Timba basin;

(A2) Salvajina dam delivering water to a WTP to be constructed in Pance; and,

(A3) La Balsa delivering water to a WTP to be constructed in Pance.

In addition, a smart combination of specific alternatives can also comply with the water demand. Five combinations of alternatives – so-called combos – were defined for the remaining alternatives:

(C1): A7 + A8 + A10;

(C2): A6 + A8 + A11;

(C3): A8 + A9 + A11;

(C4): A4 + A6 + A8 + A9; and

(C5): A5 + A6 + A8 + A9

In Table 3.4 the evaluation results are shown. The higher the net outranking flow (Φ), the better the alternative (Brans and Mareschal, 1994). The table shows that combo C3 seems to be the most adequate solution to solve the drinking water supply for Cali with a Φ of 0.55. This combo is followed by combo C2, which obtained a Φ of 0.34, which represents a good option for the city. Salvajina dam and La Balsa (A2 and A3) are also good options, giving 0.05 and 0.01 Φ, respectively. However, these alternatives imply an important modification would need to be undertaken in the current distribution network. In addition, extracting water from La Balsa point would require pumping raw water up approximately 40 m to the WTP, and then it would be distributed by gravity. These restrictions are represented in the low Φ values obtained.

Table 3.4. Analysis of alternatives using PROMETHEE method based on complete ranking

	MCA including all criteria				MCA excluding legal and social criteria			
Rank	Alternative/Combo	Φ	Φ^+	Φ^-	Alternative/Combo	Φ	Φ^+	Φ^-
1	C3	0.5464	0.5886	0.0422	C3	0.6726	0.7429	0.0703
2	C2	0.3354	0.4801	0.1447	C2	0.3209	0.5621	0.2412
3	A2	0.0530	0.2840	0.2310	A1	0.1008	0.3758	0.2750
4	A3	0.0141	0.2642	0.2501	C5	–0.1403	0.2535	0.3938
5	A1	–0.0253	0.2826	0.3079	A2	–0.1497	0.2353	0.3850
6	C1	–0.0988	0.2113	0.3101	C4	–0.1868	0.2262	0.4130
7	C5	–0.3985	0.1521	0.5506	A3	–0.2146	0.2023	0.4169
8	C4	–0.4264	0.1357	0.5621	C1	–0.4028	0.1141	0.5169

The remaining alternatives/combos obtained a negative Φ, indicating a low viability of the alternatives/combos to solve the drinking water problems in Cali. The combos C1, C4 and C5 (obtained the lower Φ values (–0.1, –0.43 and –0.40, respectively). These combos would necessitate the construction of multiple dams. The alternatives that involve the construction of dams are not well perceived by the communities and would require much time to obtain environmental and construction licenses, thereby decreasing their timely potential as a source for drinking water. This is observed in the high Φ^- values obtained by these alternatives, and therefore in the low values observed for Φ (Table 3.4). In the case of the Timba basin option (alternative 1), the acquisition of large areas of land and negotiations for large pipeline trajectories until the new WTP is built would be required. The options linked to the 100,000 m^3 reservoir may be susceptible to drought-flood-contamination events.

By not considering legal aspects and social acceptance criteria in the assessment, the following results can be highlighted: RBF with deep wells (C3) achieved a 0.67 Φ, with a 0.74 Φ^+ value, and the Cali River basin with RBF (C2) achieved a 0.34 Φ, with a 0.57 Φ^+ value. This indicates that the use of RBF continues to be the best alternative, leaving out the social and legal aspects. A1 (Timba basin) obtained a positive Φ value (0.10), significantly improving its position (from 5th to 3rd). However, this alternative has great potential for legal and social constraints, which can impede its selection as a feasible solution.

Overall, RBF in combination with the Cali River basin (C2) or with the deep wells (C3) seem to be reliable solutions for the water supply problem. Figure 3.8 presents a potential RBF configuration for the city of Cali. The numbers enclosed in circles represent potential extraction well locations. This site was identified during an extensive desktop study that considered secondary information as well (i.e. land use plans, subsurface contamination, river morphology, distance to river course, distance to WTP and interaction with other infrastructures). The extraction capacity, constructability (how easy will the RBF configuration be to construct?), operational ease and maintainability, costs (consideration of likely construction costs and on-going maintenance costs), and the potential lowering of groundwater table were evaluated.

Figure 3.8. Scheme of potential locations to study RBF near the Puerto Mallarino WTP

The desktop study considered factors such as potential production capacity, potential water quality improvements, costs, environmental impacts, O&M considerations and regulatory considerations. Both the quality and quantity aspects of implementing RBF in Cali showed promising results, but it must be studied further to determine its technical feasibility. In addition, the high concentration of sediments transported by the Cauca River could lead to an important reduction of its water yield.

3.4 Conclusions

The drinking water supply system of Cali is vulnerable due to its dependence on WTPs abstracting water from the Cauca River. Therefore, alternatives are being considered and evaluated with a multi-criteria analysis (MCA). RBF in combination with the deep wells and RBF with the Cali River basin options seem to be ideal alternatives in order to guarantee safe drinking water in the amounts demanded by the city, while also having a lower environmental impact during construction and operation.

MCA has been shown to be a suitable tool in the analysis of problems where political, social and stakeholders' interests are involved. However, it is subjected to individual preferences that can alter the results depending on what the developers favor. Selection of a broad range of criteria, in addition to the weighting process, plays an essential role, since it allows compensating subjective decisions and guidelines proposed by institutions. The participation of experts and stakeholders in this process provided a comprehensive conceptualization of the problem, facilitating the construction of an integrated multiple-criteria framework to assess the selection of the alternatives. This analysis provided transparency for the decision-making process and engaged stakeholders in the search for solutions that best suit the addressed needs.

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CHAPTER 4

PARTICULATE MATTER CHARACTERIZATION OF CAUCA RIVER WATER IN COLOMBIA

"Muddy water is best cleared by leaving it alone"

Alan W. Watts, The Way of Zen

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4 Particulate matter characterization of Cauca River water in Colombia

4.1 Introduction

In rural and urban areas of Colombia safe drinking water supply is one of the most serious concerns for public health. Health risks in drinking water supply are predominantly associated with water quality problems in surface water, because approximately 80% of the water supply in Colombia depends on surface water (Ministerio de Desarrollo de Colombia, 1998). In the past decades, forests have been replaced by bared surfaces due to urbanization, which has potentially increased the concentration of particulate matter in streams and rivers (Mulliss et al., 1996). Particulate matter creates turbidity and imparts color to the water. The more sediments enter the water, the higher the turbidity, and the lower the transparency. Turbidity may be caused by silt, clay, organic and inorganic compounds, plankton, and microscopic organisms (ASTM, 2003).

Erosion is considered to be one of the contributors to turbidity, which also occurs naturally due to the action of wind, rain and the river flow. The effect of river flows on particulate matter concentration mainly depends on the slopes, the presence of rocks and rocky fragments (e.g. mountain rivers), promoting riverbed deepening by scouring, destabilizing the riverbank. Flowing water has a tremendous capacity to carry material, often for a long distance (Toy et al., 2002). Furthermore, other natural and anthropogenic factors, such as industrial, urban or agricultural activities, can increase the concentration of organic and inorganic based particulate matter, such as clay, silt and fine sand, and stimulate growth of algae and zooplankton (Kerr, 1995).

Particulate matter can be responsible for interference with drinking water treatment processes, such as filtration and disinfection, and can even be a source of disease-causing organisms (EPA, 2013). Hence, the consequences for drinking water treatment depend on the specific compounds of particulate matter in a water source. The objective of this study therefore is to characterize the particulate matter of the highly turbid water of the Cauca River in Colombia, which passes through the city of Cali. The particulate matter concentration of this water source has become a great constraint for the city’s water treatment (Gutiérrez et al., 2016a). Additionally, the upstream Palo River was investigated, as this river is a major tributary to the Cauca River in terms of water discharge (mean annual flow of 35.9 m^3/s) and suspended sediments (mean annual sediment load of 0.645 x 10^6 ton) according to CVC and Universidad del Valle (2004, 2000).

4.2 Materials and methods

4.2.1 Study area

Cali is the third largest city of the country, and it is the capital of the Valle del Cauca Department, located in the southwest part of Colombia (Figure 4.1). 77% of the drinking water demand in the city is covered by Cauca River water through the water treatment plants (WTPs) Puerto Mallarino and Río Cauca (Gutiérrez et al., 2016a).

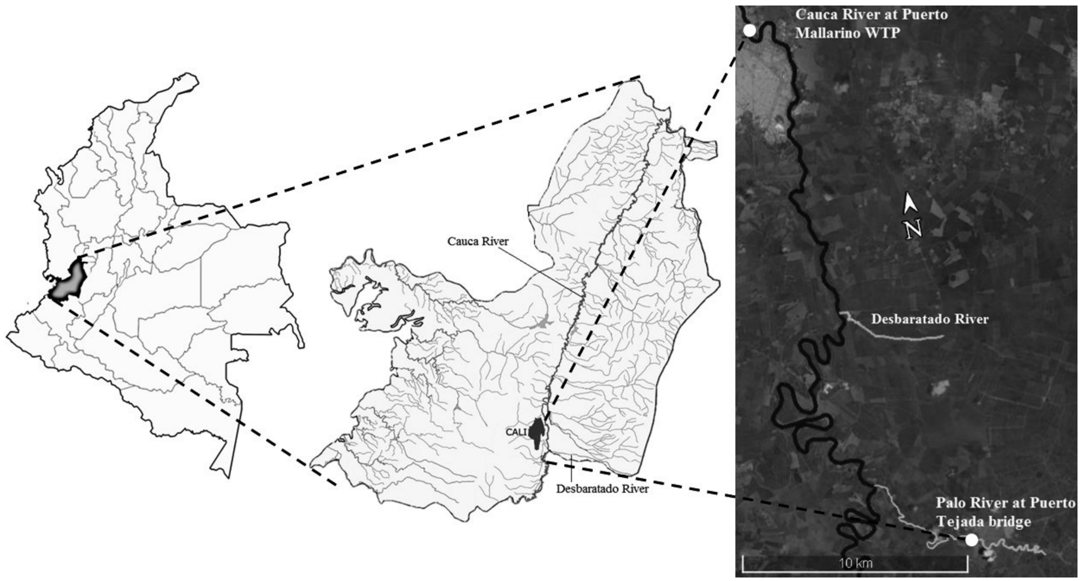

Figure 4.1. Cauca River at Puerto Mallarino water intake and its tributary Palo River
Source: Adapted from SGC (2011)

The Cauca River is the second most important surface water source in Colombia and is the main tributary of the Magdalena river basin, with a length of 1,350 km and an area of approximately 63,300 km^2. The Cauca River runs through the western region of the country, which has geological characteristics related to oceanic crust with volcanic rocks (IDEAM, 2004). The Cauca river basin is divided and classified into three sections: the Upper Cauca, the Middle Cauca and the Lower Cauca. The Upper Cauca area, where Cali is located, has the highest population density, with its extensive demand for domestic, agricultural and industrial water supply (CVC and Universidad del Valle, 2004a).

The study was executed at two points in the Cauca River basin: the Cauca River at WTP Puerto Mallarino water intake (3°26’46” N, 76°28’30” W), and the Palo River at Puerto Tejada bridge (3°13’48” N, 76°25’20” W), which is a tributary of the Cauca River upstream WTP Puerto Mallarino (Figure 4.1).

4.2.2 Approach

The approach of the study was to characterize the particulate matter contained in a section of the Cauca River (next to WTP Puerto Mallarino). Therefore, first the possible sources of particulate matter in the Cauca and Palo rivers were identified, by studying literature and reports, in order to determine the characteristics of the particle matter and its potential origin. Afterwards, water samples from both rivers were extracted and water quality analyses were conducted in order to investigate the origin of the particulate matter in relation to potential natural and anthropogenic sources.

4.2.3 Sampling protocol

Water sampling

River water samples were taken in both rivers in 2012 during dry and rainy seasons. Subsequently, bi-monthly samples were taken in the Cauca River in the period 2013-2014. In the Upper Cauca, a bimodal temporal distribution of precipitations exists: dry period from January to March and from July to September; rainy periods from April to June and from October to December. During this survey, because reduced rainy periods occurred, the rainy season samples correspond to the first showers of the season.

The parameters used to characterize particulate matter in the rivers were: turbidity, total suspended solids (TSS), particle size distribution, non-soluble iron (Fe^{3+}), and chlorophyll-a (Chl-a). Phosphate (PO_4^{3-}) and nitrate (NO_3-N) were also measured to evaluate the potential for biological activity. In addition, chemical oxygen demand (COD), true color and volatile suspended solids (VSS) were measured in the Cauca River to obtain an indication of the organic fraction of the particulate matter.

Since the Palo River has a depth smaller than one meter, the sampling was done at half the depth of the water course. For the Cauca River two samples were extracted, one at 20% of the depth and one at 80% of the depth of the water course, considering that the depth of the water course is greater than one meter (Curtis et al., 1979; Nordin Jr. and Dempster Jr., 1963) (Figure 4.2). To extract the water samples a cylindrical stainless steel column was used (40 cm long and 10 cm ID), designed to sample vertically from the top of the column once the column reached the selected depth.

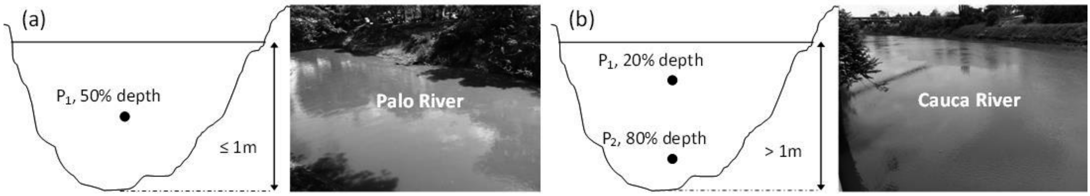

Figure 4.2. Water sampling points for (a) Palo River and (b) Cauca River

Sediment sampling

For characterization of the riverbed sediments of the Cauca River, four water samples from the Cauca River were extracted. Two water samples were extracted during rainy conditions (November 2012 and 2014), and two water samples were extracted during dry conditions (September 2013 and 2014). Cauca River raw water was extracted and deposited in a 1-m^3 tank for three days on the dates mentioned above. Afterwards, the tank was drained and the sediments collected. Part of the sediments was oven-dried for seven days at 30 °C, and then the following parameters were analyzed: soil organic matter (SOM), cation exchange capacity (CEC), and specific surface area (SSA). Another part of the sediments was oven-dried at 105 °C for 12 h and Atterberg limits (liquid and plasticity limits) and mineralogical composition were determined. In addition, two samples of the riverbed bottom were extracted by using a Petersen dredge at two different points 20 m away from each other, but both next to the WTP Puerto Mallarino. Both riverbed bottom sediments were oven-dried at 105 ºC for 12 h. Elemental speciation of the sediments was realized.

4.2.4 Water sample analysis

Liquid phase analysis

The determination of the parameters was done according to the Standard Methods (Rice et al., 2012). Turbidity was determined by the Nephelometric Method 2130 B; TSS by 2540 D Total Suspended Solids Method (dried at 103-105 °C); VSS by 2540 E Fixed and Volatile Solids (ignited at 550 °C); and particle size determination in water samples by using a wet sample dispersion unit (Model Hydro 2000SM, Malvern). Fe^{3+} was determined by measuring total iron minus dissolved Fe^{2+}, where total iron was determined through the 3500-Fe B Phenanthroline Method and Fe^{2+} by using the same method but filtering the samples in situ with 0.45 µm Whatman Protran Nitrocellulose Membrane Filters. ESS Method 150.1 Spectrophotometric was used to determine Chl-a; 5220 D Closed Reflux Colorimetric Method for COD; 4500-P D Stannous Chloride Method for PO_4^{3}; and 4500-NO_3^- D Nitrate Electrode Method for NO_3-N. TOC values correspond to field measurements done in the Cauca River through an electrical probe (Hach UVAS plus sc UV Absorbance / %Transmittance Sensor). True color was determined by spectrophotometric method 2120C.

Particle size distribution and specific surface was determined by wet laser diffraction instrument (Model Hydro 2000SM, Malvern).

Solid phase analysis

The SOM was measured by the weight loss-on-ignition (WLOI) method at 475 ºC for 12 h as recommended by Wang et al. (2011) for river sediments. The CEC of the samples was determined by the ammonium acetate method of Schollenberger and Dreibelbis (Pansu and Gautheyrou, 2006). Qualitative and quantitative mineralogical composition was determined by X-ray diffraction technique, XRD, (X'Pert Pro MRD, PANalytical). The elemental composition was determined using X-ray Fluorescence Spectrometry, XRF, (Kregsamer et al., 2002). Atterberg limits were determined by deformation test ASTM D4318 (ASTM, 1999). The liquid limit (LL) and plasticity limit (PL) allowed determining the plasticity index (PI) and classifying the type of sediments in agreement to the plasticity chart (Casagrande, 1948).

