# ESMP ACTION 9: WATER QUALITY MANAGEMENT FOR RESERVOIRS (MANGANESE)

For the project
Climate Resilient Water Sector in Grenada
(G-CREWS)

Date: March/April 2025

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## List of abbreviations

| | |
|---|---|
| AFM | Activated Filter Media |
| BMUV | German Federal Ministry for the Environment, Nature Conservation, Nuclear Safety and Consumer Protection |
| CANARI | Caribbean Natural Resources Institute |
| GCF | Green Climate Fund |
| G-CREWS | Climate-Resilient Water Sector in Grenada |
| GIS | Geographical Information System |
| GoG | Government of Grenada |
| Mn | Manganese |
| NAWASA | National Water and Sewerage Authority |
| NGO | Non-governmental Organization |

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## 0. EXECUTIVE SUMMARY

The Les Avocats and Mardigras water treatment supply networks have experienced persistent challenges due to elevated manganese (Mn) concentrations. In both cases, the manganese ap-pears to originate from sources upstream of the dams. These two water sources are geographically close and share similar upper catchment characteristics. The Mardigras (Apsley Dam) is fed by one main stream and several smaller tributaries located some distance from the dam. In contrast, the Les Avocats Dam receives inflow from one main stream that discharge directly in the upper part and there is another stream on the left side immediately downstream the dam wall.

Field investigations suggest that the manganese is primarily entering the system via one of these two tributaries, likely from spring sources. Manganese concentrations peak at the dams and treatment plants during the dry season, especially under drought conditions when surface water flows are significantly reduced. Currently, neither treatment facility is equipped with specific infrastructure for manganese removal.

As a result, fine manganese particles accumulate on the interior linings of transmission mains, causing dark brown discoloration and contributing to system downtime or service interruptions as scouring releases these deposits. This necessitates frequent and extensive flushing of trans-mission and distribution mains, which increases non-revenue water and reduces water availability to consumers during dry periods.

To address the issue, NAWASA has also implemented pipeline pigging using probes and high-pressure water, a method that is labour, energy, and logistics-intensive, and requires extended system shutdowns. These quality challenges, operational costs, and consumer dissatisfaction prompted NAWASA to explore advanced treatment options targeting manganese removal, including the use of Activated Filter Media (AFM).

In October 2024, GIZ approached NAWASA with the opportunity to engage a Limnologist who was present in Grenada in March and April 2025. The manganese issue was identified as a critical gap to be analysed and reported on by the expert through this assignment.

## 1. INTRODUCTION

### 1.1. G-CREWS PROJECT

Water is a scarce resource within the state of Grenada and climate change has already begun to aggravate the problem with an increasing average temperature and more erratic rainfall. Frequent heavy rainfall events make water supply outages more common due to high turbidity in the raw water supply. The main objective of the G-CREWS project is to increase systemic climate change resilience in Grenada's water sector. To achieve its objective, the project supports the water sector's comprehensive transformation on multiple levels, which represents a nationwide 'paradigm shift' for Grenada's overall resilience. This paradigm shift will include citizens and businesses as water users, the public sector as provider of potable water and infrastructure. Through appropriate governance, regulation, economic incentives and raising awareness, be-haviour changes are expected to be triggered. The G-CREWS project is developed in the following five components:

- Climate-Resilient Water Governance
- Climate-Resilient Water Users
- Climate-Resilient Water Supply Systems
- Additional Contributions of the Water Sector to Grenada's climate goals
- Regional learning and replication

Jointly financed by the Green Climate Fund (GCF), the German Federal Ministry for the Environment, Nature Conservation, Nuclear Safety and Consumer Protection (BMUV) under its International Climate Initiative (IKI), and the Government of Grenada. Over 7 years, the Government of Grenada, the Grenada Development Bank and the National Water and Sewerage Authority (NAWASA) in partnership with the German Development Corporation (GIZ) implements the project's five components. The project has a total budget of 45.297 Million Euros (Approximately $130 million XCD). All citizens of Grenada, including the agricultural and commercial sectors, are expected to benefit from improved water supplies, especially during times of drought and after extreme weather events.

## 1.2. ESMP Action 9: Water Quality Management for Reservoirs (Manganese)

Elevated manganese concentrations in the raw water at the Les Avocats and Mardigras water treatment plants (WTPs) are impairing treated water quality by promoting the formation of a manganese-based biofilm along the interior of service mains. This issue becomes more severe during drought conditions, when frequent valve adjustments and planned service interruptions coincide with reduced surface water availability and inconsistent potable water supply. As a result, manganese deposits are dislodged during line scouring, leading to noticeable discoloration, customer complaints, and increased operational burdens but they are not of health concern at levels normally causing acceptability problems in drinking water. Manganese is an essential element for many living organisms, including humans. For example, some enzymes require manganese (e.g. manganese superoxide dismutase), and some are activated by the element (e.g. kinases, decarboxylases). Adverse health effects can be caused by inadequate intake or overexposure. Manganese deficiency in humans appears to be rare, because manganese is present in many common foods (WHO, 2011). Extensive flushing and costly line cleaning, often using already limited water resources, are required to restore service quality.

## 1.3. Overall Goal

Ultimately, NAWASA's goal is to find sustainable and cost-effective solutions to eliminating all issues related to manganese (Mn) concentrations at the raw water sources for the Les Avocats and Mardigras Water Supply Networks.

### 1.4. Strategic Approach – Understanding the Issue

NAWASA believes that before pipeline pigging and tertiary treatment can be adequately instituted, it is imperative that there is an understanding of the physio-chemical features of the water sources that feed these two (2) water treatment plants in order to strategically develop targeted approaches to mitigating the issue. As such, it was proposed this assignment to be added to the Limnologists scope of works for the Grenada Mission.

### 1.5. Expected Impacts of Source Investigations

At the start of the mission it was expected that the data captured and analysed will confirm the source points, concentrations at these points and provide recommendations to derive suitable interventions to achieve manganese removal to ultimately reduce its impact on the water treatment and transmission infrastructure served by the Mardigras and Les Avocats WTPs.

### 1.6. Project Stages

This assignment of Mn research and environmental flow study had these major stages:

- Data collection and trip preparation-1 business day
- Project kick-off and knowledge sharing – 1 business day
- Field visits, reconnaissance and water sampling – 10 business days
- Analysis of samples and collection additional samples – 3 business days
- Collection of supplementary data as GIS, discharge, precipitation, land use, geology – 2 business days
- Production of final investigative report – 5 business days

**Total: ~22 business days**

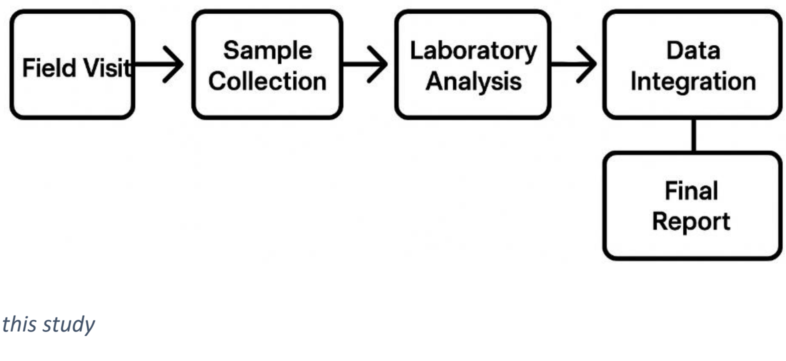


*Figure 1: Major stages of this study*

### 1.7. Key Project Stakeholders and Responsibilities in the Assignment

- Limnologist – Expert in the study of the biological, chemical and physical features of fresh water bodies

- GIZ Project Lead – Focal point for collaboration between GFA, GIZ, NAWASA & Limnologist
- Production & Quality Department - NAWASA
    - Manager – Authorizes the utilization of staff for assistance with assignment
    - Laboratory Supervisor – Directly assigns tasks to Laboratory and Field Technicians
    - Laboratory Technicians – Conduct water sampling and analysis at NAWASA's Laboratory and assist is sample collection
    - Field Technicians – Conduct onsite sampling and analysis along with Field Technicians and manage transportation logistics.
    - Plant Operators – Provide onsite expertise of operations at dams and treatment plants
- Planning and Development Department – NAWASA
    - Water Resources Technicians – Assist Limnologist with manoeuvring water course, isolation of tributaries and sampling of streamflow data

## 2. EXECUTION OF THE ASSIGNMENT

The locations of Mardigras and Les Avocats (figure 1) were visited on 20th and 24th March by Dr. Romina Álvarez Troncoso (Limnologist) and Mr. David Gabriel, the laboratory supervisor in NAWASA and other colleagues from the team.

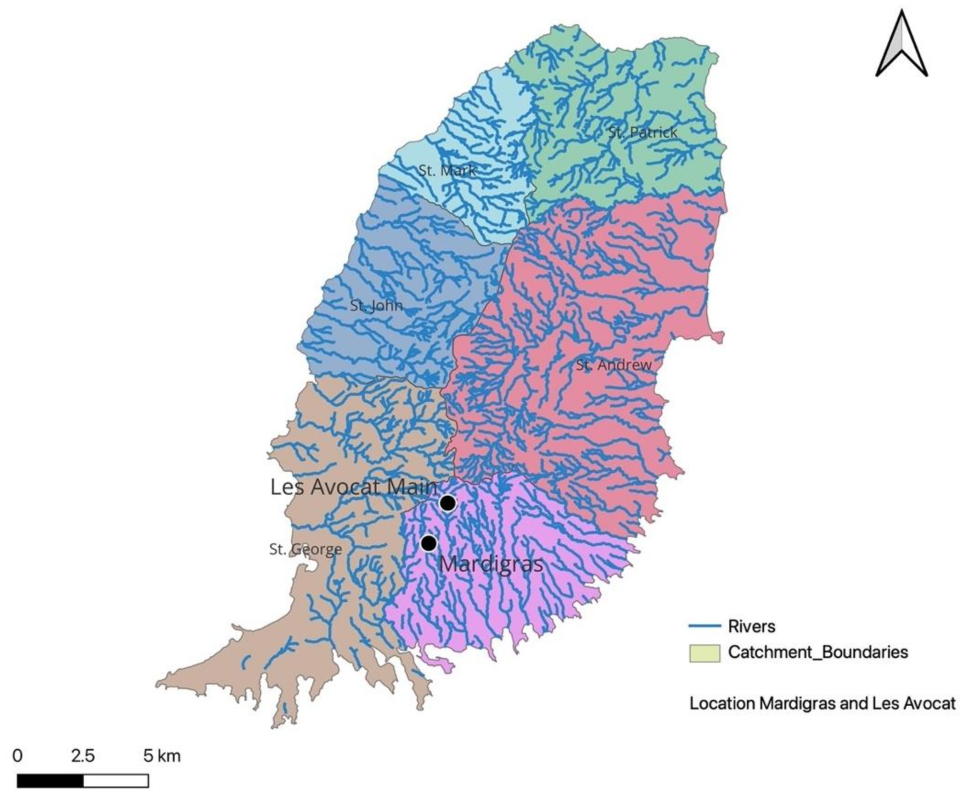


*Figure 2: Location of the reservoirs Mardigras and Les Avocats*

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Both reservoirs experience water scarcity and elevated levels of dissolved manganese (Mn) during the dry season, which deteriorates water quality and impairs pipe function, leading to discoloration and unpleasant taste in the drinking water.

In the following lines the problem is analysed in detailed, explaining the possible sources and causes of the about the origin of the Mn in the reservoir and possible solutions to improve the water quality, especially during the dry season.

The first step was to define the locations of the sampling sites in both reservoirs. There were defined not only for the locations in each of the reservoirs, but also the locations in the treatment plan and also the tributaries and associated springs.

