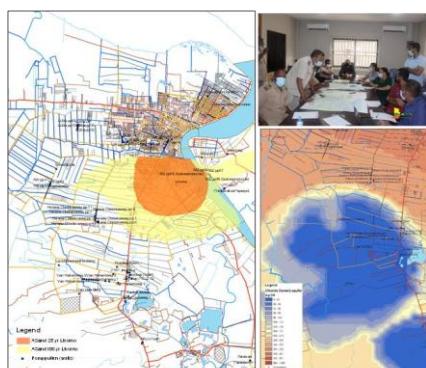


The United Nations Environment Programme (UNEP) on behalf of the Climate Technology Centre and Network (CTCN)

Report on Managed Aquifer Recharge (MAR) techniques and feasibility in Suriname

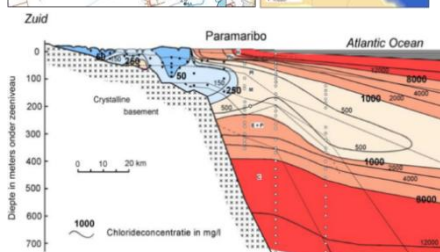


Consultancy services for

Enhance the resilience of Suriname’s water supply system by modelling drought risks and developing a roadmap of prioritized alternatives for aquifer recharge

Acronym: ARADIS

Climate Technology Centre and Network (CTCN)



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List of acronyms

ARADIS	Aquifer Recharge Against Droughts In Suriname
ASR	Aquifer Storage and Recovery
ASTR	Aquifer Storage, Transfer and Recovery
BCM	Billion Cubic Metre
BF	Bank Filtration
HACAS	Hydrogeological Assessment of the Coastal Aquifers in Suriname
LBF	Lake Bank Filtration
MAR	Managed Aquifer Recharge
O&M	Operation and Maintenance
RBF	River Bank Filtration
RWH	Rain Water Harvesting
SAT	Soil Aquifer Treatment
SWG	Stakeholder Working Group
SWM	Surinaamsche Waterleiding Maatschappij

Executive summary

This report evaluates the technical feasibility of various managed aquifer recharge (MAR) techniques in Suriname.

The study explores several potential MAR solutions to enhance groundwater availability, mitigate seawater intrusion, and improve water quality, while considering the specific hydrogeological conditions of the region.

In the young coastal plain, deep well injection into the Coesewijne aquifer can sustain recovery from abstraction wells and combat seawater intrusion near SWM production wells. Although technically feasible, this approach is complex in terms of design, operation, and maintenance (O&M) and requires a reliable freshwater source near the coast.

Induced swamp infiltration through drain collectors in sand and shell ridges offers a low-cost solution for small-scale irrigation and household water supply.

In the savanna belt, induced river bank filtration using wells along rivers and creeks incised into the Zanderij aquifer can improve groundwater quality and levels.

Additionally, water spreading from the Lelydorp III mine pit lake shows potential to enhance aquifer recharge and maintain downstream well field yields.

Rainwater harvesting and small-scale recharge provide low-cost, community-based options for supplementary irrigation or household use during droughts.

While streambed channel modifications like sand dams are technically feasible, they are less suitable for Suriname due to local geological and hydrological conditions.

The study identifies practical MAR approaches to improve groundwater management and resilience in Suriname's coastal plain.

1 Introduction

This feasibility assessment of managed aquifer recharge (MAR) in Suriname is part of the project titled *Enhance the resilience of Suriname's water supply system by modelling drought risks and developing a roadmap of prioritized alternatives for aquifer recharge*. For practical purposes the title is shortened to *Aquifer Recharge Against Droughts In Suriname* (ARADIS).

This report is part of the analytical phase (phase 2) of the project, in which the drought risks, water demand and MAR potential are mapped, followed by site selection by the stakeholder working group (SWG) for the pilot MAR.

1.1 Objectives

In Suriname, problems are expected for the future water supply of various sectors, which will be exacerbated by climate change. As far as drinking and industrial water supply is concerned, groundwater is by far the most important source. This resource is already overexploited in some areas, as indicated in the Hydrogeological Assessment of the Coastal Aquifers in Suriname (HACAS) study (RTI, Acacia Water and ILACO, 2016). One of the strategies to cope with these developments is managed aquifer recharge (MAR). MAR is the intentional recharge of water into an aquifer under controlled conditions to enhance groundwater resources for later recovery or environmental benefit. Though applied in many countries in various forms, MAR is still a new and rather unexplored strategy in Suriname.

1.2 Methodology

This report assesses the technical feasibility of various Managed Aquifer Recharge (MAR) techniques in the coastal plain of Suriname. The analysis will be combined with assessments of drought risks, water demand, aquifer characteristics, and water balances, as part of Phase 2 of the project. Based on this integrated approach, the best technology at five sites will be identified where MAR techniques are both technically feasible and economically viable, offering suitable solutions for stakeholders in need of water.

At the end of Phase 2, the five selected sites and their corresponding MAR systems will be presented to the SWG, who will then select the final site and appropriate technique to be designed as a pilot project in Phase 3.

In this report, the basic concepts and purposes of MAR are presented in chapter 2, including an overview of operational MAR systems in Suriname. In chapter 3, various MAR techniques are assessed, with a description of the MAR concept and purpose, followed by an analysis of the water source to be used, where in Suriname it is technically feasible and how the MAR should be managed. The results are summarized in a MAR technical feasibility matrix in chapter 4, fitting the local context.

2 Managed aquifer recharge

2.1 Purposes of MAR

Managed aquifer recharge (MAR) is a useful water management tool in a variety of areas to enhance the quality and increase the quantity of water supply. It is a nature-inspired solution that intentionally recharges aquifers with surface water, rainwater or (treated) wastewater for later use or environmental benefits. Apart from direct benefits of increasing the availability of water in an aquifer, reducing evaporation, and helping to improve or maintain the water balance, MAR can provide other community and environmental benefits. For example, MAR projects that utilize stormwater in urban areas of Paramaribo could help mitigate floods and improve water quality of local streams and coastal water bodies. MAR can also be used in the coastal area of Suriname to improve groundwater quality by controlling saltwater intrusion augmenting the sustainability of the existing drinking water supply wells.

MAR is defined by Dillon et al. (2009) as “the purposeful recharge of water to aquifers for subsequent recovery or for environmental benefit”. MAR can be used to improve water security and resilience to droughts. In particular in areas coping with an increase in climate extremes, both in rainfall and in droughts, MAR can be a beneficial technique.

An aquifer can be recharged with many types of source water, including surface water from rivers or lakes, captured stormwater, treated wastewater, and groundwater drawn from other aquifers or remotely from the same aquifer. When choosing a MAR site, one must be sure that the quality of the recharge water is compatible with the reactive potential of the aquifer matrix and possibly the vadose zone. Depending on the situation, MAR can be part of the solution to various issues, including water scarcity, water security, water quality degradation, land subsidence, falling water tables, seawater intrusion, streamflow depletion, and endangered groundwater dependent ecosystems (Dillon et al., 2022). For all type of MAR systems and short term and long-term impacts on the system should be considered.

Selection of suitable sites for MAR and the choice of method depends on the hydrogeology, topography, hydrology and land use of the area (Figure 1). Similar types of MAR projects are commonly clustered in the same area due to shared physical attributes favoring the economics of those MAR types for a given type of source water and MAR purpose (Dillon et al., 2009).

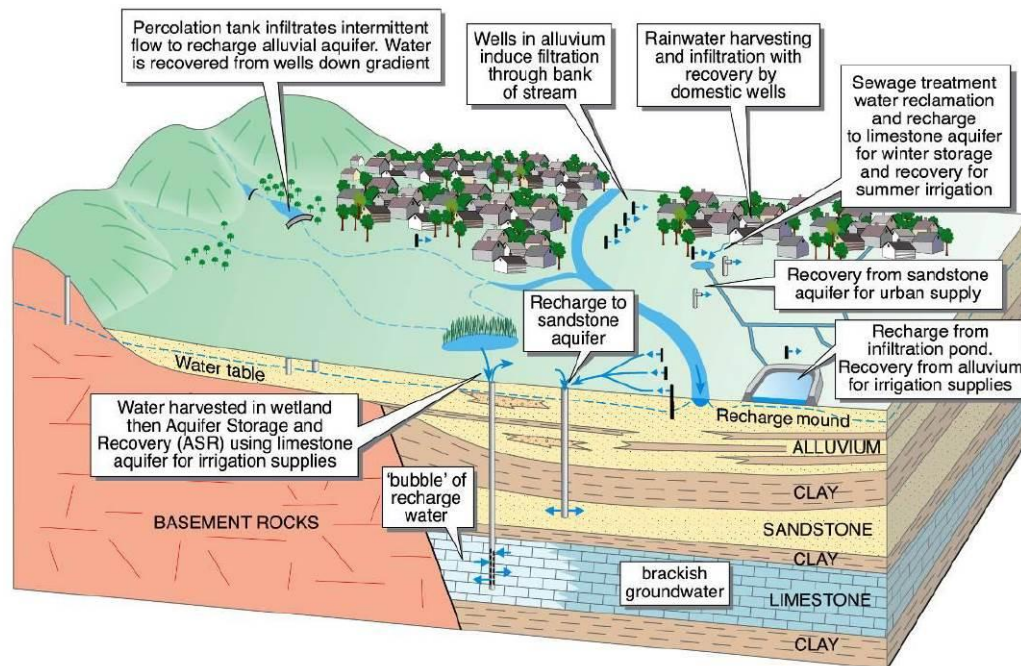


Figure 1. Different MAR techniques require specific site conditions, depending on hydrogeology, topography, hydrology, and land use (source: Dillon et al, 2022).

2.2 Basic concepts of MAR

The main considerations for MAR include water source, recharge method, aquifer storage, recovery of water and use management, as highlighted by Burke et al (2003) (Figure 2).

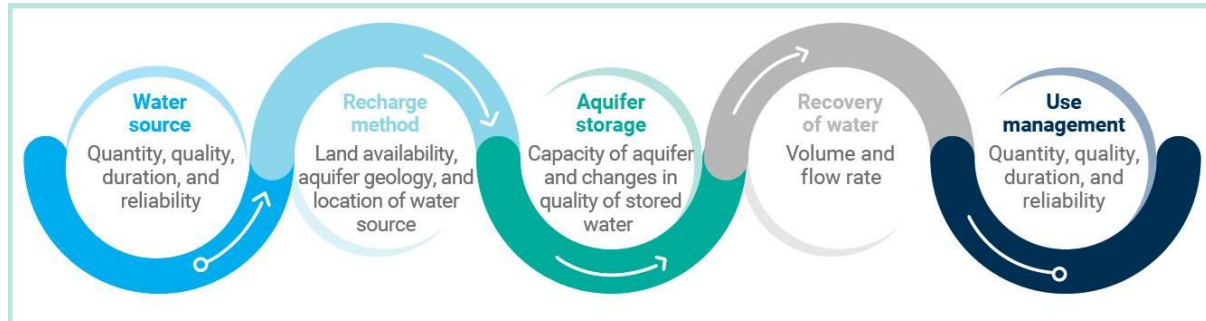


Figure 2. Managed Aquifer Recharge considerations (source: Burke et al, 2003)

In our assessment of feasible MAR techniques and suitable locations in Suriname we have considered six critical elements that are needed on the ground for a successful implementation of a MAR project:

- 1) A site with a sufficient water demand and need for aquifer recharge (e.g. drought risk)
- 2) An adequate source of water for infiltration
- 3) An appropriate recharge method
- 4) A suitable aquifer for storage and recovery
- 5) The availability of land for implementation of the system
- 6) Good local capability to effectively manage the MAR system

2.2.1 Water demand

The volumetric demand for recovered water (within an economic scale) or a clearly defined environmental benefit of recharge is essential for MAR. The purposes for which water will be recovered also need to be defined. Generally, this will provide the revenue stream to pay for the water supply cost elements of the project. Demand may be steady, seasonal, or solely to secure water

supplies during occasional droughts. Environmental benefits may include prevention of saline intrusion, sustaining base flow in streams and protecting wetlands and groundwater-dependent ecosystems.

2.2.2 Source waters

An aquifer can be recharged with many types of source water, including surface water from rivers or lakes, captured stormwater, treated wastewater, and groundwater drawn from other aquifers or remotely from the same aquifer. Use of desalinated water from seawater or brine is another possibility. Most applications of MAR have used surface water due in part to its availability. Requirements for treatment to address the chemical and microbiological quality of natural surface water are normally less than those for stormwater or treated wastewater. For some applications, surface water may be adequate for recharge by itself or with limited treatment. Stormwater is usually an abundant but sporadic resource, however treatment and storage as a source water for MAR can be challenging. Treated wastewater has advantages in terms of being available throughout the year and in particular during dry periods when demands are the highest and conventional resources are less available. It requires extensive treatment before recharge.

2.2.3 Water quality

When choosing a MAR site, one must be sure that the quality of the recharge water is compatible with the reactive potential of the aquifer matrix and possibly the vadose zone. This usually means comprehensive investigations during a pilot phase. Water intended for recharge can sometimes contain pollutants, including trace elements, nutrients, pathogens, and contaminants of emerging concern. Two main issues emerge with respect to the source water used for recharge: the safety of water quality for human health and the environment, and clogging of the recharge facility.

2.2.4 Recharge methods

Many methods can be used to enhance recharge to aquifers. These can be broadly grouped as recharge wells (chapter 3.1), bank filtration (chapter 3.2), water spreading (chapter 3.3) and streambed channel modifications (chapter 3.4). Small-scale recharge such as rainwater harvesting use various infiltration methods or wells.

Recharge wells

Recharge wells are used to inject water into deep, confined aquifers or those overlain by low-permeability layers. Common approaches include Aquifer Storage and Recovery (ASR), Aquifer Storage, Transfer and Recovery (ASTR), and dry wells. ASR involves injecting water into a well for storage and recovering it from the same well, particularly useful in brackish aquifers where storage is the primary goal and water treatment is less critical. ASTR, on the other hand, stores water in one well and recovers it from another, allowing extended residence time for additional natural treatment. Dry wells, typically shallow, enable high-quality water infiltration into deep unconfined aquifers where water tables are very deep.

Bank filtration

Bank filtration involves extracting groundwater from wells or infiltration galleries (drains) located near or under rivers or lakes, inducing seepage from the surface water body into the aquifer. This process naturally filters the water as it flows to the supply well, improving and stabilizing the recovered water quality. Commonly used in alluvial aquifers, bank filtration serves as a natural pre-treatment method, enhancing resilience against spills, floods, and droughts compared to direct surface water abstraction, and preventing excessive groundwater drawdown beneath large urban centers.

Water spreading

Water spreading techniques enhance groundwater recharge by directing surface water into unconfined aquifers through ponds, basins, or wetlands. Infiltration ponds, divert surface water into off-stream basins, allowing it to soak through the unsaturated zone. Dune filtration, practiced in the Netherlands, involves pond infiltration in dunes with extraction from lower-elevation wells or ponds to improve water quality and balance supply and demand. Soil Aquifer Treatment (SAT), intermittently infiltrates treated sewage effluent through ponds to remove nutrients and pathogens during passage through the unsaturated zone before recovery from wells. Infiltration galleries consist of buried trenches with permeable materials, facilitating water infiltration to unconfined aquifers. Rainwater harvesting for aquifer storage, collects roof runoff into wells or sumps filled with sand or gravel for percolation to the water table and subsequent pumping. These methods provide natural filtration, enhancing water quality compared to direct surface abstraction.

Streambed channel modifications

Surface and subsurface impoundments in streambeds can capture or slow down runoff, promoting infiltration through the bed to enhance storage in unconfined aquifers for downstream extraction. These structures, typically built in seasonal or ephemeral streams, commonly include recharge weirs, underground dams, and sand dams.

2.2.5 Aquifer

A suitable aquifer is critical for MAR. It must be capable of an adequate rate of recharge (hydraulic conductivity), have sufficient storage capacity (thickness, porosity), and normally be capable of retaining the water where it can be recovered. Low salinity and marginally brackish aquifers are preferred so that mixing with fresh recharge water should still allow recovered water to be fit for use.

2.2.6 Management capability and stakeholder involvement

Hydrogeological and geotechnical knowledge, knowledge of water storage and treatment design, water quality management, water sensitive urban design, hydrology and modeling, monitoring and reporting are all required to effectively manage the MAR system and to meet requirements of local authorities.

Active stakeholder engagement and public education are critical to the success of a proposed MAR project. Stakeholder involvement can be crucial to identify local priorities and shape the project to local conditions. In addition to key stakeholders, the general public should be informed about the importance and vulnerability of groundwater systems, and MAR as a cost-effective management solution. A public that is knowledgeable of groundwater conditions, management challenges, and alternative solutions is more likely to support MAR.

2.2.7 Overall advantages of MAR

Depending on the situation, MAR can be part of the solution to various issues, including water scarcity, water security, water quality degradation, land subsidence, falling water tables, seawater intrusion, streamflow depletion, and endangered groundwater dependent ecosystems (Dillon et al, 2022).

Compared to traditional surface water infrastructure like dams, MAR has several advantages: it requires lower capital investment, utilizes less land, and minimizes evaporation losses. MAR also provides subsurface treatment of water, enhancing water quality by naturally filtering contaminants. It can make use of brackish aquifers and is scalable, starting with small pilot projects that can expand as confidence in the system grows. Furthermore, MAR can reduce energy demand and contribute to

greenhouse gas emission targets by integrating renewable energy. Its cost-effectiveness and environmental benefits make it an attractive option for sustainable water management.