4.3 Results

4.3.1 Identification of potential sources of particulate matter

The Cauca River basin in the Cauca department, where the river springs, has an area of 7,394.8 km^2. The largest part of the Cauca department is used for commercial farming of pine, coffee, plantain, flowers, cassava, and beans. There are also small scale fishing activities, cattle breeding and agriculture exploitation by indigenous groups and the paper and sugar industry plays an important role in the land use. In addition, sugar cane occupies extensive areas of land (Colombo et al., 2014), and extensive and intensive cattle breeding near riverbanks has lead to considerable deforestation (Universidad del Valle and UNESCO-IHE, 2008). Furthermore, illicit crops are grown in steep areas beside the water sources (Kryt, 2013; Pinzón and Sotelo, 2011), and artisanal and large scale miners, extracting gold (open-pit and underground), magnesite, bentonite, feldspar, bauxite and coal in tributary rivers (Kryt, 2013; Pérez-Rincón, 2014; PGN, 2011), have affected soil and water resources (EMCALI and Universidad del Valle, 2006). The part of the Cauca River basin situated in the Valle del Cauca department (downstream of the Cauca department) is mainly used for extensive livestock farming in natural pastures, followed by sugar cane and perennial crops. The sugar cane plantations are burned to remove the outer leaves before harvesting causing vegetation loss (Colombo et al., 2014; Pérez-Rincón, 2014; Sarria-Villa et al., 2016). Only a small portion of the basin is occupied by forest (Ekstrand et al., 2009). Therefore, around 54% of the total area has some degree of erosion, of which 31% is severely eroded (Ekstrand et al., 2009). Slums and informal settlements along the Cauca riverbank are found where people discharge solid waste and wastewater (Universidad del Valle and UNESCO-IHE, 2008), sand and stone aggregates are extracted from riverbed and transported to construction sites (CVC and Universidad del Valle, 2004a). An additional potential source for particulate matter is the South Canal (Vélez et al., 2006), a storm water canal located 11 km upstream of the WTP Puerto Mallarino, that discharges into Cauca River. This canal also collects industrial and domestic wastewater, and leachate from a closed landfill.

The basin of the Palo River has also been suffering from continuous soil deterioration (Cifuentes, 2014). Moreover, large sugar mills are located in the lower Palo River basin, in addition to food and beverage processing industries, paper-manufacturing factories and other factories installed in the industrial and commercial Parks (Cifuentes, 2014; Mora and Durán, 2006). In this area, there are also semi-permanent agricultural activities such as the cultivation of sugar cane, corn, soybeans and sorghum. The middle and upper basins of the Palo River are characterized as agricultural areas with traditional cultural farming practices. In the middle and lower basin, the surface water is affected by progressive industrial and domestic discharges, the slums situated around the river, extensive and intensive agricultural activities and cattle breeding activities along its entire basin (Cifuentes, 2014). In Table 4.1 a systematic overview of the potential sources of particulate matter in the Upper Cauca River and the Palo River is presented, with its characteristics.

Table 4.1. Systematic overview of potential sources of particulate matter

Source	Compounds	Seasonal
Agriculture	Sand, silt, clay, organics, phosphates, nitrates, microorganisms	higher during / after rain higher during harvest
Deforestation	Sand, silt, clay	higher during / after rain
South Canal	Organics, sand, silt, clay, heavy metals	higher during / after rain
Industrial and domestic waste water	Organics, heavy metals	lower during / after rain
Mining	Sand, silt, clay, ferric oxides, heavy metals	higher during / after rain
Construction / urbanization	Sand, silt, clay	higher during / after rain
Illegal slums on riverbanks	Sand, silt, clay, organics, phosphates, nitrates	lower during / after rain
River sand exploitation	Sand, silt, clay	lower during / after rain
Forest fires and/or burning	Sand, silt, clay, organics	higher during / after rain
Natural disasters	Sand, silt, clay, ferric oxides	higher during / after rain

As can be seen from Table 4.1, inorganic materials such as sand, silt and clay particles are expected to be the main compounds contributed from all the different sources identified. Only industrial and domestic wastewater are not expected to contribute to their contents. The contribution from each source towards a particular compound is expected to be seasonally-dependent due to the variable effect of precipitation on the release and/or dilution of the compounds. Thus, while a lower contribution to the heavy metal concentrations from industrial and domestic wastewater discharges are expected to be found during rainy conditions due to dilution processes, a higher contribution may be expected from the South Canal under the same conditions due to the resuspension of deposited sediments containing sediment-bound heavy metals (first flush effect).

4.3.2 Seasonal fluctuation of turbidity and TSS

Both the dry and rainy seasons were characterized by lower than average precipitation (Cenicaña, 2014). The sampling points in the Cauca River (at 20% depth (P1) and at 80% depth from surface (P2)) showed a substantial strength of agreement (McBride, 2005), where, with a sample size of 13, the concordance correlation coefficient was 0.98 and 0.99 for turbidity and TSS, respectively. This indicates a well-mixed water mass at the measuring point at WTP Puerto Mallarino, and therefore the samples at different depths were further considered as duplicates.

There was a considerable difference in the turbidity and TSS values between the dry and rainy seasons for both rivers as demonstrated by the higher turbidity and TSS values during the rainy season than during the dry season (Figure 4.3). During the dry season the turbidity ranged between 24 and 107 NTU in the Cauca River, and between 28 and 131 NTU in the Palo River. During the rainy season the turbidity ranged from 32 to 465 NTU in the Cauca River and from 70 to 840 NTU in the Palo River. The turbidity and TSS peaks were thus higher in the Palo River than in the Cauca River.

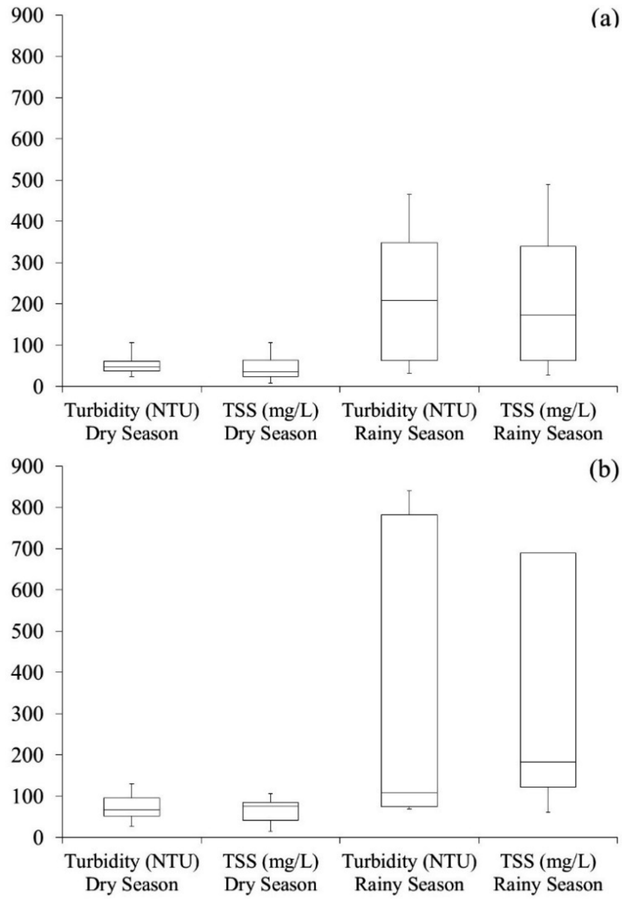

Figure 4.3. Boxplots of turbidity and TSS in Cauca River (a) and Palo River (b). The line through the middle is the median value. The top and bottom lines correspond to the 75th and 25th percentile, respectively. The whiskers extend to the minimum value at the bottom and the maximum value on top

River discharges were monitored, obtaining relatively constant values during the monitoring campaign for both rivers (116 to 255 m^3/s, with a mean of 150 m^3/s for the Cauca River; 33 to 73 m^3/s, with a mean of 43 m^3/s for the Palo River). Pearson correlation coefficient, r, was determined between river discharges and turbidity and TSS, finding a weak relationship for both rivers (0.53 for turbidity and 0.59 for TSS in the Cauca River; 0.31 for turbidity and 0.27 for TSS in the Palo River).

4.3.3 Turbidity and TSS relation

Turbidity was plotted against TSS data (Figure 4.4), showing similar correlations for both rivers, although scattering was observed in both rivers. This scattering was more obvious for TSS values below 100 mg/L in both rivers during the dry season (see the weak r coefficient in Figure 4.4a), displaying lower overall values of both turbidity and TSS than the found during the rainy season.

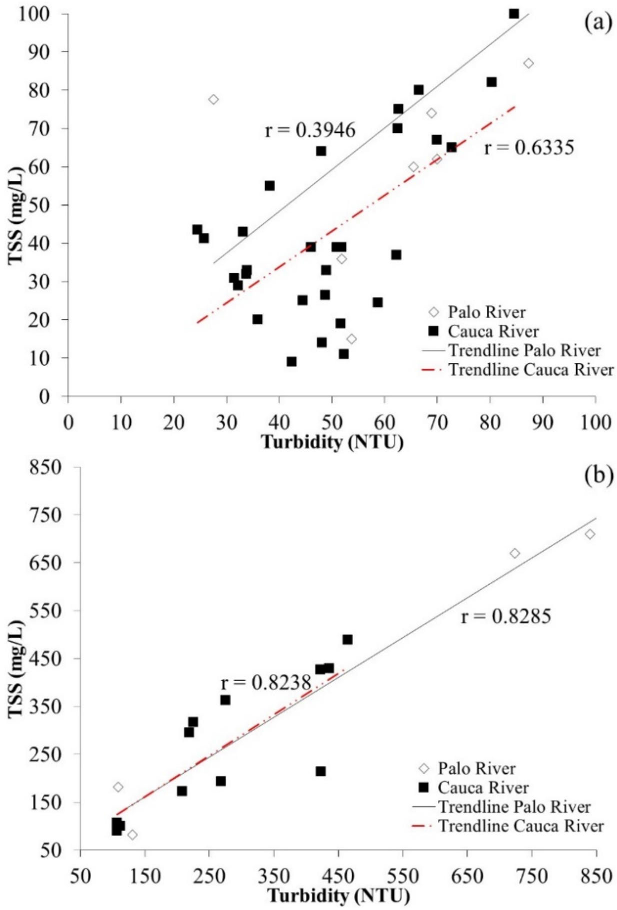

Figure 4.4. Relationship between turbidity and TSS for Cauca River and Palo River during dry (a) and rainy (b) season

For several samples high turbidity values at relatively low TSS values were observed, while during the rainy season the TSS and turbidity measurements showed a lower scatter around the 1:0.9 line, presenting the largest deviations at TSS concentrations above 250 mg/L. The TSS and turbidity parameters had a positive strong relationship during the rainy season (r=0.82). In the Palo River, only four data points above the 100 mg/L were obtained during the monitoring campaign[1].

[1] No more data could be obtained due to safety issues at the sampling site; therefore, for Palo River, it was not possible to establish an accurate relationship of turbidity and TSS at high turbidity events.

4.3.4 Particle size distribution

The relationships between TSS and particle size distribution are illustrated in Figure 4.5; only minor differences were observed between the dry and rainy seasons for both rivers. On average, TSS comprised of 5% particles smaller than 2 µm, 80% particles between 2 and 50 µm and 15% of particles between 50 and 250 µm, for both rivers.

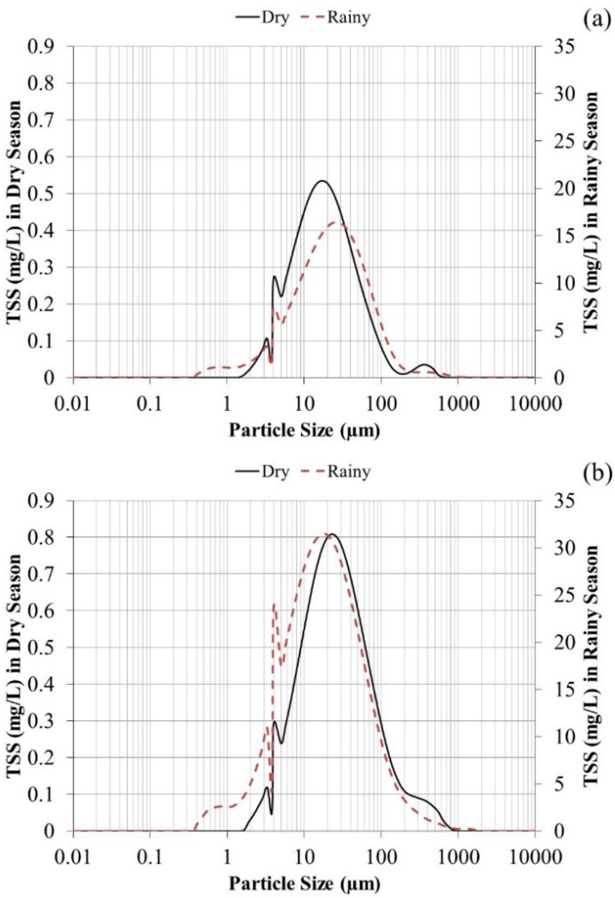

Figure 4.5. TSS distributed by particle size for: Cauca River during dry and rainy season (a) and Palo River during dry and rainy season (b)

For both rivers, a slightly higher content of fine particles (< 2.0 µm) was observed during the rainy season than during the dry season. In addition, Figure 4.5 shows a wider right tail in the Palo River (b) than in the Cauca River (a), indicating that TSS in the Palo River also contained particles with a larger size than the ones found in the Cauca River.

4.3.5 Analyses of water samples

Volatile suspended solids

Figure 4.6 presents the VSS fractions found in the Cauca River in 70 samples, classified in relation to TSS ranks. For all TSS ranks the volatile fraction is lower than the fixed fraction. However, differences in fractions among ranks can be observed. For TSS > 100 mg/L (i.e. rainy events), the volatile fraction represented about 28% of the TSS, while for lower TSS values (i.e. dry events), the volatile fraction was around 40% of the TSS. A considerable scattering was observed for all the TSS ranks (STD close to 0.11, 0.12 and 0.20 for TSS < 50 mg/L, 50 mg/L < TSS < 100 mg/L and TSS > 100 mg/L, respectively).

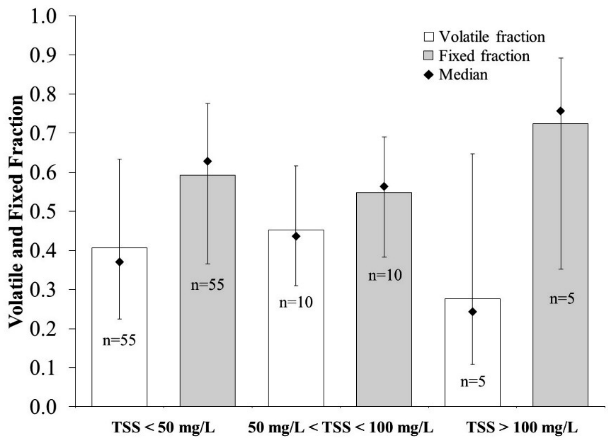

Figure 4.6. VSS fraction related to TSS. The top line of the bar is the arithmetic mean of the samples. The point represents the median value. The whiskers extend to the minimum value at the bottom and the maximum value at the top

Iron and phosphate

Fe^{3+} concentrations were constant during the dry period until an intense rain event altered the iron concentration in both the Palo River and the Cauca River. The Fe^{3+} concentrations were 1.97 to 8.85 mg/L for the Cauca River, and 2.38 to 6.10 mg/L for the Palo River, respectively, and consistent during the study. Figure 4.7 shows that at higher TSS concentrations, also higher Fe^{3+} concentrations were measured in both rivers and for high TSS values (> 100 mg/L) a broader range of Fe^{3+} concentrations was measured.

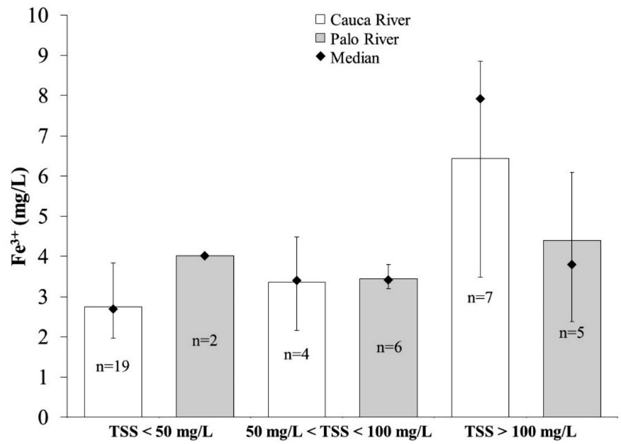

Figure 4.7. TSS and non-soluble iron. The top line of the bar is the arithmetic mean of the samples. The point represents the median value. The whiskers extend to the minimum value at the bottom and the maximum value at top

Phosphate concentrations also increased with increasing TSS (Figure 4.8). During both the dry and rainy seasons for both rivers, phosphate concentrations exceeded the usual values in surface waters under natural conditions (0.005 - 0.02 mg/L; UNESCO, 1996). For the Cauca River, phosphate concentrations ranged between 0.05 to 1.21 mg/L, exceeding the values reported in a previous study (0.04 – 0.08 mg/L; CVC and Universidad del Valle, 2004). For the Palo River, it ranged from 0.22 to 3.90 mg/L. At TSS > 100 mg/L, thus much higher concentrations were found in the Palo River than in Cauca River.

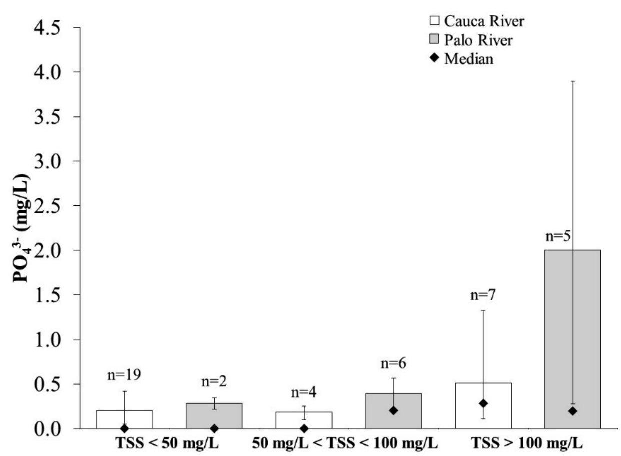

Figure 4.8. TSS and phosphate. The top line of the bar is the arithmetic mean of the samples. The point represents the median value. The whiskers extend to the minimum value at the bottom and the maximum value at top

Other water quality parameters

COD values found in this study were 103 to 160 mg/L for the Cauca River and 124 to 179 mg/L for the Palo River, respectively. In the Cauca River, N-NO_3 concentrations were found between 2.5 and 11.0 mg/L for dry conditions, and 4.5 and 11.0 mg/L during the rainy season. While, in the Palo River values were measured between 1.3 and 10.0 mg/L for dry conditions and ranging from 6.1 to 9.7 mg/L during the rainy season. Thus, no considerable differences in N-NO_3 concentrations between both rivers were observed, only some differences between both seasons in the Palo River.