*Table 1: Sample points located in Les Avocats and Mardigras*

| Source/Treatment Plant/Customer | Sample Point |
|---|---|
| **Les Avocat** | Dam Lower Layer |
| | Dam Upper Layer |
| | Distribution Line Leaving Treatment Plant |
| | Left Stream Entering Dam |
| | Mix Spring & Upper Small Dam |
| | Right Stream Entering Dam |
| | Small Dam 2 (Upper) |
| | Small Dam 3 (Lower) |
| | Small Stream Near Upper Gate |
| | Spring Entering Sed Basin |
| | Spring Near Left Dam Wall |
| | Water At Base of Dam Right Side |
| | Water Entering Sed Basin from Dam |
| | Water Leaving Sed Basin |
| **Mardigras** | Dam Lower Layer |
| | Dam Upper Layer |
| | Tap From Clear Well |
| | Tap On Pump Line From Dam |

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The following pictures show the main sampling sites and some details from them.

| | |
|---|---|
| Mardigras Treatment Plant (Sources) (Raw Water) with Dam lower Layer and Dam Upper Layer | Tap From Clear Well |
|  |  |
| Tap On Pump Line From Dam | Dam and river downstream Mardigras |
|  |  |
| Woody debris in Mardigras | Woody debris in Mardigras |
|  |  |
| Filters in the Treatment station Mardigras | Filters in the Treatment station Mardigras |

*Figure 3: Main sampling sites*

On 20th March, a first visit to both reservoirs (figure 2, 3 and 4) was carried out, dissolved oxy-gen, temperature of water and conductivity were measured.

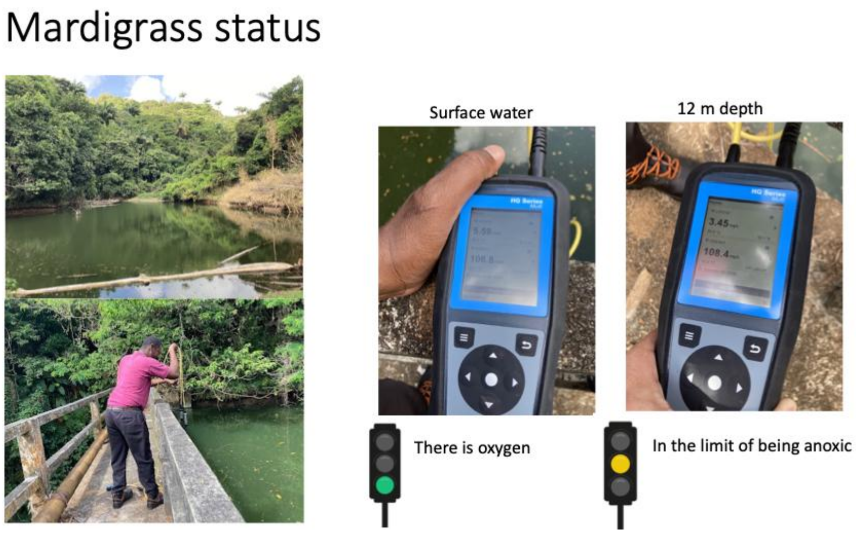


*Figure 4: Results from the sampling on 20th March in the surface and in the bottom in Mardigras*

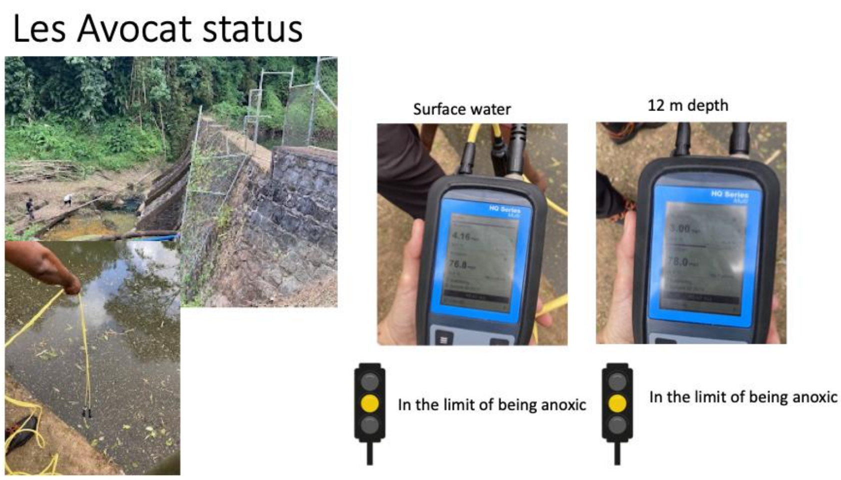


*Figure 5: Results from the sampling on 20th March in the surface and in the bottom in Les Avocat*


*Figure 6: Results from the sampling on 20th March in the spring on the left site of the Les Avocat*

After these first findings collected in the field, it was suggested to carry out a full lab analysis from two treatment plants: **Les Avocat** and **Mardigras** in all the sites, so it was carried out for the following parameters in all the locations indicated in the table 1.

- pH
- Temperature (°C)
- TDS (Total Dissolved Solids)
- Salinity
- Conductivity
- Residual Chlorine
- Turbidity
- Iron (Fe)
- Manganese (Mn)
- Dissolved Oxygen (DO)

The results of the analysis with data since February 2024 is presented in the Annex.

In the following figures it is possible to see the most relevant data for Mn and Iron expressed in mg/L:

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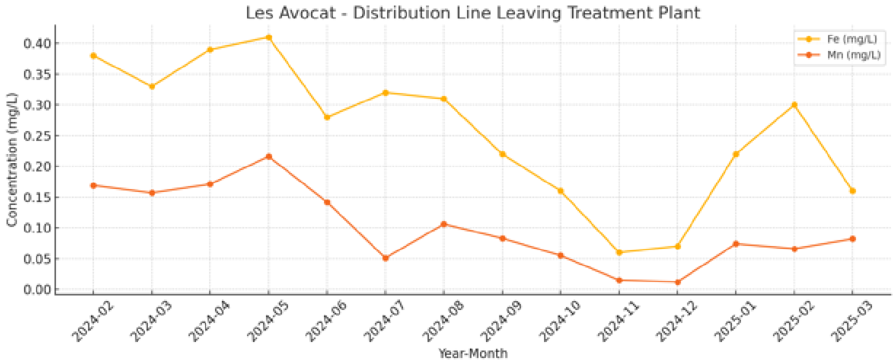


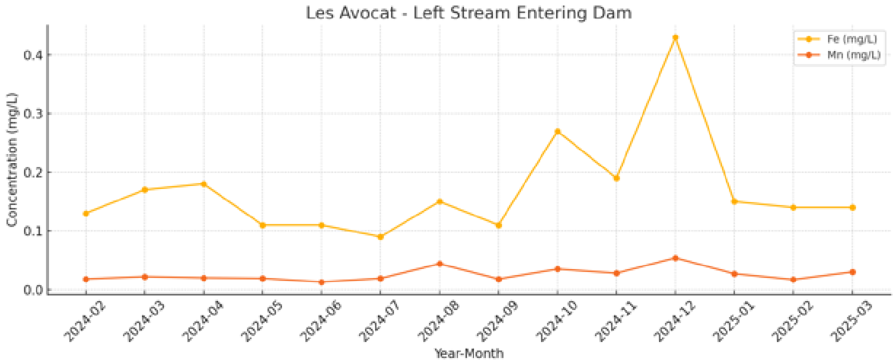


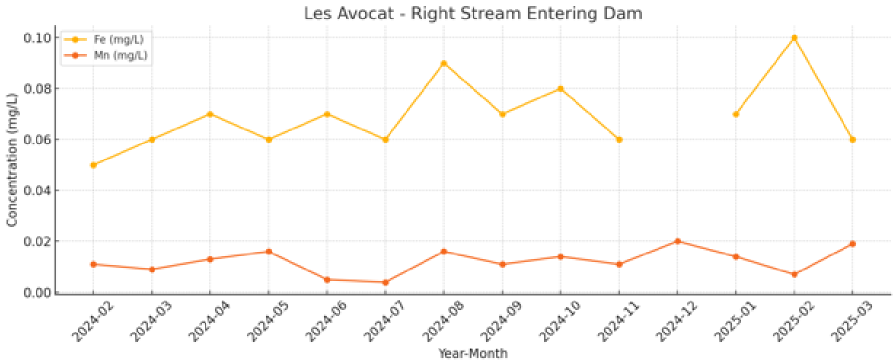


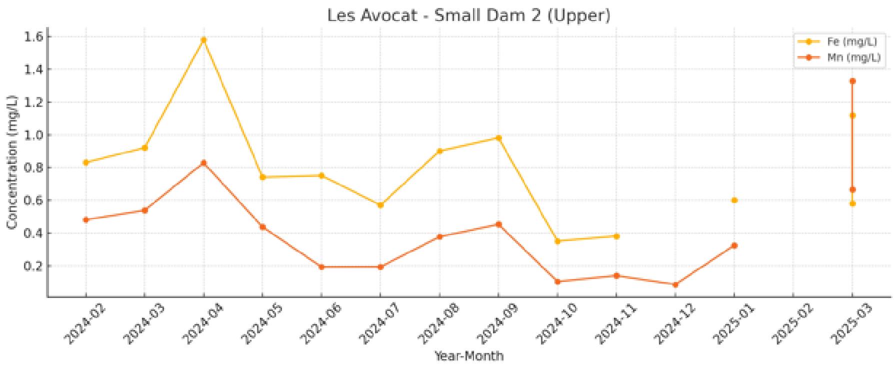

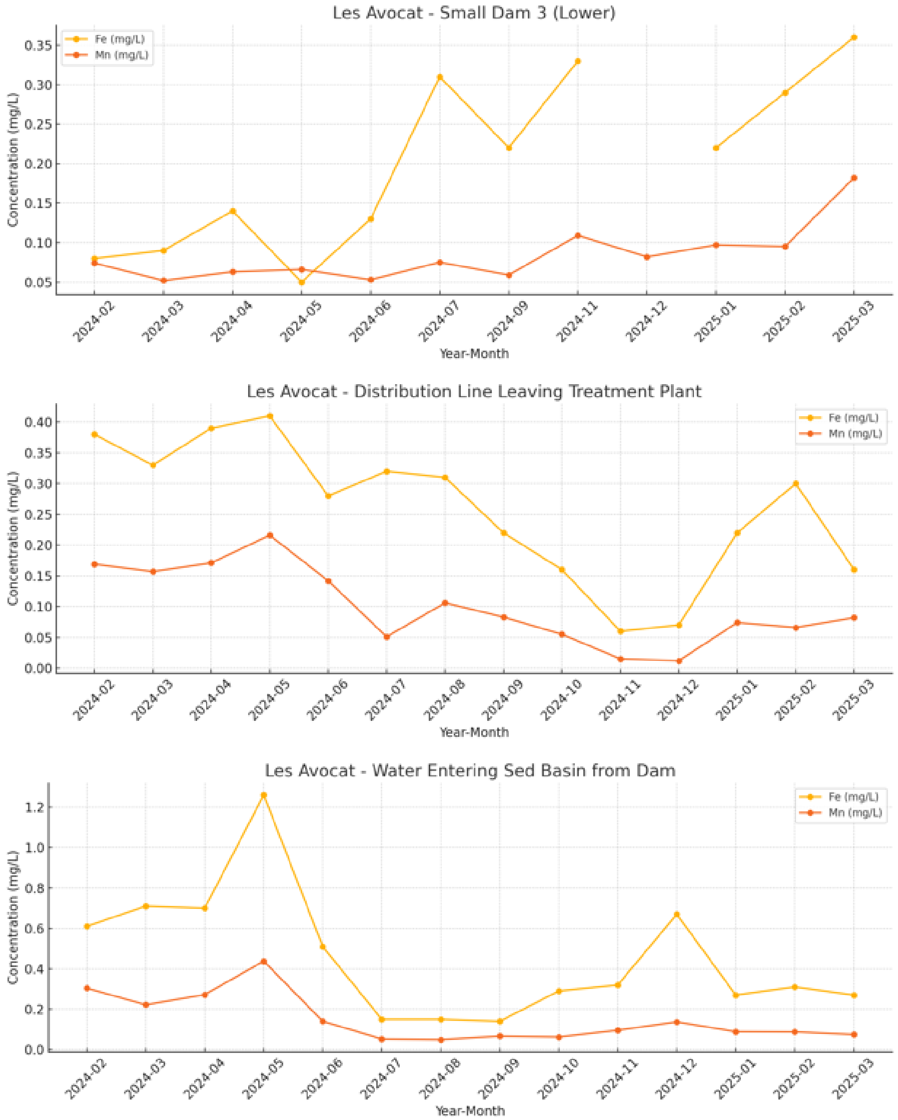


*Figure 7: Evolution of the results for Fe (mg/L) and Mn (mg/L) in Les Avocat from February 2024-March 2025*

The health-based guideline value of 0.08 mg/l for manganese is higher than the acceptability threshold of insoluble manganese. However, since dissolved manganese can also be released at the point of use or collection, the presence of discoloured water cannot be used reliably to assess if manganese is present. Therefore, aesthetic as well as health aspects should be considered when setting regulations and standards for drinking-water quality (WHO, 2022).The World Health Organization (WHO) recommends recently (2022) a guideline value of 80 micrograms per liter (µg/L) of manganese in drinking water (0.08 mg/L). At levels exceeding 0.1 mg/l, manganese in water supplies may cause an undesirable taste in beverages and stains sanitary ware and laundry. The presence of manganese in drinking-water, like that of iron, may lead to the accumulation of deposits in the distribution system.