2.2.8 Overall challenges of MAR

Various technical and regulatory challenges occur with advancing the use of MAR. Short- and long-term impacts of MAR systems on both native groundwater and surface water should be considered, including:

1. changes in groundwater recharge, flow, and discharge;
2. the water quality effects of the mixing of source water and native groundwater; and
3. chemical interactions with aquifer materials. Monitoring of groundwater levels and quality is commonly an integral part of MAR risk assessment (Dillon et al, 2022).

Successful implementation requires thorough hydrogeological assessments and careful monitoring of water quality to prevent contamination of aquifers. Water entitlement and rights are often less clear than in surface reservoirs, creating potential conflicts over access to stored water. MAR systems are constrained by the permeability of porous media, limiting the rate of recharge compared to surface reservoirs, and can result in lower volumes of recoverable water when mixing with brackish water. High initial costs, including investigations and infrastructure, can make MAR projects financially uncertain. Additionally, regulatory challenges, particularly in areas with fragmented governance, can complicate implementation. Environmental impacts, such as changes in groundwater flow and quality, must be monitored to avoid unintended consequences on ecosystems.

2.3 Global application of MAR

The last 65 years has seen unprecedented groundwater extraction and overexploitation as well as development of new technologies for water treatment that together drive the advance in intentional groundwater replenishment known MAR. Since the 1960s, implementation of MAR has accelerated at a rate of 5%/year, but is not keeping pace with increasing groundwater extraction. According to Dillon et al (2018), MAR has reached an estimated 10 km³/year, ~2.4% of groundwater extraction in countries reporting

MAR (or ~1.0% of global groundwater extraction), to sustain quantity, reliability and quality of water supplies.

For example bank filtration (chapter 3.2) is widely applied worldwide. According to Dillon et al (2019) and the sources mentioned therein, BF systems have been in place at a large scale in Europe since 1870, providing about 50% of the public water supply of Slovakia and Hungary, 9% in Germany, 7% in Netherlands and 25% in Switzerland. The city of Budapest (Hungary) is fully supplied with bank filtrate from the Danube River from 762 wells with a total maximum capacity of 1 million m³/day. In the US, bank filtration systems have been in use for more than 60 years, including the world's largest horizontal collector wells with single capacities of more than 150,000 m³/day. Today in Europe, BF is mainly used for pre-treatment, the focus lying on attenuation of water quality variations and removal of turbidity, pathogens and organic compounds. In the US, India and Egypt, BF is mainly used to remove particles and pathogens. In some countries, including China and Italy, BF is used to prevent overexploitation of aquifers. In Brazil, bank filtration technology has been applied for water quality improvement at Beberibe River in Brazil (Freitas et al, 2012).

In Latin America and the Caribbean, MAR is not yet well established, even though streambed channel modifications (chapter 3.4) such as subsurface dams have been widely used in semi-arid regions of Brazil, particularly in the state of Paraíba, as well as in Mexico and Chile (Bonilla Valverde et al, 2018). Well, shaft and borehole recharge and spreading methods are the main MAR types reported for

Argentina and Paraguay. In Cuba, water runoff has been used to prevent saline water intrusion by a system of perforated wells in storm water channels since the 1950's (Bonilla Valverde et al, 2018).

2.4 Operational MAR systems in Suriname

The oldest wellfield in Suriname along the Coropina Creek at Republiek is an example of a managed aquifer recharge (MAR) system by bank infiltration. Located in the savannah zone, the Zanderij Formation contains fresh groundwater and receives active recharge from rainfall. At Republiek wellfield groundwater is recovered from this formation. Established in 1933, the water engineers at that time deliberately positioned the wells along the Coropina creek to secure (additional) recharge. The Republiek wellfield can be considered a MAR system because it actively induces recharge from the Coropina Creek, by abstracting groundwater nearby, along the way utilizing the natural filtration capacity during underground flow and maintaining a sustainable balance between groundwater abstraction and aquifer recharge.

In a similar way, for long time community wells have been drilled in sandy river banks along creeks and rivers in the interior of Surinam. For example along Suriname and Marowijne river, river terraces can be found not only in the coastal zone but also in the far interior, upstream of the Brokopondo Reservoir (*Professor Doctor Ingenieur W. J. van Blommestein Meer*). Community wells located in these alluvial deposits induce recharge from the river. In other words, without groundwater abstraction from these wells, the river water would not recharge the local aquifer. Under natural conditions, the creeks would be solely draining the phreatic aquifer rather than recharging. These river bank infiltration systems are an old and long used MAR method, but have come under attention again recently. An example can be found in the news article '*Traditioneel gezag Saamaka pakt schaarste drinkwater op scholen Boven-Suriname aan*' (De Ware Tijd, 2025).

3 MAR techniques and feasibility in Suriname

3.1 Recharge wells

Recharge wells are used in situations where the target aquifer is deep, confined, or overlain by low permeability layers. Several different approaches are used, including aquifer storage and recovery (ASR) and aquifer storage, transfer and recovery (ASTR) to inject and recover water, as well as deep well recharge without recovery to combat salt water intrusion. Recharge the deep aquifers by means of injection wells is considered the most feasible MAR technique in the coastal plain of Suriname with thick clay layers at the surface.

3.1.1 Aquifer Storage and Recovery wells

Aquifer Storage and Recovery (ASR) is a technique designed to inject surplus water into an aquifer for storage during wet periods, allowing for extraction during times of scarcity. It is one of the most widely used deep well recharge methods, typically applied to confined aquifer units.

MAR technique

Deep well recharge is used where thick, low permeability strata overlie target aquifers, in order to recharge water directly into the aquifer. There are two typical applications:

- Aquifer Storage and Recovery (ASR), where a well is used for both injection and recovery of water.
- Aquifer Storage Transfer and Recovery (ASTR) involves water injection through a well, and recovery from another well, some distance away, to increase travel time and benefit from the water treatment capacity of the aquifer.

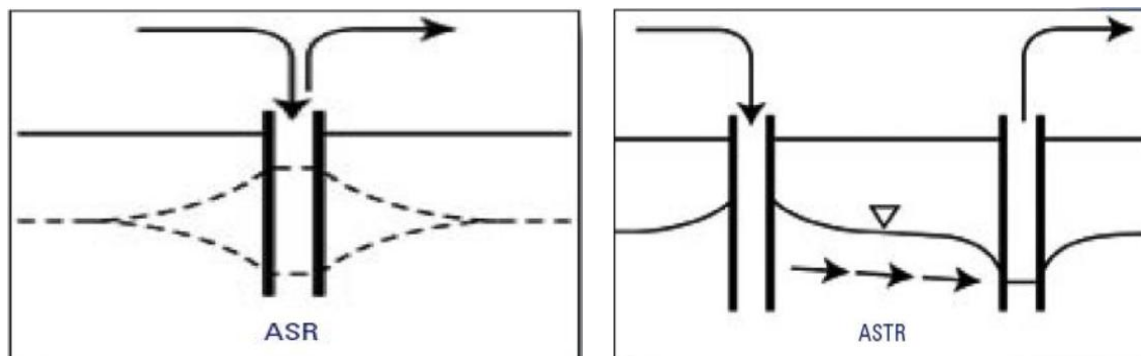


Figure 3. Schematization of Aquifer Storage and Recovery (left) and Aquifer Storage Transfer and Recovery (right). Source: IGRAC and Acacia Institute, (2007)

Water treatment can be used prior to recharge to ensure the recharge source is suitable for recharge and/or after recovery to ensure the recovered water is suitable for its intended use(s). The type of treatment required is influenced by the quality of the source of water for recharge, the intended use, the recharge method, and existing use/s of the target aquifer. For the injection of recycled or reclaimed water in AS(T)R wells, a high level of treatment before recharge is required to manage the risk of injection well clogging. A schematic diagram of the typical components of AS(T)R is presented in Figure 4.

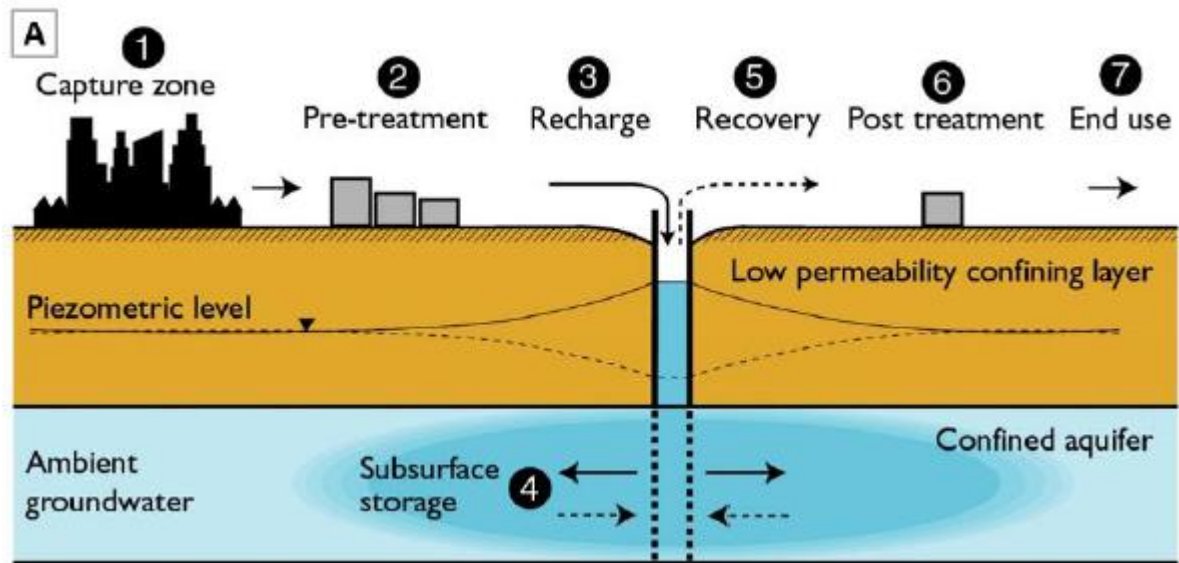


Figure 4. Schematic diagram of aquifer storage and recovery (ASR). Source: NRMCC-EPHC-NHMRC (2009)

Purpose

ASR and ASTR injection and recovery wells could serve to sustain the recovery from the abstraction wells and combat overexploitation. ASR is particularly beneficial for aquifers that have experienced long-term declines in groundwater levels due to intensive pumping for urban and agricultural needs. By recharging adequate volumes of water, ASR can help restore groundwater levels and enhance water security.

Water source

To prevent clogging and contamination of the aquifer, high-quality source water is essential for AS(T)R wells. For that reason, most operational AS(T)R sites store treated drinking water, ensuring a reliable supply for cities and communities during periods of peak demand. However, there is no need for this in Suriname (not cost-effective).

Additionally, it is also possible to recharge the aquifer through wells with pre-treated surface water or treated wastewater. However, this approach carries higher risks of clogging and contamination, requiring careful water quality monitoring and management.

Since Suriname lacks centralized wastewater treatment facilities, (pre-treated) surface water from nearby rivers and creeks is the only practical option for source water for AS(T)R wells. However, there is a significant challenge of salt water intrusion from the sea far into coastal rivers, especially during periods of low flows (droughts). To ensure the suitability of intake locations, we mapped the extent of saltwater migration upstream to identify points where freshwater can be reliably extracted for aquifer recharge without risking salinization.

The depth of salt intrusion into the estuaries of these coastal rivers primarily depends on the magnitude of the extruding force of the river discharge and the intruding force of seawater with its dissolved salts during the flood tide. The main factor influencing the depth of salt-water intrusion up the rivers is the amount of discharge of the river. The salt wedge in rivers in Suriname depends on the following factors:

- 1) the tidal effect of the Atlantic Ocean (or in the estuary between river and ocean);
- 2) the freshwater discharge from upstream;
- 3) the freshwater discharge from the Brokopondo lake (Suriname River);

- 4) the amount of water extracted from the river for irrigation purposes (Saramacca and Nickerie River);
- 5) the amount of drainage water from the rice polders and other agricultural land released into the river (e.g. Saramacca and Nickerie River).

Amatali and Naipal (1999) studied the extent of saltwater intrusion in the estuaries of the main rivers in Suriname, by taking water samples at high water slack when the salinity is at its maximum. In order to assess up to which point upstream river water would be a good source water for MAR, the findings of Amatali and Naipal (1999) were used. A threshold salinity of < 300 mg/l chlorinity was used, which is the most common definition of freshwater (e.g. Stuyfzand, 1986) and is also the threshold for water that can still be used for rice cultivation.

The extent of saltwater intrusion ($Cl = 300$ mg/l) in the estuaries of the main rivers, measured in kilometers going upriver from the mouth, is summarized in Table 1.

Table 1. Saltwater intrusion ($Cl = 300$ mg/l) in main rivers during periods of low flow, based on Amatali and Naipal (1999)

River	Kilometer upriver (km)	Discharge - low flow (m^3/s)
Corantijn River	74	320
Nickerie River	78	10
Coppename River	74	17
Saramacca River	75	5
Suriname River	67	285
Commewijne River	117	48
Marowijne River	58	202

This information is presented on the map shown in Figure 5.



Salt water intrusion during the dry period

Cl = 300 mg/l

(Amatali M.A. and Naipal S., 1999)

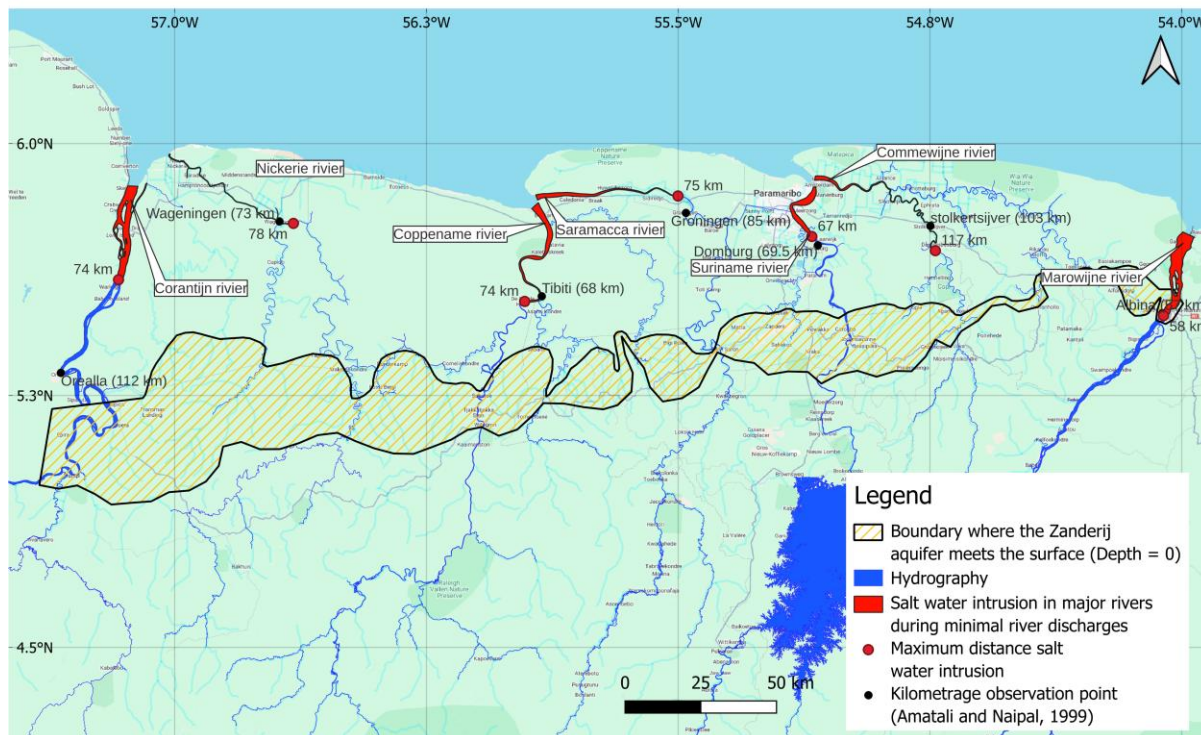


Figure 5. The maximum extent of salt water intrusion in Surinames major rivers during low flows, based on the study of Amatali and Naipal (1999).

Where suitable

Recharge of the deep aquifers by means of injection wells is suitable in the Holocene or young coastal plain of Suriname with thick clay layers at the surface. This is the northern most zone along the coast, elevated at +1 to +3 m, with a width of 40 km in the west and decreasing to 10 km in the east.

Considering the need of nearby presence of fresh river water as water source and the maximum extent of salt water intrusion in Surinames major rivers during low flows (Table 1 and Figure 5), AS(T)R wells could be suitable:

- near Nickerie river upstream of Wageningen
- near Coppename river upstream of De Goede Hoop
- near Saramacca river upstream of Kampong Baroe
- near Suriname river upstream of Paramam
- near Commewijne river upstream of Herstelling

Target aquifer

The best target aquifer to inject water is the aquifer of the Coesewijne formation, since this confined aquifer is mostly fresh and exploited by a large number of pumping stations in the coastal plain. The Coesewijne Formation consists of alternating clays and sand layers and is highly varying, with the upper Coesewijne aquifer having the best aquifer properties, with an average hydraulic conductivity of 30 m/day, (HACAS Technical Memo 2). The thickness of the formation varies from 50 m in the east to 100 m in the west of the coastal plain. Around Paramaribo, the top is encountered at -60 m around Lelydorp, and slopes to -100 m north of Paramaribo. In Nieuw Nickerie the formation is found at -200 m (Figure 6).