Chl-a data were quite irregular without showing a clear trend (1550 to 8100 µg/m^2 in the Cauca River; 920 to 5960 µg/m^2 in the Palo River). True color measurements ranged from 29 to 155 TCU and 17 to 191 TCU in the Cauca River and the Palo River, respectively. These values also correspond to the ranges found during the dry season (29 to 155 TCU for the Cauca River and 17 to 191 TCU for the Palo River). During the rainy season, values varied from 57 to 124 TCU in the Cauca River and from 33 to 121 TCU in the Palo River.

4.3.6 Analyses of solids' samples

Physical properties of particulate matter

The collected suspended sediments during the rainy season contained more clay than during dry season, 4.24% (SD 1.19) and 0.57% (SD 0.38), respectively. In addition, the collected suspended sediments had a higher specific surface area during the rainy season than during the dry season, 0.62 m^2/g (SD 0.11) and 0.38 m^2/g (SD 0.06), respectively. The sediments collected during the dry season characterize as low-plasticity silt, whilst the sediments collected during the rainy season characterize as high-plasticity silt, as defined by the Atterberg limits (Table 4.2). Slightly organic sediments (< 5% w/w) were found in both seasons. A higher CEC was found during the rainy season.

Table 4.2. Physical properties of particulate matter in the Cauca River

	Clay (%)	LL (%)	PL (%)	PI (%)	CEC (meq/100 g)	SOM (g/kg)
Dry conditions	0.57	45.8	30.3	15.5	16.4	45
Rainy conditions	4.24	60.7	34.7	26.0	23.3	47

LL: liquid limit; PL: plasticity limit; PI: plasticicy index; CEC: cation exchange capacity; SOM: soil organic matter

Sediment mineralogy

In Table 4.3, the mineralogy for suspended sediments collected during dry and rainy events is presented. The main primary minerals identified in the suspended sediments were quartz, muscovite and albite. The secondary minerals were clinochlore, pargasite and chlorite. In the suspended sediments collected during the rainy season also kaolinite and montmorillonite were identified. The latter three minerals are usually present in clay-sized particles (Prandel et al., 2014; USDA, 1999).

Table 4.3. XRD analysis results for minerals present in Cauca River suspended sediments

Sediment	Compound	Formula
Dry conditions	Quartz	SiO_2
	Albite, calcian, ordered	$(Na, Ca) Al(Si, Al)_3O_8$
	Chlorite	$Mg4.54\ Mn0.01\ Fe0.46\ Al2.12\ Si2.86\ O_{10}(OH)_8$
	Muscovite 2M	$KAl_3Si_3O_{10}(OH)_2$
	Clinochlore, ferroan, heated, oriented	$(Mg, Fe, Al)_6\ (Si, Al)_4O_{10}(OH)_8$
	Pargasite	K0.4 Na0.5 Ca1.8 Mg2.9 Ti0.4 Fe1.3 Al2.5
Rainy conditions	Quartz	SiO_2
	Albite, calcian, ordered	$(Na, Ca) Al(Si, Al)_3O_8$
	Kaolinite-montmorillonite	$Na0.3\ Al_4\ Si_6\ O_{15}(OH)_6 \cdot 4H_2O$
	Chlorite	$Mg4.54\ Mn0.01\ Fe0.46\ Al2.12\ Si2.86\ O_{10}(OH)_8$
	Muscovite 2M	$KAl_3Si_3O_{10}(OH)_2$
	Clinochlore, ferroan, heated, oriented	$(Mg, Fe, Al)_6\ (Si, Al)_4O_{10}(OH)_8$
	Pargasite	K0.4 Na0.5 Ca1.8 Mg2.9 Ti0.4 Fe1.3 Al2.5

Sediments' speciation

The speciation analysis realized with XRF is presented in Table 4.4. Both suspended sediments from the dry and rainy seasons, and riverbed sediments, are primarily comprised of silicon dioxide, representing sand particles. Alumina and ferric oxides represent the second and third fraction in both sediments, respectively. No significant differences between the composition of the suspended sediments and riverbed sediments were found. Most of the elemental concentrations in the three types of sediments were similar. Only the Na concentration in the riverbed sediments corresponded to the concentrations found in the suspended solids from the dry season and the Mg concentration corresponded to the rainy season suspended solids. In the suspended sediments Pb and Cr concentrations of 93 and 205 μg/g, respectively were obtained, whilst in the riverbed sediments these metals were not detected. Mg concentrations were seasonally variable, showing that during the dry season the concentration in the suspended sediments doubled compared to the concentrations found in the rainy season. P concentrations in the sediments remained seasonally constant.

Table 4.4. Elemental composition of suspended and riverbed sediments

Element	Suspended sediments				Riverbed sediments (n=2)	
	Dry season (n=3)		Rainy season (n=3)			
	µg/g	%	µg/g	%	µg/g	%
Si	258,399	48.87	257,371	49.04	278,078	54.68
Al	123,686	23.39	137,553	26.21	91,031	17.90
Fe	65,956	12.47	70,712	13.47	51,968	10.22
Mg	24,423	4.62	13,810	2.63	13,267	2.61
Ca	18,868	3.57	16,509	3.15	23,299	4.58
Na	11,796	2.23	6,677	1.27	11,425	2.25
K	12,867	2.43	7,969	1.52	15,524	3.05
Ti	7,132	1.35	7,252	1.38	5,634	1.11
P	1,178	0.22	1,091	0.21	1,004	0.20
S	801	0.15	1,642	0.31	961	0.19
Mn	1,239	0.23	1,549	0.30	1,084	0.21
Ba	1,075	0.20	985	0.19	448	0.09
Zr	222	0.04	148	0.03	ND	–
Cr	205	0.04	205	0.04	ND	–
Sr	169	0.03	169	0.03	ND	–
Cl	200	0.04	300	0.06	200	0.04
Zn	161	0.03	161	0.03	161	0.03
Ni	79	0.01	157	0.03	ND	–
Cu	80	0.02	160	0.03	ND	–
Pb	93	0.02	93	0.02	ND	–
Rb	91	0.02	91	0.02	ND	–
Nb	0	0.00	ND	--	ND	–
V	ND	–	224	0.04	ND	–
C	ND	–	ND	--	14,465	2.84

4.4 Discussion

4.4.1 River discharges and/or precipitation events as particulate matter precursors

Previous studies have reported that TSS commonly depends on changes in river discharge (Meybeck et al., 2003; Susfalk et al., 2008; Ziegler et al., 2011). However, an upstream reservoir (Salvajina dam) controls the water discharge in the Cauca River; therefore, river discharges does not depend on precipitation events only, but mainly on the operation of the dam gates (Ramírez et al., 2010). Thus, in the Cauca River considerable changes in water discharges were not observed during the monitoring campaigns, despite the variations in turbidity and TSS values. Göransson et al. (2013) also reported the lack of relationship between discharge and TSS and turbidity in a regulated river system. Thus, a comparison with other tropical lowland rivers shows that the Cauca River exhibited some unusual features in its temporal patterns of turbidity and TSS values (Jansson, 1992; Wu et al., 2014). Turbidity and TSS values in the Cauca River were higher than expected for tropical lowland rivers, while seasonal changes in flow were not evident. After the construction of the Salvajina´s dam, lower discharges were observed in the Cauca River, but the sediment loads have been increasing over the years, leading to the occurrence of earlier and longer turbidity peaks (EMCALI, 1987).

4.4.2 Particulate matter source

In Table 4.5 the expected origins of the different measured parameters are described, also in relation to literature, while different scenarios of water discharge (high or low) were considered. These are further discussed in subsequent sections.

Table 4.5. Identified particulate matter sources

Parameter	Expected results								Findings from this survey							
Source	River Discharge	TSS-Turbidity	True Color	PO_4^{3-}	$N\text{-}NO_3$	COD	Fe^{3+}	PSD	River Discharge	TSS-Turbidity	True Color	PO_4^{3-}	$N\text{-}NO_3$	COD	Fe^{3+}	PSD
Natural erosion - Riverbank erosion (shear stress forces)	High	+	+	-	-	-	-	+								
	Low	-	-	-	-	-	-	-								
Human-induced erosion - Deforestation - Agriculture	High	-	-	-	-	-	-	-	High	+	+	+	+	+	+	-
	Low	+	+	+	+	+	+	-								
Mining	High	+	+	-	-	-	-	+								
	Low	+	+	+	+	+	+	+								
Point discharges - Industry - Domestic wastewater	High	-	-	-	-	-	-	-	Low	+	+	+	+	+	+	+
	Low	+	+	+	+	+	+	-								

+: increase -: decrease

Note: No measurements were realized in the different sources mentioned; therefore, the findings at the right side of the table correspond to data measured in the Cauca River and Palo River during rainy season (high) and dry season (low)

Natural erosion

As pointed out by different authors, the relationship between turbidity and TSS is watershed specific, but is generally strong (Gippel, 1995; Lewis et al., 2002; Packman et al., 1999; Susfalk et al., 2008; Wu et al., 2014). The weak relationship between turbidity and TSS suggests the presence of suspended colored organic compounds interfering with turbidity measurements, which is supported by the high true color values found in both rivers and the relatively high VSS percentages (Gippel, 1995; Packman et al., 1999). This is generally found in lentic water bodies like bogs, wetlands, and lakes with high concentrations of decaying vegetation in the water (Furukawa et al., 2014; Mitchell and Prepas, 1990; Volk et al., 2002). The presence of colored organic compounds may be associated with the effect of the Salvajina´s dam, leading to the accumulation of organic matter because of the stagnant phase in the dam (Nadon et al., 2015). These particles remain in suspension as wash load once the stored water is delivered to the river. The larger particle sizes found in Palo River may be a consequence of the higher velocities leading to higher shear stress forces in the Palo River able to re-suspend larger particles from the river bottom.

The geological formations involving the Upper Cauca River basin are presented in the Figure 4.9. The Arquía complex is comprised by dunites, amphibolites and metagabbro, and shale. Mineralogically contains olivine, metal minerals, plagioclase and quartz (López et al., 2009; Rodríguez and Arango, 2013). The Cajamarca complex is embraced by shale and quarzites. The Quebradagrande complex contains igneous, volcanic, pyroclastic rocks. Mineralogically contains pyroxene, clinopyroxene (augite), glass, plagioclase (andesine - labradorite) and olivine. The alteration minerals are zeolite, carbonates, uraite, epidote, chlorite, saussurite (López et al., 2009).

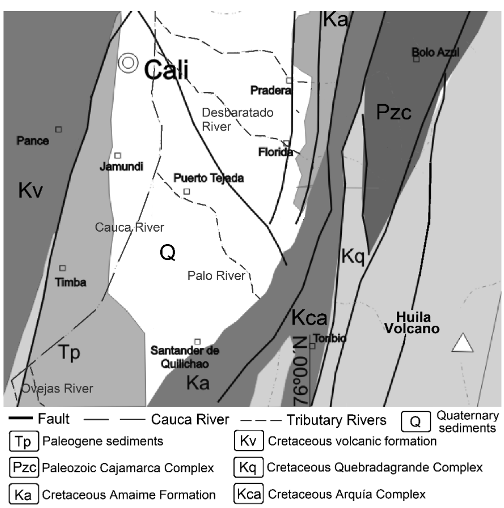

Figure 4.9. Geological formations comprising the Upper Cauca River basin

Source: Modified from López et al. (2009)

The mineralogy of the geological formations corresponds to the minerals found in the XRD analysis (Table 4.3) in the suspended sediments during both the dry and rainy seasons, which supports the Mg and Fe (Table 4.4) mineral silicates represented by the chlorite, clinochlore and pargasite, and with plagioclase represented by the albite. The shale may contribute to the clay content observed in Table 4.2, which is represented by the kaolinite and montmorillonite found during the rainy season (Table 4.3).

Human-induced erosion

In the Cauca River basin, the main anthropogenic sources of sediments to waterways are likely to be land clearing and degradation from over grazing and a loss of soil cover associated with extensive scale cropping. Also, people, migrating to forest frontiers due to forced displacement (slums), have caused deforestation because of forest burning and clearing for subsistence (Conpes, 2009). Therefore, the suspended sediment variations in the river are probably due to eroded soils caused by precipitation events in both the catchments of both rivers.

The phosphorus concentrations in the sediments collected during both the dry and rainy seasons were alike (Table 4.5), showing similar values to the reported ones in areas where intense agricultural activities have been developed (Ballantine et al., 2008; Owens and Walling, 2002). Ballantine et al. (2008) reported a lack of consistency between the seasonal variability and the phosphorus data measured in their study, stating that phosphorus content increases content in river sediments as agricultural activities were more intensive in the catchment areas. The contribution of agricultural practices is supported by the link between phosphates and TSS (Figure 4.8). The higher phosphate concentrations found in the Palo River at higher TSS values (TSS > 100 mg/L) may be due to both the extensive and intensive agricultural practices in the Palo River basin, having as a result that large areas of bared soils, containing phosphates from fertilizers, are washed out during the first rainfall events. In the Cauca River, lower phosphate concentrations were observed at TSS > 100 mg/L than in the Palo River, due to the lower degree of agricultural activities per land surface and to the higher dilution capacity of the Cauca River associated to its higher flow.

Nitrate concentrations values (2.5 to 11.0 mg $N\text{-}NO_3$/L) measured in the Cauca River were much higher than the values reported by CVC and Universidad del Valle (2004) during a ten-year measuring period (1993 to 2003). In that period, $N\text{-}NO_3$ concentrations ranging from 0.1 to 0.4 mg $N\text{-}NO_3$/L were observed near WTP Puerto Mallarino. In the Palo River $N\text{-}NO_3$ concentrations were measured ranging from 1.3 to 10.0 mg $N\text{-}NO_3$/L, indicating a considerable deterioration of the Cauca River basin. The measured values are common in contaminated rivers and river catchments affected by agricultural activities (Meybeck, 1982; Mitchell et al., 2009). As observed in Table 4.5, the nitrate concentration is expected to decrease as water discharge increases due to dilution. However, during this survey a similarity was observed in values obtained in Cauca River for both seasons, suggesting an increase in nitrate discharges entering into the Cauca River as the river discharge increases, mainly associated to runoff containing soil-bound nitrate. As stated in other studies, agricultural coverage have a significant influence on both TSS and nitrate-N, predominantly during rainy periods (Ahearn et al., 2005; Buck et al., 2004; Chu et al., 2013).

In the Palo River, the differences between seasons in nitrogen to phosphorus (N:P) ratio indicates that during shower events the phosphorus concentration migrating from the catchment to the river increased considerably, decreasing the molar N:P ratio (24:1 for dry conditions and 18:1 for rainy conditions respectively in the Palo River). The variation between seasons in the Palo River may be attributed to the infrequent rain events leading to the soil loss from the catchment having a higher phosphorus than nitrate content (Figure 4.8). The Chl-a results indicate, according to Mitchell and Prepas (1990), a low presence of phytoplankton and/or algae in both surface waters. The development of phytoplankton and/or algae may be limited by the turbidity (Correll, 1999; Hecky and Kilham, 1988; Skidmore et al., 1998), affecting the light intensity and/or light quality, and by the effect of turbulent mixing of the rivers inhibiting its growth (Hondzo and Lyn, 1999; Smayda, 2002), supported by the similar turbidity and TSS values at different depths in the Cauca River. Although the N:P in both seasons exceeds the Redfield ratio (16:1) (Hecky and Kilham, 1988), the high phosphorus and nitrate concentrations found in both rivers during both seasons indicate that both parameters cannot be pointed out as a limiting nutrient for algal growth (Correll, 1999).

Although a weak relationship between TSS and turbidity was obtained, a similarity in slopes of the two relationships of both rivers was found. This indicates that the sources of suspended solids of the Cauca River and the Palo River were related in both rivers (Lewis et al., 2002), where smaller particles (< 2.0 μm) were found during the rainy season (see Figure 4.5). The slightly higher content of colloidal particles during the rainy season (Figure 4.5) may be due to changes in vegetation coverage and decomposed organic matter in the runoff and to the resuspension of the cake layer deposited onto the riverbed. Higher true color values were observed in the Palo River, associated to the higher concentration of colloidal particles found in the Palo River.

The higher non-soluble iron concentrations found at high TSS values, where higher water discharges occurred, also suggests a contribution of deforestation and agriculture activities to suspended particulate matter in the river. In the Cauca and Palo rivers, a relation between iron concentrations and TSS was found during both seasons (Figure 4.7), which is supported by the orange-brown coloration of the river waters. The presence of iron in both rivers can be explained by the orange-brown coloration of the soils in the Upper Cauca River and the Palo River basins, indicating the existence of iron oxide minerals (Bastidas-Obando and Carbonell, 2010; Kritzberg and Ekström, 2012). Although literature has, to the authors' knowledge, not reported relationships between turbidity and non-soluble iron in rivers, Riera and Armengol (1995) stated a strong relationship between both parameters in reservoirs associated with mineral particles, suspended sediments and detrital organic matter due to inputs from the watershed.