According to the results, only in May 2024 the Mn exceed this value in the distribution line and in December 2024 in the left stream entering the dam and in February, March and April 2024 in Small Dam 2.

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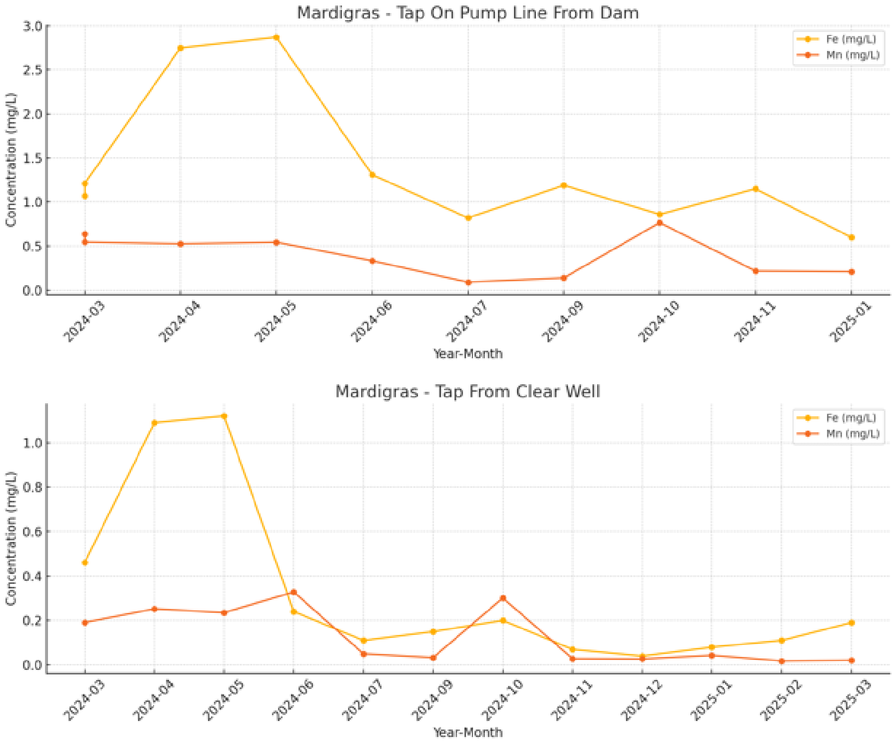
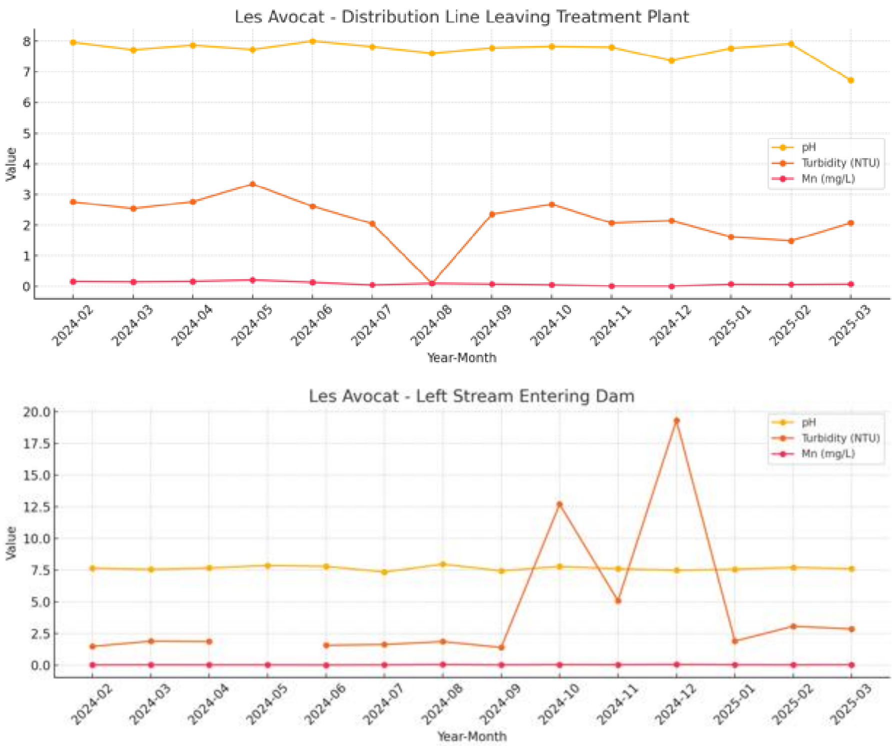



*Figure 8: Evolution of the results for Fe (mg/L) and Mn (mg/L) in Mardigras from March 2024-March2025*

According to the results, the Mn on the tap on pump was very high except in the period from June to September2024 and the period from November 2024 to January 2025. In the Tap from clear well, the Mn only exceed this maximum value (0.8 mg/L) in April and May 2024, in the whole period.



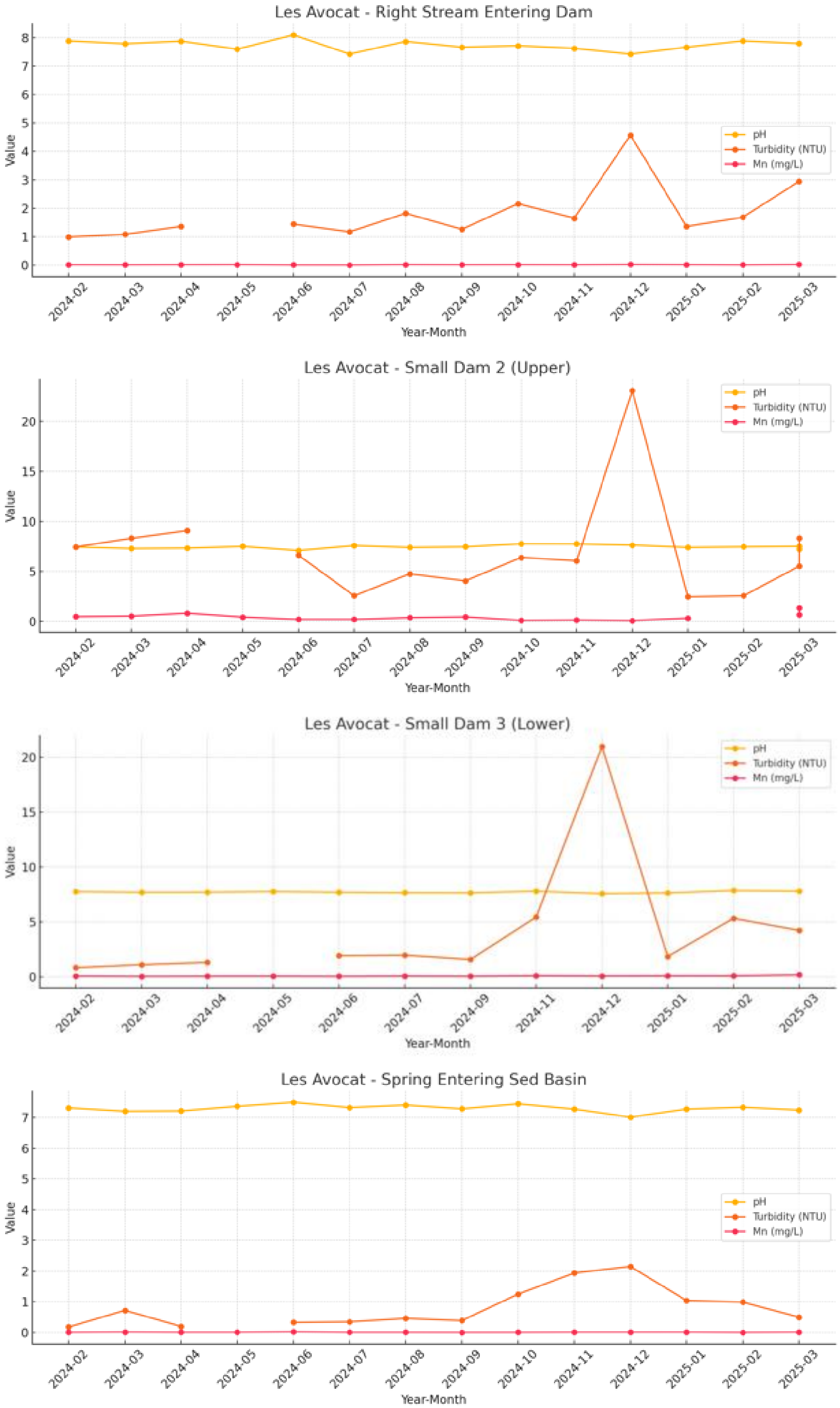



*Figure 9: Evolution of the results for pH (units of pH) and turbidity (NTU) and Mn (mg/L) in Les Avocat from February 2024 till March 2025*

According to the results, only in May 2024 when the Mn exceed the recommended value in the distribution line, also the turbidity was a bit higher and the pH a bit lower. And the same in December 2024 in the left stream entering the dam (higher values of turbidity) and in the right stream and in in Small Dam 2 and 3 in 12/2024 02. In the spring entering the location of “sediment basin”, turbidity was higher in November and December 2024.

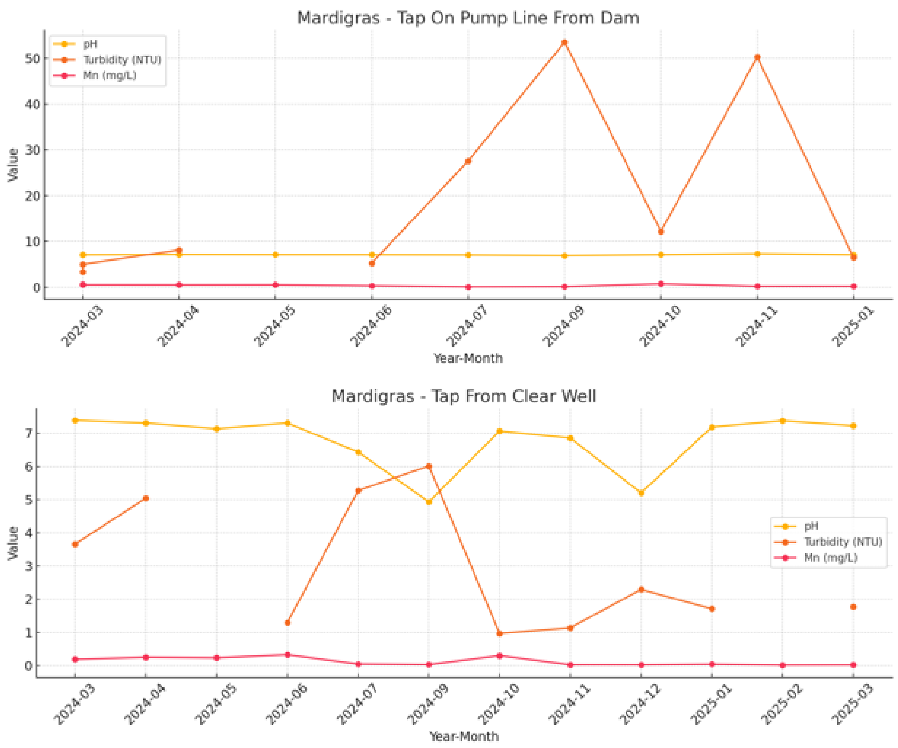



*Figure 10: Evolution of the results pH (units of pH) and turbidity (NTU) and Mn (mg/L) in Mardigras since 03/2024-03/2025*

According to the results, the Mn on the tap on pump was very high except in the period from May and September 2024 and November 2024 and January 2025. In those periods the pH was the same but the turbidity higher. In the Tap from clear well, the Mn did not exceed this maxi-mum value in the whole period but there is a peak of high values of turbidity on the period from July and September2024 and low value of pH, accordingly and also in December 2024.