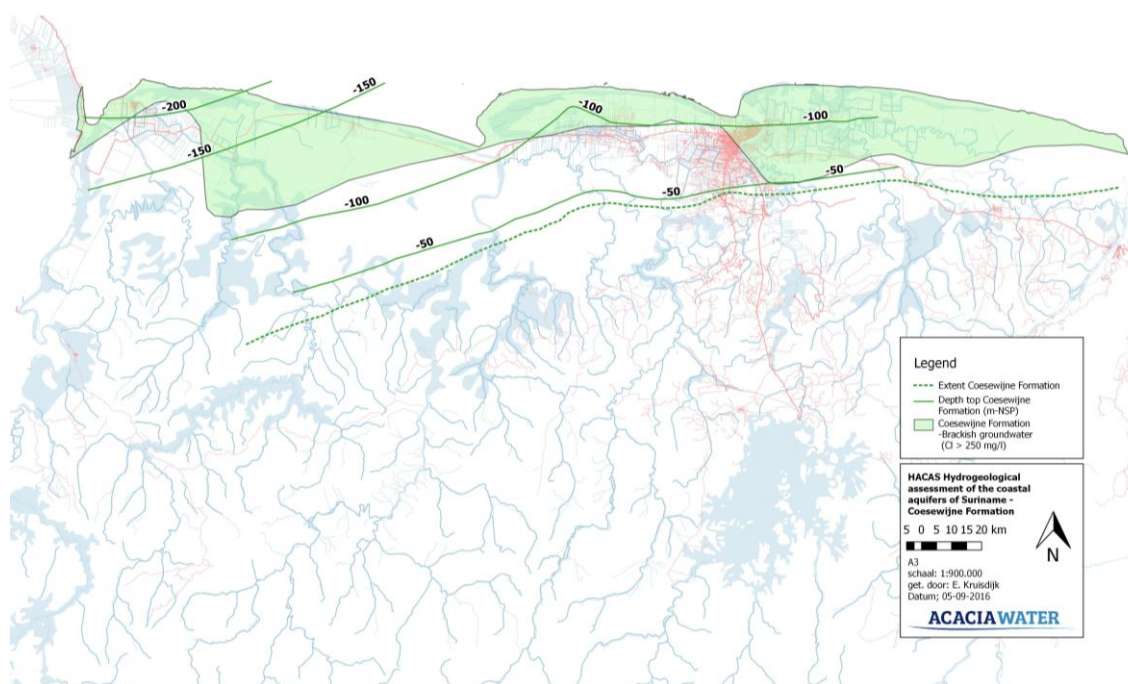


Figure 6. Extent, depth and brackish part of the Coesewijne Formation. Source: HACAS study (RTI, Acacia Water and ILACO, 2016).

MAR use management

Both ASR and ASTR systems require pretreatment of source water, along with continuous monitoring and regular regeneration of the injection wells, to reduce the well screen clogging process. While ASR operation can be expensive, the cost per cubic meter of recharged water remains relatively low due to the ability to infiltrate large volumes efficiently.

The decrease in well capacity due to clogging necessitates specialized operation and maintenance (O&M) expertise and regeneration of wells. Additionally, after recovery, the extracted water may need post-treatment to meet drinking water standards, particularly when pre-treated surface water or treated wastewater was used for recharge.

Clogging of recharge wells is a critical challenge in MAR systems due to their vulnerability to clogging. In Aquifer Storage Transfer and Recovery (ASTR) systems, which use separate injection and recovery wells, clogging is often caused by (bio)chemical precipitation, such as the formation of hydrous ferrihydrite. In contrast, Aquifer Storage and Recovery (ASR) systems, which use the same well for both injection and recovery, may experience partial unclogging during the recovery phase, reducing the severity of clogging (Dillon et al., 2019).

Due to the costly and complex infrastructure involved, ASR and ASTR systems are generally better suited to urban areas, where O&M facilities are more readily available, and the economic viability of such investments is higher.

3.1.2 Recharge wells to combat salt water intrusion

Some SWM production wells suffer from (slightly) saline water intrusion. These risks will increase due to climate change. A measure to prevent further seawater intrusion can be to recharge surplus freshwater into the coastal aquifer. This can build up a barrier against further seawater intrusion and repulse the seawater back. Infiltration of treated wastewater or surface water into the coastal aquifers

can benefit existing (initial non-recharged) aquifers from SWM water-utilities, to combat further salt water intrusion.

MAR technique

Recharge of fresh water into a confined aquifer by means of deep injection wells, without recovery purposes, to build up a barrier to prevent further seawater intrusion as schematized in Figure 7. For the injection of recycled or reclaimed water, a high level of treatment before recharge is required to manage the risk of injection well clogging

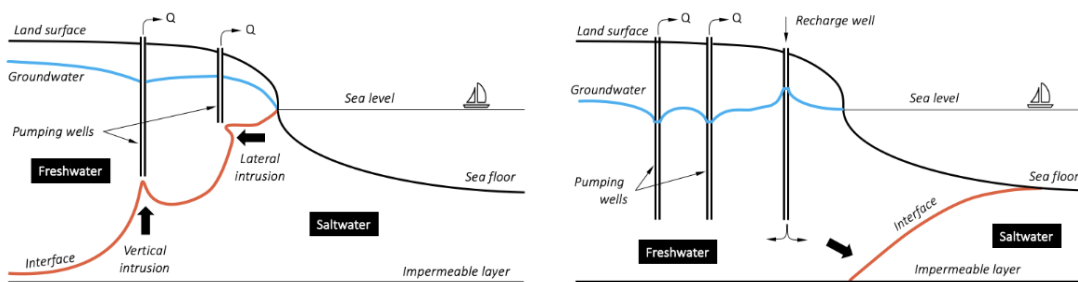


Figure 7. Pumping-induced saltwater intrusion (left) and the build up of a barrier to prevent further seawater intrusion by recharging water with a recharge well (right). Source: INOWAS platform¹.

Purpose

Deep well injection of fresh water could serve to combat seawater intrusion near production wells that are affected by salinization. In general the Tertiary formations have good hydraulic properties in most parts of the coastal plain. They sustain wells with capacities from 10 to 100 m³/hr. The main limitation for groundwater development is its salinity. An important marker is the 250 mg/l chloride contour, which is the salinity standard for drinking water in Suriname.

As an example, the 25-year capture zones of the production wells in the Coesewijne formation near Paramaribo, which were modelled as part of the HACAS study (RTI, Acacia Water and ILACO, 2016) are shown in Figure 8, with the brackish part of the Coesewijne formation indicated in pink. This map shows that some of the SWM production wells are affected by salinization (Cl > 250 mg/l), mainly the Leiding 9A production wells.

¹ <https://www.inowas.com/applications/a07-assessment-of-saltwater-intrusion/>

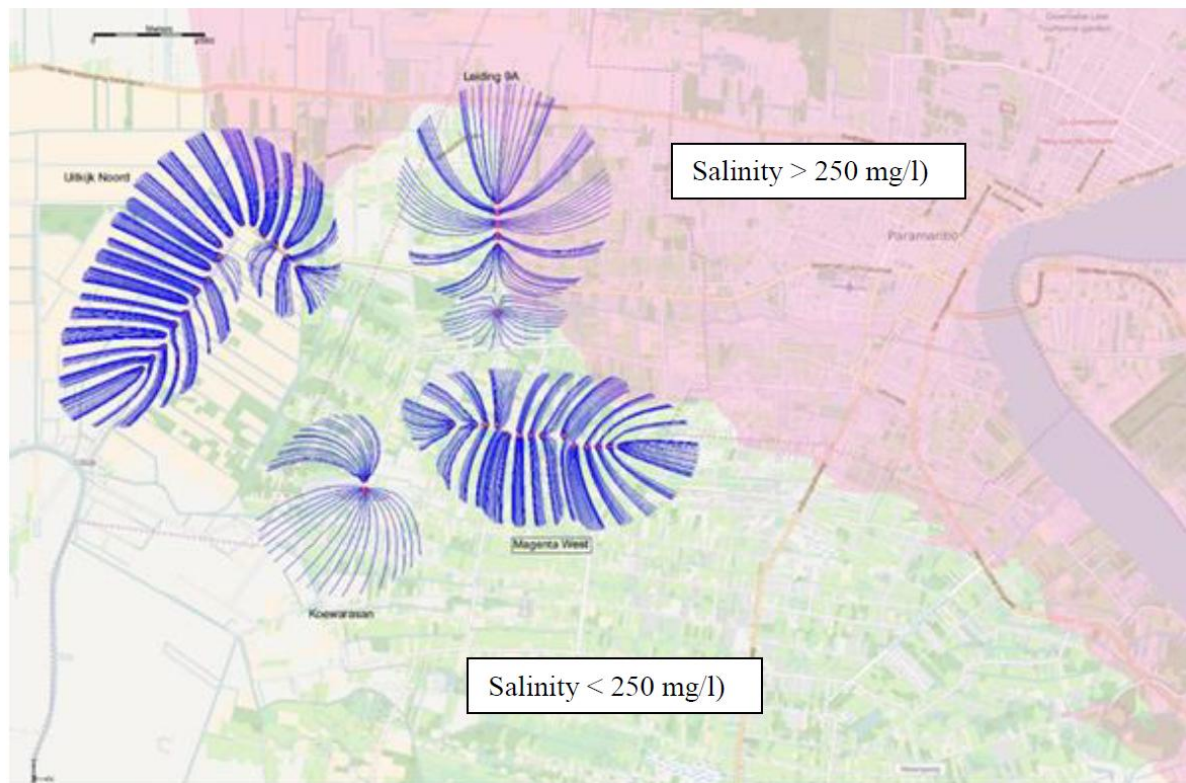


Figure 8. The 25 year capture zones of the production wells in the Coesewijne formation near Paramaribo. Source: HACAS study (RTI, Acacia Water and ILACO, 2016).

It should be noted that groundwater beyond the critical 250 mg/l chloride contour is not very salty. Groundwater salinity (chlorinity) remains below 1000 or 1500 mg/l in the entire coastal plain and in all aquifers. This implies that groundwater salinities in production wells will not sharply rise once they start to abstract groundwater from beyond the contour line. Nevertheless, managed aquifer recharge in the coastal zone north of the critical production wells could be a feasible option to avoid further depletion of fresh groundwater resources.

Water source

Water from nearby rivers or creeks could be infiltrated, as well as treated wastewater, if available. Since the infiltrated water is not recovered for water supply, as with AS(T)R wells, water quality of the source water does not need to meet drinking water quality standards. However, similar to AS(T)R there is a significant risk of clogging and contamination as well as the challenge of salt water intrusion from the sea far into coastal rivers, especially during periods of low flows (droughts). See chapter 3.1.1. for more information about the water source.

Where suitable

Recharge wells to combat salt water intrusion are suitable in the Young Coastal Plain in between the coast and the SWM production wells that are affected by salinization. The target aquifer would be confined aquifer(s) used for drinking water supply, such as the Coesewijne Formtion. See chapter 3.1.1. for more information about where this type of MAR is suitable and the target aquifer.

MAR use management

Recharge wells to combat salt water intrusion require pretreatment of source water, along with continuous monitoring and regular regeneration of the injection wells, since well screen clogging is inevitable over time. The decrease in well capacity due to clogging necessitates specialized operation and maintenance (O&M) expertise and regeneration of wells. The effectiveness of MAR on the extent

of seawater intrusion needs to be monitored carefully during operation, for optimalization of the MAR operational design. Due to the costly and complex infrastructure involved, and frequent monitoring requirements, deep recharge wells are generally better suited to urban areas, where O&M facilities are more readily available, and the economic viability of such investments is higher.

3.2 Bank Filtration

Bank Filtration (BF), or induced bank infiltration, comprises one of the simplest forms of MAR, as no pretreatment is needed. BF schemes commonly consist of a gallery (drain) or a line of wells at a short distance from, and parallel to the bank of a surface water body. Pumping of the wells lowers the water table adjacent to the river (riverbank filtration; RBF) or lake (lake bank filtration; LBF), inducing this water to enter the aquifer system. During the subsurface passage of water through the riverbed (or lake bottom) and aquifer, dissolved and suspended contaminants as well as pathogens are (partly) removed due to a combination of physical, chemical, and biological processes. Induced bank infiltration systems are typically installed near perennial streams and lakes that are hydraulically connected to an aquifer through the permeable, unconsolidated deposits that form the stream bed or lake bottom.

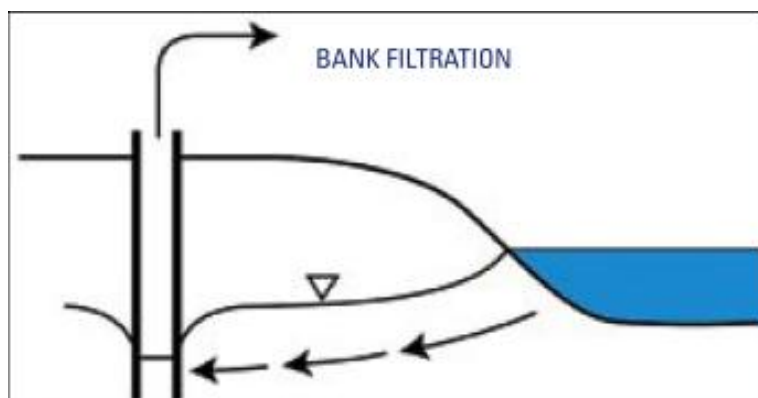


Figure 9. Schematic of the principle of bank filtration (source: IGRAC and Acacia Institute, 2007).

3.2.1 Riverbank Filtration (RBF)

MAR technique

A large variety of bank filtration schemes has been designed according to site-specific conditions. Collection wells can have either vertical or horizontal screens, depending on the thickness of the aquifer. Where aquifer material beneath a stream is thin, collector wells or infiltration galleries can be installed at the base of the aquifer to allow greater recharge of the aquifer than would otherwise be possible. Some induced bank infiltration schemes have been supplemented with infiltration ponds or recharge shafts to improve water quality and increase recharge. An artificial deposit can be applied to the riverbed, creating a reduced environment to prevent pollution of infiltrated water by organic material.

Where rivers or creeks flow, there is water stored in the river and riverbank sediments. This natural storage and groundwater flow can be effectively utilized through riverbank filtration (RBF) systems.

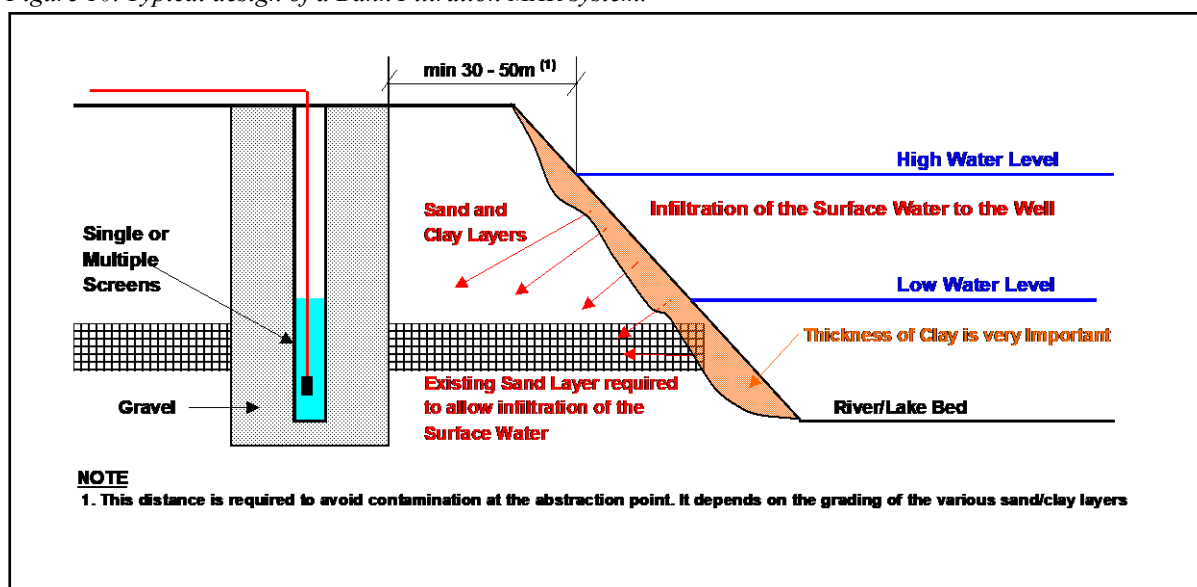
RBF usually consists of a gallery, a well or a line of (drilled) wells at a short distance from the river. Groundwater abstraction from the boreholes or gallery lowers the groundwater table adjacent of the river, increasing the natural infiltration of river water into the aquifer. During groundwater flow from

the riverbed to the well screen contaminates as wells as pathogens are removed due to physical, chemical and biological processes.

RBF schemes are typically installed near rivers that are hydraulically connected to the aquifer through permeable sediments such as sand and gravel. An important design criterion for RBF is the guarantee of a minimal travel time of 30 to 60 days of the water from the river to the abstraction point, to reach satisfactory purification.

A typical design of a Bank Filtration is shown in Figure 10. The main component is the abstraction device which is generally a drilled or hand dug well either vertical or horizontal screens, depending on the thickness of the aquifer. Where the permeable sediments are thin, infiltration galleries can be installed at the base of the aquifer to allow greater recharge than would otherwise be possible.

Figure 10. Typical design of a Bank Filtration MAR system.



A typical approach for design of a small-scale RBF system is

- the drilling of shallow observation wells to check water quality, groundwater flow and the type / depth of sediments (including the thickness of the clay layer along the riverbank).
- the drilling of a production well for a constant discharge test (72 hrs) during which the groundwater levels are observed in the observation wells.
- evaluation of the test and calculations with a (simple) groundwater model to design the abstraction wells, estimate the storage capacity of the aquifer and to verify the 60 days travel time of the water.