Mining

Although other heavy metal concentrations were not measured during this survey, the increase of TSS-turbidity during shower events may also be related to legal and illegal mining activities and the removal of dragging materials (Ekstrand et al., 2009; Universidad del Valle and UNESCO-IHE, 2008). Open-pit and underground mining activities in the Palo River basin, and other sub basins draining to the Cauca River, has been identified to be developed, leading to soil degradation and an augmentation in the turbidity levels in some of the tributary rivers (Conpes, 2009). The high aluminum and iron concentrations found in both dry and rainy conditions (Table 4.4), indicate an important contribution from mining activities to the particulate matter content in the Cauca River. Gischler (2005) reported releases of aluminum hydroxide and iron to the Jamundí and Claro Rivers, tributaries to the Cauca River, due to bauxite and coal extraction in the basin of both rivers. As stated by Gischler (2005), the orange-brown color of the Cauca River has the same color as the clay where the bauxite is found. However, it is expected that the contribution of mining to particulate matter found in the Cauca River is negligible based on the scale of mining activities compared to the agricultural practices. This is also supported by the weak influence of river discharge, on e.g. non-soluble iron concentrations, expecting lower concentrations at higher river discharges in case of excessive mining activities (see Table 4.5).

Point discharges

In the Cauca River, higher COD values were found during the rainy season than during dry season, due to the effect of the so-called South Canal on the Cauca River. COD values found in this study were 103 to 160 mg/L for the Cauca River and 124 to 179 mg/L for the Palo River, respectively. The values were much higher than the typical values reported earlier (CVC and Universidad del Valle, 2004a; Reyes, 2009). As pointed out by CVC and Universidad del Valle (2004), COD concentrations in the Cauca River usually range between 10 and 30 mg/L. According to the report by Reyes (2009), COD values in the Palo River have ranged between 4.7 and 33 mg/L. Storm water, transported by the South Canal, carries domestic and industrial wastewater discharges, and leachates from the already closed landfill of the city of Cali. In addition, large amounts of sediments are deposited on the canal bottom. During rainy events, resuspension of the deposited sediments, containing contaminants, occur (first flush effect), showing important modifications in water quality at the Cauca River once shower events occur (Galvis et al., 2014). The first flush effect has been recognized as an important contributor to sediment peaks during strong rainy events (Universidad del Valle and UNESCO-IHE, 2008; Vélez et al., 2006). During the rainy season, low river discharges existed because of the operation of the Salvajina´s dam diminishing the dilution capacity of the contaminants washed out from the South Canal to the Cauca River. Gischler (2005) reported chromium concentrations in the South Canal of 94.9 µg/g, while the concentration measured in the suspended sediments during both the dry and the rainy seasons was 205 µg/g (Table 4.4). The effect of the South Canal was only expected during the rainy season. However, also chromium and lead concentrations were found in suspended sediments in both seasons. This indicates that the influence of the South Canal on the particulate matter composition is rather small. Further studies must be conducted in order to establish the sediments and contaminants contribution of the South Canal to the Cauca River.

4.5 Conclusions

The particulate matter concentration has been considered as a key parameter for drinking water treatment. Considering the importance of the Cauca River for the water supply of Cali, Colombia, the composition of the particulate matter in this river was studied. Characterization of the particulate matter in the Cauca River has shown that the TSS did not depend on river flows, but merely on precipitation events in the Cauca and Palo river basins due to the erosion of soils. Nevertheless, a high scattering was obtained between TSS and turbidity values in both rivers, potentially due to the different sources contributing to both parameters, such as color and particle size. A similar particle size distribution was found during the dry and rainy season for both rivers, having a slightly higher content of particles smaller than 2 µm during rainy conditions due to changes in vegetation coverage and decomposed organic matter in the runoff. In the Palo River, larger particle sizes were found than in the Cauca River due to the higher velocities registered in Palo River, which has a consequence for the shear stress forces able to re-suspend larger particles. Non-soluble iron was found to correlate well with the TSS load in the Cauca River, also pointing out the importance of erosion of soils during shower events. At high TSS values also higher concentrations of phosphate were found in the Palo River, where extensive and intensive agricultural practices exist. In Cauca River, lower phosphate and nitrate concentrations were observed, potentially due to the extensive and intensive agricultural practices in the Palo River basin, leading to large areas of bared soils containing nutrients from fertilizers. Mining activities were found to have a minor contribution to particulate matter in the rivers, also based on the scale of mining activities compared to the agricultural practices. Although the South Canal has been considered to have an important effect on the particulate matter content in Cauca River during precipitation events, this study suggests a small contribution. However, further studies analyzing the temporal suspended sediment carried by the canal and its elemental composition must be conducted.

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CHAPTER 5

NATURAL RECOVERY OF INFILTRATION CAPACITY IN SIMULATED BANK FILTRATION OF HIGHLY TURBID WATERS

"Eventually, all things merge into one, and a river runs through it. The river was cut by the world's great flood and runs over rocks from the basement of time. On some of the rocks are timeless raindrops. Under the rocks are the words, and some of the words are theirs. I am haunted by waters"

Norman Maclean, A River Runs Through It and Other Stories

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5 Natural recovery of infiltration capacity in simulated bank filtration of highly turbid waters

5.1 Introduction

Riverbank filtration (RBF) is a surface water treatment method for drinking water, using extraction wells located near the river in order to ensure direct aquifer recharge. As the surface water travels through the sediments, contaminants, such as pathogenic microorganisms, are removed (Schubert, 2003). RBF systems, like other filters, are, to some degree, vulnerable for clogging. Suspended particles in river water can affect the hydraulic conductivity of the bed and limit aquifer recharge (Caldwell, 2006). Streambed clogging may occur on the surface (external clogging) or within the porous media (internal clogging). Experience from the Netherlands has suggested that streambeds primarily consisting of gravels are at a far greater risk of clogging than those consisting primarily of finer grade materials (Stuyfzand et al., 2006). Also, the properties of the suspended particles in the river, such as particle size, affect the extent and clogging degree of the streambed and aquifer (Pavelic et al., 2011; Veličković, 2005).

External clogging corresponds to the cake build-up on the surface of the streambed due to the deposition of suspended solids, which reduces its permeability. Internal clogging, or deep bed clogging, occurs when the suspended particles enter the porous media and get stuck in the subsurface before abstraction (Du et al., 2014). Once a cake is built-up, penetration of particles into the porous media is prevented, and external – or cake clogging - rather than internal clogging will dominate (Fallah et al., 2012; Sacramento et al., 2015). Cake and deep bed clogging may also happen simultaneously (mixed clogging), caused by the movement of particles within the porous media and the accumulation of sediments in the upper layer (Du et al., 2014). With this mixed clogging, the hydraulic conductivity of the soil decreases over time, but it decreases much faster in the top layer (Du et al., 2014). Cake clogging may be reversible, but this is typically not the case for deep bed clogging (Pholkern et al., 2015; Seiler and Gat, 2007).

Physical, mechanical, chemical and biological clogging are the main obstruction mechanisms occurring in the streambed. The physical clogging occurs when inorganic and organic suspended solids in the river (e.g., clay, silt particles, algae cells, microorganisms, flocs) become trapped in the streambed pore channels as water flows from the river and through the aquifer (Bouwer, 2002; Caldwell, 2006; Hubbs, 2006a; Pavelic et al., 2011; Schubert, 2002).

Particle size distribution and suspended solids concentration in the river water are considered the main factors affecting the physical clogging process (Blaschke et al., 2003; Bouwer, 2002; Pavelic et al., 2011; Platzer and Mauch, 1997). Mechanical clogging refers to air entrainment during recharge from vadose zone to the phreatic aquifer or gas binding from microbiological activities (e.g., methane) (Martin, 2013). Chemical clogging is the loss of hydraulic conductivity of the streambed due to the precipitation of initially soluble water constituents, due to changes in redox potential and pH values caused for example by mixing with native groundwater (e.g., carbonate precipitates, iron hydroxides) (Bouwer, 2002; Caldwell, 2006). The accumulation of precipitates in pores might lead to chemical clogging in the aquifer and nearby the abstraction well (Schubert, 2002). Biological clogging is caused by the accumulation of bacterial cells in the streambed (Baveye et al., 1998; Bouwer, 2002; Engesgaard et al., 2006). The growth of these bacterial cells is dependent on physical-chemical factors associated with both soil and water (Pavelic et al., 2011).

Naturally occurring flow forces may induce sufficient scouring of the streambed, thereby self-regulating the thickness of the formed cake layer and restoring its hydraulic conductivity. Vertical sedimentation forces induce the deposition of particles on the streambed. Horizontal forces onset the resuspension of the deposited particles. The extent of scouring is determined by the magnitude of the shear stress and the properties of the streambed and cake layer, deposited onto the streambed. Scouring or self-cleansing capacity of RBF systems is commonly assessed in terms of streambed particle size (considering critical shear stress) and the shear stress exerted by the river flow. Reported shear stress values typical for river streambeds range between 1 to 100 N/m^2, considering a value of 20 N/m^2 as reasonable (Hubbs, 2006b). However, van Rijn et al. (2007) reported shear stress values for individual sediments ranging from 0.08 to 0.4 N/m^2. The shear stress for the mobilization in porous media of colloidal particles, such as clay, have been reported to range from 0.1-1 N/m^2 (Manga et al., 2012; Mays, 2013). Thus, the incipient motion of sediments depends on critical shear stress, which is a function of streambed-armor layer characteristics. For particles finer than 62 µm, the critical shear stress increases as particle size decreases due to the cohesive effects (van Rijn et al., 2007).

Erosion and deposition exhibit dissimilar behavior for cohesive and non-cohesive sediments (Winterwerp and van Kesteren, 2004). Cake layers composed from the deposition of cohesive materials, carried by the rivers, will increase the resistance to erosive processes, meaning higher shear stresses to move the sediments deposited on the streambed. In addition, cohesive sediments have a different shear stress for deposition than for erosion (Krishnappan, 2007). The cake layer may affect the surface water/groundwater interaction and therefore may influence the abstraction capacity yield by altering the permeability of the streambed (Packman and MacKay, 2003). The mechanisms affecting the infiltration velocity based on the movement and settlement of particles on streambeds and the streambed–aquifer clogging are represented in Figure 5.1.

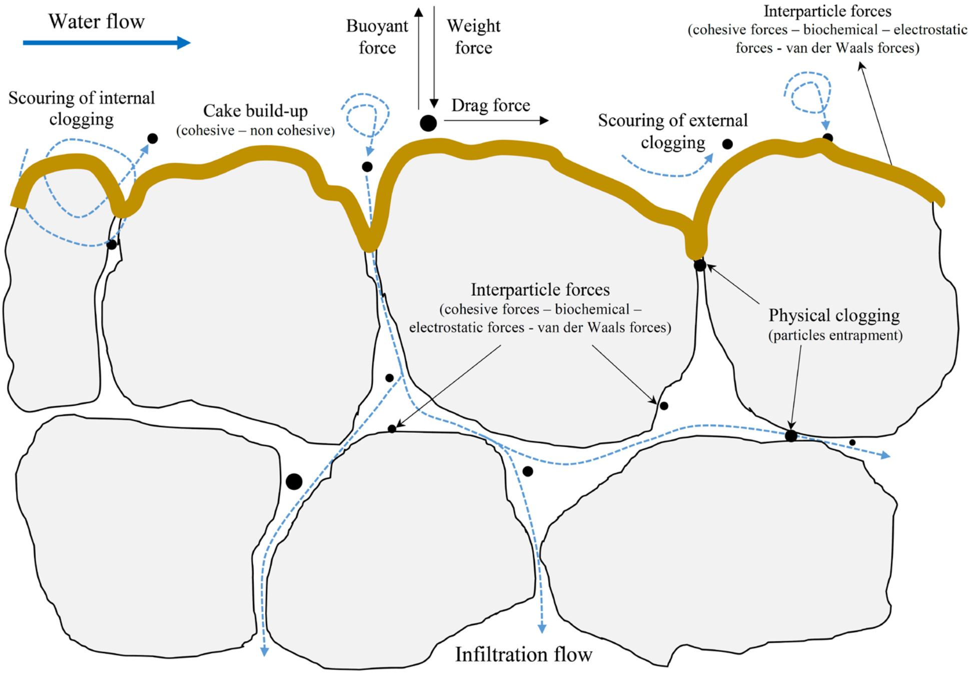

Figure 5.1. Mechanisms influencing infiltration rate related to riverbed clogging and self-cleansing processes

The streambed infiltration velocity (q) thus depends on the characteristics of the streambed sediments and the suspended sediments being transported by the river, and it is expected to vary according to the characteristics of the flow (i.e., streambed velocity and flow velocity profile across the river), leading to the deposition and resuspension of particles. The minimum shear stress, τ_c, is defined by the gravitational and cohesive forces that resist particle motion in ideal conditions. When the friction velocity on the sediment bed is greater than the threshold velocity, sediment particles on the bed will become mobilized. The variables that influence the infiltration velocity in the porous media considering the clogging and self-cleansing processes are (e.g., Cunningham et al., 1987; Wang, 1999; Winterwerp and van Kesteren, 2004; Huang et al., 2006; Pugh, 2008; Al-Madhhachi et al., 2013; Zheng et al., 2014): initial infiltration velocity (q_o), density of the fluid (ρ_w) and suspended particles (ρ_s), dynamic viscosity of the water (μ), suspended particle diameter (d_s), d_{50} particle size of the streambed media, surface water depth, bed slope, flow velocity (u), suspended particle concentration ($\emptyset_{sed}$), porosity of streambed, and particle attachment and detachment coefficients.

The main purpose of this study is to evaluate the effect of the concentration of suspended solids and different compositions of the suspension on physical clogging and recovery of the infiltration capacity by subsequent self-cleansing for highly turbid waters. To the authors´ knowledge, this has not yet been studied previously. To achieve this, physical modeling with an experimental RBF set-up was conducted in order to assess the effect of flow velocity, particle size of the streambed media, suspended particle diameter, and suspended particle concentration on the infiltration velocity during clogging and self-cleansing. Special attention was paid in this study to differentiate between cake and deep bed clogging.

5.2 Materials and Methods

5.2.1 Experimental setup

A straight tilting flume with two channels (duplicate) was used for simulation of the river flow (Figure 5.2). Infiltration columns placed at the bottom were used to determine the effect of variable shear stress conditions on self-cleansing and infiltration. The channels had dimensions of 500 cm length by 19 cm width and were constructed of smoothed wood. The lateral walls were made of wood and Plexiglas. The infiltration columns were made of transparent Plexiglas (50 cm long and 10.8 cm ID). The columns were equipped with four piezometers for the monitoring of head loss over the height of the porous media and four sampling ports (placed 10 cm from each other). The bottom of the channels was roughened by gluing 0.2-0.8 mm sand onto them, leaving the sides smooth. Flow characteristics were measured with an electromagnetic flowmeter (EM). Turbidity was measured at the different ports of the columns using a turbidity meter (HACH 2100P). The infiltration velocity ($q = Q/A$, where $Q = V/t$ and A is the area of column perpendicular to the water flow) and pressures were monitored for the duration of the experiments to assess porous media clogging and infiltration recovery. The experiments were conducted at room temperature (about 20 ^{o}C).

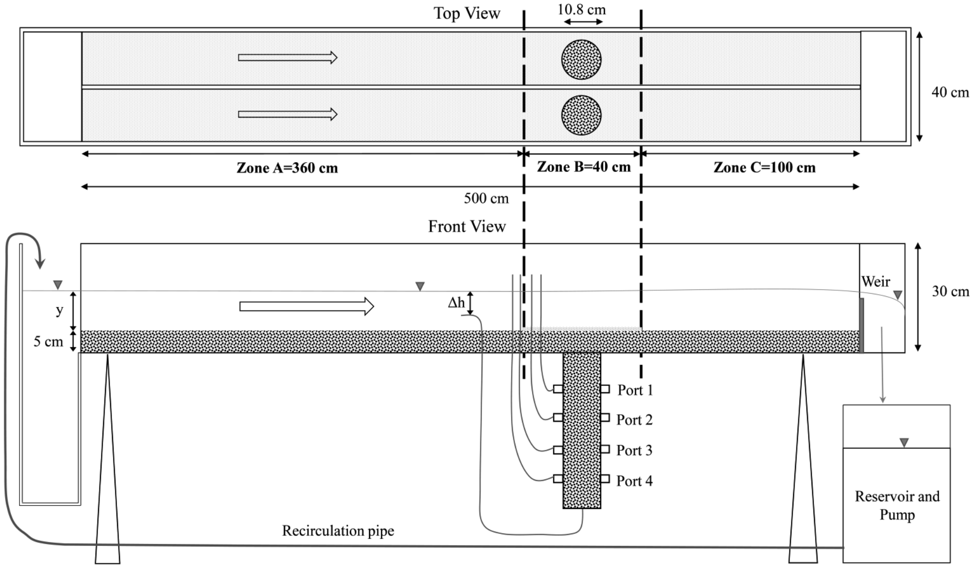

Figure 5.2. Scheme of the experimental setup

5.2.2 Sediments

Suspended sediments

The suspended sediments were selected based on characteristics of the natural sediments identified in a highly turbid river (Cauca River in Cali, Colombia) (Gutiérrez et al., 2016), where particle size distribution and specific surface was determined by wet laser diffraction instrument (Model Hydro 2000SM, Malvern). Sediment properties for dry and rainy conditions are summarized in Table 5.1.