## 3. ECOLOGICAL IMPACT OF MANGANESE IN TROPICAL RIVERS

**Manganese (Mn)** is a naturally abundant metal that plays essential biological roles but can become an environmental contaminant at high concentrations. Mn is a chemical element; it has symbol Mn and atomic number 25, is a hard, brittle, silvery metal, often found in minerals in combination with iron. Tropical river systems often experience dynamic manganese cycling due to geological reasons, warm temperatures, varied redox conditions, and both natural and human inputs. Below is a structured overview of manganese sources, cycling, and ecological impacts in tropical rivers, along with case examples and mitigation strategies.

### 3.1 Sources of Manganese in Tropical Rivers

- **Natural Sources**: Manganese is released from **weathering of rocks and soils** (especially in Mn-rich tropical laterite soils) and via **erosion** into rivers. Volcanic activity and geothermal inputs (e.g. hydrothermal vents or hot springs) can introduce Mn to water bodies as well. Natural **organic matter decay** and **anoxic sediments** can mobilize manganese from riverbeds. For example, crustal weathering and soil leaching are major natural contributors of Mn to surface waters.

- **Anthropogenic Sources: Mining activities** (Mn ore mining, as well as other mining like gold or tin that co-release Mn) are a significant source of Mn pollution in tropical rivers. Industrial discharges from st**eel manufacturing, battery production, alloy processing**, and other metal industries also introduce Mn into waterways. **Landfill leachate, agricultural runoff (certain fertilizers or pesticides), and wastewater effluents** can contain manganese. In tropical regions with legacy mining, **acid mine drainage** (from exposed sulfide ores generating acid) often leaches Mn along with iron and other metals into rivers. This reason was not found in Grenada

### 3.2 Role of Redox Conditions, pH, and Organic Matter in Mn Cycling

- **Redox-Sensitive Cycling**: Manganese is highly sensitive to redox conditions and can change form between insoluble oxides and dissolved ions. In **oxygen-rich (oxic) waters**, Mn is typically present as Mn(III/IV) oxides/hydroxides (solid phases) which tend to settle in sediments. Under **low-oxygen or anoxic conditions**, these oxides are microbially or chemically reduced to soluble Mn(II) which dissolves into the water column. Thus, **anoxic zones** in tropical rivers (e.g. in flooded wetlands, sediments, or stratified pools) can release dissolved Mn. Studies in tropical systems have shown Mn accumulating in bottom waters when oxygen drops—e.g. a Cuban reservoir had >8 mg/L Mn in anoxic bottom water during the warm season(Betancourt et al., 2010). When oxic conditions return, Mn(II) can oxidize and re-precipitate as Mn oxides, sometimes coating sediments or forming concretions.
- **Influence of pH: pH** affects manganese solubility and oxidation state. At **higher pH (alkaline)**, Mn(II) more readily oxidizes to Mn(IV) oxide or can precipitate as carbonates, thus lowering dissolved Mn. By contrast, **acidic pH** keeps Mn in soluble form. However, very low pH also means high $H^+$ ion concentration, which can **compete with $Mn^{2+}$ for binding sites** on organisms and minerals. In fact, experiments show protons ($H^+$) can reduce Mn toxicity to algae by competing for uptake sites. In tropical rivers with acidic soils or acid mine drainage, Mn can stay dissolved and mobile. In neutral to slightly alkaline rivers, manganese may precipitate out unless persistent reducing conditions exist.
- **Role of Organic Matter: Organic matter (OM)** influences Mn cycling in two ways: (1) **Indirectly via redox** – high OM in tropical rivers fuels microbial respiration, which can consume oxygen and create anoxic conditions that reduce Mn oxides to $Mn^{2+}$. As a result, Mn bound in sediments is released into the water under decaying organic-rich conditions. (2) **Binding/complexation** – unlike some metals, manganese does **not strongly complex with dissolved organic carbon (DOC).** Studies indicate Mn is only weakly bound to organics, so humic substances do not significantly sequester dissolved Mn in rivers. This means much of the Mn remains in inorganic form (as free ion or simple complexes) and bioavailable. Nonetheless, particulate organic matter can co-precipitate with Mn oxides or reduce them. In tropical wetlands or floodplains, **microbes can use Mn-oxides as electron**

**acceptors** (after oxygen is depleted) to decompose organic matter , thus coupling Mn reduction to carbon cycling. Conversely, certain bacteria oxidize $Mn^{2+}$ to Mn oxides, affecting how OM is processed and influencing nutrient trapping on Mn oxide surfaces.

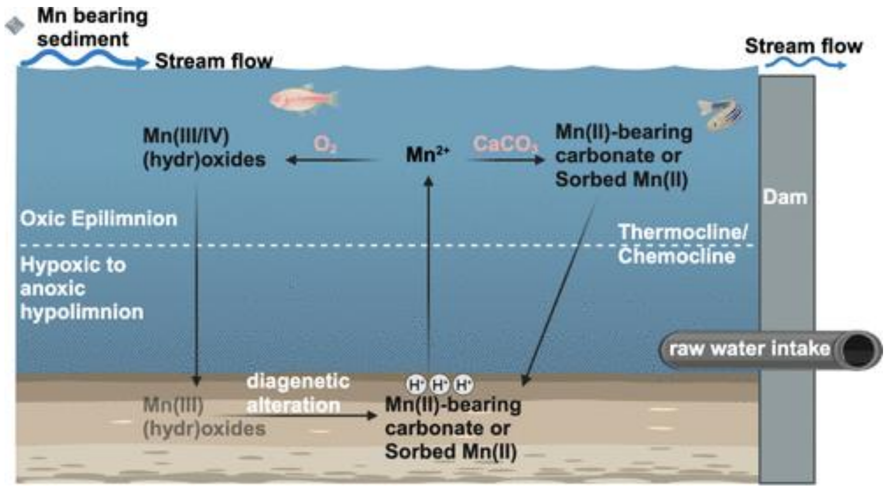



*Figure 11: Cycle of Manganese (Mn) in a reservoir extracted from Sang et al., 2024*

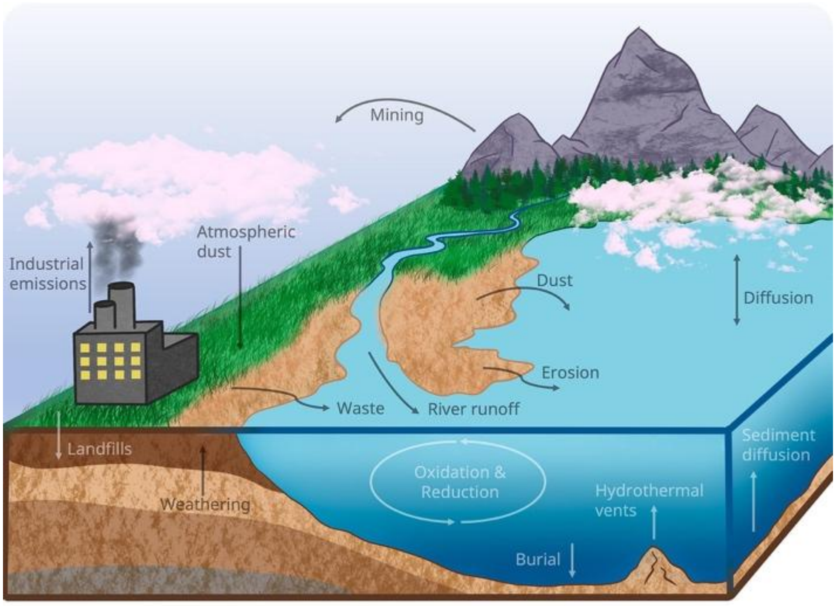



*Figure 12: Process of the cycle of Manganese (Mn) extracted from the presentation on 10th April prepared for stakeholders' involvement*

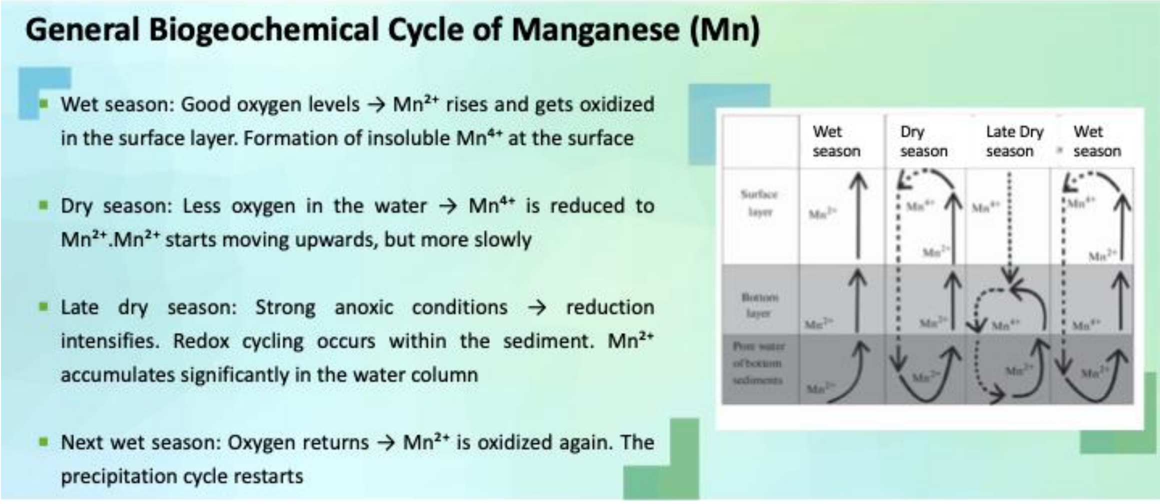



*Figure 13: Process of the cycle of Manganese (Mn) in a reservoir or lake (extracted from the presentation on 10th April prepared for stakeholders' involvement)*

### 3.3 Bioavailability and Potential Toxicity to Aquatic Organisms

- **Speciation and Bioavailability**: The bioavailability of Mn depends on its chemical form. **Dissolved Mn(II)** is the most bioavailable form to aquatic life, readily taken up by organisms, whereas particulate Mn (oxide or bound in sediment) is less immediately bioavailable. Warm tropical water temperatures can enhance Mn uptake by aquatic biota, and low salinity (freshwater) also promotes higher uptake compared to marine systems. Manganese is an essential micronutrient for microbes, plants, and animals, and organisms often regulate its uptake to meet nutritional needs. However, when external concentrations exceed what organisms can regulate, Mn can bioaccumulate (freshwater organisms can concentrate Mn thousands-fold above water levels) and potentially cause toxicity.
- **Toxicity Thresholds**: In general, manganese is **less acutely toxic** to aquatic life than many other heavy metals (such as mercury, lead, or copper). Lethal concentration (LC50) values for fish are often in the tens to hundreds of milligrams per liter range, indicating low acute toxicity. For example, 96-hr LC50s in fish have been reported from ~34 mg/L up to several g/L, and a 28-day no-effect level around 1–10 mg/L for some species. That said, **chronic exposure** to moderately elevated Mn can produce sublethal effects well below these acute levels. Water quality guidelines for protecting aquatic life typically recommend keeping Mn low (e.g. earlier guidelines were ~0.1 mg/L in freshwater, and more recent chronic criteria range around 0.6–1.9 mg/L depending on water hardness. These limits acknowledge that long-term exposure even to **0.5–2 mg**/L Mn may impair sensitive species.
- **Modifying Factors: Water hardness** strongly influences Mn toxicity. In harder water (higher $Ca^{2+}$/$Mg^{2+}$), those cations compete with $Mn^{2+}$ for biological uptake sites, reducing Mn toxicity. Soft, low-mineral tropical streams (<50 mg/L $CaCO_3$ hardness) leave organisms more vulnerable to Mn toxicity. **pH** also modifies toxicity; for instance, low pH can increase dissolved Mn but excess $H^+$ can compete at biological membranes, somewhat mitigating uptake by algae. **Dissolved organic**

**carbon** in water, surprisingly, shows little effect on Mn toxicity because Mn does not form strong DOC complexes.

- **Toxic Effects**: At a cellular level, excess manganese can catalyze the production of **reactive oxygen species**. Evidence in fish shows that elevated Mn exposure induces oxidative stress, tissue damage, inflammation, and even neurodegenerative changes in the brain. Manganese readily enters fish through gills (and possibly olfactory nerves) and is distributed via blood to the liver, kidneys, and nervous system. Prolonged high Mn can disrupt ion balance (e.g. induce iron deficiency in algae and plants, inhibiting chlorophyll synthesis). In aquatic plants and phytoplankton, manganese is needed for photosynthesis in trace amounts, but too much Mn can impair growth (e.g. by replacing iron in critical enzymes or generating oxidative stress).