Some larger riverbank infiltration schemes are supplemented with infiltration ponds or recharge shafts to improve water quality and increase recharge. A layer of specific materials can be applied to the riverbed, typically consisting of carefully selected sand and gravel, to enhance the filtration process and improve water quality, creating a reduced environment to reduce pollution of infiltrated water by organic material.

Many RBF schemes are operational, ranging from large schemes for supplying drinking water to cities like Budapest and Berlin to small schemes for local water supply of villages or small towns consisting of a few wells along the river or lake bank.

Purpose

The management purpose of induced bank infiltration schemes are water quality improvement and groundwater level control.

Large scale BF schemes enable large amounts of groundwater to be abstracted from wells or galleries for public water supply without serious adverse effects on the groundwater table further inland. Also, particles, bacteria, viruses, parasites and easily biodegradable compounds are removed, and concentrations of persistent organic contaminants and heavy metals reduced in the filtration process. Small scale BF schemes are a cost-effective means to provide water for rural and small town water supply with a year round high quality, especially when compared to the usage of surface water. During periods of low discharge, small BF schemes can use groundwater from the natural storage.

Water source

The typical source of water is perennial river water for RBF or lake water for LBF.

Where suitable

This type is characterised by extraction wells near riverbanks or lake shores, allowing surface water to pass briefly through the subsurface before extraction. This is commonly used in alluvial aquifers for natural pre-treatment of surface water, to achieve a high level of resilience against spills, shock loads, floods and droughts compared to direct surface water abstraction, or to prevent excessive drawdown of groundwater beneath large urban centers. For these systems the river or lake need to be in direct hydraulic contact with the aquifers and the soil sufficiently permeable.

Zanderij Aquifer

Bank Filtration (BF) requires a phreatic aquifer within an unconsolidated, permeable geological formation containing shallow, fresh groundwater. In Suriname, these conditions are met where the Pliocene Zanderij Formation outcrops.

The Zanderij Formation, deposited during the Pliocene (5.33–2.58 Ma), consists mainly of coarse, white and brown kaolinitic sands interbedded with kaolinite clays, formed by braided streams and alluvial fans under semi-arid conditions. Intensive weathering and leaching have given the savannah sands their characteristic bright white appearance. The formation crops out in the savannah belt and dips below Quaternary sediments in the coastal plain, reaching depths of –40 to –50 m at the coastline (Figure 11).

The savannah belt, where the Zanderij Formation outcrops, is an undulating landscape of Pliocene sands, ranging in width from 50 km in the west to 5 km in the east (Figure 11). It lies between the crystalline basement to the south and the “old” coastal plain to the north, with elevations varying from +10 m above sea level in the north to +50 m in the south.

In the savannah zone, groundwater recharge occurs through infiltrating rainfall, but the water does not flow further into the Zanderij or deeper formations to the north. Instead, it is locally drained by black-water creeks and the bordering swamps of the coastal plain (Groen, 2002).

Figure 11 shows the outline of the savannah belt where the Zanderij Formation outcrops, along with depth contour lines of the aquifer and the brackish part of the Zanderij Aquifer, based on data from the HACAS study (RTI, Acacia Water, and ILACO, 2016).



Outline Zanderij Aquifer

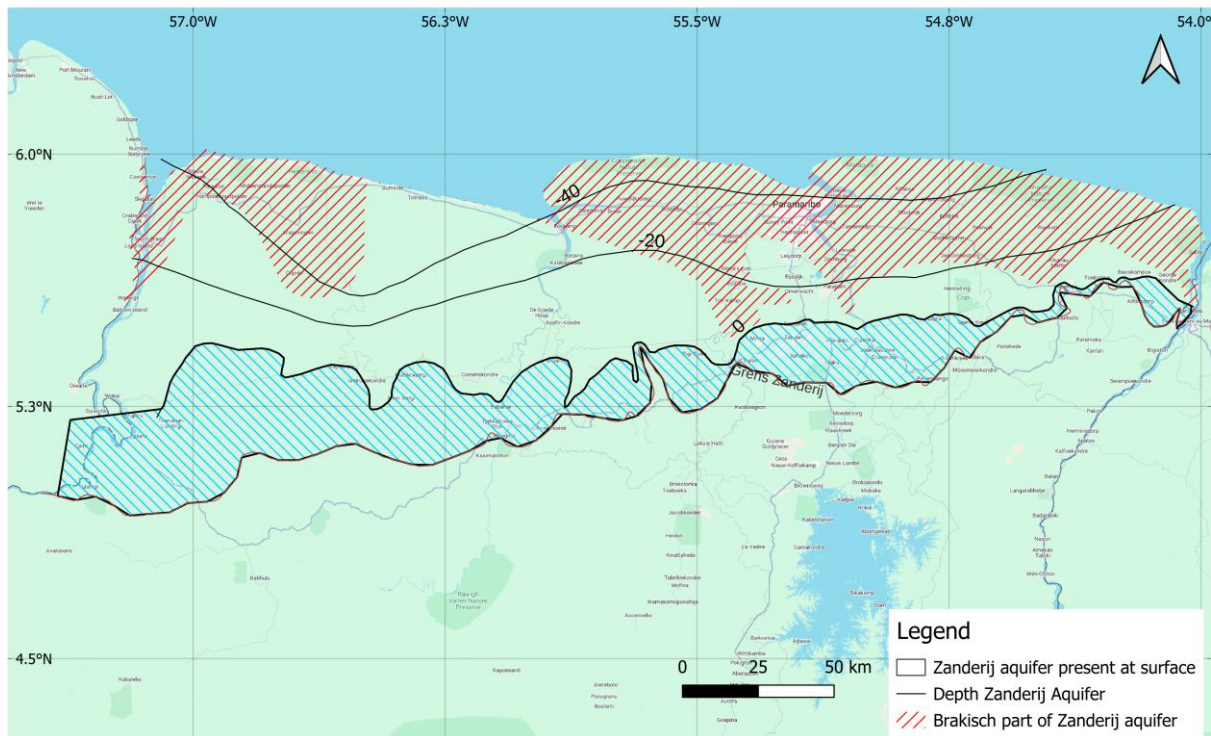


Figure 11. Outline of the savanna belt where the Zanderij Formation outcrops, the depth contour lines and brackish part of the Zanderij Aquifer. Based on data from the HACAS study (RTI, Acacia Water, and ILACO, 2016).

River bank filtration (RBF)

The oldest wellfield in Suriname along the Coropina Creek at Republiek can be considered a RBF system. In fact, it is the oldest well field and still producing the best water quality from the Zanderij aquifer. The Suriname Water Supply Company (SWM) could expand the existing Republiek station or create new ones along other creeks like the Para creek or along the Saramacca river or along the Suriname river south of Paranam. RBF could be applied in many places in Suriname along the rivers and creeks which are in contact with the underlying Zanderij aquifer. These creeks run through the savannah belt into the coastal plain (Figure 12).



Creeks and rivers incised in Zanderij aquifer

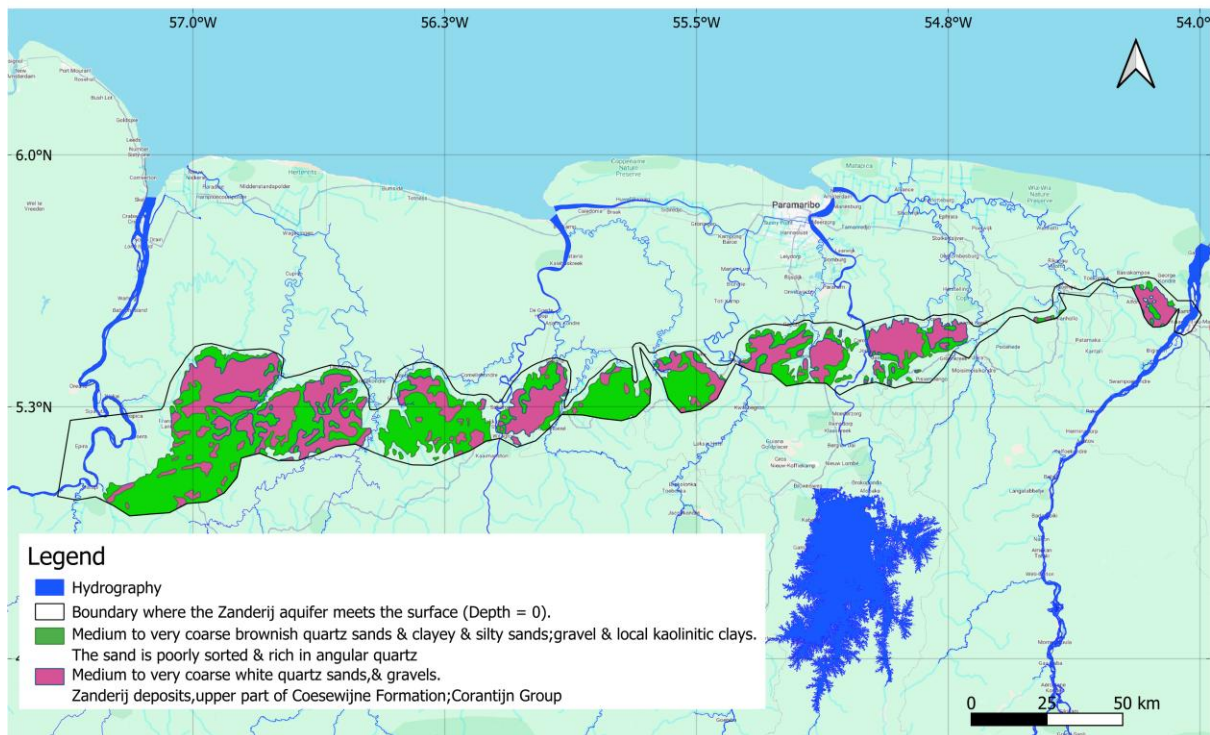


Figure 12. Creeks and rivers that incise the Zanderij Formation in the Savannah belt. Geology after GMD (1977)

The geological map of Suriname with scale 1:500,000 (GMD, 1977), recognizes two different units with Zanderij deposits, shown with geology code #11 (green) and #12 (pink) in Figure 12:

- 11) Medium to very coarse brownish quartz sands & clayey & silty sands. Zanderij Formation
- 12) Medium to very coarse white quartz sands & gravels. Zanderij deposits, upper part of Coesewijne Formation

Small scale and large scale MAR is feasible in this area along creeks and rivers which have a reliable discharge and water quality and where the Zanderij aquifer has a sufficient thickness and is hydraulically connected to surface waters.

In Annex 2, detailed maps are provided for all creeks and rivers that intersect the Zanderij aquifer. These maps indicate that, according to the geological map (GMD, 1977), stretches of the Boven Coesewijne, Casewinica kreek, Cassipora kreek, Coesewijne rivier, Commewijne rivier, Coropina kreek, Kopi krika, Mapane kreek, Marataka rivier, Saramacca rivier, Suriname rivier, Tibiti rivier, Wayambo rivier are hydraulically connected with high permeable sands of the Zanderij Aquifer. Conversely, other creeks and rivers such as the Arawara krika, Blackawatra of Boven Cottica, Corantijn rivier, Curmotibo rivier, Goliath kreek, Kabalebo rivier, Kabo krika, Kaijwando krika, Matapi krika, Nickerie rivier, Para rivier, Patamacca kreek and Peninica kreek appear to be less suitable for RBF. According to the geological map (GMD, 1977) these water courses intersect the savanna belt within lower permeable units. It should be noted that detailed hydrogeological site investigations are necessary to verify where the permeable units of the Zanderij Aquifer have sufficient thickness and are indeed hydraulically connected to the creeks and rivers.

One of the new well fields recommend by the HACAS study (RTI, Acacia Water, and ILACO, 2016) at Paranam near the Suriname river can be considered a RBF scheme. However, it is recommended to consider a location a bit further to the south, since salt water might intrude in the Suriname river as far inland as Paranam (Figure 5) which could induce the infiltration of saline water when an RBF scheme is constructed here.

RBF in the interior

In the interior of Suriname, river bank filtration (RBF) is suitable only very locally, primarily in sandy river banks along creeks and rivers. These areas can support small-scale drinking water supply and irrigation systems from shallow wells (and springs).

Community wells have long been drilled in suitable sandy deposits found along the Suriname and Marowijne rivers, upstream of the Brokopondo Reservoir (chapter 2.3). These wells induce river recharge to the local aquifer, effectively reversing the natural drainage of rivers. These traditional RBF systems have been in use for a long time and have recently regained attention as an established MAR method.

However, mapping suitable RBF locations in the interior is challenging, as these sandy riverbank deposits are highly localized and cannot be accurately identified through satellite imagery or remote sensing data. Nevertheless, RBF systems could be considered where sediment banks and layers border rivers and creeks, providing a valuable source of drinking water and irrigation for local communities, particularly benefiting women who are predominantly responsible for agricultural and water provisions in hinterland communities.

MAR use management

RBF provides potable water without expensive treatment and is a cost-effective solution compared to a surface water treatment or long distance water conveyance. For small scale RBF there is the additional advantage that the storage capacity of the sediments around the river bed river provides a source of water during the dry period when there is no flow in the river.

Quality improvement of the water (compared to usage of the surface water directly) is the main advantage of RBF's. Also, effects on the piezometric heads are limited compared to the abstraction of groundwater.

If the aquifer extends below the river, water supply is more certain during periods limited flow. This is especially relevant for smaller systems which provide drinking water to villages or small towns

The clogging of wells has always been a hot topic in MAR systems because of their vulnerability. Bank filtration wells in the anoxic fluvial plain are prone to clog by aquifer particles that are retained by the borehole wall if damaged by residual drilling muds (Dillon et al, 2019).

The biggest risks for RBF and LBF (chapter 3.2.2) are upstream contaminations and wastewater effluent that can impact surface water quality, and thus groundwater due to direct connection between aquifer and stream water. Disadvantages are that the surface of the riverbed may need to be scraped during periods of low water level, if clogging of the river or lake-bed is excessive and increases the entrance resistance of the river water into the sediments. Long term contamination of river water by persistent organic compounds (such as pesticides and pharmaceuticals) or residual contaminants from mining activities (such as mercury or cyanide from small-scale gold mining) may contaminate

groundwater, and is therefore a threat to RBF schemes. Monitoring river water quality and quality of abstracted water should therefore be an integrated part of the operational routine.

There are alarming report of rivers and creeks being polluted by mining activities (mainly) and housing developments. Particularly mercury pollution of the Suriname is a concern.

Sources of contamination of river and creek water

Mining activities in Suriname, particularly gold mining, pose significant risks to water quality in rivers and creeks due to the widespread use of harmful chemicals like mercury and, in some cases, cyanide.

The National Land Monitoring System of Suriname (GONINI) provides information about mining concessions. Based on the information available in the Gonini Geoportal², mining activities are concentrated in the crystalline basement area of central eastern Suriname along the Saramacca River, the Suriname River and the shores of the Brokopondo Reservoir and along the Marowijne River. Detailed maps of the mining rights are included in Annex 1.

The map below (source: GONINI) shows with red squares observations of traces of Mercury found on-site in sediment, fish, urine, blood etc. These mercury observations suggest that contaminating activities can be found along the major rivers in the entire country, not only the rivers along the east.

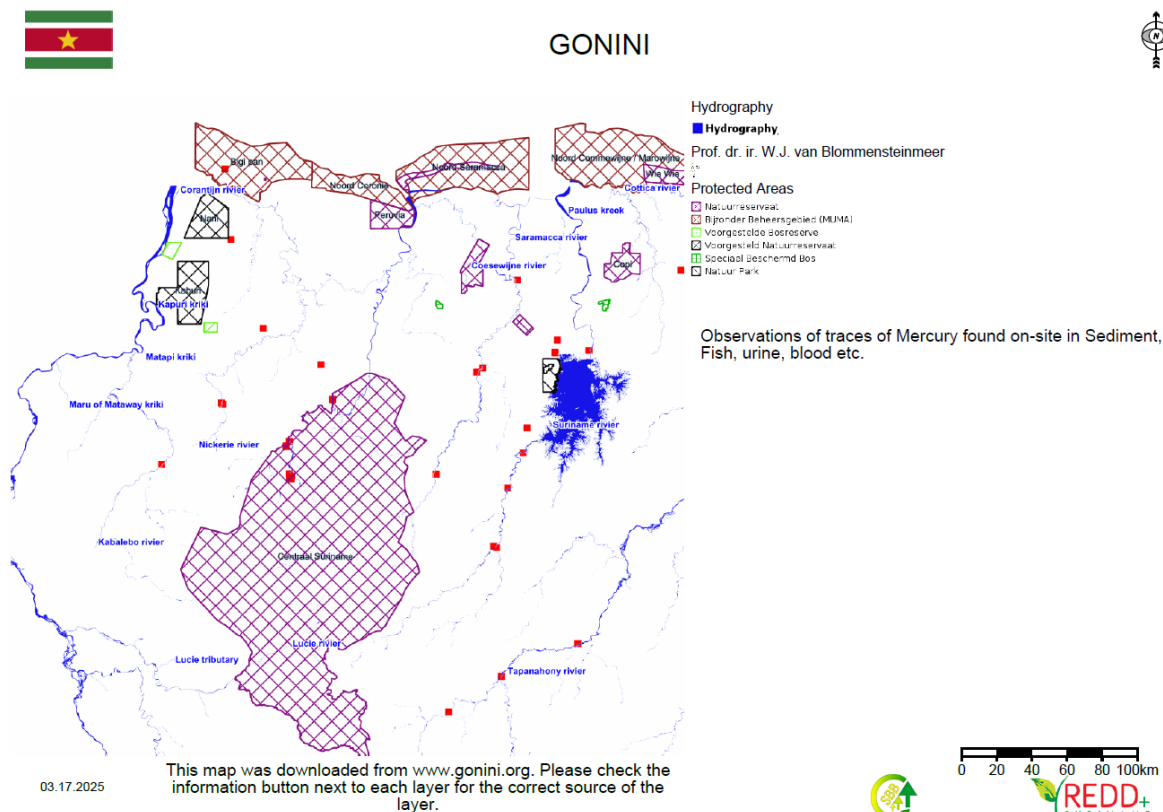


Figure 13. Observations of traces of mercury (red squares) found on-site in sediment, fish, urine, blood. Source: GONINI geoportal.