Table 5.1. Properties of natural suspended sediments, Cauca River in Cali, Colombia (Gutiérrez et al., 2016b)

	Dry conditions (*n=18*)						Rainy conditions (*n=8*)					
	d_{s_10} (µm)	d_{s_50} (µm)	d_{s_90} (µm)	Clay (%)	SOM (g/kg)	PI (%)	d_{s_10} (µm)	d_{s_50} (µm)	d_{s_90} (µm)	Clay (%)	SOM (g/kg)	PI (%)
Mean	7.2	25.6	125.7	0.57	0.38	15.5	5.3	23.0	85.3	4.24	0.62	26.0
Min	4.8	17.9	64.1	0.23	−	−	3.8	17.2	74.7	2.88	−	−
Max	10.3	36.2	264.1	1.67	−	−	6.9	26.8	91.8	6.20	−	−
SD	1.3	4.7	55.8	0.38	−	−	1.0	3.5	5.9	1.19	−	−

SOM: soil organic matter PI: plasticity index

Considering the characteristics described in Table 5.1, the whole sample of sediments collected in the Cauca River may be regarded as inorganic - non-cohesive. Therefore, inorganic fine sediments were used to simulate the natural suspended sediments in the Cauca River: IMERYS Polwhite E clay (0.5-10 µm, d_{s_50}=3.5 µm), M300 silt from Sibelco (3-40 µm, d_{s_50}=17 µm), and S90 fine sand from Sibelco (63-180 µm, d_{s_50}=150 µm). The IMERYS Polwhite E corresponds to the clay + very fine silt subclass as classified by the American Geophysical Union.

Streambed material

Three streambed/aquifer configurations were used: (1) streambed and columns from coarse sand from Sibelco (1.0 to 1.6 mm, d_{50}=1.36 mm); (2) streambed from medium sand from Sibelco (0.2 to 0.8 mm, d_{50}=0.61 mm) and columns from coarse sand (1.0 to 1.6 mm, d_{50}=1.36 mm); and (3) streambed and columns from medium sand (0.2 to 0.8 mm, d_{50}=0.61 mm). The grain sizes were selected in order to emulate an alluvial formation based on the characteristics found in the Cauca River section next to the main water treatment plant of the city of Cali, Colombia (CVC and Universidad del Valle, 2004a).

5.2.3 Experimental procedure

The experiments consisted of two subsequent phases: (1) clogging of Zone B (see Figure 5.2 and Figure 5.3), followed by (2) scouring conditions flowing from Zone A to Zone C. The clogging experiments of the streambed in Zone B were conducted for two sediment concentrations (1 g/L and 6 g/L), an initial infiltration velocity of 6 m/d, and two streambed media (d_{50}=0.61 mm and d_{50}=1.36 mm). After packing the columns, the soil was saturated from the bottom up with tap water, which was pumped at a 2 mL/min constant flow with a peristaltic pump (Watson-Marlow Sci-Q 205S/CA). The bottom of the column was connected to a saturated tube discharging to the atmosphere at an elevation above the top of the streambed but below of the water level in the channel (Figure 5.2 and Figure 5.3).

The scouring experiments were carried out with tap water at different shear stresses. Physicochemical characteristics of the tap water used during the experiments from seven water samples were: pH = 7.9 – 8.0, ionic strength = 0.00724 ± 0.00038 mol/L and sodium adsorption ratio (SAR) = 1.216 ± 0.041. The data of the samples was provided by the water company of Delft, the Netherlands (Evides Waterbedrif). The pH of tap water used is similar to the pH found in the Cauca River (6.5 – 7.5) (CVC and Universidad del Valle, 2004b).

As mentioned before, IMERYS Polwhite E (kaolinite) was used for representing the clay fraction of the suspended sediments. For kaolinite, at similar pH and SAR conditions as the used tap water, critical coagulation concentrations of about 0.5 to 0.7 mmol$_c$/L have been reported (Goldberg et al., 1991).

Streambed critical shear stress

The shear stress is the force of moving water against the streambed of the channel ($\tau = \rho_w ghS$, where g is the gravitational force, h is the water depth in the channel and S is the water surface slope). The shear stress for incipient motion of the streambed material was determined by placing 5-cm height of the streambed material (Figure 5.2) onto the flume bottom and then moving water at different bed slopes and flows (different shear stresses) until bed movement occurred. The shear stress in the flume that resulted in bed movement was established as the critical shear stress (τ_c) for the clean streambed. A 14-cm constant water level (h) during the experiments was maintained by using an adjustable weir at the downstream end of the flume and by modifying the water discharge and the flume slope.

Clogging experiments

The turbid influent water (Figure 5.3) was pumped into the flume from a reservoir. Zone B was isolated from the rest of the flume by wooden plates in order to clog solely this region and the infiltration column. During the clogging experiments, the turbid solution in the reservoir was thoroughly mixed during the whole experiment. Additionally, the entering turbid solution in Zone B was continuously mixed by using a four-bladed propeller stirrer placed at the upper zone of the water level at a velocity fast enough to achieve a uniform particle distribution and slow enough to allow the deposition of particles and avoid the disturbance of the bed. The water level in Zone B was controlled by using a laser sensor (optoNCDT 1302).

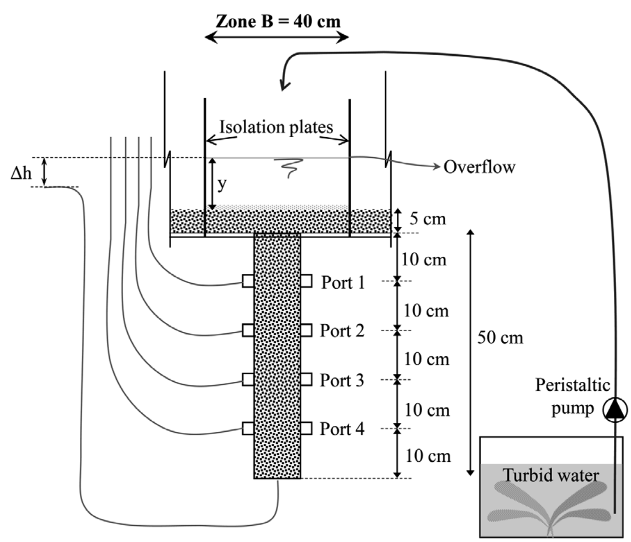

Figure 5.3. Scheme of clogging experiments

Synthetic turbid solutions were infiltrated into the columns (1 g/L and 6 g/L). An initial filtration velocity 6 m/d was used, based on values reported in the literature for RBF systems (Dawe, 2006; Hubbs, 2006a). The initial filtration velocity was achieved by maintaining a constant head (Δh) between the water level in the flume and the outlet level in the columns (Figure 5.3). In addition to the different tested concentrations, four different suspended particle sizes were used to prepare the turbid solutions: (1) clay 0.5-10 µm, d_{s_50}=3.5 µm; (2) silt 3-40 µm, d_{s_50}=17 µm; (3) fine sand 63-180 µm, d_{s_50}=150 µm; and (4) mixed clay, silt and fine sand 0.5-180 µm. The mixed material was comprised of 5% clay, 80% silt and 15% fine sand, in agreement with the composition of the sediments in the Cauca River (Gutiérrez et al., 2016).

The experiments ran for periods between 24 to 168 h, depending on the sediment concentration. The pressure was continuously monitored through the piezometers during the experiments. Water samples (15 mL) were extracted from each sampler port by using a multichannel peristaltic pump (Watson-Marlow Sci-Q 205S/CA) at a slow flow rate (1 mL/min) per channel in order to avoid disturbances of the porous media and deposited sediments. Turbidity values were determined through a portable turbidimeter (2100Q from HACH). Tap water was used to prepare the turbid solutions that were continuously stirred in order to ensure their homogeneity. The height of the cake layer was continuously measured by using a metric ruler, taped to the transparent Plexiglas wall (Zone B).

Infiltration and self-cleansing experiments

Movable bed conditions were used in Zones A, B, and C of the flume (Figure 5.2). Zone A had a 360-cm length, designed to achieve a fully-developed fluid flow. Zone B had a 40-cm length, including the 10.8-cm diameter of the column. Zone C had a 100-cm length, designed to observe the deposition and resuspension of sediments. Zones A, B, and C were covered with 5-cm of the streambed material.

Self-cleansing was assessed based on the threshold Shields parameter, θ_c, which is a non-dimensional number indicating the initiation of sediment transport in channels. The θ_c was calculated from the experimentally determined critical shear stress, τ_c, found in equation (1), and verified from the theoretical equation (2) by Soulsby and Whitehouse (1997),

$$\theta_c = \frac{\tau_c}{g(\rho_s - \rho_w)d_{50}} \qquad \text{(eq. 1)}$$

$$\theta_c = \frac{0.3}{1+1.2D_*} + 0.055[1 - \exp(-0.02D_*)] \qquad \text{(eq. 2)}$$

Where the dimensionless grain size, D_*, is defined as

$$D_* = \left[\frac{g\left((\rho_s/\rho_w)-1\right)}{(\rho_w/\mu)^2}\right]^{1/3} d_{50} \qquad \text{(eq. 3)}$$

Three Shields parameters (θ) were evaluated (approximately $0.5\theta_c$, θ_c, $2\theta_c$ depending on the bed particle size) during the self-cleansing experiments. The assessed θ values were selected based on both the experimentally determined τ_c and the calculated threshold Shields parameter for each streambed. Both, the experimentally determined (applying eq. 1) and theoretically calculated (applying eq. 2) τ_c gave values of 0.72 and 0.66 N^2/m for d_{50}=1.36 mm and d_{50}=0.61 mm, respectively. Julien (1998) reported values between 0.47-1.3 N/m^2 and 0.27 – 0.47 N/m^2 for very coarse sand (1-2 mm) and coarse sand (0.5-1 mm), respectively. In order to make the experiments comparable, three shear velocities ($u_* = \sqrt{\tau/\rho_w}$) were assessed (0.017 m/s, 0.029 m/s and 0.041 m/s), corresponding to flow velocities in the channels ($u = Q/A$, where Q is the volumetric flow in the channel and A is the transversal area to the water flow) of 0.318 m/s, 0.327 m/s and 0.342 m/s, respectively, for both streambeds considering critical Shields parameters (θ_c=0.034 and 0.031 for d_{50}=1.36 mm and d_{50}=0.61 mm, respectively). Julien (1998) reported values from 0.029 – 0.039 and 0.029 and 0.033 for very coarse sand (1-2 mm) and coarse sand (0.5-1 mm), respectively. Each streambed velocity was applied during approximately 3 hours, in order to avoid the interference from ripples and dunes formations in Zone B. Specific discharges and water pressures were monitored in the infiltration columns as indicators of clogging.

5.3 Results

5.3.1 Cake and deep bed clogging

Cake layer formation

Figure 5.4a presents the variations in the cake layer formation rate (mm cake height per suspended sediment load, mg ($Q\emptyset_{sed}t$, where t is time)) for different suspended sediment sizes, ds, and under two different suspended sediment concentrations, $\emptyset sed$.

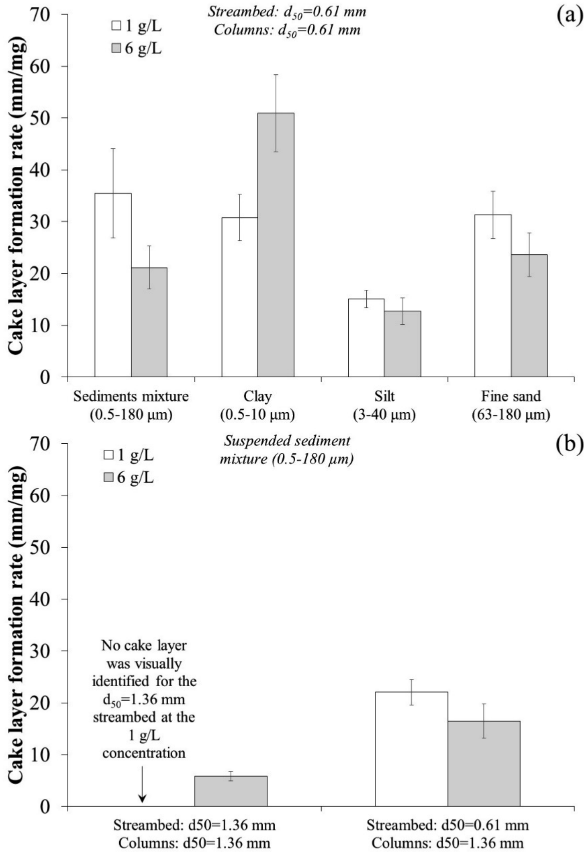

Figure 5.4. Cake layer formation rate as a function of (a) suspended sediment size and (b) streambed particle size; both for 1 and 6 g/L suspended sediment concentration. The top line represents the arithmetic mean. The whiskers extend to the standard error

From Figure 5.4a it can be observed that the fastest cake formation occurred when passing clay through the porous media. In addition, for all the suspended sediments, except for clay, a higher cake layer formation rate occurred at the lower sediment concentration. The cake layer formation rate is given as mm/mg sediment load, and therefore not related to time, which means that, although at higher sediment concentration the cake layer formation is faster the relative, contribution of passing suspended sediments to cake layer formation is smaller, except for clay.

The cake layer formation rate as a function of the streambed particle size is presented in Figure 5.4. A higher cake formation rate for the same streambed-column configuration (streambed: d_{50}=0.61 mm, columns: d_{50}=0.61 mm) than for the different streambed-column configuration (streambed: d_{50}=0.61 mm, columns: d_{50}=1.36 mm) was observed. For the large streambed particle size (d_{50}=1.36 mm), no cake layer was formed for the low sediment concentration of 1 g/L. For the fine streambed particle size (d_{50}=0.61 mm), a higher cake layer formation velocity occurred at the low sediment concentration.

Deep bed clogging

Turbidity measurements were done over the column height as indicator for assessing deep bed clogging. The values shown in Figure 5.5 correspond to the average of samples withdrawn each 3-4 h during the run of each experiment. The water containing clay particles (0.5-10 µm) presented the lowest turbidity measurements over the column heights for both sediment concentrations. For the silt-size particles (3-40 µm) at the higher sediment concentration (6 g/L), the turbidity increased as the travel distance increased. The turbidity for both sediment concentrations and both streambed particle sizes over the column height is illustrated in Figure 5.5. For the larger streambed particle size (d_{50}=1.36 mm) the turbidity was stable over the height of the column with an average of 6.3 NTU and 31.9 NTU for 1 and 6 g/L, respectively. For both sediment concentrations higher turbidity values were observed in the top 35 cm of the column with the smaller streambed particle size (d_{50}=0.61 mm) than with the larger streambed particle size (d_{50}=1.36 mm).

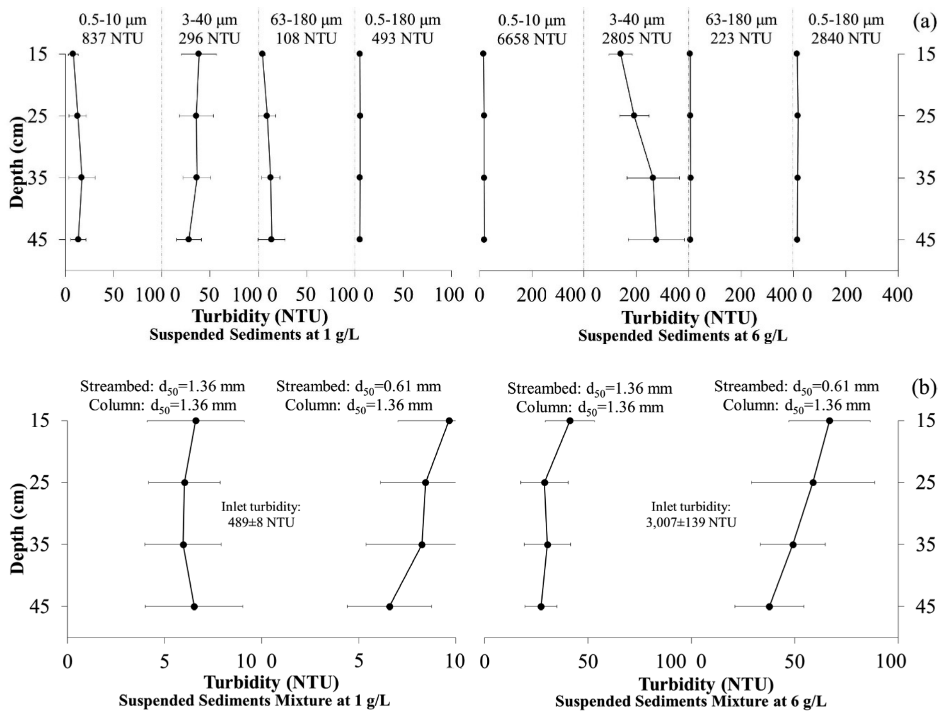

Figure 5.5. Turbidity at different column heights as a function of (a) suspended sediment size and (b) streambed size. The point represents the arithmetic mean of the samples. The whiskers extend to the standard deviation

In Figure 5.6 the permeability, *k*, changes per each segment of the columns are shown as relative permeabilities (*k* between ports divided by the clean-bed permeability, k_o) as a function of the injected sediment load. As observed in Figure 5.6, the higher permeability reduction occurred in the first 15 cm (top layer) for all the suspended sediment sizes tested, which is linked to cake clogging. This happened faster at the lower suspended sediments concentration. Deep bed clogging, represented by the permeability reduction in the lower segments, was evidenced for all sediment sizes, being higher as the particle size decreased (clay > silt > fine sand). For fine sand, the top layer was not clogged, nor deep bed clogging was observed at the higher suspended sediment concentration (Figure 5.6c). The mixture of suspended sediments presented the highest and fastest cake clogging occurrence, and the lowest deep bed clogging (except for fine sand).