### 3.4 Influence on Microbial Communities and Nutrient Cycling

Microorganisms are key mediators of the **manganese cycle** in aquatic environments. Certain bacteria and fungi derive energy by **oxidizing Mn(II) to Mn(IV) oxides** or by **reducing Mn(IV) to Mn(II),** effectively using manganese transformations in their metabolism. In tropical rivers, warm temperatures and abundant organic matter support active microbial Mn cycling:

- **Mn-Oxidizing Microbes**: These bacteria (often lithotrophic) enzymatically oxidize dissolved $Mn^{2+}$ into insoluble Mn(III/IV) oxide. The process can form dark brown/black Mn oxide deposits on rocks or sediments. This **scavenges nutrients and contaminants**: freshly formed Mn oxides have high sorption capacity and can bind phosphate, arsenic, and other trace metals, temporarily removing them from the water column. Thus, manganese oxidation can **intersect with nutrient cycles** by sequestering phosphate or co-precipitating with iron, influencing nutrient availability in the river.
- **Mn-Reducing Microbes**: Under oxygen-depleted conditions (common in sediments or wet-land areas), heterotrophic bacteria use Mn(IV) oxides as an **electron acceptor** (similar to how others use oxygen or nitrate) to break down organic matter. This **reduces Mn(IV) to Mn(II),** releasing $Mn^{2+}$ back into the water and simultaneously mineralizing organic carbon. In doing so, these microbes contribute to **carbon decomposition and nutrient regeneration**. For example, manganese reduction can oxidize organic carbon and also oxidize toxic sulfide ($H_2S$) to sulfate, linking the Mn cycle with the sulfur cycle and affecting alkalinity.
- **Microbial Community Shifts**: Elevated Mn concentrations can alter the composition of microbial communities. Some specialized Mn-oxidizers may proliferate on Mn-rich substrates (forming biofilms on rocks with Mn deposits). Conversely, too much Mn(II) (which can be toxic to some microbes) might inhibit sensitive bacteria or reduce overall microbial diversity. However, many aquatic microbes have tolerance mechanisms for Mn, given it's common in natural waters.

Overall, manganese cycling by microbes contributes to the **self-purification capacity** of rivers (through metal sequestration in sediments) but can also lead to periodic remobilization of Mn (during anoxic events), affecting nutrient cycles and water chemistry.

### 3.5 Effects on Fish, Invertebrates, and Other Aquatic Life

Excess manganese can adversely affect a range of aquatic organisms, from microscopic plank-ton to fish and amphibians:

- **Fish**: Chronic exposure to elevated Mn in water can cause physiological and behavioural harm to fish. Manganese bioaccumulates in fish tissues (especially liver and gills). Symptoms of Mn toxicity in fish include **neurological effects** (e.g. abnormal swimming, loss of coordination), reduced growth, and organ damage. Studies on goldfish, for example, show high water Mn leads to **abnormal behaviour, lethargy, loss of appetite, and liver/kidney impairment**, and can be fatal over time. In zebrafish (a common tropical model species), waterborne $Mn^{2+}$ exposure altered neurochemical balance and behaviour, indicating neurotoxic impacts. Early life stages (eggs and larvae) of fish tend to be more sensitive. There is also evidence that Mn exposure in fish can trigger oxidative stress in the brain and nerve tissues, potentially leading to Parkinson-like symptoms in extreme cases (paralleling mammalian neurotoxicology).
- **Aquatic Invertebrates**: Freshwater invertebrates (insects, crustaceans, mollusks) are generally somewhat tolerant of manganese, but high concentrations can reduce survival, reproduction, and growth. Water hardness modifies this - in s**oft water**, sensitive invertebrates like Daphnia (water fleas) experience toxicity at lower Mn levels. Manganese can impair invertebrate physiology; for instance, studies on aquatic **amphipods and snails** find reduced feeding and activity under sublethal Mn exposure. In crustaceans, Mn can interfere with molting and osmoregulation at high doses. Some invertebrates also accumulate Mn in exoskeletons or shells. Notably, manganese exposure has been shown to **suppress immune responses** in aquatic animals: in one study, fish and lobster exposed to high Mn had altered counts of immune cells and reduced activity of antimicrobial enzymes. This suggests Mn pollution could make aquatic organisms more susceptible to disease.
- **Plants and Algae**: Manganese is a required micronutrient for algae and aquatic plants (needed for photosynthesis enzymes), but an excess can be toxic to primary producers. Very high Mn can inhibit algal growth by causing oxidative stress or by inducing iron deficiency in algae (since excess Mn can block iron uptake). Some algae may tolerate elevated Mn by binding it to their cell walls. There is also an interesting interaction: moderate Mn presence might **ameliorate toxicity of other heavy metals** to microalgae, possibly by competition or co-precipitation. Aquatic macrophytes (larger plants) can accumulate Mn in their tissues; while they rarely show acute toxicity, elevated Mn can affect root functions and nutrient absorption for the plants.
- **Amphibians**: Although not always considered, amphibious life stages (e.g. frog tadpoles in tropical streams) can also be impacted. Reported 96-hr LC50 for a tropical frog tadpole (Microhyla) was around 14–16 mg/L Mn, indicating some sensitivity. Sublethal effects on amphibians might include developmental delays or behavioural changes when manganese is elevated.
- **Community-Level Effects**: If manganese pollution is severe, it can shift community structure. More tolerant species (e.g. hardy catfish or mosquito larvae) may

dominate, while sensitive species (certain insect larvae, snails, or fish fry) decline. Over time, this can reduce bio-diversity in the river. Additionally, Mn oxides depositing on stream substrates can alter habitat conditions as for example, coating spawning gravels or clogging the gills of filter-feeding organisms. While acute mass kills from manganese are uncommon, **chronic exposure** can lead to reduced reproduction and fitness, ultimately impacting fish and invertebrate populations and food web dynamics.

## 4. MITIGATION AND MANAGEMENT STRATEGIES OF MANGANESE IN GRENADA

Reducing the negative ecological impacts of manganese in tropical rivers involves both **preventive measures** to limit Mn release and **remediation techniques** to remove or stabilize Mn al-ready in the environment:

- **Pollution Source Control**: The most effective mitigation is preventing excessive manganese from entering rivers. This includes enforcing stricter regulations on **mining operations** (e.g. proper design and maintenance of tailings dams to prevent failures, treatment of mine drain-age). Industrial facilities that use manganese (steel mills, battery factories) should treat effluents to remove metals before discharge. Where Mn-rich **land runoff** is an issue (such as from agriculture or deforested land with Mn-rich soils), soil conservation and erosion control (reforestation, riparian buffers) can help reduce Mn-laden sediment washing into rivers.
- **Water Treatment Technologies**: For affected water bodies, several **remediation technologies** are used to extract manganese:
    - **Oxidation and Filtration**: Adding oxidants (like potassium permanganate, chlorine, or aeration) converts soluble $Mn^{2+}$ to insoluble $MnO_2$, which can then be filtered. This is commonly used in drinking water plants to protect consumers, but on a larger scale, aerating stratified polluted rivers or reservoirs (through aerators or oxygenation systems) can precipitate Mn and allow it to settle rather than remain in the water column. For example, hypolimnetic oxygenation in reservoirs has been used to keep bottom waters oxic, thus preventing Mn release from sediments.
    - **Adsorption and Ion Exchange**: Using specialized filter media or natural adsorbents (zeolites, activated carbon, or even agricultural waste materials) can capture dissolved manganese from water. Newer adsorption methods (e.g. coating sand or resin with Mn-oxidizing biofilm, or using low-cost biosorbents) have shown promise in pilots to reduce Mn in tropical waters.
    - **Constructed Wetlands and Bioreactors**: As semi-passive systems, constructed wet-lands with the right plants and microbes can gradually remove Mn. Some wetlands use manganese-oxidizing bacteria on substrate to trap Mn in situ. Similarly, bioreactor units can be installed in stream channels to promote manganese precipitation on a substrate.
    - **Dredging or Capping Sediments**: In extreme cases where river or lake sediments are highly contaminated with Mn and continually releasing it, environmental managers might dredge out the polluted sediments or cap them

with a clean layer to prevent Mn diffusion into the water. This is a heavy-handed approach and can be disruptive, so it's considered case-by-case.

- **Monitoring and Natural Attenuation**: Regular **water quality monitoring** for manganese is important in tropical rivers at risk. Early detection of rising Mn levels can trigger interventions. In some situations, simply restoring natural flow regimes and allowing periodic flushing can help – during high flows, manganese-rich stagnant zones might be cleared out. **Natural attenuation** through dilution (in large river volumes) and sedimentation can gradually reduce bioavailable Mn if new sources are curtailed

## 5. CONCLUSION

Manganese in Grenada rivers is a double-edged sword: it is a natural part of river geochemistry and an essential micronutrient, yet when concentrations spike due to anthropogenic inputs or anoxic conditions, it can become a pollutant with harmful ecological effects. Key factors like redox status, pH, and organic matter govern how manganese moves between sediments, water, and organisms.

Elevated Mn can adversely impact aquatic life, from microbes up to fish, by disrupting physiological processes and food webs. Fortunately, through better management of pollution sources and targeted remediation (oxidation, filtration, wetland treatment, etc.), it is possible to mitigate manganese's ecological impact. Maintaining well-oxygenated water, protecting rivers from mining waste, and monitoring water chemistry are all critical to ensuring that manganese remains in balance as a nutrient rather than becoming a toxin in tropical freshwater ecosystems.

### 5.1 General Recommendations for Both Waterbodies

- In dry season, make weekly measures in situ and in lab all of the following parameters (during the wet season every two weeks):
    - pH
    - Temperature (°C)
    - TDS (Total Dissolved Solids)
    - Salinity
    - Conductivity
    - Residual Chlorine
    - Turbidity
    - Iron (Fe)
    - Manganese (Mn)
    - Dissolved Oxygen (DO)
    - Redox
    - Study carefully the relation between pH Manganese (Mn) and Dissolved Oxygen (DO)

- Use the information from the water quality to create a combined system for mixing water and ensure the maximum quality, especially in dry season using the best quality and quantity as possible.
- Improve the collection of data, the analysis of the samples and remove floating debris from the reservoir surface.
- Pump from the surface area in both reservoirs when the stratification of the reservoir hap-pens and the quality of water on bottom is not good enough.