Catchment protection

² <https://www.gonini.org/>

Water quality and water protection are crucial issues in designing and managing bank filtration MAR systems. Upstream of RBF schemes, catchment management and protection are required. Figure 14 shows the rivers and creeks incising the Zanderij Aquifer (red shaded area) and their upstream watersheds. The numbers shown on the map correspond to the watershed ID's in Table 2, which presents the catchment areas in km².

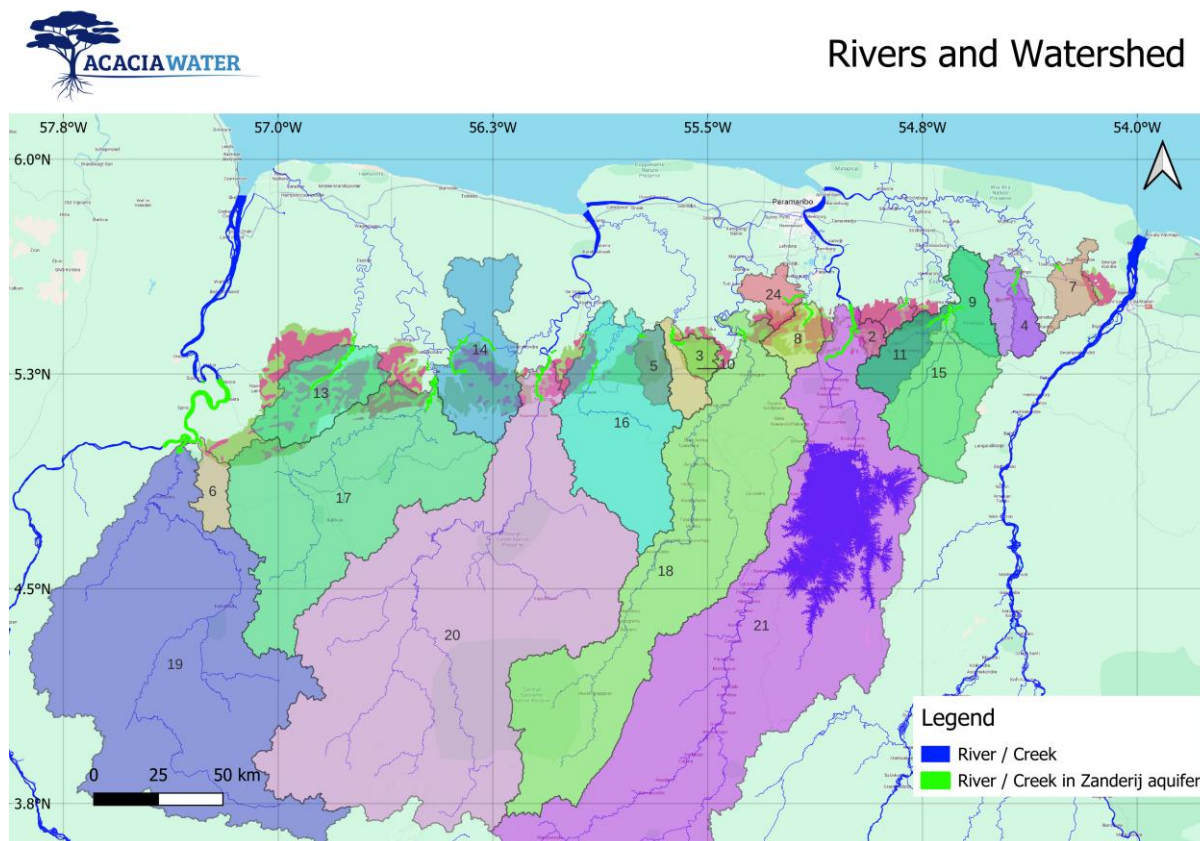


Figure 14. Rivers and creeks in the Zanderij Aquifer (shaded area) and their watersheds.

Table 2. Upstream catchment area (km²) of rivers and creeks incising the Zanderij Aquifer.

Watershed ID	Name of river / creek	Upstream catchment area (km ²)
1	Casewinica kreek	101
2	Cassipora kreek	114
3	Coesewijne rivier sub-watershed	197
4	Patamacca kreek	234
5	Kabo krika	313
6	Matapi krika	337
7	Curmotibo rivier	350
8	Para rivier	406
9	Peninica kreek	521
10	Coesewijne rivier	539
11	Mapane kreek	546
12	Cottica rivier	572
13	Marataka rivier	1175
14	Wayambo rivier	1757

15	Commewijne rivier	2650
16	Tibiti rivier	2967
17	Nickerie rivier	5360
18	Saramacca rivier	7046
19	Kabalebo rivier	9554
20	Coppename rivier	13047
21	Suriname rivier	14190

3.2.2 Lake Bank Filtration (LBF)

For Lake bank filtration (LBF), the same principles as for RBF (chapter 3.2.1) apply. LBF could be applied in artificial lakes incised in the Zanderij aquifer, such as the abandoned Lelydorp III mine pit lake in Para District (Figure 20). The option to use this abandoned mine for water spreading is discussed in more detail in chapter 3.4. Repurposing existing dewatering wells from the former mine as LBF wells for large scale water supply could enhance recharge efficiency and support controlled groundwater management. While operation can be expensive, the cost per cubic meter of abstracted water remains relatively low due to the ability to infiltrate large volumes efficiently.

3.2.3 Induced swamp infiltration through drain systems in sand ridges

Before the start of the Suriname Water Supply Company in 1933 people relied on shallow wells dug into the sand ridges in the Quaternary marine coastal plain. Under the HACAS project (RTI/Acacia Water/ILACO, 2016) groundwater development in sand ridges was again investigated in the Commewijne District, which suffered from water shortage, as the Tertiary sand aquifers contain mainly brackish groundwater in this district. In the HACAS study a conceptual design was made of a 4 km long horizontal well draining a broad and thick sand ridge south of the village of Tamanredjo, with a projected production of 12,000 m³/day.

University of Suriname started hydrogeological investigations into the sand ridges in the Coronie District in 2022 and 2023. As part of this study, Groen (2023) studied the feasibility of groundwater recovery from sand ridges for water supply to small communities like Hamilton. The calculations show that a 100m collector drain, operated 8 hours per day, could produce 7 m³ of water per day; sufficient for the drinking water supply of a community of 70 people or irrigating about 1500 m² in the dry season. Production could be increased to serve to a few hundred people by lowering the drainage level and the length of the drain.

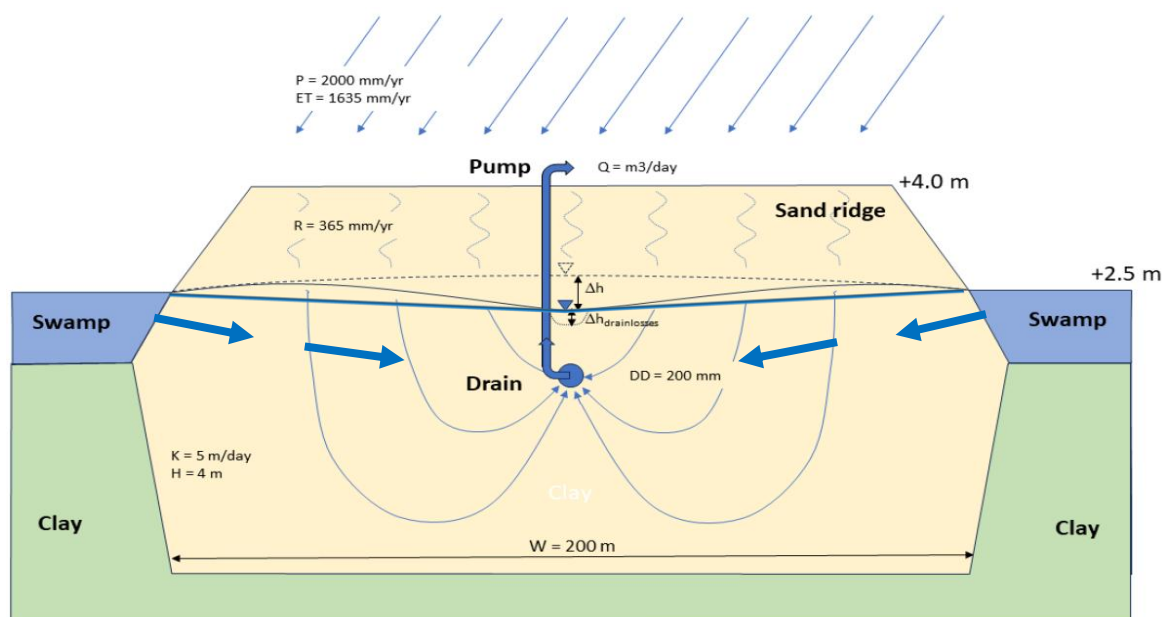


Figure 15. Schematization of a drain system in a sand ridge, inducing aquifer recharge from nearby swamps. Source: adjusted from Groen (2023).

MAR technique

Induced swamp infiltration through drain collector systems in sand ridges can be categorized as a bank filtration MAR system. Water recovery from the sand and shell ridges may be of interest for small scale water supply for rural households or as supplementary irrigation for farmers, who experience problems of prolonged and frequent droughts during the last decades. Water can be recovered through collector drains (Groen, 2023), which are recharged by induced infiltration from the neighbouring swamps.

Purpose

The purpose of a Bank Filtration system in sand ridges is to enhance groundwater recharge and improve water quality by utilizing the natural filtration capacity of sand. This system provides a reliable and sustainable low-cost water supply for drinking, irrigation, or small-scale community use. By leveraging the natural filtration of sand ridges, the system reduces the need for expensive water treatment infrastructure, while also increasing groundwater availability during dry periods. It is particularly useful in rural or remote areas as alternative for more conventional but expensive water supply options.

Water source

The water source is swamp water near sand ridges, which can be found in many parts of the coastal zone of Suriname (Figure 16).



Fresh water sources (ESA Worldcover 2021)

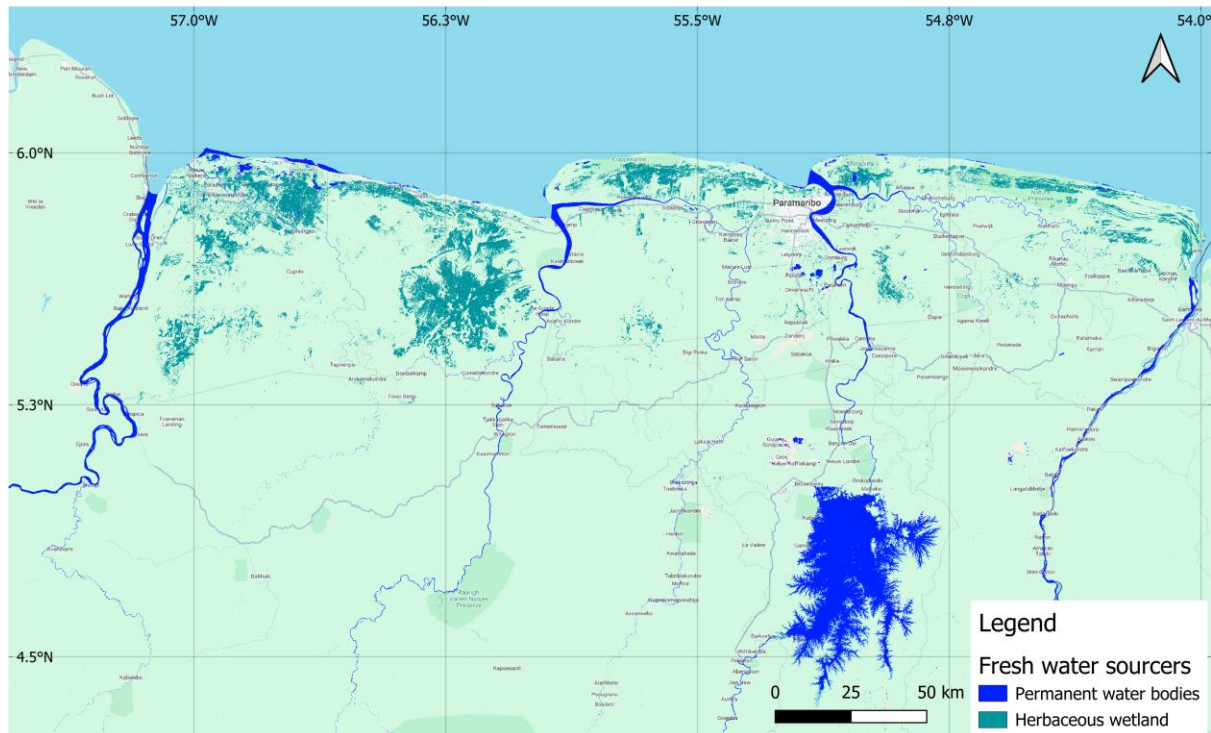


Figure 16. Map showing the permanent water sources (rivers, creeks and lakes) and the herbaceous wetland (swamps) in the coastal zone of Suriname. Based on ESA Worldcover 2021 landuse.

Where suitable

The superficial Lelydorp sand ridges in the Pleistocene or old coastal plain (Coropina Formation) form a local aquifer with a thickness of 2 to 8 m and contain fresh groundwater. The same holds for the sand ridges of the Holocene or young coastal plain (Coronie Formation), where brackish groundwater is generally found at only a few meters' depth. These sand ridges originally contained brackish groundwater, but have been flushed during the recent Holocene (Groen, 2002).

These sand ridges are narrow and elongated land forms midst clayey swamp and tidal deposits. Typical widths are 50 to 400 m; lengths can vary from a few hundred meters to several kilometres. Although some of them are only recently formed (Commewijne phase from 1500 to 500 yr ago), saline water has been completely flushed out from the sands by the abundant rainfall (Groen et al., 2000; Groen, 2002). Depending on the thickness of the sand deposits the ridges contain fresh groundwater up to depths of 3 to 10. This is based mainly on well data and geoelectrical 1D and 2D soundings (IWACO, 1981; Groen, 2002; Groen et al, 2007; RTI/Acacia Water/ILACO, 2016)

Groundwater from these sand ridges was traditionally recovered from open dug wells, which are still used in remote places without a public water-supply system, like in Commewijne District. Generally, the sand ridges form elongated bodies with widths up to 100 m, which do not permit large scale groundwater exploitation. In some areas bundles of ridges form wide complexes where groundwater can be recovered by long strings of shallow wells or drains in large quantities. The ridges south of Tamanredjo form one of these complexes where groundwater exploration has been carried out as described in the Technical Memo 1 of the HACAS study (RTI, Acacia Water and ILACO, 2016). The sand ridges can be found on the geological map of Suriname (GMD, 1977) as presented in Figure 17.

The sand ridges around Paramaribo have been mapped in more detail as part of the reconnaissance soil survey and can be found on the 1:100,000 soil maps of Suriname (Figure 18).

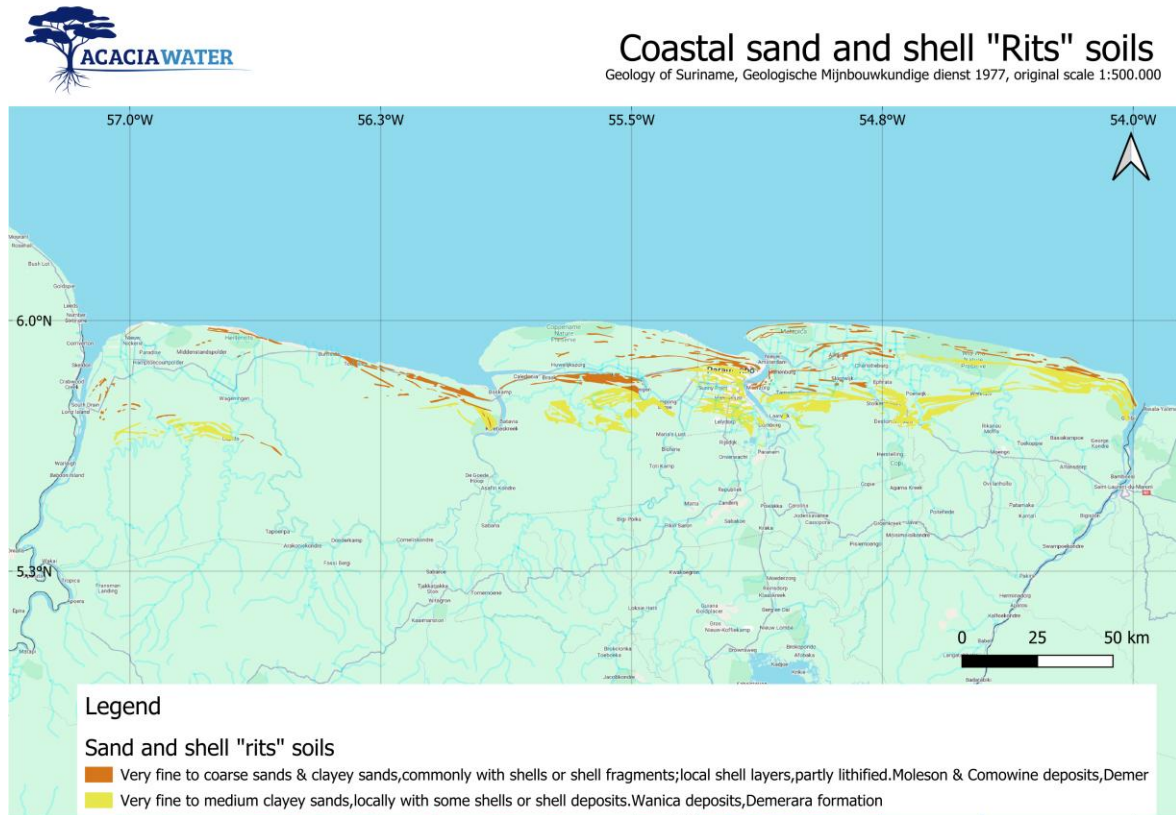


Figure 17. The sand and shell ridges (rits gronden) in the coastal plain of Suriname, based on the 1:500,000 geological map of Suriname (GMD, 1977).