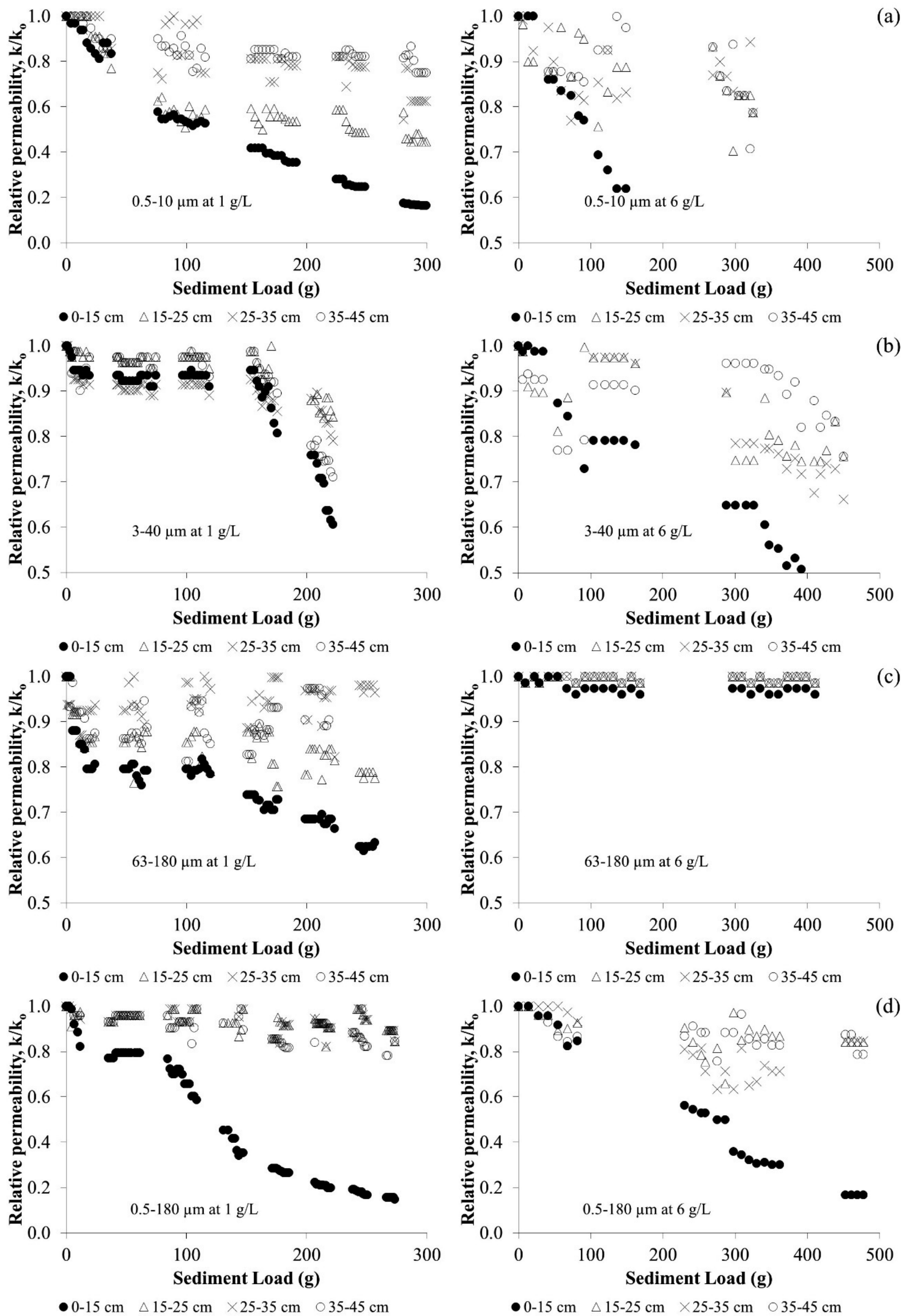

Figure 5.6. Relative permeability as a function of sediment load into (a) clay, (b) silt, (c) fine sand and (d) mixed sediments for different sediment loads of 1 g/L (left) and 6 g/L (right). Note the different relative permeability ranges featured on each axis

5.3.2 Infiltration velocity during clogging

Figure 5.7 presents the variations in the infiltration velocity for different turbid solutions in relation to the infiltrated sediment mass ($(q - q_o)/Q\emptyset_{sed}t$) (in m/d/mg). This infiltration velocity decline was higher for a sediment concentration of 1 g/L, compared to 6 g/L, apart for clay. This is in-line with the faster development of cake layer at 1 g/L (velocity expressed per sediment load). It must be taken into account that the analysis was realized using suspended sediment load instead of time to make them comparable. For fine sand, no reduction of the infiltration velocity occurred at 6 g/L, whilst a slight reduction was observed for 1 g/L.

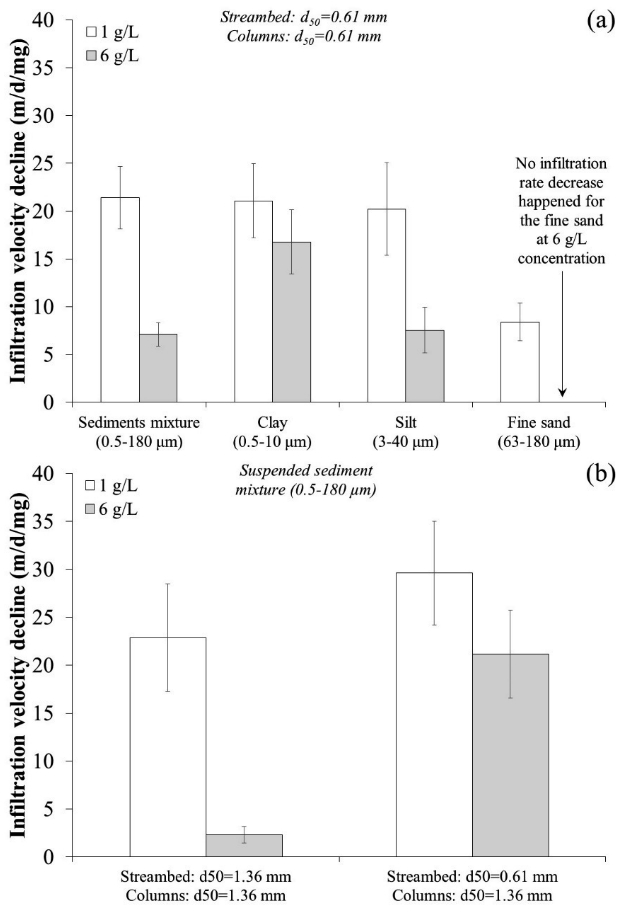

Figure 5.7. Infiltration velocity decline as a function of (a) suspended sediment size and (b) streambed particle size. The top line represents the arithmetic mean. The whiskers extend to the standard error

In Figure 5.7b, the changes in infiltration velocities are compared for two streambed particle sizes (d_{50}=1.36 mm and d_{50}=0.61 mm), where the column particle size was the same for both

(d_{50}=1.36 mm). The mixture of suspended sediments was used for this experiment. Higher infiltration velocity decline per weight of sediment load was observed at the lower sediment concentration. When comparing the infiltration velocity decline for mixed sediments in the same particle sizes for both column and streambed (d_{50}=0.61 mm) versus different particle sizes (streambed d_{50}=0.61 mm; columns d_{50}=1.36 mm), a much larger infiltration velocity decline was obtained for the different particle sizes.

5.3.3 Cake layer scouring

The removal of the cake layer by scouring forces was registered during the assessment of three Shields parameters (θ): $0.5\theta_c$, θ_c, and $2\theta_c$, compared to no flow with τ_c=0 and subsequently θ=0. The shear velocities were of 0.017, 0.029 and 0.041 m/s, respectively. The tests were conducted for the medium sand streambed (d_{50}=0.61 mm). Figure 5.8 illustrates the cake layer removal as a function of streambed velocities for the cake layers composed of different suspended sediments. For the experiments conducted with clay particles (0.5-10 µm), a relatively high removal (32-46%) of the cake layer was observed at $\theta=0.5\theta_c$. However, little additional cake layer was being removed at θ=1 and no extra removal was observed at $\theta=2\theta_c$. At the higher sediment concentration, a much thicker cake layer was formed, which also resulted in a thicker remaining clay layer after scouring (8 mm). Compared to clay, the cake layer made of silt (3-40 µm) was consistently harder to remove, though at each increased shear stress a fraction of the layer was removed. Most silt particles from the removed cake layer were re-suspended in the water, but it was also observed that silt particles were partly re-settled in the subsequent Zone C (Figure 5.2). The re-settlement suggests a potential clogging effect downstream the evaluated zone. At the same time, the newly-cleaned streambed may become clogged with material scoured upstream. For the fine sand cake layer (63-180 µm), most of the deposited sediments were easily removed at the lower streambed velocity as observed in Figure 5.8. Although, the fine sand sediments were moved from their initial position, the formation of ripples and dunes were observed in Zone C. As a consequence, scouring of the original streambed was also onset (d_{50}=0.61 mm). The cake layer formed by the mixture of sediments presented the highest resistance to erosion of all the suspended sediments assessed, with only 23-31% of the cake layer being removed.

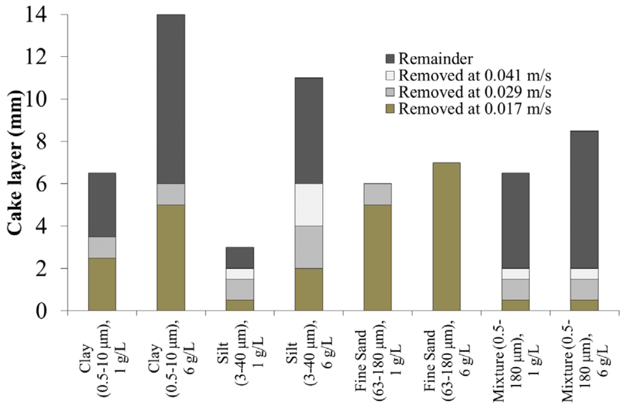

Figure 5.8. Cake layer scouring for different suspended sediment sizes

5.3.4 Infiltration velocity after scouring

Figure 5.9 compares the recovery of the infiltration velocity during the self-cleansing experiments. Relative infiltration velocities as a function of the initial infiltration velocity (q/q_0), i.e., at clean bed conditions, are shown. The results for θ_c=0 correspond to the infiltration velocity of the clogged streambed, before starting the self-cleansing experiments. In none of the experiments, independent of suspended sediment type or concentration, the infiltration velocity recovered to its initial capacity regardless of the bed shear stress applied.

Although the remainder of the cake layer after bed scouring was the thickest for the mixed suspended sediments (Figure 5.8), comparable to the clay layer, the flow velocity recovery was the highest (84-96%) for the mixed suspended sediments at both concentrations compared to the uniform suspended sediment sizes (Figure 5.9a). During the clogging experiments with the mixed suspended sediments, cake layer cracks were observed. For the lower suspended sediments concentration, the recovery was higher even if the infiltration velocity reduction during the clogging experiment was high (Figure 5.7). Though the cake layer of the largest uniform suspended sediment sizes (fine sand, 63-180 µm) was completely removed for both concentrations, no recovery of the infiltration velocity was obtained. As observed in Figure 5.9b, no differences in the infiltration recovery existed between both streambed sizes at the lower concentration. On the other hand, a higher infiltration capacity occurred for the smaller streambed size (d_{50}=0.61 mm) at the higher suspended sediment concentration, which may be explained by movement of the original streambed as cracking of the cake layer was observed.

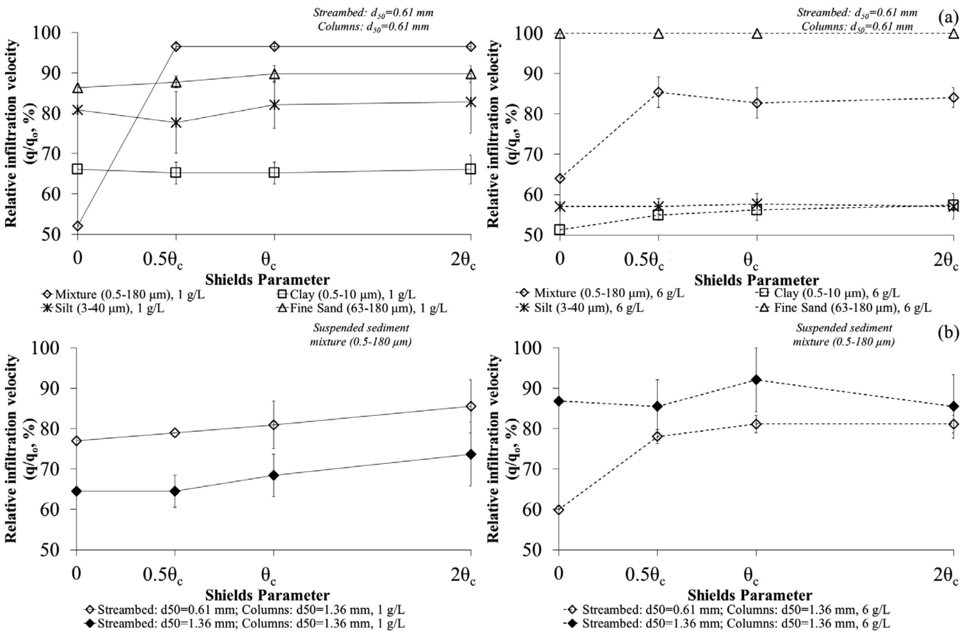

Figure 5.9. Infiltration velocity recovery as a function of Shields parameter at different clogging conditions: (a) after clogging at 1 g/L and (b) after clogging at 6 g/L. The point represents the arithmetic mean of the samples. The whiskers extend to the standard deviation

5.4 Discussion

5.4.1 Cake clogging or deep bed clogging

When comparing the different types of suspended sediments, deep bed clogging was observed most predominantly for the experiments with silt. The low cake formation velocity and the high infiltration velocity decline for silt particles at the higher suspended sediments concentration is linked to the non-cohesive nature of the silt (Winterwerp and van Kesteren, 2004), where, the weakness of physicochemical processes limits the attachment of silt particles to each other and onto the sand particles. Therefore, the entrapped particles can be easily remobilized by the water flow reaching lower layers, leading to deep bed clogging. The clay particles were found to be mostly retained in the cake layer, which may then be explained by the cohesiveness of clay particles (Krishnappan, 2007). The cohesive nature of clay leads to particles aggregation of clay sediments (floc formation), particularly at high concentrations (Klassen et al., 2013). Therefore, although both turbidity values tested during this research were high (1 g/L and 6 g/L), the findings show that the 1 g/L suspended solids led to higher cake layer formation velocities for non-cohesive particles, while 6 g/L suspended solids concentration was favorable for higher cake layer formation velocities in cohesive particles, having the opposite effect on the formation of deep bed clogging.

The suspended sediments mixture pinpoints the effect of the interparticle forces acting among the sediments (e.g., van der Waals) and the interaction between them and the bed particles, leading to larger particles with the ability to be retained on the top layer (cake filtration) due to the clay content. Also, the interaction amongst different suspended particles onsets new clogging mechanisms, e.g.: (1) entrapment and sedimentation of fine sand sediments in small voids, (2) entrapment of silt particles in existing voids and new voids because of the trapped fine sand, and (3) straining, hydrodynamic bridging and interparticle forces of clay and the retained suspended sediments (Veličković, 2005). When reviewing the cake layer and deep bed turbidity measurements (Figure 5.4 and Figure 5.5), the fine sand behaved very similar to the mixed sediments. Nevertheless, the low infiltration velocity reduction for the fine sand experiments reveals that although the cake layer may have had the same thickness, it was more permeable than is the case for mixed sediments.

Different clogging mechanisms influence the infiltration capacity reduction in relation to the streambed size. The smaller voids due to the smaller bed particle size are likely to retain more suspended sediment particles by entrapment (Winterwerp and van Kesteren, 2004). In this case mixed bed clogging occurs, where cake clogging plays the most important role in the precluding of the water passage through the media as reported for slow sand filtration (Grace et al., 2016). On the other hand, deep bed clogging is the dominant mechanism for the large streambed size. The larger voids have a larger storage capacity for particles, and then enhance the mobility of particles into the media before clogging (Veličković, 2005), favoring deep bed clogging occurrence. This behavior has been widely reported for rapid sand filtration, where suspended and colloidal particles are depth filtered (Ripperger et al., 2012). The presence of larger voids can enhance the mobility of fine particles because of the higher flow velocities leading to higher hydrodynamic forces and to the weaker interparticle bonding forces (Jacobsen et al., 1997; Reddi et al., 2000). The weak support exerted by the filling material of the columns, which, being larger than the particles of the streambed, was not able to retain the particles previously entrapped, and due to the changes in flow velocities between the transition from d_{50}=0.61 mm (streambed) to d_{50}=1.36 mm (column) contributed to sudden releases of particles.

5.4.2 Self-cleansing of cake layer

As stated by various researchers, bed scouring depends on streambed particle size (Caldwell, 2006; Stuyfzand et al., 2006). The suspended particle type has demonstrated to be the most important variable governing the self-cleansing of the streambed for an uncovered, clean streambed (e.g., absence of plants, biofilm). The initial high removal velocity found with the cake layer made of clay may be referred as entrainment and/or floc erosion. The absence of additional removal may be related to the interaction strength between the sandy bed and the mud (clay) layer due to the cohesive and adhesive characteristics of the clay, leading to a much higher erosion threshold (Jacobs et al., 2011). However, it must be noted that a recirculating flume was used during the experiments. Thus, the resuspended clay conveyed to a turbidity current, which could have affected the cake layer erodibility by the so-called hindered erosion (Winterwerp and van Kesteren, 2004). The much thicker cake layer formation obtained at the higher suspended sediments concentration highly impacted the initial scouring of the clay cake. This is related to the lower cake layer compression on the top layer and therefore a weaker strength to erosion (Mahdi and Holdich, 2013; Mays and Hunt, 2005). The non-cohesive nature of silt leads to a weak interaction between the bed and the cake layer, which is favorable for the erodibility of the cake formation. The ripples and dunes formations that occurred for the fine sand cake layer induced mass erosion of both the cake layer and the bed due to the wave-induced shear stress (Winterwerp and van Kesteren, 2004). The continuous removal but the high resistance to erosion of the cake layer made of the mixture of fine sediments is explained by the strong interparticle forces among the suspended sediments, avoiding a high resuspension velocity as observed when sediments were tested individually. Our findings indicate an important interaction between the streambed and the suspended sediment size. The smaller the bed particle size, the higher the interaction strength. This behavior is related to the stronger physicochemical forces from small particle sizes acting to preserve the particles joined.