### 5.2 Proposal for Mardigras in Dry Season

- Check every week the levels of oxygen, hypoxic conditions begin when DO falls below 3 mg/L. Create an annual register to follow up.
- During the dry season, if the reservoir is stratified (there is a thermocline so the oxygen conditions can be limitant on hypolimnion) is better to try to avoid the use of the bottom part of the reservoir with more Mn, and use the water from the surface.
- Design a floating surface water intake structure that allows to maximize the water intake with good quality and avoid to take water with high levels of Mn.
- Design a system that oxygenates the surface of the reservoir, using the energy in the dam, create a pumping system that circulates the water on the surface. That movement will imply a circulation of water, improving the DO concentration and avoiding the blooms in the surface.
- Remove all the woody debris from the surface of the reservoir, debris adds organic material that worsens the problem.

*Figure 14: Ideas for designing a floating surface intake for Mardigras*

### 5.3 Proposal for Mardigras in wet season

- Check every two weeks the levels of oxygen, hypoxic conditions begin when DO falls below 3 mg/L. Add the results to the annual register to follow up.
- Remove all the woody debris from the surface of the reservoir, debris adds organic material that worsens the problem.

### 5.4 Proposal for Les Avocats in dry season

- Check every week the levels of oxygen, hypoxic conditions begin when DO falls below 3 mg/L. Create an annual register with complete analytics of water quality to follow up.
- When the Mn levels are very high during the dry season in all the layers of the reservoir (sur-face and bottom layer), create a by-pass from the main tributary (the one on the right site, upper part) and take only the water from there, both quality and quantity are perfect. There is a possibility of estimate the amount of water needed and combine it with the water from the surface of the Les Avocat reservoir and with the spring on the left side, trying to get water with the lowest Mn concentration as possible.
- The Mn levels of the spring on the left site are naturally very high. Prepare an estimation of the amount of water from the spring and the potential impact over the total amount of water uptake. Use a table with options depending on the need of water
- Intake from the surface of reservoir when it is possible and avoid the intake from the down-stream of the canal (downstream the dam).
- Remove all the woody debris from the surface of the reservoir, debris increases organic matter that worsens the problem

### 5.5 Proposal for Les Avocats in dry season

In the following lines a monitoring program is proposed:

- Check every two weeks the levels of oxygen in the reservoir and in the spring, hypoxic conditions begin when DO falls below 3 mg/L. Create an annual register to follow up with complete analytics of water quality
- Check the Mn levels during the year in the reservoir, in the spring and in the tributary.
- Remove all the woody debris from the surface of the reservoir, debris adds organic material that worsens the problem.

### 5.6 Summary

*Table 2: Summary*

| Site | Season | Action | Reason |
|---|---|---|---|
| **Mardigras** | Dry | Pump from surface intake | Avoid Mn-rich hypolimnetic water |
| **Mardigras** | Dry | Design a system that oxygenates the surface of the reservoir, using the energy in the dam, create a pumping system that circulates the water on the surface | That movement will imply a circulation of water, improving the DO concentration and avoiding the blooms in the surface. |
| **Les Avocats** | Dry | Monitor DO and Mn weekly (and water quality parameters) | Detect hypoxia, guide operations |

**ESMP ACTION 9: WATER QUALITY MANAGEMENT FOR RESERVOIRS (MANGANESE)**

| Site | Season | Action | Reason |
|---|---|---|---|
| **Les Avocats** | Dry | Use mainly water from tributary right margin (by-pass the reservoir) | Reduce the Mn amount in water and facilitate the process of water treatment |
| **Both** | All year | Remove surface debris | Reduce organic matter and Mn load |
| **Both** | All year | Monitor DO and Mn every two weeks (and water quality parameters) | Create the database for acquiring the information. Learn from the behaviour of the water quality and allow anticipation |

### 5.7 Project Monitoring

The progress of this investigative project was monitored by correspondences and interim updates from key stakeholders including the Expert and NAWASA personnel. These updates were provided at the end of each stage including field visits and sampling, water sample analyses, collection of supplementary data and production of final report.

Different meetings were organized including a working event on STAKEHOLDER ENGAGEMENT ON WATER QUALITY (Mn study) AND NATIONAL ECOFLOW on 10th April from 8.30-12pm in St. George.

Below, it is detailed the Stakeholder Engagement on Water Quality and National Ecoflow agenda:

*Table 3: Agenda Stakeholder Engagement on Water Quality and National Ecoflow*

| Time | Duration | Session | Who |
|---|---|---|---|
| **8:30 am** | 30 mins. | Registration | GIZ |
| **9:00 am** | 15 mins | Movie | |
| **9:15 am** | 15mins | Welcome from MoIID | Ms. Jocelyn Paul-Thomas |
| **9:30 am** | 15 mins | Welcome from NAWASA | Mr. Lenon A. Bullen (NAWASA) |
| **9:45 am** | 15 mins | Manganese Presentation | Dr. Romina Álvarez-Troncoso |
| **10:00 am** | 30 mins | 1. Introduction to NAWASA ESMP and Water Quality<br>2. Challenges<br>3. Newest developments<br>4. Other initiatives etc.<br>**5. Goal 10: Water Stewardship (Quality) – Ensure a consistent supply of good quality water for distribution through monitoring and additional programs.**<br>a. Strategic actions to achieve Goal 10:<br>b. Implement a water quality monitoring (bacteriological, chemical and radiological) program. | Mr. Todd LaBarrie (NAWASA) |

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| Time | Duration | Session | Who |
|---|---|---|---|
| | | c. Replace/upgrade parts of the treatment process to allow for the effective treatment of turbid water.<br>d. Introduce SOPs and BMPs in the treatment and water distribution system.<br>e. Implement a water main flushing program. | |
| **10:30 am** | 20 mins | Q&A | |
| **10:50 am** | 10 mins | Movie | |
| **11:00 am** | 20 mins | Presentation on National ecoflow<br>• Methodology<br>• Proposal for a national Eco flow to be adapted by WRMU | Dr. Romina Álvarez-Troncoso |
| **11:20 am** | 30 mins | Q&A | |
| **11:50 am** | 10 mins | Final remarks | Ms. Chrystal Willians |
| **12:00 pm** | | End of Session - Lunch | |

And some pictures of the workshop:

*Figure 15: Pictures of workshop*

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**ESMP ACTION 9: WATER QUALITY MANAGEMENT FOR RESERVOIRS (MANGANESE)**

## ANNEX: RESULTS EXTRACTED FROM THE LAB ANALYSIS FOR THE SITES SELECTED IN MARDIGRAS AND LES AVOCAT

*Table 4: Monthly manganese parameters concentrations*

In the case of Mn, the concentrations [mg/L] are presented in different sampling points at Les Avocats (Feb 2024 – Mar 2025). WHO drinking water guideline: 0.4 mg/L. In red is market the values higher than that recommendation:

| Sample Date | Source | Sample Point | pH | Temp (°C) | TDS (mg/L) | Salinity (‰) | Cond (µS/cm) | $Cl_2$ (mg/L) | Turbidity (NTU) | Fe (mg/L) | Mn (mg/L) | DO (m/L) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 24.Mar.25 | Les Avocat | Dam Lower Layer | 7.15 | 24.5 | 81.6 | 0.08 | 168.4 | | 9.69 | 0.88 | 0.402 | 4.86 |
| 24.Mar.25 | Les Avocat | Dam Upper Layer | 7.39 | 24.6 | 78.6 | 0.08 | 162.7 | | 9.25 | 0.77 | 0.381 | 5.18 |
| 28.Mar.25 | Les Avocat | Dam Upper Layer | 7.91 | 25.9 | 77 | 0.08 | 166.4 | | 6.03 | 0.19 | 0.052 | 9.19 |
| 27.Feb.24 | Les Avocat | Distribution Line Leaving Treatment Plant | 7.96 | 24.9 | 126.2 | 0.12 | 254 | 0.7 | 2.76 | 0.38 | 0.169 | |
| 20.Mar.24 | Les Avocat | Distribution Line Leaving Treatment Plant | 7.72 | 24.9 | 116.1 | 0.11 | 244 | 1.16 | 2.54 | 0.33 | 0.157 | |
| 10.Apr.24 | Les Avocat | Distribution Line Leaving Treatment Plant | 7.87 | 24.5 | 126.2 | 0.12 | 263 | 0.3 | 2.77 | 0.39 | 0.171 | |
| 13.May.24 | Les Avocat | Distribution Line Leaving Treatment Plant | 7.73 | 26 | 139.5 | 0.14 | 297 | 1.74 | 3.34 | 0.41 | 0.216 | |
| 18.Jun.24 | Les Avocat | Distribution Line Leaving Treatment Plant | 8 | 22.6 | 131.1 | 0.13 | 276 | 1.1 | 2.62 | 0.28 | 0.142 | |
| 26.Jul.24 | Les Avocat | Distribution Line Leaving Treatment Plant | 7.82 | 25.5 | 82.2 | 0.08 | 175.1 | 0.2 | 2.05 | 0.32 | 0.051 | |
| 23.Aug.24 | Les Avocat | Distribution Line Leaving Treatment Plant | 7.61 | 26.7 | 99 | 0.10 | 206.8 | 1.6 | 0.1 | 0.31 | 0.106 | |
| 23.Sep.24 | Les Avocat | Distribution Line Leaving Treatment Plant | 7.78 | 25.9 | 94.2 | 0.09 | 199.1 | 1.2 | 2.36 | 0.22 | 0.083 | |
| 28.Oct.24 | Les Avocat | Distribution Line Leaving Treatment Plant | 7.83 | 26.9 | 85.6 | 0.08 | 187.2 | 0.4 | 2.68 | 0.16 | 0.055 | |
| 29.Nov.24 | Les Avocat | Distribution Line Leaving Treatment Plant | 7.8 | 24.9 | 81.7 | 0.08 | 171.8 | 1.4 | 2.07 | 0.06 | 0.015 | |
| 20.Dec.24 | Les Avocat | Distribution Line Leaving Treatment Plant | 7.37 | 23.4 | 86.8 | 0.09 | 176.7 | 0.2 | 2.15 | 0.07 | 0.012 | |
| 17.Jan.25 | Les Avocat | Distribution Line Leaving Treatment Plant | 7.77 | 24.1 | 105.9 | 0.10 | 209.6 | | 1.62 | 0.22 | 0.074 | |