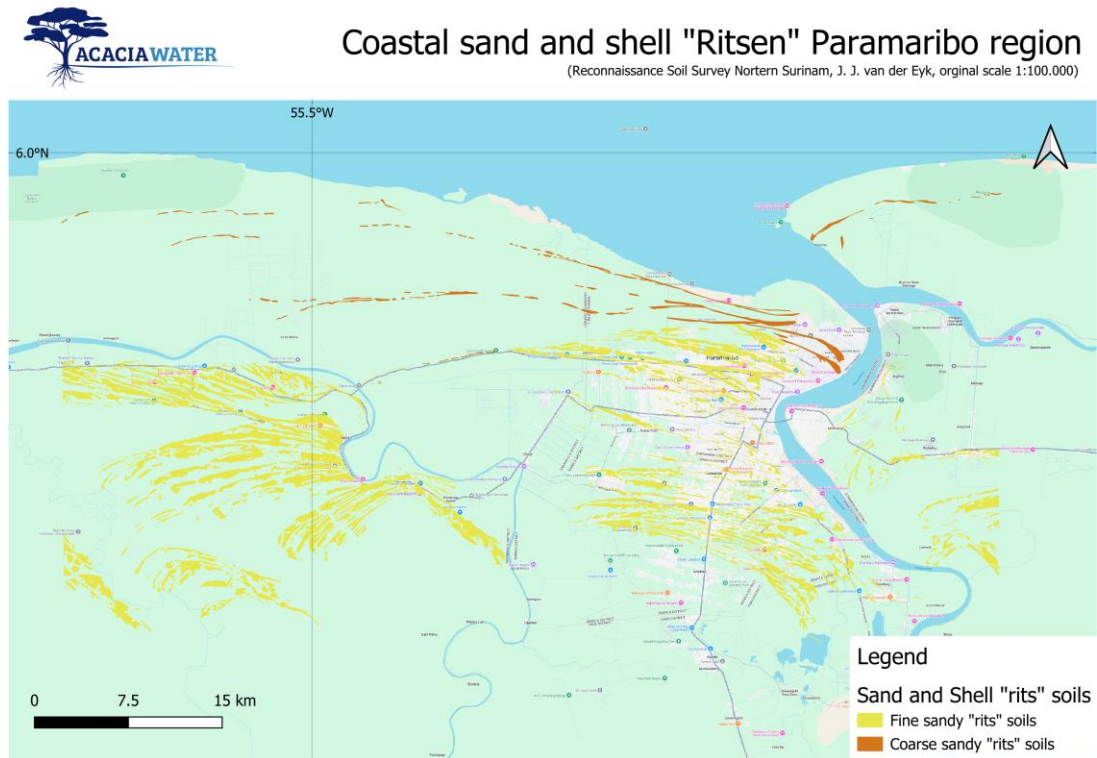


Figure 18. The sand and shell ridges (*rits gronden*) around Paramaribo, based on the 1:100,000 soil map of Northern Suriname (Van der Eyk, 1957).

MAR use management

Bank filtration in sand ridges in coastal zone of Suriname is a MAR technique that utilizes the natural filtration capacity of sand ridges to induce swamp infiltration through drain collectors. This method requires no pretreatment, as the sand naturally filters the water, significantly improving its quality.

Bank filtration in sand ridges is a sustainable and low-cost solution, making it an attractive alternative to deep well drilling or long-distance water supply systems in rural areas that currently lack a protected freshwater supply. However, it is essential to protect the phreatic aquifer from contamination by maintaining a buffer zone along the drain, involving vegetation management, fencing, and access road construction. Regular maintenance and monitoring are necessary to prevent clogging from organic matter or fine sediments from nearby swamps.

3.3 Water spreading

Spreading techniques are among the simplest, oldest, and most widely applied methods of artificial recharge. Water spreading is applied in cases where the aquifer to be recharged is at or near to the ground surface. Recharge is achieved by infiltration through permeable material at the surface, which is managed to maintain infiltration rates.

3.3.1 Rain water harvesting and small-scale recharge

Small-scale options recharge aquifers through collection tanks or sand filters. A common approach is rainwater harvesting from roof drainage.

collected clean fresh rain water could also be infiltrated in shallow aquifers by means of infiltration ponds or large recharge basins. This might do well in combination of large clean and protected retention ponds, constructed wetlands and lakes in more (sub-)urbanized areas, in a.o. the north of Paramaribo, where these large retention facilities will also benefit drainage (of only clean storm and rainwater, not sewerage) during floodings.

MAR technique

One way to collect rainwater is rooftop water harvesting, where a hard roof surface intercepts rainwater whereinafter it is conveyed to a storage tank via a system of gutters. If properly stored and treated this water is of high quality and can be used for domestic purposes.

Since roofs have a very high surface runoff (of above 80%), most of the rain can be harvested. Rooftop water harvesting can provide an extra source of water. Depending on the amount of rain, the roof size and the size of the rainwater tank, water can be provided for several persons.

The first flush can contain dust, leaves, insects and bird droppings. In general, applies that the rougher the surface of the roof the lower the water quality. Simple first flush separators, such as a tipping gutter system, can improve the water quality substantially.

The storage tank should be closed, so that water quality remains good at to avoid related breeding of disease vectors (mosquito larvae).

In case storage tanks are placed above the ground, the top of the tank should be at least 50 cm below the lowest point of the roof, so that gutter and pipes can be placed, and water can flow to the tank. This limits the size of the tank at houses with lower roofs. In case storage tanks are built in the ground, soils needs to be deep enough.

Small-scale drinking water MAR system for 25 – 50 people, typically includes rain water collection roof, with a first flush discharge valve, rain water collection tanks, and infiltration and abstraction points (Figure 19).

Suitable for (peri-)urban and rural communities of the coastal region. Precondition is the availability of >20 m² of land for construction and a roof area of 200 m² or more from which infiltration water can be harvested during rainy seasons. Drinking water can be abstracted from the aquifer with a hand pump or directly from a rainwater storage tank.

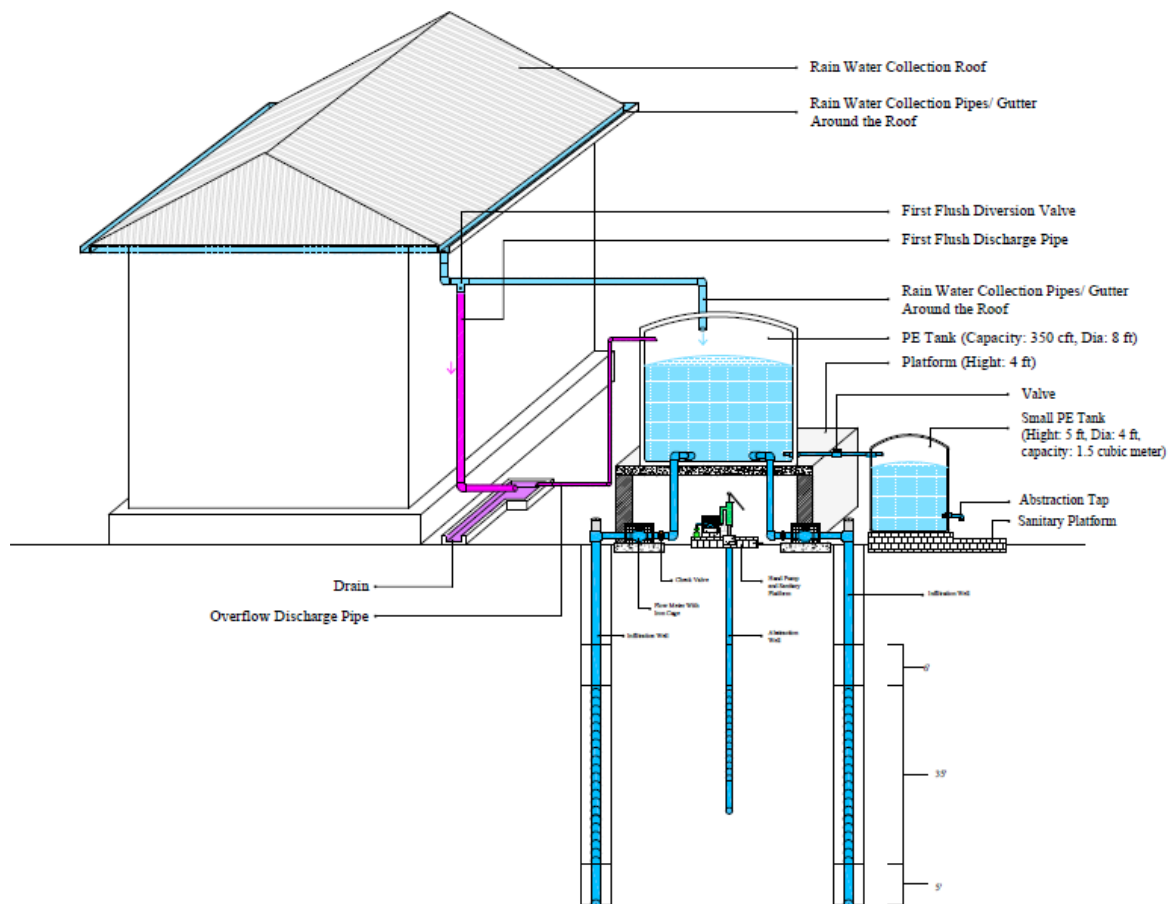


Figure 19. Construction drawing of a typical small-scale drinking water supply system using rain water harvesting and recharge. Source: Acacia Water (2021).

Purpose

In general, smaller scale spreading techniques are suitable for water supply to medium sized communities and agriculture in rural areas. Harvesting rainwater and small scale recharge has the purpose of strategic storage for supply during droughts and/or to combat salinization.

Water source

Rainwater collected on roofs.

Where suitable

In large urban areas (Paramaribo) or at schools or farms with large roof area.

MAR use management

Rainwater harvesting and small-scale recharge is a low-cost MAR technique that is particularly suitable for community-based implementation. To ensure good water quality and prevent contamination, regular cleaning and maintenance of the roof and collection system including the first flush system are essential. Although the volume of water recharged is relatively small compared to larger MAR systems, the low cost, simplicity of construction, and local ownership make these systems valuable for enhancing local groundwater availability, especially in areas with limited access to more advanced recharge infrastructure.

3.3.2 Water spreading in mine pit lakes

Water spreading involves the use of ponds or spreading basins to recharge an unconfined aquifer, which is subsequently pumped to provide a water supply or for other purposes. Constructed or natural wetlands may also be used for water spreading. In Suriname, the use of abandoned bauxite mines for infiltration could be an interesting option.

MAR technique

Water spreading in mine pit lakes as a MAR scheme involves raising the water level to increase hydraulic pressure, thereby promoting greater infiltration through the permeable sediments. This can be achieved using existing lake water or by supplementing it with additional water conveyed from nearby creeks or rivers.

In the case of the Lelydorp III mine pit lake in Para, the lakebed at the bottom is considered low permeable, limiting direct vertical infiltration. However, the lake's sides intersect the highly permeable Zanderij Aquifer, offering significant potential for lateral infiltration. During mining operations, Alcoa/Suralco pumped large volumes of clean groundwater to drain the mine, highlighting the aquifer's recharge capacity.

Purpose

The purpose of water spreading in mine pit lakes is to enhance groundwater recharge and sustainably replenish the aquifer, improving groundwater availability, and maintain downstream well field yields, while also making efficient use of existing mine pit lakes.

Water source

The water source consists of the existing water in mine pit lakes, which may be supplemented with additional water conveyed from nearby creeks or rivers to raise the lake's water level and enhance aquifer recharge.

Where suitable

In the area between the Rijdsdijk road and Paranam in the Para district, the landscape of the old coastal plain has been significantly altered by extensive and deep bauxite mining activities and the bauxite refinery at Paranam. The abandoned mines have since transformed into large lakes.

The Lelydorp III mine pit lake intersects both the Pleistocene coastal deposits and the underlying Zanderij Aquifer. This lake could therefore be suitable as infiltration basin to recharge the Zanderij Aquifer, making it a potential candidate for use as an infiltration pond to recharge the aquifer.

It is possible that the Lelydorp III mine pit lake is already facilitating unmanaged aquifer recharge. One option to enhance groundwater recharge of the Zanderij Aquifer is to raise the water level of the lake, thereby increasing the infiltration rate. This would be particularly beneficial for the Van

Hattemweg and Lelydorp well fields, located approximately 3-4 km to the northwest (downstream) of the lake (Figure 20).

Alternatively, instead of raising the lake's water level, another option is to induce aquifer recharge by abstracting water from wells along the shore of the lake. This approach would effectively create a Lake Bank Filtration (LBF) scheme as described in Chapter 3.2.2.



Figure 20. Lelydorp III mine pit lake in the Para district, and the Van Hattemweg and Lelydorp well fields.

MAR use management

Using existing bauxite mine pit lakes as large infiltration basins for MAR offers a cost-effective solution for enhancing groundwater storage. The primary advantage is the ability to infiltrate large quantities of water at relatively low costs. Additionally, mine pit lakes make efficient use of space and require minimal maintenance, making them an attractive option for MAR.

Protecting and utilizing these mine pit lakes as catchments for excess rainwater would not only make use of existing infrastructure but also convert abandoned, out-mined land into sustainably useful areas.

However, a key point of attention is water quality. Before utilizing existing bauxite mine pit lakes as large infiltration basins for MAR, it is essential to assess and, where possible, control potential geohydrochemical interactions between infiltrated water and aquifer materials. This ensures the maintenance of good groundwater quality in the downstream Van Hattemweg and Lelydorp well fields. Proper monitoring may be necessary to timely signal contamination of the aquifer.

Management strategies should include regular water quality assessments, sediment control, and

monitoring of infiltration rates to ensure sustainable and safe recharge. Basic monitoring of the sedimentation rate and infiltration rate relative to the estimated rate of open-water evaporation will assist in operational management decisions.

3.4 Streambed channel modifications

In streambeds, surface and subsurface impoundments can be designed to capture or slow down runoff, which infiltrates through the bed to enhance storage in unconfined aquifers and is extracted down-valley. These are often low-technology structures, designed to meet local conditions. Common techniques include constructing check dams, sand dams and recharge weirs to detain surface runoff, allowing increased infiltration into underlying aquifers.

For MAR through streambed channel modifications to be effective, the underlying geology must permit water infiltration and storage. Suriname's coastal region mainly features clayey soils while Suriname's interior is characterized by crystalline basement, which will hinder infiltration and reduce the efficacy of streambed modifications.

In addition, the presence of ephemeral (seasonal) streams is ideal for implementing structures like check dams. In Suriname, where rivers and creeks flow perennially, the benefits of such modifications are limited.

Thirdly, the high sediment loads in Suriname's rivers and creeks can lead to rapid siltation of recharge structures, diminishing their effectiveness over time. Fourthly, suitable topographical features such as gentle slopes are essential for constructing effective recharge structures. The low-lying and flat nature of Suriname's coastal plain may limit the effectiveness of streambed modifications aimed at enhancing infiltration, while in the hilly terrains of Suriname's interior, the subsoil is unsuitable and the need for MAR interventions is low (high rainfall, low water demand).

While streambed channel modifications have proven effective in various regions worldwide, their suitability in Suriname is considered low, given the geological and hydrological conditions.

4 MAR technical feasibility matrix

This report assesses the technical feasibility of various MAR techniques in the coastal plain of Suriname. In order to select the most promising technologies and sites to manage aquifers and recharge groundwater in the context of Suriname, the results of this analysis are summarized in the MAR technical feasibility matrix presented below (Table 3).





The MAR technical feasibility need to be combined with assessments of drought risks, water demand, aquifer characteristics and water balances, as well as the environmental, social, and economic benefits and costs for all stakeholders, in order to identify the best MAR technology and most suitable sites (five) where MAR could be implemented.





At the end of Phase 2, the five selected sites and their corresponding MAR systems will be presented to the SWG, who will then select the final site and appropriate technique to be designed as a pilot project in Phase 3.

In the MAR technical feasibility matrix presented on the next page (Table 3),

- **Quantity** gives a relative indication of usual storage or abstraction capacity (1 - 3 water drops), and a typical infiltration rate or abstraction rate.
- **Costs** gives a relative indication of total costs, CAPEX and OPEX (\$ - \$\$\$), and a typical cost indication per cubic meter stored or abstracted water (based on previous Acacia Water project experience and ASR literature including Ross, 2022).
- **O&M** indicates the relative ease or complexity of operation and maintenance of such a MAR system, considering the required expertise and experience, monitoring intensity.