The infiltration velocity never recovered to its initial capacity regardless of the bed shear stress assessed. An overview of cake layer removal and infiltration velocity recovery per sediment type is presented in Table 5.2. For the homogeneous suspended sediments (clay, silt, fine sand), the infiltration velocity did not show any increase even if the cake layers were partly removed. For the mixed suspended sediments (5% clay, 80% silt, and 15% fine sand), cake layer cracks during the clogging experiments were observed. Therefore, uneven erosion patterns occurred during scouring experiments caused by the presence of the existing cake cracks increasing the longitudinal cracks extent on cake layer formation (Jacobs et al., 2011). Even if a high mobilization of the mixture cake layer during the scouring experiments occurred (Figure 5.8), the immediate infiltration velocity recovery is therefore probably associated with preferential flows caused by the ameliorated cake cracking on the surface.

Table 5.2. Overview of cake layer removal and infiltration velocity recovery per sediment type

Sediment type	Sediment concentration (g/L)	Cake layer removal (mm)	Average infiltration velocity recovery 0.5-2θ_c (m/d)			Average infiltration velocity recovery 0.5-2θ_c (q/q_o, %)
			q_o	q after clogging	q after scouring	
Clay	1	6.5	8.8	5.82	5.82	66.1
	6	14	6.45	3.30	3.69	57.3
Silt	1	3	6.09	4.92	5.03	82.6
	6	11	6.13	3.50	3.50	57.0

Sediment type	Sediment concentration (g/L)	Cake layer removal (mm)	Average infiltration velocity recovery 0.5-2θ_c (m/d)			Average infiltration velocity recovery 0.5-2θ_c (q/q_o, %)
			q_o	q after clogging	q after scouring	
Fine sand	1	7	5.78	4.99	5.185	89.7
	6	6.5	5.86	5.86	5.86	100.0
Mixture	1	6.5	5.74	2.99	5.54	96.5
	6	8.5	5.90	3.78	4.95	84.0

The entrapment of particles in the deeper voids can be considered deep bed clogging and, consequently, there is a reduced chance of natural recovery of infiltration capacity because of the scouring of these particles compared to cake clogging (Goldschneider et al., 2007). In smaller streambed particle sizes, the clogging particles cannot penetrate as deeply, and cake clogging occurs (Brunke, 1999; Veličković, 2005).

It was found that the sediment concentration affected the occurrence of cake and/or deep bed clogging depending on the type of sediment, which in turn influenced the infiltration recovery. Thus, for clay particles the higher concentration favored the cake layer formation limiting the deep bed clogging, while for silt, fine sand and the mixture of sediments the higher sediment concentration, the lower the cake layer formation velocity leading to higher deep bed clogging. The concentration did not show an evident effect on the self-cleansing of the cake layer on sediments other than clay, which suggests that the infiltration recovery was merely a function of deep bed clogging.

5.5 Conclusions

Based on the presented research it may be concluded that, during (simulated) riverbank filtration, high recovery of the infiltration velocity (84-96%) at low shear stresses was possible for high turbidity water with a mixture of different sediments, as found in natural water bodies. Clay and silt behaved very differently, due to the difference in cohesiveness. Clay was found to produce a persistent sticky cake layer, whereas silt penetrated deeper into the bed, both resulting in an absence of infiltration velocity recovery. The cake layer of fine sand sediments was easiest to remove, resulting in dune formation on the streambed, nevertheless due to deep bed clogging by the sand particles in the coarser streambed the infiltration velocity did not recover. The interaction between the mixed suspended sediments (5% clay, 80% silt, and 15% fine sand), resulted in uneven erosion patterns during scouring of the streambed allowing for the infiltration velocity to recover to 84-96%. Altogether it may be concluded that natural recovery of infiltration capacity during river bank filtration of highly turbid waters is expected to occur, as long as the river carries a mixture of suspended sediments. The fine streambed formation avoids the occurrence of deep bed clogging, which increases the chances of being self-cleaned.

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CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

"Making your mark on the world is hard. If it were easy, everybody would do it. But it's not. It takes patience, it takes commitment, and it comes with plenty of failure along the way. The real test is not whether you avoid this failure, because you won't. It's whether you let it harden or shame you into inaction, or whether you learn from it; whether you choose to persevere"

Barack Obama

6 Conclusions and Outlook

Riverbank filtration (RBF) is considered as a non-conventional technology for water abstraction, relying on natural, subsurface processes for water quality improvement. However, in developing countries, such as Colombia, the use of non-conventional alternatives, which have not previously been used in the local environment, present a high resistance among institutions to be considered as potential solutions to water supply problems, even more if the technology has not been proven yet for the poor water quality conditions found in the surface waters. This thesis reports on the investigation towards the feasibility of using the RBF technology for highly turbid rivers in Colombia, resulting in the following conclusions and outlook.

6.1 Overall conclusion

Among others, the size, cohesiveness and concentration of the particulate matter, and the particle size of the streambed, which are locally and seasonally specific, were found to play an important role in the site selection for the potential application of RBF. This has been especially evidenced in highly deteriorated river basins, such as the Cauca River basin, where the particulate matter suspended in the water is seasonally variable, placing in risk the continuity of the water supply systems. The particulate matter concentrations (suspended sediment loads) highly varied among seasons, but minor differences in the particle sizes where measured. Clogging of the streambed or aquifer by high suspended sediment loads was identified to be the predominant threat for RBF in turbid rivers. This thesis has shown an important effect of minor differences in the particle size on the infiltration capacity between the surface water and the streambed/aquifer because of clogging processes. Nevertheless, in this thesis it was demonstrated that, although single-sediment solutions may indeed clog a RBF system, in reality a RBF system with river water composed of mixed suspended sediments – as found in nature - may control its infiltration velocity already at low shear stresses recovering to 84-96% of its initial capacity. Therefore, the overall conclusion of this thesis is that RBF is a sustainable alternative for drinking water (pre)treatment for turbid rivers in developing countries. However, the decision-making process responds to more than only technical issues, and therefore, the development of an integrated multi-criteria framework must be considered for supporting the selection of water sources alternatives where political, social and stakeholders' interests are involved.

6.2 Specific conclusions

6.2.1 Feasibility of RBF for highly turbid river in developing countries

The use of the RBF may be beneficial in highly turbid and contaminated surface rivers, such as many Colombian surface waters, due to its capacity to remove a high variety of pollutants associated to the highly suspended sediment loads carried by the rivers. Nevertheless, the high suspended sediments concentrations in the river water may lead to two different types of clogging: (1) streambed clogging due to the cake formation and (2) clogging of the aquifer or deep bed clogging. As shown in Chapter 5, deep bed clogging is irreversible and, therefore, entails a decrease of the water infiltration. However, shear stress forces as low as may control the cake layer thickness and be capable of natural infiltration rate recovery as demonstrated during the simulated riverbank filtration experiments in Chapter 5, as well as avoid the deposition of the suspended matter.

With RBF, a better water quality can be obtained at the abstraction wells, requiring only a few additional treatment steps to produce drinking water. Also, the current practice of frequent intake shut-downs during high turbidity peaks can be avoided (Chapter 3). Upon application of RBF in conventional surface WTPs in Colombia, many of the treatment processes currently employed (e.g., sand filtration, sedimentation, coagulation-flocculation) will function more efficiently or more stable, leading to simpler plant operation and control. This aspect is especially important in developing countries, where large amounts of chemicals are commonly used to guarantee a safe produced drinking water (Chapter 2).

6.2.2 Integrated multiple-criteria framework for the selection of water sources alternatives in developing countries

Socio-territorial and environmental management problems are commonly found in developing countries such as Colombia, where slums, due to the armed conflict, are frequently located on the banks of rivers and other protection zones. Additionally, obtaining environmental permits for the execution of major projects such as dams, can take many years mainly due to bureaucratic procedures and obstacles placed by both legally settled communities and slums. Those conflicts delay the development of projects, which must be highly considered in the selection of alternatives. Hence, political, social and stakeholders' interests are involved in the decision-making process for the selection of water sources and/or alternatives to solve their drinking water issues, among others.

The construction of an integrated multiple-criteria framework, with the participation of experts and stakeholders, has shown to be an important mechanism to assess the selection of the alternatives in developing countries, providing transparency for the decision-making process and engaged stakeholders in the search for solutions that best suit the addressed needs

(Chapter 3). The selection of a broad range of criteria, in addition to the weighting process, compensate subjective decisions and guidelines proposed by institutions. Likewise, this process avoids skipping alternatives that have not been considered previously due to the existing gaps in the knowledge about its functioning under conditions that have not been proven yet, which generates resistances among the water companies and environmental institutions.

6.2.3 Seasonal changes of the particulate matter composition in a highly turbid river

An RBF system may be feasible to be used for highly turbid waters; however, a comprehensive study must be conducted in which the seasonal variation of the characteristics of the seasonal suspended particulate matter and shear stress exerted by the river flow must be determined and analyzed. The particulate matter composition has been identified as a key variable determining the functioning of the RBF technology. Considering the importance of the Cauca River for the water supply of Cali, Colombia, and the high turbidities reported during the last decade, the seasonal characterization of the particulate matter in this river has been assessed, showing that, in addition to differences in the particulate matter concentrations, some differences in their constituents occur. The differences are related to the different sources contributing during rainy and dry seasons, which was evidenced in parameters such as color and particle size. A similar particle size distribution was found during both seasons; however, a slightly higher content of particles smaller than 2 μm during rainy conditions due to changes in vegetation coverage and decomposed organic matter in the runoff (Chapter 4). The higher presence of clay and colloidal particles (< 2 μm) may lead to the formation of a sticky cake layer onto the streambed. It must be considered that the higher shear stresses exerted during the rainy season may limit the deposition of the very small particles suspended in the water.

6.2.4 Infiltration capacity recovery for bank filtration systems in a highly turbid river because of physical clogging and self-cleansing processes

As a consequence of the suspended sediments in river water, cake formation on the riverbed and clogging of the aquifer may occur leading to a decline in the production yield of riverbank filtration systems, particularly in highly turbid river waters. Naturally occurring flow forces may induce sufficient scouring of the riverbed, thereby self-regulating the thickness of the formed cake layer. This thesis assessed the recovery of the infiltration capacity in a simulated riverbank filtration system because of physical clogging and subsequent self-cleansing processes. It may be concluded that a mixture of different sediments, as found in natural water bodies, is capable of natural infiltration rate recovery at low shear stresses during simulated riverbank filtration. Clay and silt behaved very differently, due to the difference in cohesiveness. Clay was found to produce a persistent sticky cake layer, whereas silt penetrated deeper into the bed, both resulting in a poor recovery of infiltration rate. The cake layer of fine sand sediments was easiest to remove, resulting in dune formation on the streambed. However, the infiltration rate did not recover in the case of deep bed clogging by the sand particles in a streambed consisting of coarse grains. The interaction between the mixed suspended sediments (5% clay, 80% silt, and 15% fine sand), resulted in uneven erosion patterns during scouring of the streambed allowing for the infiltration rate to recover to 85-96%. Altogether it may be concluded that natural recovery of infiltration capacity during river bank filtration of highly turbid waters is expected to occur, as long as the river carries a mixture of suspended sediments and the stream bed size is not too coarse.

6.3 Outlook: piloting RBF in Cali, Colombia

As a follow-up of the PhD research, a new project is being developed. The Universidad del Valle, through the royalties' project "MGA: investigación recurso hídrico de las cuencas de los ríos Cauca y Dagua recuperado Cali, Valle del Cauca, Occidente", supports a pilot study to explore the feasibility of using RBF in a highly turbid river (Cauca River). This pilot study is beyond the scope of this PhD thesis, but illustrates the impact of the research for encouraging new technology adoptation in developing countries. It may be concluded that, apart from scientific findings, this thesis has onset the debate for RBF application in Colombia, resulting in the real-life application of RBF at Puerto Mallarino, the largest WTP of Cali.

For the water company, the main aim of applying RBF at this specific site is to reduce both investment and operational costs. The top soil layers consist of alluvial sediments from the Cauca River that can be used for RBF. For more details about the surface water, groundwater and soil characteristics see Appendix A. The soil profile, the theoretical hydraulic conductivities per layer and the computed hydraulic conductivity from the pumping test are presented in Appendix B. The initial surface water quality (Cauca River) and groundwater quality in the constructed wells of the pilot study are presented in Appendix C.

As found in several RBF experiences, the production yield is stabilized approximately in one year. Therefore, it was recommended that in the pilot study a monitoring campaign must address the behavior of external and internal clogging in the RBF prototype submitted to highly turbid waters and assess the changes in the water production yield.

In addition, since RBF involves the extraction of surface water through the ground, it was recommended that during the pilot study adjustment of the the Colombian normativity must be addressedin order to determine whether the extracted water should be classified as a groundwater or surface water source. In general, regulations that could generate uncertainty within implementing and environmental authorities pertain to requirements for the granting of the correct extraction concessions, in addition to several technical regulations. Existing groundwater well spacing and pollutant retention regulations could prove restrictive to RBF well development.

Appendix

Appendix A. Surface water, groundwater and soil characteristics

Surface and ground water

Surface water

The surface water regime of the Cauca River depends on the groundwater´s regime, in which the groundwater delivers water to the Cauca River most time during both dry and rainy seasons. Monthly-average water levels of the Cauca River from the Juanchito measuring station (CVC, 2017) located next to the WTP Puerto Mallarino in a river stage for a 32-year period is presented in Figure A.1. Operation of the upstream Salvajina Dam (year 1985) have a significant impact on river stage, which explains the inconsistent rainy season (April to June and October to December) timing indicated by Figure A.1. Regardless, highest water levels are typically in April and November, and the lowest in August and September.

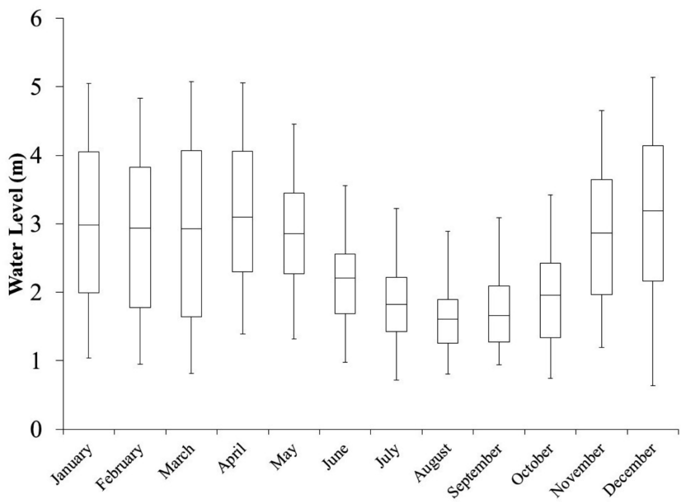

Figure A.1. Boxplots of recorded water depths of Cauca River at Juanchito station from 1985 to 2016. The line through the middle is the median value. The top and bottom lines correspond to the 75th and 25th percentile, respectively. The whiskers extend to the minimum value at the bottom and the maximum value on top

Scouring or self-cleansing capacity of RBF systems is commonly assessed in terms of riverbed particle sizes (considering its critical shear stress) and the shear stress exerted by the river flow. Viscosity and density of the fluid contributes to shear stress forces (Hubbs et al., 2007), but under tropical conditions as the case study, it is expected to be constant in time (Lewis Jr., 2008). The velocity of the fluid at the streambed is a function of stream surface slope and resistance to flow transmitted by the streambed. These parameters vary with time and location, and determine the sediment in transport at any given time on a streambed

(Hubbs et al., 2007). In Figure A.2, the calculated percentiles of shear stress in the river stage for a six-year period (2009-2014) are presented, considering a slope of 2.36×10^{-4} m/m (CVC and Universidad del Valle, 2004b).

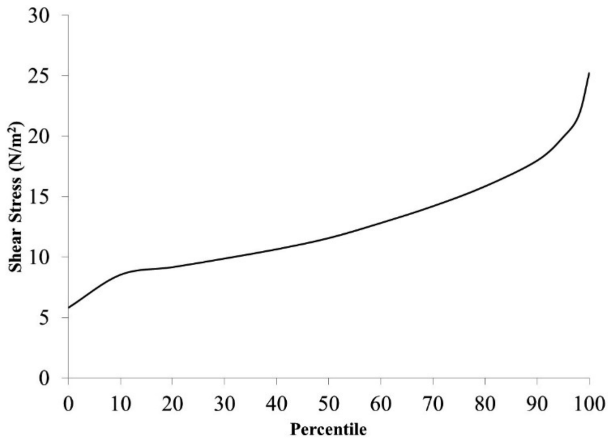

Figure A.2. Shear stress at Puerto Mallarino WTP

The shear stresses exerted by the Cauca River at the Puerto Mallarino WTP ranges from 5.8 to 25.2 N/m^2. Shear stress values have been reported to range between 1 to 100 N/m^2 as typical for river streambeds, considering a value of 20 N/m^2 as reasonable (Hubbs, 2006). Therefore, a potential RBF seems to be feasible based on the shear stress of the Cauca River. However, incipient motion of sediments depends on critical shear stress, which is a function of riverbed and clogging layer characteristics. Then, a pilot study is needed in order to assess the water yield reduction through time.