## ESMP ACTION 9: WATER QUALITY MANAGEMENT FOR RESERVOIRS (MANGANESE)

| Sample Date | Source | Sample Point | pH | Temp (°C) | TDS (mg/L) | Salinity (‰) | Cond (µS/cm) | $Cl_2$ (mg/L) | Turbidity (NTU) | Fe (mg/L) | Mn (mg/L) | DO (m/L) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 27.Feb.25 | Les Avocat | Distribution Line Leaving Treatment Plant | 7.91 | 24.1 | 106.6 | 0.10 | 219.7 | 0 | 1.49 | 0.30 | 0.066 | |
| 28.Mar.25 | Les Avocat | Distribution Line Leaving Treatment Plant | 6.73 | 25.3 | 104.3 | 0.10 | 223 | 0.43 | 2.07 | 0.16 | 0.082 | 5.74 |
| 27.Feb.24 | Les Avocat | Left Stream Entering Dam | 7.66 | 23.4 | 87.9 | 0.09 | 178.1 | - | 1.48 | 0.13 | 0.018 | |
| 20.Mar.24 | Les Avocat | Left Stream Entering Dam | 7.56 | 24.1 | 88.3 | 0.08 | 182.3 | | 1.89 | 0.17 | 0.022 | |
| 10.Apr.24 | Les Avocat | Left Stream Entering Dam | 7.67 | 24.4 | 88.7 | 0.09 | 184 | | 1.86 | 0.18 | 0.020 | |
| 13.May.24 | Les Avocat | Left Stream Entering Dam | 7.87 | 24.8 | 76.8 | 0.08 | 161.2 | | | 0.11 | 0.019 | |
| 18.Jun.24 | Les Avocat | Left Stream Entering Dam | 7.8 | 21.1 | 76.8 | 0.08 | 158 | | 1.57 | 0.11 | 0.013 | |
| 26.Jul.24 | Les Avocat | Left Stream Entering Dam | 7.36 | 25.2 | 66.9 | 0.07 | 142 | | 1.63 | 0.09 | 0.019 | |
| 23.Aug.24 | Les Avocat | Left Stream Entering Dam | 7.97 | 25.1 | 75.2 | 0.07 | 159.8 | | 1.86 | 0.15 | 0.044 | |
| 23.Sep.24 | Les Avocat | Left Stream Entering Dam | 7.45 | 25.9 | 74.5 | 0.07 | 159.9 | | 1.4 | 0.11 | 0.018 | |
| 28.Oct.24 | Les Avocat | Left Stream Entering Dam | 7.79 | 25.4 | 63.4 | 0.06 | 135.2 | | 12.7 | 0.27 | 0.035 | |
| 29.Nov.24 | Les Avocat | Left Stream Entering Dam | 7.61 | 24.6 | 68.1 | 0.07 | 142.4 | | 5.08 | 0.19 | 0.028 | |
| 20.Dec.24 | Les Avocat | Left Stream Entering Dam | 7.49 | 24.4 | 52.7 | 0.05 | 110.2 | | 19.32 | 0.43 | 0.054 | |
| 17.Jan.25 | Les Avocat | Left Stream Entering Dam | 7.57 | 22.8 | 84.2 | 0.08 | 170.8 | | 1.9 | 0.15 | 0.027 | |
| 27.Feb.25 | Les Avocat | Left Stream Entering Dam | 7.72 | 23 | 86.5 | 0.08 | 174.4 | | 3.07 | 0.14 | 0.017 | |
| 28.Mar.25 | Les Avocat | Left Stream Entering Dam | 7.61 | 23.7 | 81.2 | 0.08 | 168.1 | | 2.86 | 0.14 | 0.030 | 6.2 |
| 24.Mar.25 | Les Avocat | Mix Sprine & Upper Small Dam | 7.33 | 25.9 | 159 | 0.16 | 337 | | 0.88 | 0.27 | 0.418 | 2.81 |
| 27.Feb.24 | Les Avocat | Right Stream Entering Dam | 7.89 | 23.7 | 75.3 | 0.07 | 157 | - | 0.99 | 0.05 | 0.011 | |
| 20.Mar.24 | Les Avocat | Right Stream Entering Dam | 7.79 | 24.1 | 76 | 0.07 | 157.1 | | 1.08 | 0.06 | 0.009 | |
| 10.Apr.24 | Les Avocat | Right Stream Entering Dam | 7.88 | 23.7 | 77.1 | 0.08 | 158.2 | | 1.36 | 0.07 | 0.013 | |
| 13.May.24 | Les Avocat | Right Stream Entering Dam | 7.6 | 25.3 | 86.9 | 0.09 | 184.4 | | | 0.06 | 0.016 | |
| 18.Jun.24 | Les Avocat | Right Stream Entering Dam | 8.1 | 19.1 | 78.1 | 0.07 | 157.3 | | 1.44 | 0.07 | 0.005 | |
| 26.Jul.24 | Les Avocat | Right Stream Entering Dam | 7.43 | 24.8 | 72.1 | 0.07 | 151.7 | | 1.17 | 0.06 | 0.004 | |
| 23.Aug.24 | Les Avocat | Right Stream Entering Dam | 7.87 | 23.4 | 81.3 | 0.06 | 172.1 | | 1.82 | 0.09 | 0.016 | |

## ESMP ACTION 9: WATER QUALITY MANAGEMENT FOR RESERVOIRS (MANGANESE)

| Sample Date | Source | Sample Point | pH | Temp (°C) | TDS (mg/L) | Salinity (‰) | Cond (µS/cm) | $Cl_2$ (mg/L) | Turbidity (NTU) | Fe (mg/L) | Mn (mg/L) | DO (m/L) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 23.Sep.24 | Les Avocat | Right Stream Entering Dam | 7.67 | 26.1 | 73.6 | 0.07 | 158.4 | | 1.26 | 0.07 | 0.011 | |
| 28.Oct.24 | Les Avocat | Right Stream Entering Dam | 7.72 | 25.3 | 66.3 | 0.06 | 140.9 | | 2.16 | 0.08 | 0.014 | |
| 29.Nov.24 | Les Avocat | Right Stream Entering Dam | 7.63 | 23.5 | 89.1 | 0.07 | 185.6 | | 1.65 | 0.06 | 0.011 | |
| 20.Dec.24 | Les Avocat | Right Stream Entering Dam | 7.43 | 23.6 | 50.2 | 0.05 | 103.3 | | 4.57 | < 0.02 | 0.020 | |
| 17.Jan.25 | Les Avocat | Right Stream Entering Dam | 7.67 | 22 | 76.3 | 0.07 | 148.3 | | 1.36 | 0.07 | 0.014 | |
| 27.Feb.25 | Les Avocat | Right Stream Entering Dam | 7.89 | 22.3 | 76.8 | 0.07 | 153.1 | | 1.68 | 0.10 | 0.007 | |
| 28.Mar.25 | Les Avocat | Right Stream Entering Dam | 7.8 | 23.6 | 73.1 | 0.07 | 154 | | 2.94 | 0.06 | 0.019 | 7.7 |
| 27.Feb.24 | Les Avocat | Small Dam 2 (Upper) | 7.46 | 26.1 | 161.7 | 0.16 | 343 | | 7.46 | 0.83 | 0.480 | |
| 20.Mar.24 | Les Avocat | Small Dam 2 (Upper) | 7.3 | 26.4 | 160.1 | 0.16 | 342 | | 8.32 | 0.92 | 0.538 | |
| 10.Apr.24 | Les Avocat | Small Dam 2 (Upper) | 7.34 | 25.7 | 151.1 | 0.15 | 321 | | 9.08 | 1.58 | 0.828 | |
| 13.May.24 | Les Avocat | Small Dam 2 (Upper) | 7.51 | 27.7 | 349 | 0.16 | 333 | | | 0.74 | 0.436 | |
| 18.Jun.24 | Les Avocat | Small Dam 2 (Upper) | 7.1 | 22.1 | 158.9 | 0.15 | 322 | | 6.63 | 0.75 | 0.192 | |
| 26.Jul.24 | Les Avocat | Small Dam 2 (Upper) | 7.59 | 26.1 | 92.4 | 0.09 | 198.1 | | 2.57 | 0.57 | 0.193 | |
| 23.Aug.24 | Les Avocat | Small Dam 2 (Upper) | 7.41 | 25.9 | 144.6 | 0.14 | 304 | | 4.76 | 0.9 | 0.376 | |
| 23.Sep.24 | Les Avocat | Small Dam 2 (Upper) | 7.47 | 27.5 | 125.8 | 0.12 | 277 | | 4.06 | 0.98 | 0.452 | |
| 28.Oct.24 | Les Avocat | Small Dam 2 (Upper) | 7.77 | 26.2 | 77 | 0.07 | 166.5 | | 6.4 | 0.35 | 0.103 | |
| 29.Nov.24 | Les Avocat | Small Dam 2 (Upper) | 7.76 | 24.9 | 73.1 | 0.07 | 154 | | 6.07 | 0.38 | 0.139 | |
| 20.Dec.24 | Les Avocat | Small Dam 2 (Upper) | 7.64 | 24.2 | 52 | 0.05 | 108.4 | | 23.1 | < 0.02 | 0.085 | |
| 17.Jan.25 | Les Avocat | Small Dam 2 (Upper) | 7.41 | 23.9 | 153.4 | 0.15 | 319 | | 2.47 | 0.60 | 0.324 | |
| 27.Feb.25 | Les Avocat | Small Dam 2 (Upper) | 7.47 | 24.2 | 139.8 | 0.13 | 288 | | 2.57 | | | |
| 25.Mar.25 | Les Avocat | Small Dam 2 (Upper) | 7.52 | 24.2 | 141.4 | 0.14 | 292 | | 5.53 | 0.58 | 1.328 | |
| 28.Mar.25 | Les Avocat | Small Dam 2 (Upper) | 7.25 | 27.6 | 147.3 | 0.15 | 321 | | 8.32 | 1.12 | 0.665 | 4.61 |
| 27.Feb.24 | Les Avocat | Small Dam 3 (Lower) | 7.76 | 25.6 | 148 | 0.14 | 301 | | 0.83 | 0.08 | 0.074 | |
| 20.Mar.24 | Les Avocat | Small Dam 3 (Lower) | 7.7 | 26.2 | 142.7 | 0.14 | 305 | | 1.11 | 0.09 | 0.052 | |

**ESMP ACTION 9: WATER QUALITY MANAGEMENT FOR RESERVOIRS (MANGANESE)**

| Sample Date | Source | Sample Point | pH | Temp (°C) | TDS (mg/L) | Salinity (‰) | Cond (µS/cm) | $Cl_2$ (mg/L) | Turbidity (NTU) | Fe (mg/L) | Mn (mg/L) | DO (m/L) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 10.Apr.24 | Les Avocat | Small Dam 3 (Lower) | 7.71 | 26.1 | 144.7 | 0.14 | 309 | | 1.32 | 0.14 | 0.063 | |
| 13.May.24 | Les Avocat | Small Dam 3 (Lower) | 7.77 | 27.1 | 145.1 | 0.14 | 333 | | | 0.05 | 0.066 | |
| 18.Jun.24 | Les Avocat | Small Dam 3 (Lower) | 7.7 | 23.1 | 145.8 | 0.14 | 297 | | 1.93 | 0.13 | 0.053 | |
| 26.Jul.24 | Les Avocat | Small Dam 3 (Lower) | 7.66 | 26 | 96.6 | 0.10 | 207.1 | | 1.98 | 0.31 | 0.075 | |
| 23.Sep.24 | Les Avocat | Small Dam 3 (Lower) | 7.65 | 26.9 | 130.3 | 0.13 | 283 | | 1.58 | 0.22 | 0.059 | |
| 29.Nov.24 | Les Avocat | Small Dam 3 (Lower) | 7.8 | 25.1 | 76.9 | 0.08 | 167.9 | | 5.45 | 0.33 | 0.109 | |
| 20.Dec.24 | Les Avocat | Small Dam 3 (Lower) | 7.57 | 24.7 | 54.5 | 0.05 | 114.5 | | 20.95 | <0.02 | 0.082 | |
| 17.Jan.25 | Les Avocat | Small Dam 3 (Lower) | 7.64 | 23.6 | 137.3 | 0.13 | 283 | | 1.85 | 0.22 | 0.097 | |
| 27.Feb.25 | Les Avocat | Small Dam 3 (Lower) | 7.86 | 24.4 | 139.5 | 0.13 | 288 | | 5.33 | 0.29 | 0.095 | |
| 28.Mar.25 | Les Avocat | Small Dam 3 (Lower) | 7.8 | 27.8 | 142.4 | 0.14 | 314 | | 4.23 | 0.36 | 0.182 | 6.55 |
| 28.Mar.25 | Les Avocat | Small Stream Near Upper Gate | 7.53 | 24.5 | 111.3 | 0.11 | 234 | | 1.22 | 0.03 | 0.021 | 5.03 |
| 27.Feb.24 | Les Avocat | Spring Entering Sed Basin | 7.32 | 25 | 127.4 | 0.13 | 256 | | 0.18 | 0.16 | 0.008 | |
| 20.Mar.24 | Les Avocat | Spring Entering Sed Basin | 7.21 | 25.2 | 127 | 0.13 | 267 | | 0.72 | 0.01 | 0.017 | |
| 10.Apr.24 | Les Avocat | Spring Entering Sed Basin | 7.22 | 24.9 | 129.8 | 0.13 | 271 | | 0.20 | 0.06 | 0.009 | |
| 13.May.24 | Les Avocat | Spring Entering Sed Basin | 7.37 | 25.9 | 128.8 | 0.13 | 274 | | | 0.02 | 0.010 | |
| 18.Jun.24 | Les Avocat | Spring Entering Sed Basin | 7.5 | 23.2 | 132.6 | 0.13 | 275 | | 0.33 | 0.04 | 0.024 | |
| 26.Jul.24 | Les Avocat | Spring Entering Sed Basin | 7.33 | 25 | 124.8 | 0.13 | 261 | | 0.35 | 0.05 | 0.008 | |
| 23.Aug.24 | Les Avocat | Spring Entering Sed Basin | 7.41 | 25.9 | 134.7 | 0.13 | 276 | | 0.46 | 0.03 | 0.008 | |
| 23.Sep.24 | Les Avocat | Spring Entering Sed Basin | 7.29 | 25.7 | 128.9 | 0.13 | 273 | | 0.39 | 0.03 | 0.006 | |
| 28.Oct.24 | Les Avocat | Spring Entering Sed Basin | 7.45 | 25.6 | 129 | 0.12 | 273 | | 1.25 | 0.04 | 0.007 | |
| 29.Nov.24 | Les Avocat | Spring Entering Sed Basin | 7.28 | 24.8 | 123 | 0.12 | 257 | | 1.94 | 0.07 | 0.012 | |
| 20.Dec.24 | Les Avocat | Spring Entering Sed Basin | 7.02 | 25.1 | 121.6 | 0.12 | 255 | | 2.15 | < 0.02 | 0.013 | |
| 17.Jan.25 | Les Avocat | Spring Entering Sed Basin | 7.28 | 24 | 129.5 | 0.12 | 260 | | 1.04 | 0.03 | 0.014 | |
| 27.Feb.25 | Les Avocat | Spring Entering Sed Basin | 7.34 | 24.2 | 129.2 | 0.12 | 266 | | 0.99 | 0.01 | 0.006 | |