Table 3. Technical feasibility matrix of MAR techniques in Suriname

Technology	Purpose	Suitable locations	Main advantages	Main constraints	Quantity	Costs	O&M
Recharge Wells - ASR & ASTR (deep well injection and recovery)	to sustain the recovery from abstraction wells and combat overexploitation	in the Young Coastal Plain with thick clay layers at the surface Target aquifer (confined): Coesewijne Formation	infiltration of large quantities of water at relatively low cost, sustain the recovery from abstraction wells, ASR: clogging partially removed during infiltration	complex design and construction, special O&M expertise required, continuous monitoring required, high potential for well clogging (regular regeneration of wells required), high quality requirements of source water (pretreatment required)	 5 – 50 m ³ /h per well	\$\$\$ USD 0.5-2 per m ³ abstracted	Complex
Recharge Wells – MAR to combat salt water intrusion (deep well injection)	to keep existing production wells threatened by salinization operational	in the Young Coastal Plain with thick clay layers at the surface Target aquifer (confined): Coesewijne Formation	infiltration of large quantities of water at relatively low cost; cost-effective measure to combat salt-water intrusion	complex construction, intensive monitoring required, high potential for well clogging (regular regeneration of wells required); source water near-coast not readily available	 5 – 50 m ³ /h per well	\$\$\$ USD 0.2-1 per m ³ stored	Moderately complex
Bank Filtration – along rivers and creeks (RBF) with shallow well abstraction	water quality improvement and groundwater level control	in the Savanna Belt along rivers and creeks Target aquifer (phreatic): Zanderij Formation	large quantities of good quality water can be withdrawn, no pretreatment required, organic contaminants in source water filtered out in soil	moderately complex design, continuous monitoring required, potential for well clogging, catchment protection needed to minimize risk of contaminations from upstream mining activities (mercury) and housing developments	 2 – 20 m ³ /h per well	\$\$ USD 0.2-1 per m ³ abstracted	Moderately complex
Bank Filtration – along lake (LBF) with shallow well abstraction	water quality improvement and groundwater level control	in the Savanna Belt along mine pit lakes such as Lelydorp III Target aquifer (semi-confined): Zanderij Formation	large quantities of good quality water can be infiltrated, no pretreatment required, organic contaminants in source water filtered out in soil, use of existing dewatering wells	continuous monitoring required, high potential for well clogging, potential for contaminations from former bauxite mining activities need investigation	 2 – 20 m ³ /h per well	\$\$ USD 0.2-1 per m ³ abstracted	Moderately complex

Bank Filtration – in sand ridges along swamps using collector drains	as water supply option in rural or remote areas for drinking, irrigation or small-scale community use	in superficial sand and shell ridges along the coast near swamps Target aquifer (phreatic): Young Coastal Plain (Coronie Formation) & Old Coastal Plain (Coropina Formation)	could be a viable low costs solution as alternative to deep well drilling or long distance water supply, no pretreatment required	phreatic aquifer protection of the area along the drain against pollution is vital; regular maintenance and monitoring are necessary to prevent clogging of the drain	 0.5 - 2 m ³ /h per 100m drain	\$ USD 0.2-1 per m ³ abstracted	Moderately complex
Water Spreading - rain water harvesting and small scale recharge	as small scale supplementary irrigation water or household use during droughts	in Paramaribo or at schools or farms with large roof area	low cost structures, community based,	large roof area required, cleaning and maintenance of roof required, infiltration of small quantities of water	 80 m ³ /y per 200 m ² roof	\$ USD 20 – 40 per m ³ stored	Rather easy
Water spreading - infiltration ponds using mine pit lakes (and raise water level)	enhance groundwater recharge and sustainably replenish the aquifer	in the Savanna Belt along mine pit lakes such as Lelydorp III Target aquifer (semi-confined): Zanderij Formation	infiltration of large quantities of water at relatively low cost, relatively easy to construct and implement, particularly beneficial for the Van Hatteweg and Lelydorp well fields	open surface water bodies are sensitive to contamination (including related breeding of disease vectors), lake protection and detailed quality monitoring required, potential for high evaporation	 10- 100.000 m ³ /yr	\$\$ USD 0.5-2 per m ³ stored	Easy operation but intense monitoring required
Streambed channel modifications - using sand dams, subsurface dams or recharge dams	Reduce flash flood and increase base flow	Seasonal rivers and creeks	low cost structures, community based, low maintenance, structures are installed in streambeds, and therefore do not interfere with land use	limited benefits as rivers and creeks flow perennially, unsuitable geology (clayey soils and basement rocks) in most parts of Suriname, high sedimentation rates, unsuitable topographical features	 200 – 5,000 m ³ /yr	\$ USD 0.5-2 per m ³ stored	Rather easy

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6 Colophon

Client	: The United Nations Environment Programme (UNEP) on behalf of the Climate Technology Centre and Network (CTCN)
Beneficiary	: Government of the Republic of Suriname; Ministry of Spatial Planning and Environment
Project	: Enhance the resilience of Suriname's water supply system by modelling drought risks and developing a roadmap of prioritized alternatives for aquifer recharge.
Subject	: Report on Managed Aquifer Recharge (MAR) techniques and feasibility in Suriname
File/ Code	: IS-471
Acronym	: ARADIS project
Author	: Harmen van den Berg, Koen Exterkate
Validated by	: Arjen de Vries, Theo Kleinendorst, Jacobus Groen
Contributions	: NA
Authorisation	: R. Patandin
Date	: May 8 th , 2025

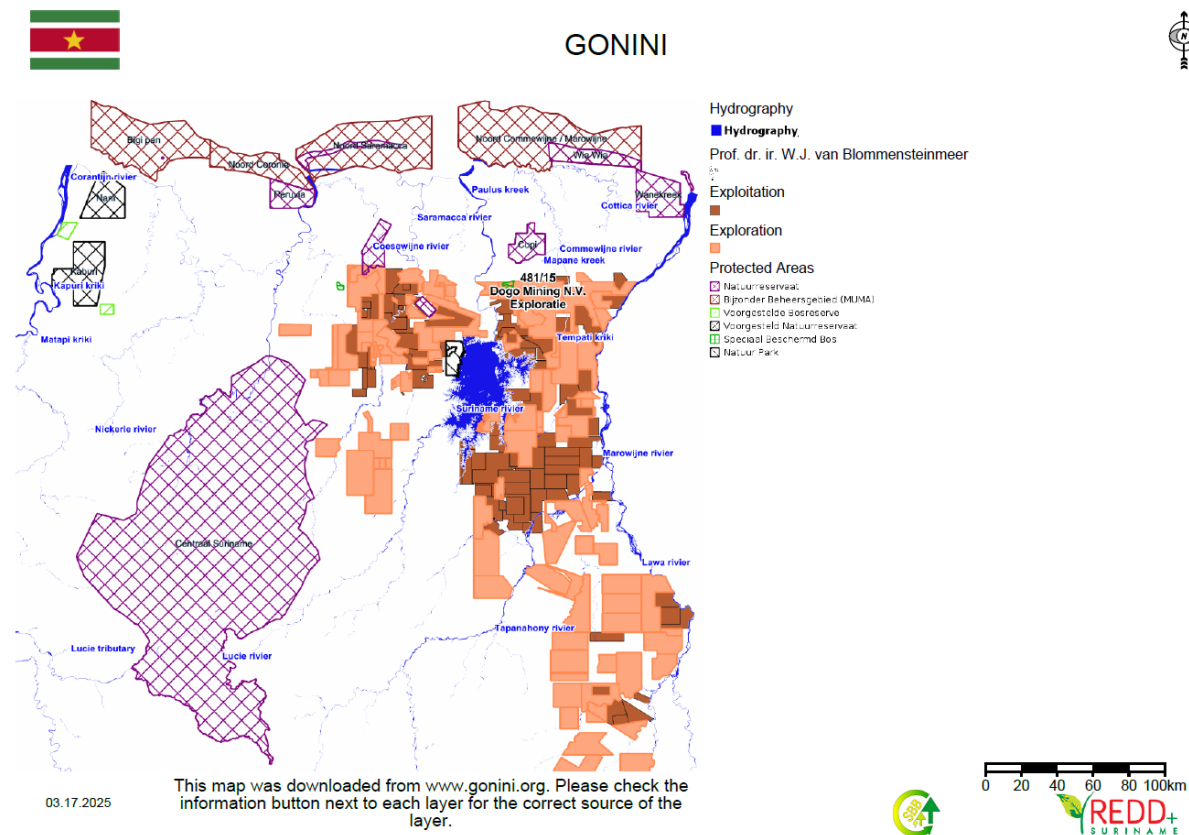
Annexes

Annex 1 – Mining in Suriname

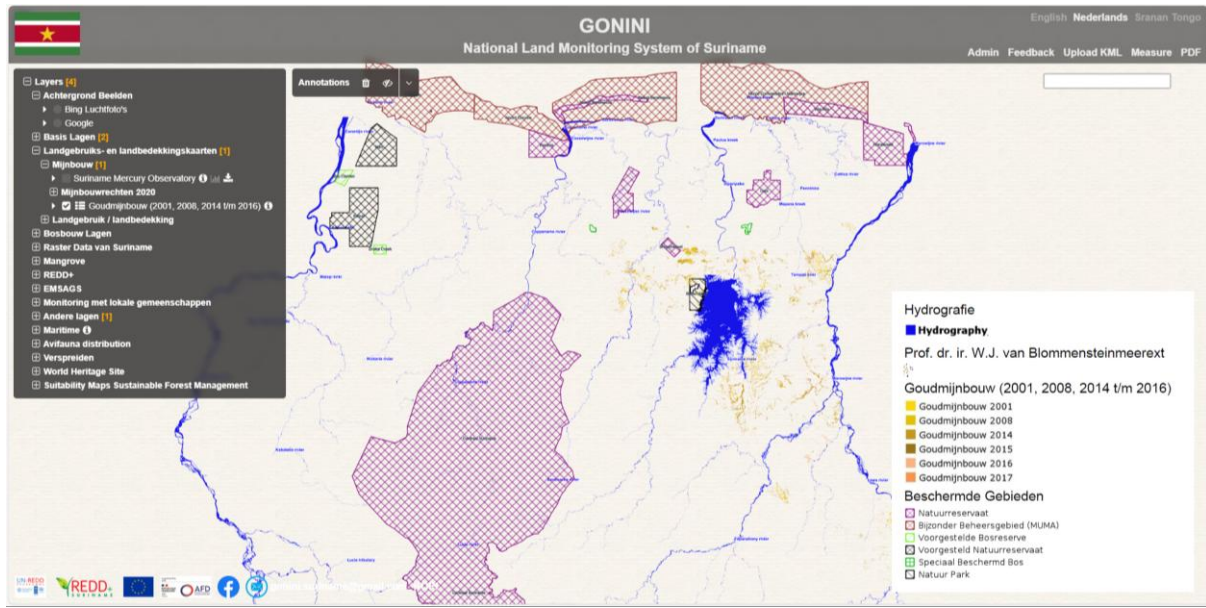
Source: the GONINI National Land Monitoring System of Suriname

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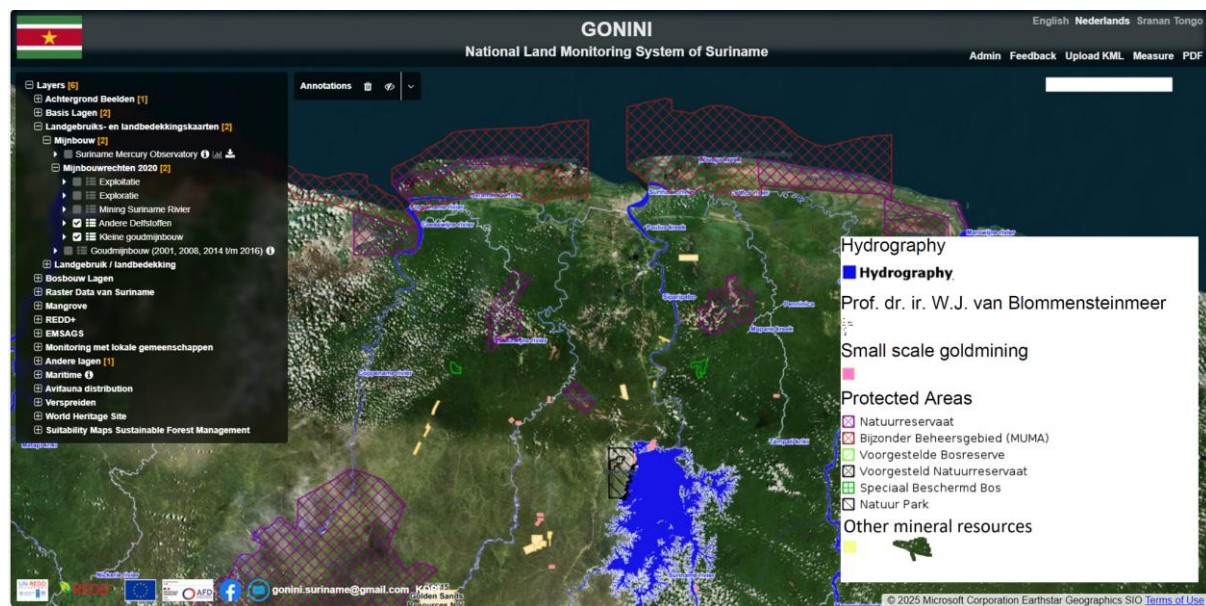
The map below shows the exploitation and exploration mining rights in 2020.



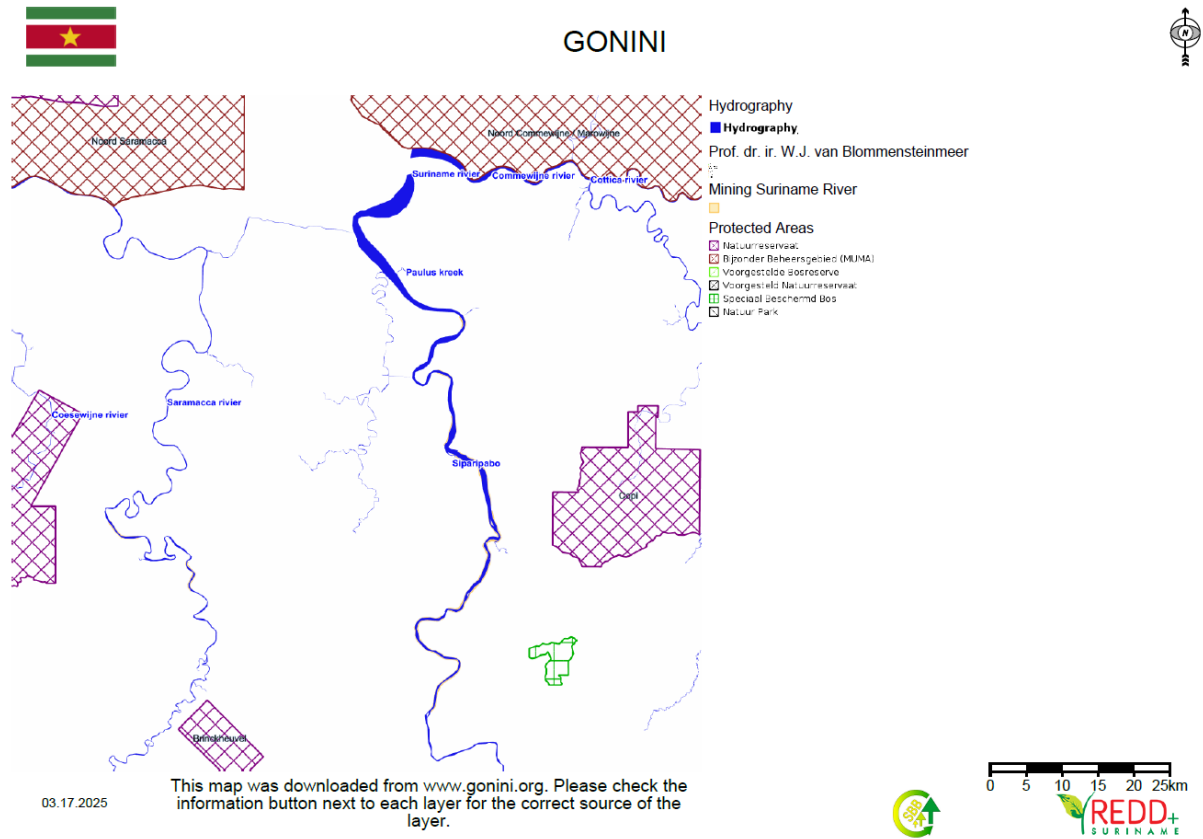
The map below shows the goldmining activities in 2001, 2008, 2014, 2014, 2016 and 2017.



The map below shows the mining rights of small scale goldmining (pink polygons) and other mining minerals (beige polygons), located in the crystalline basement of the interior, concentrated in the eastern part of Suriname along the Saramacca river, along the shores of the Brokopondo Reservoir of Suriname river and Tempati creek.



The map below shows the Mining Rights in Suriname River (yellow polygons), downstream of Bokopondo Reservoir.