Currently, there are concerns about water quality of the Cauca River. The water contains high concentrations of pollutants from domestic and industrial discharges. The Cauca River also contains very high concentrations of suspended solids, reaching turbidity values up to 10,000 NTU during rainy season (Gutiérrez et al., 2016). At low levels of dissolved oxygen due to contamination events (DO < 2.5 mg/L O_2) and/or high concentrations of suspended solids (turbidity > 2,500 NTU) it is difficult to treat the water, with the result that EMCALI has to close the treatment plant intakes. This leaves a large proportion of the population of Cali at risk of shortages during these events, with only two emergency reservoirs with a joint capacity of 180,000 m^3 (up to 8 h of water) located at Puerto Mallarino available to bridge these periods (Gutiérrez et al., 2016).

High turbidity events in the Cauca River lead to the WTP's intake shutdowns, if over a certain threshold (2,500 NTU). High turbidity peaks generally occur during the rainy season (April to June and October to December). Turbidity peaks occur on only a few occasions each year, and they last for periods as long as 10 hours (Gutiérrez et al., 2016). For most of the year, turbidity values do not fluctuate greatly and 95% of the time they remain below 568 NTU. The average annual turbidity is less than 190 NTU (Gutiérrez et al., 2017).

DO concentrations in the vicinity of Puerto Mallarino typically drop after heavy rainfalls with the increase of organic waste concentrations (CVC and Universidad del Valle, 2004a). The resulting low DO concentrations also lead to WTP intake shutdowns, as it is an indicator of high pollution peaks from mainly domestic, as well as industrial, wastewater. The 180,000 m^3 reservoirs can only handle events of poor raw water quality if their duration does not exceed eight hours. In Chapter 3 are shown the shutdown events that occurred between 2000 and 2014 because of turbidity and contamination events, and the effect of the reservoirs in the attenuation of those events since its implementation in 2009. Low DO concentration events caused intake shutdowns at Puerto Mallarino more frequently than high turbidity peaks; however, in recent years turbidity events have become more frequent and therefore increasingly significant.

Other raw water quality impacts can cause operational issues at WTP Puerto Mallarino as well. These include, for example, microorganisms, organic carbon, iron and manganese. Despite significant increases during flood events, the Cauca River generally contains high microorganism concentrations at other times. This means that a high level of inactivation is required in order to reach the required drinking water standard (< 1/100 mL). Total organic carbon (TOC) levels vary greatly, with maximum levels of up to 9 mg/L. This is of concern as organic carbon is a precursor for disinfection by-products. Total iron and manganese are also relatively high; the maximum allowable effluent concentration for iron is 0.3 mg/L. Currently, much of the iron and manganese is being oxidized by the pre-chlorination step, meaning high chlorine doses are then being used, thereby causing the pH to drop significantly in the pre-treated water.

Groundwater

The groundwater level in the vicinity of Puerto Mallarino is 5 m below surface level (at 80 m inland from the riverbank) (EMCALI, 2007). Closer to the river, the groundwater level will tend towards river stage (minimum 6.2 m from surface level). Therefore, the top layer of the subsoil is unsaturated. The degree of saturation of the second soil layer is dependent on the distance from the river but can be assumed to be greater than 0.8 m in most cases. The thick sand layer is completely saturated.

Groundwater quality in the Valle del Cauca region has been classified by CVC and Universidad del Valle (2007) (Figure A.3). The area surrounding Puerto Mallarino has groundwater of qualities classified as belonging to the three lowest classes (3- 5). Class 3 (yellow) groundwater can be described as water of good quality and can in most cases be used without restriction, unless concentrations of iron, manganese or the total hardness are too high. In these cases, any pumped groundwater would require treatment. Class 4 or 5 (orange and red) groundwater will always require some form of treatment (CVC and Universidad del Valle, 2007). Given that any water extracted via RBF wells will be subjected to subsequent treatment processes within the WTP, this should not pose any problem. It is, however, worth keeping in mind that the proportion of groundwater pumped and its quality could hold implications for the necessary treatment processes.

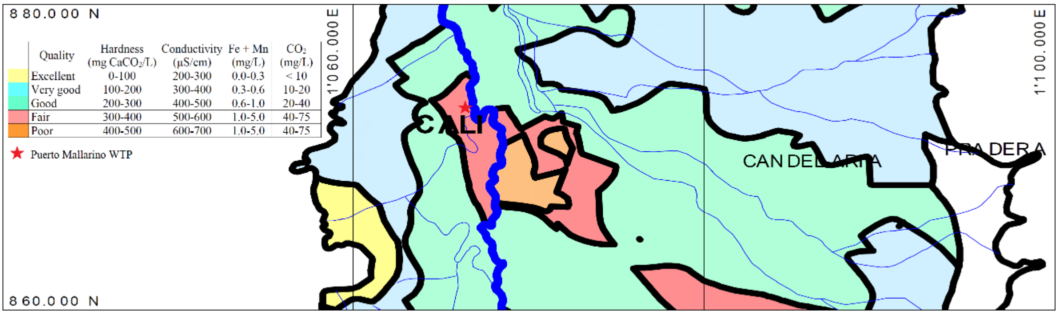

Figure A.3. Groundwater quality in the area surrounding Puerto Mallarino WTP

RBF filtrate contains a proportion of groundwater. There are a number of known sites with potential soil and groundwater contamination in the vicinity of Puerto Mallarino. If RBF wells were to be situated in these areas, there is some risk that the pumped filtrate would be contaminated with unfiltered pollutants. Naturally, in siting RBF facilities, these sites should be avoided. Sites of potential contamination include the Puerto Mallarino sludge disposal site, a gas station located in Candelaria (Combustibles Juanchito S.A.S.), and the entire eastern bank of the Cauca River.

Soil

Soil profiles in the vicinity of the WTP Puerto Mallarino WTP have been performed by EMCALI through cone penetration tests (EMCALI, 2007). Additionally, INGEOMINAS and DAGMA (2005) developed some penetrations by mechanical probing in the former landfill of the city (Navarro), located 11 km upstream of the WTP Puerto Mallarino. From these studies may be generalized the soil profile presented in Table A.1.

Table A.1. Soil profile from secondary data in the surroundings to the Puerto Mallarino WTP

Range depth (m)	Layer description	K (m/s)
0 to -3	Silt with construction waste material, organics (6-12%), sand (1-35%) and some gravel with a maximum grain size of 25 mm	5.6×10^{-5} [a]
-3 to -7	Silt with a sand and gravel content of 2-30%	6.4×10^{-5} [a]

Range depth (m)	Layer description	K (m/s)
-7 to -40	Sand that might be silty and is medium grained and loosely packed	$6.3x10^{-5} – 6x10^{-4}$ [a]
-40 to -65	Clay with a high plasticity	$2.3x10^{-9}$ [b]
-65 to -70	Sand, medium to coarse grained	$1.4x10^{-4} – 52x10^{-9}$ [b]

[a] Saturated hydraulic conductivity of the soil profile (EMCALI, 2007; INGEOMINAS and DAGMA, 2005)
[b] Estimated saturated hydraulic conductivity of the soil profile based on Todd and Mays (2005)

Considering the texture of the soil profile, reflected in the hydraulic conductivities, and the need of travel times adequate for the removal of the contaminants contained in the surface water, a maximum 40 m depth may be used for a potential RBF system. Likewise, that distance must be considered for a pilot study. Hydraulic conductivities reported in the surrounding area were likely to be in the range of $6.3x10^{-5}$ – $6x10^{-4}$ m/s. A thorough investigation about the geotechnical and hydrogeological conditions in site is needed in order to determine its feasibility. The riverbed profile has been characterized by CVC and Universidad del Valle (2004a), stating that the riverbed generally consists of silty sands and fine-grained soils with some gravel present.

Existing municipal land use plans for the prototype area have been examined to establish those areas along the banks of the Cauca River whose existing zoning would allow for RBF facility development. Land use plans on both the eastern and western banks of the river were examined. Whilst the western bank falls under the jurisdiction of the Municipality of Cali, the eastern bank comes under the jurisdiction of the Municipality of Candelaria. In the western bank, to the north and south of Puerto Mallarino, a narrow strip of land (typically 50-300 m) between the bank of the Cauca River and the existing flood protection dyke is predominantly a river protection zone. According to the Cali Land Use Plan, this strip is intended to preserve riparian forest species and to allow the continuity of ecosystem corridors (Alcaldía de Santiago de Cali, 2014). It is intended to remain unoccupied, with the only other permitted use for the land being the construction of river hydraulic structures. The existing Puerto Mallarino intake structure is located within this zone.

Much of the protection zone strip to the north of the WTP (downstream) is narrower than that to the south, and currently inhabited (potentially with squatter settlements). Although relocation of these settlements would be possible, sites to the north of the plant have been initially ignored for this reason. Upstream of Puerto Mallarino, the protection zone strip initially widens to accommodate the large river meander directly to the east of the WTP. Satellite imagery has also indicated reduced riverbank settlement to the south of this meander. As such, this area has been given preference over the northern strips for RBF well placement.

In the eastern bank of the Cauca River (Municipality of Candelaria), has been established a protective 100 m strip from the edge of the river that is to be treated as public ecological area (Alcaldía de Candelaria, 2014). The presence of wells should not heavily impact the environmental objectives of this area. However, the deep meander immediately adjacent to

Puerto Mallarino (opposite bank) has been zoned as a recreational and tourist area, with discotheques, motels and sporting facilities present. More significantly, it is also noted that within this area is the Combustibles Juanchito S.A.S. facility, a fuels and other waste collection, storage and disposal business. The presence of this facility leads to some concerns regarding groundwater quality in the immediate vicinity of this facility. Therefore, the western bank is selected for studying the potential of RBF for the city of Cali.

Design of the pilot facility for the city of Cali, Colombia

For wells situated relatively close to river courses and in meanders, RBF filtrate will contain a proportion of groundwater that may typically range from 30-50 percent (Grischek et al., 2003). This means that the quality of the groundwater can be a key determinant in the overall quality of the filtrate. Therefore, potential well sites have been assessed against their previous, current and future contamination potential.

The distance of the wells from the river course is a key determinant in the production quantity of wells and the ability of the riverbank/bed to remove pollutants; but this is largely dependent upon local conditions. For the pilot study, a short distance from the river was selected to minimize the impact of background groundwater on water abstraction. The best place for pumping a large quantity of river filtrate is on an island in the middle of a water course or within the inside curve of a meander (Grischek et al., 2003). In a simplified modelling study Grischek et al. (2003) demonstrated that situating a well gallery in a natural meander could deliver proportions of river filtrate to groundwater up to 78 percent.

Soil characterization, including the stratigraphy and lithology were realized by mechanical probing on the bank of the Cauca River adjacent to WTP Puerto Mallarino. During this study, the soil profiles were determined through the construction of two wells, where two mechanical boreholes and two geoelectrical surveys were conducted (Figure A.4). A 6" pumping well was drilled next to the WTP intake, at 20 m from the riverbank. A 4" monitoring well was drilled at 130 m from the riverbank in order to establish the groundwater characteristics and the portion of groundwater entering into the bank filtration well.

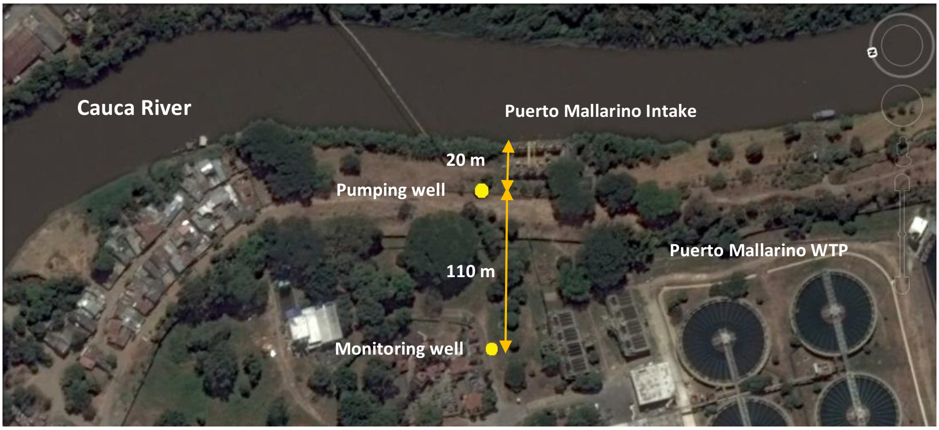

Figure A.4. Location of the pumping well and the monitoring well at the WTP Puerto Mallarino, Cali, Colombia

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Appendix B. Soil profile and horizontal hydraulic conductivities in the pilot study

The soil profile, the theoretical hydraulic conductivities per layer and the computed hydraulic conductivity from the pumping test are presented in Table B.1. It must be considered that 10 m of filters were placed in a range depth from -19 to -29 m.

Table B.1. Soil profile from geoelectrical surveys and mechanical boreholes in the WTP Puerto Mallarino

Range depth (m)	Layer description	K (m/s)[a]	K (m/s)[b]
0 to -6	Yellowish gray clay and silty clays	$2.3x10^{-9} – 9.3x10^{-7}$	
-6 to -9	Medium-to-coarse grain sands	$1.4x10^{-4} – 5.2x10^{-4}$	
-9 to -15	Sand and gravels	$5.2x10^{-4} – 5.2x10^{-3}$	
-15 to -21	Gravels and sand	$3.1x10^{-3} – 5.2x10^{-3}$	
-21 to -24	Gravels, sand and clay	$5.2x10^{-4} – 5.2x10^{-3}$	$1.6x10^{-3}$
-24 to -29	Gravels and sand	$3.1x10^{-3} – 5.2x10^{-3}$	
-29 to -34	Gravels, sand and clay	$5.2x10^{-4} – 5.2x10^{-3}$	
-24 to -40	Gravels, clay and sand	$2.9x10^{-5} – 5.2x10^{-3}$	

[a] Estimated saturated hydraulic conductivity of the soil profile based on Todd and Mays (2005)

[b] Computed saturated hydraulic conductivity from the pumping test by using Cooper and Jacob equation $K = \frac{15.8\left(\frac{Q}{\Delta s}\right)}{b}$, where Q is the discharge, Δs is the water drawdown and b is the aquifer thickness

Appendix C. Initial surface water and groundwater quality in the pilot study

The water quality parameters were selected for the further monitoring in the pilot based on the contaminants found in both the surface water and the groundwater. Moreover, parameters from the Decree 1594/84 (Colombian regulation for water use and residual liquids) were included. The wells depth was selected in agreement with the soil profile from secondary data in the surroundings to the WTP Puerto Mallarino (Table A.1).

Figure A.4 presents the localization and characteristics of the pilot study. Initially, the analysis of physical, chemical and biological parameters were performed for determining the initial condition of contaminants in the surface water and groundwater (pumping and monitoring well). The results of the initial conditions concerning to the water quality are presented in Table C.1.

Table C.1. Initial condition of surface water and groundwater quality in the pilot study

Parameter	Unit	Cauca River	Pumping Well	Monitoring Well
True Color	PCU	90	59	98
Dissolved Oxygen, DO	mg O_2/L	5.23	2.65	2.75
pH	units	6.77	6.66	6.55
Temperature	°C	24.2	25.7	25.3
Turbidity	NTU	30	17.1	9.96
Electrical conductivity	µS/cm	111	307	310
Total Organic Carbon, TOC	mg/L	1.51	9.76	< 0.07
Nitrite, NO_2^-	mg/L	0.001	0.001	0.001
Nitrate, NO_3^-	mg/L	0.2	0.3	1.7
Sulphate, SO_4^{2-}	mg/L	24.44	18.78	8.61
Phosphate, PO_4^{3-}	mg/L	2.07	7.05	5.8
Total Phosphorus	mg/L	0.017	0.018	0.022
Chloride, Cl^-	mg/L	10.7	11.5	11.5
Chemical Oxygen Demand, COD	mg/L	21.4	20.5	13.7
E. Coli	CFU/100 mL	20,000	70	90
Total Coliforms	CFU/100 mL	170,000	5,700	2,500
Total Alcalinity	mg $CaCO_3$/L	281	1,588	1,931
Total Hardeness	mg $CaCO_3$/L	49	139	125
Manganese	mg/L	0.01	0.4	0.3
Total Fe	mg/L	3.19	3.19	6.53
Dissolved Fe	mg/L	0.039	0.039	0.068
Cadmium	µg/L	< 0.02	< 0.02	< 0.02
Chromium	µg/L	< 0.09	< 0.09	< 0.09
Lead	µg/L	< 0.32	< 0.32	< 0.32
Mercury	µg/L	1.75	< 0.24	< 0.24

Note: the data in the wells corresponds to values before pumping

Curriculum Vitae

Juan Pablo Gutiérrez Marín was born on November 10th, 1977 in Cali, Colombia. He received his degree as Sanitary Engineer at Universidad del Valle in 2001, and his Master of Science in Civil Engineering with emphasis in Environmental and Water Resources Engineering at the University of Puerto Rico at Mayagüez campus in 2008 addressing his thesis on the fate and transport of explosive chemicals in soils. His master thesis was titled as "Effects of flow reversal on two-dimensional transport of explosive chemicals in soils". Most of his experience has been posed in the design of drinking water supply systems, physical and computational modeling of transport of contaminants in soil and groundwater, surface water and groundwater, and distribution water networks. In 2009, he started teaching at Universidad del Valle, engineering faculty, offering courses related to water supply, sewerage and groundwater hydrology for undergraduate and graduate programs. From August 2011 he started his PhD at the Technological University of Delft, the Netherlands, under the supervision of prof. Dr. Ir. Luuk C. Rietveld and Dr. Ir. Doris van Halem, conducting his PhD research on the feasibility of using the riverbank filtration technology for highly turbid rivers, in order to achieve a proper technology transfer for the local conditions of Colombia.

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