## ESMP ACTION 9: WATER QUALITY MANAGEMENT FOR RESERVOIRS (MANGANESE)

| Sample Date | Source | Sample Point | pH | Temp (°C) | TDS (mg/L) | Salinity (‰) | Cond (µS/cm) | $Cl_2$ (mg/L) | Turbidity (NTU) | Fe (mg/L) | Mn (mg/L) | DO (m/L) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 28.Mar.25 | Les Avocat | Spring Entering Sed Basin | 7.25 | 26.2 | 124.1 | 0.12 | 269 | | 0.50 | 0.03 | 0.013 | 5.38 |
| 27.Feb.24 | Les Avocat | Spring Near Left Dam Wall | 7.56 | 25.4 | 162.7 | 0.16 | 341 | | 0.10 | 0.08 | 0.610 | |
| 20.Mar.24 | Les Avocat | Spring Near Left Dam Wall | 7.42 | 25.8 | 161.4 | 0.16 | 341 | | 0.16 | 0.10 | 0.302 | |
| 10.Apr.24 | Les Avocat | Spring Near Left Dam Wall | 7.49 | 25.4 | 163.5 | 0.16 | 344 | | 0.08 | 0.24 | 0.401 | |
| 13.May.24 | Les Avocat | Spring Near Left Dam Wall | 7.55 | 26.2 | 159.8 | 0.16 | 342 | | | 0.16 | 0.454 | |
| 18.Jun.24 | Les Avocat | Spring Near Left Dam Wall | 7.6 | 21.1 | 165.4 | 0.16 | 388 | | 0.20 | 0.16 | 0.390 | |
| 26.Jul.24 | Les Avocat | Spring Near Left Dam Wall | 7.44 | 26.5 | 153.7 | 0.16 | 331 | | 0.09 | 0.11 | 0.152 | |
| 23.Aug.24 | Les Avocat | Spring Near Left Dam Wall | 7.57 | 26 | 167.2 | 0.16 | 353 | | 0.17 | 0.14 | 0.450 | |
| 23.Sep.24 | Les Avocat | Spring Near Left Dam Wall | 7.5 | 26.4 | 160.9 | 0.16 | 345 | | 0.09 | 0.13 | 0.213 | |
| 28.Oct.24 | Les Avocat | Spring Near Left Dam Wall | 7.53 | 26 | 162.8 | 0.16 | 346 | | 0.22 | 0.13 | 0.362 | |
| 29.Nov.24 | Les Avocat | Spring Near Left Dam Wall | 7.49 | 24.6 | 154.4 | 0.15 | 324 | | 0.11 | 0.07 | 0.196 | |
| 20.Dec.24 | Les Avocat | Spring Near Left Dam Wall | 7.5 | 25.2 | 158.7 | 0.16 | 333 | | 0.08 | 0.11 | 0.235 | |
| 17.Jan.25 | Les Avocat | Spring Near Left Dam Wall | 7.45 | 23 | 166 | 0.16 | 333 | | 0.36 | 0.13 | 0.330 | |
| 27.Feb.25 | Les Avocat | Spring Near Left Dam Wall | 7.55 | 24.8 | 166 | 0.15 | 345 | | 0.26 | 0.18 | 0.384 | |
| 05.Mar.25 | Les Avocat | Spring Near Left Dam Wall | 7.5 | 25.5 | 164.5 | 0.15 | 325 | | 0.30 | 0.10 | 0.247 | |
| 24.Mar.25 | Les Avocat | Spring Near Left Dam Wall | 7.46 | 25.9 | 160.1 | 0.16 | 336 | | 0.37 | 0.04 | 0.053 | 1.92 |
| 25.Mar.25 | Les Avocat | Spring Near Left Dam Wall | 7.45 | 23.4 | 157.9 | 0.16 | 332 | | 0.52 | 0.11 | 0.262 | |
| 28.Mar.25 | Les Avocat | Spring Near Left Dam Wall | 7.41 | 26.7 | 157.1 | 0.16 | 345 | | 0.34 | 0.14 | 0.368 | 2.24 |
| 28.Mar.25 | Les Avocat | Water At Base Of Dam Right Side | 6.66 | 26.2 | 131.8 | 0.13 | 284 | | 13.8 | 9.35 | 2.75 | 1.47 |
| 27.Feb.24 | Les Avocat Treatment Plant (Sources) | Water Entering Sed Basin from Dam | 7.27 | 24.3 | 78.9 | 0.08 | 164.7 | | 2.56 | 0.61 | 0.304 | |
| 20.Mar.24 | Les Avocat Treatment Plant (Sources) | Water Entering Sed Basin from Dam | 7.17 | 24.8 | 79.5 | 0.08 | 166.6 | | 0.38 | 0.71 | 0.222 | |
| 10.Apr.24 | Les Avocat | Water Entering Sed Basin from Dam | 7.28 | 25 | 79.3 | 0.08 | 167.5 | | 3.80 | 0.70 | 0.272 | |

## ESMP ACTION 9: WATER QUALITY MANAGEMENT FOR RESERVOIRS (MANGANESE)

| Sample Date | Source | Sample Point | pH | Temp (°C) | TDS (mg/L) | Salinity (‰) | Cond (µS/cm) | $Cl_2$ (mg/L) | Turbidity (NTU) | Fe (mg/L) | Mn (mg/L) | DO (m/L) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 13.May.24 | Les Avocat | Water Entering Sed Basin from Dam | 7.23 | 25.5 | 78.1 | 0.08 | 164.6 | | | 1.26 | 0.438 | |
| 18.Jun.24 | Les Avocat | Water Entering Sed Basin from Dam | 7.5 | 23.2 | 160.7 | 0.07 | 160 | | 6.19 | 0.51 | 0.140 | |
| 26.Jul.24 | Les Avocat | Water Entering Sed Basin from Dam | 7.35 | 25.2 | 68.9 | 0.07 | 146.3 | | 4.79 | 0.15 | 0.053 | |
| 23.Aug.24 | Les Avocat | Water Entering Sed Basin from Dam | 7.49 | 26 | 78.4 | 0.08 | 166.7 | | 3.01 | 0.15 | 0.050 | |
| 23.Sep.24 | Les Avocat | Water Entering Sed Basin from Dam | 7.32 | 25.8 | 73.7 | 0.07 | 158 | | 5.15 | 0.14 | 0.067 | |
| 28.Oct.24 | Les Avocat | Water Entering Sed Basin from Dam | 7.64 | 26.4 | 64.5 | 0.06 | 140.2 | | 12.6 | 0.29 | 0.063 | |
| 29.Nov.24 | Les Avocat | Water Entering Sed Basin from Dam | 7.47 | 24.3 | 68.8 | 0.07 | 143.3 | | 7.56 | 0.32 | 0.096 | |
| 20.Dec.24 | Les Avocat | Water Entering Sed Basin from Dam | 6.64 | 24.3 | 54.9 | 0.05 | 114.7 | | 43.51 | 0.67 | 0.137 | |
| 17.Jan.25 | Les Avocat | Water Entering Sed Basin from Dam | 7.44 | 24.3 | 81.4 | 0.08 | 166.9 | | 3.85 | 0.27 | 0.089 | |
| 27.Feb.25 | Les Avocat | Water Entering Sed Basin from Dam | 7.53 | 23.7 | 81.5 | 0.08 | 167.2 | | 3.76 | 0.31 | 0.088 | |
| 28.Mar.25 | Les Avocat | Water Entering Sed Basin from Dam | 7.26 | 25.7 | 75.1 | 0.07 | 164.2 | | 5.30 | 0.27 | 0.075 | 4.7 |
| 20.Mar.24 | Les Avocat | Water Leaving Sed Basin | 7.29 | 25.6 | 80.8 | 0.08 | 171.6 | | 2.46 | 0.72 | 0.267 | |
| 10.Apr.24 | Les Avocat | Water Leaving Sed Basin | 7.59 | 25.4 | 81 | 0.08 | 171.6 | | 2.67 | 0.66 | 0.251 | |
| 13.May.24 | Les Avocat | Water Leaving Sed Basin | 7.42 | 26.6 | 79.9 | 0.08 | 173.8 | | | 1.21 | 0.380 | |
| 18.Jun.24 | Les Avocat | Water Leaving Sed Basin | 7.14 | 23.6 | 79.7 | 0.08 | 163.8 | | 2.89 | 0.33 | 0.192 | |
| 26.Jul.24 | Les Avocat | Water Leaving Sed Basin | 7.47 | 25.6 | 66.8 | 0.07 | 142.8 | | 3.44 | 0.14 | 0.058 | |
| 23.Aug.24 | Les Avocat | Water Leaving Sed Basin | 7.52 | 26 | 163 | 0.07 | 163 | | 2.91 | 0.15 | 0.060 | |
| 23.Sep.24 | Les Avocat | Water Leaving Sed Basin | 7.43 | 26.9 | 73 | 0.07 | 160.1 | | 3.69 | 0.12 | 0.061 | |
| 28.Oct.24 | Les Avocat | Water Leaving Sed Basin | 7.52 | 26.8 | 71 | 0.07 | 153.3 | | 3.98 | 0.14 | 0.050 | |
| 29.Nov.24 | Les Avocat | Water Leaving Sed Basin | 7.18 | 24.7 | 68.8 | 0.07 | 144.5 | | 3.52 | 0.12 | 0.062 | |
| 20.Dec.24 | Les Avocat | Water Leaving Sed Basin | 6.02 | 24.6 | 61.8 | 0.06 | 129.7 | | 5.02 | < 0.02 | 0.027 | |

## ESMP ACTION 9: WATER QUALITY MANAGEMENT FOR RESERVOIRS (MANGANESE)

| Sample Date | Source | Sample Point | pH | Temp (°C) | TDS (mg/L) | Salinity (‰) | Cond (µS/cm) | $Cl_2$ (mg/L) | Turbidity (NTU) | Fe (mg/L) | Mn (mg/L) | DO (m/L) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 17.Jan.25 | Les Avocat | Water Leaving Sed Basin | 7.51 | 23.8 | 83.2 | 0.08 | 165.6 | | 3.08 | 0.23 | 0.065 | |
| 27.Feb.25 | Les Avocat | Water Leaving Sed Basin | 7.62 | 24.1 | 82.1 | 0.08 | 169.6 | | 1.98 | 0.29 | 0.076 | |
| 28.Mar.25 | Les Avocat | Water Leaving Sed Basin | 7.33 | 26.8 | 79.6 | 0.08 | 177 | | 3.64 | 0.27 | 0.107 | 6.65 |