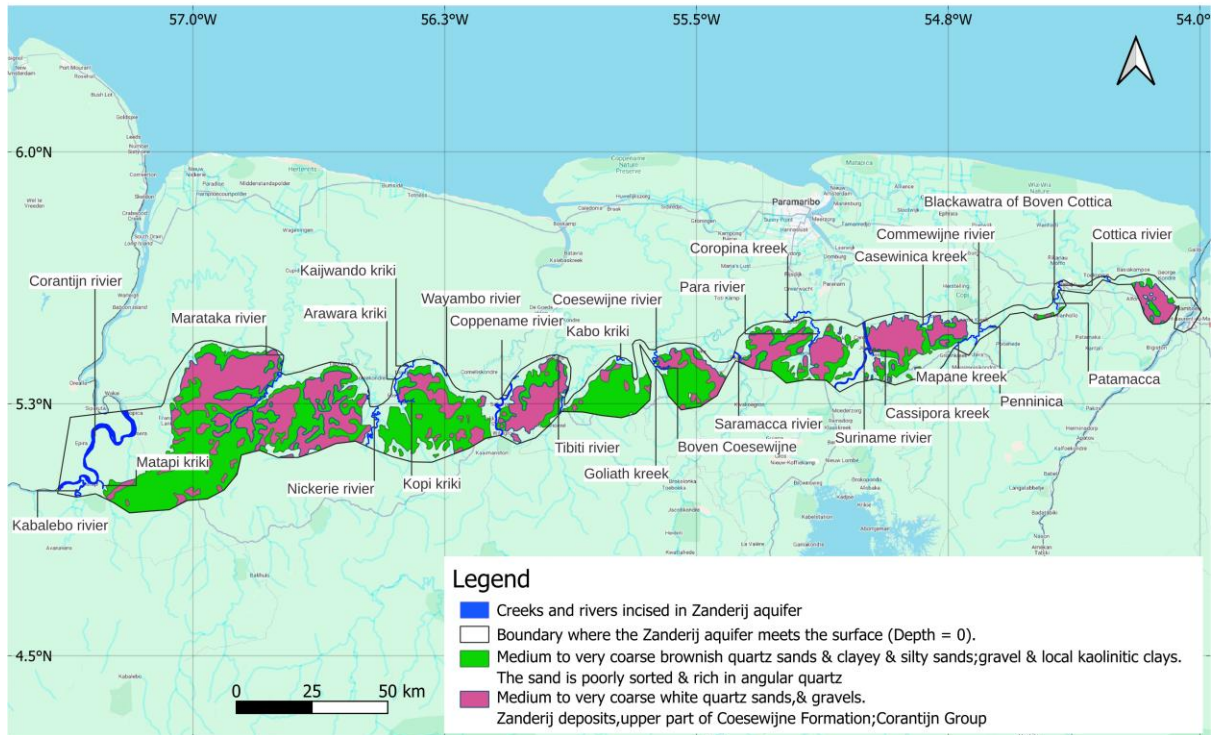


Annex 2 – Detailed maps of creeks and rivers incised in the Zanderij Aquifer

The map below provides an overview of the rivers and creeks incised into the Zanderij Aquifer, with labels corresponding to the detailed zoom-in maps presented in the following sections.



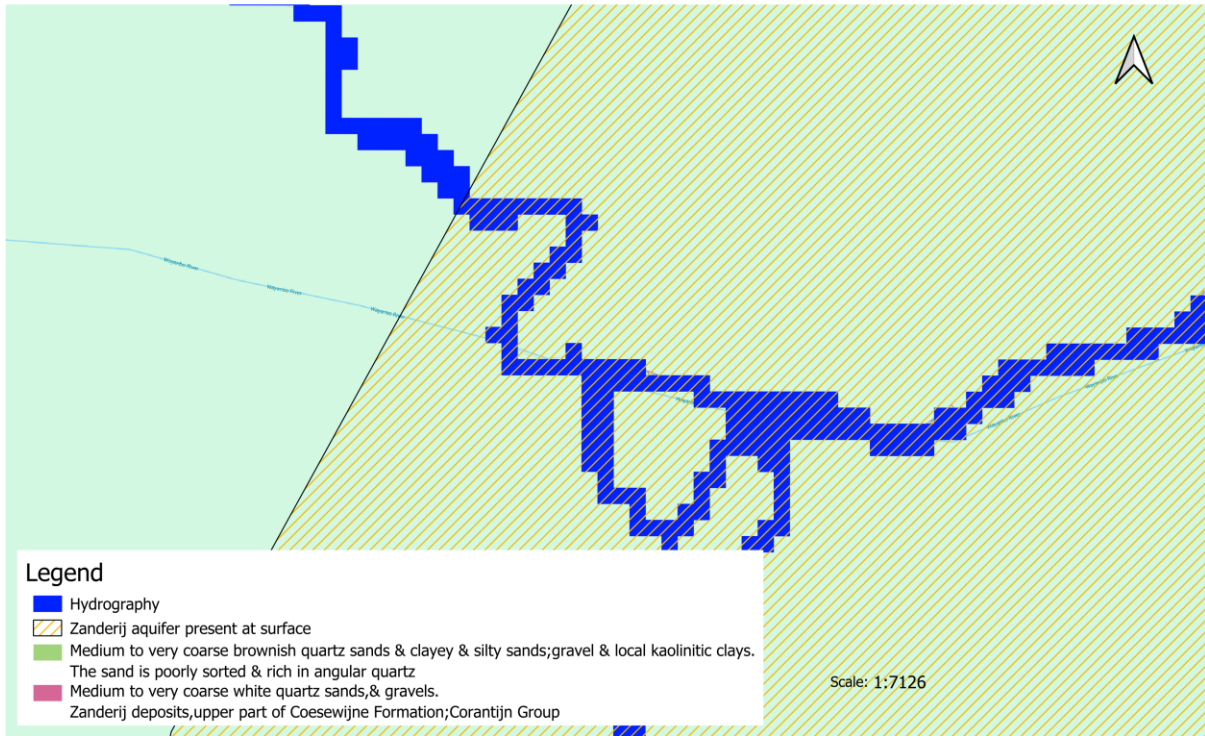
Creeks and rivers incised in Zanderij aquifer





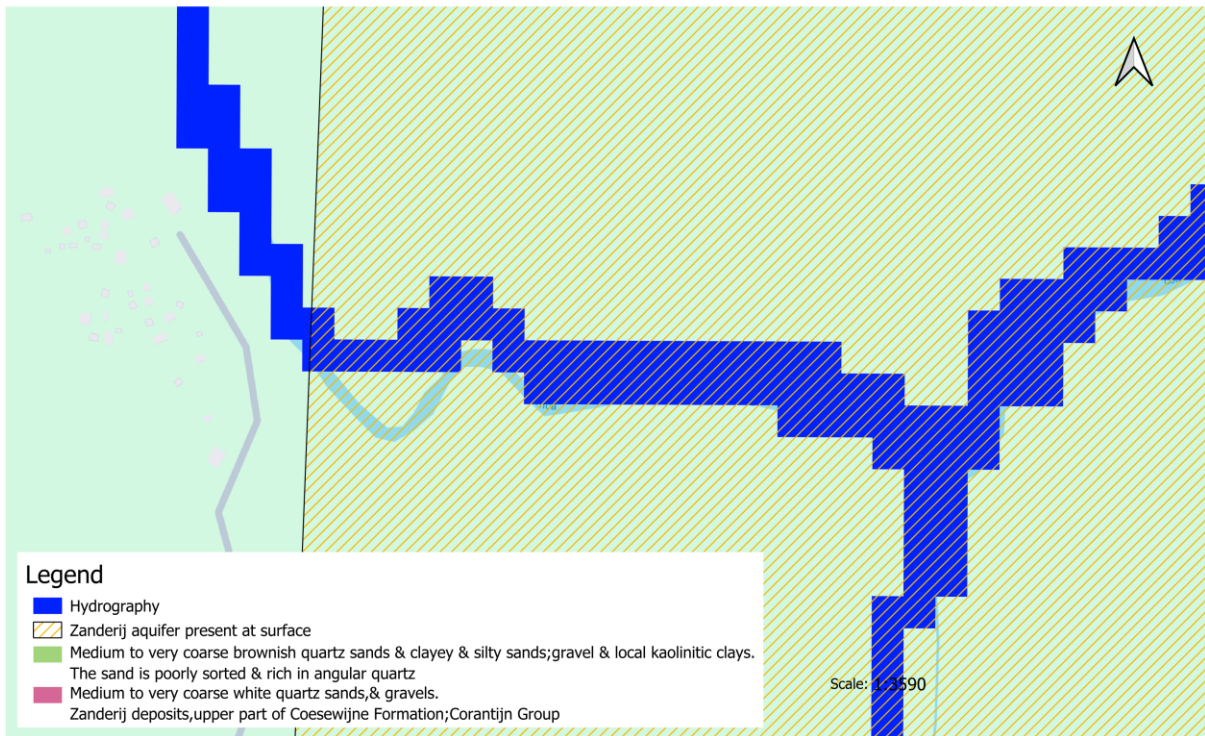
Creeks and rivers incised in Zanderij aquifer

Zoom-in at Arawara krika,



Creeks and rivers incised in Zanderij aquifer

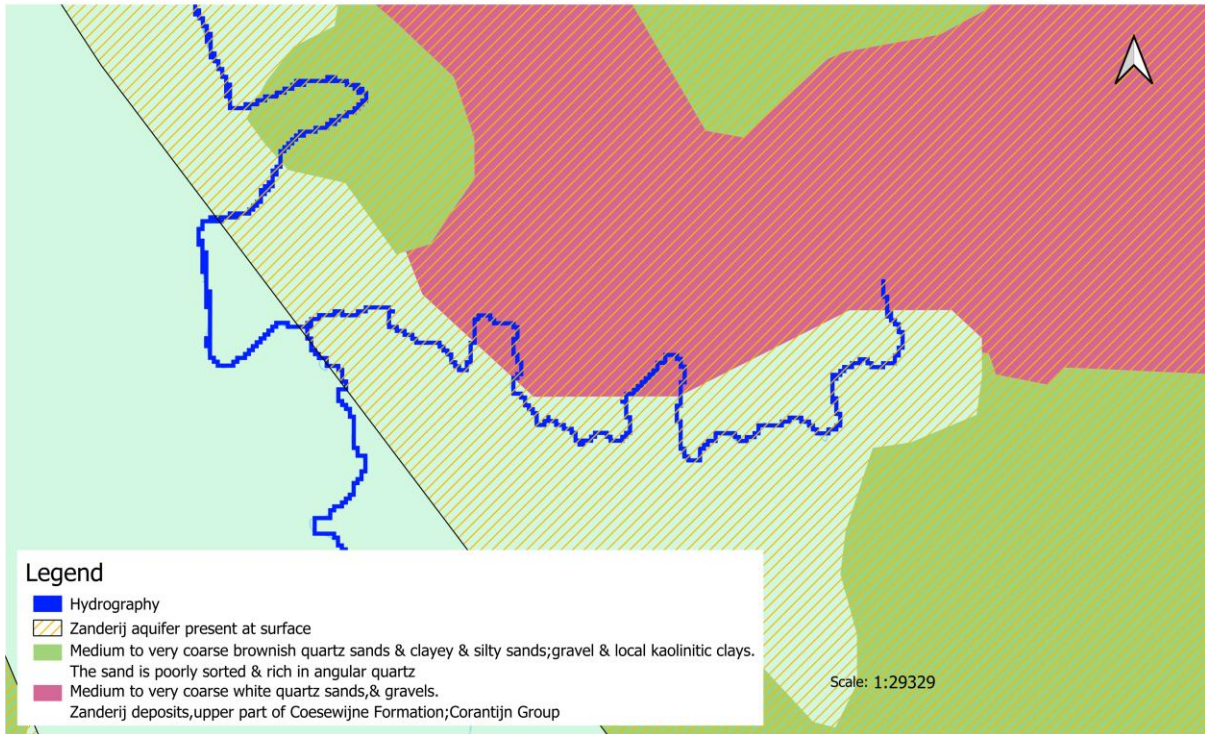
Zoom-in at Blackawatra of Boven Cottica,





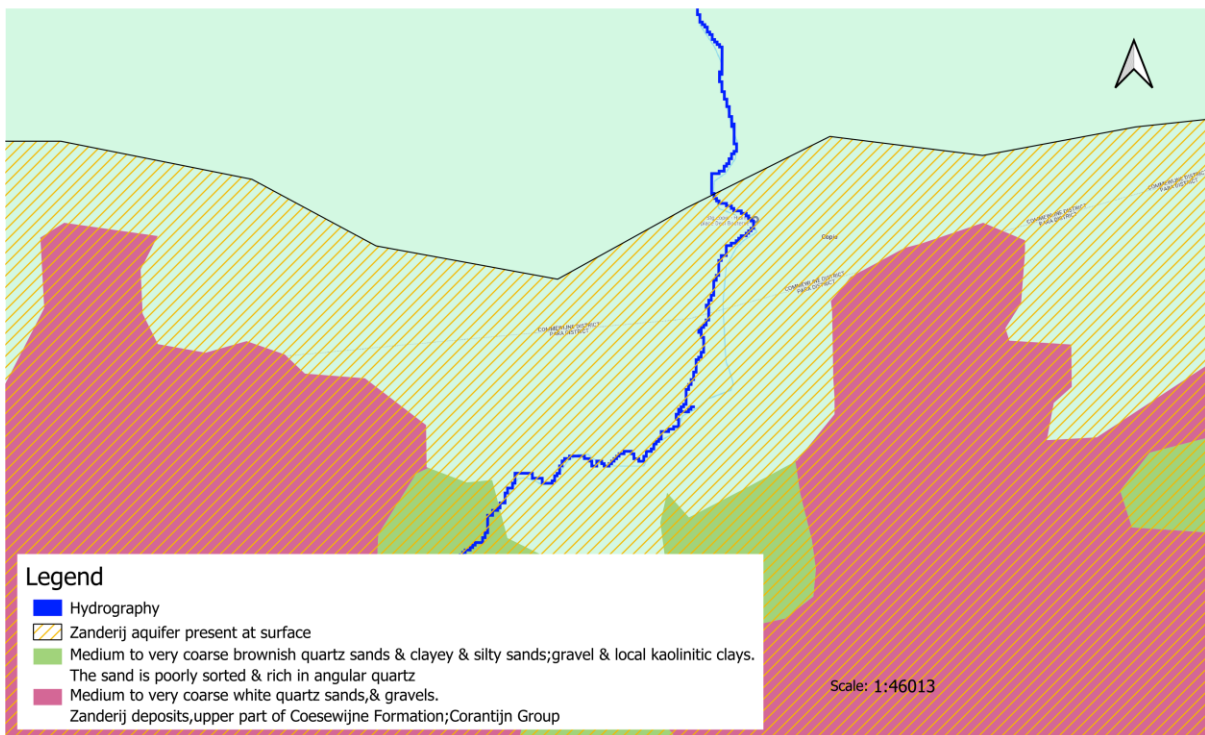
Creeks and rivers incised in Zanderij aquifer

Zoom-in at Boven Coesewijne,



Creeks and rivers incised in Zanderij aquifer

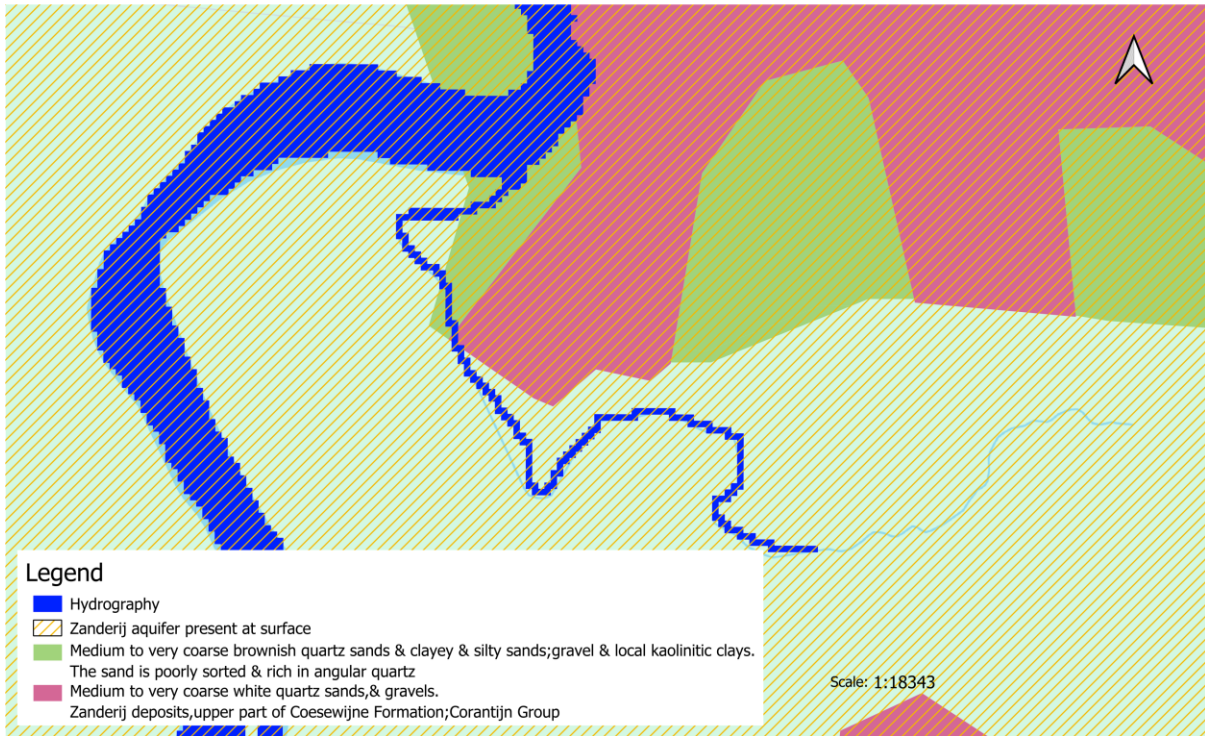
Zoom-in at Casewinica creek,





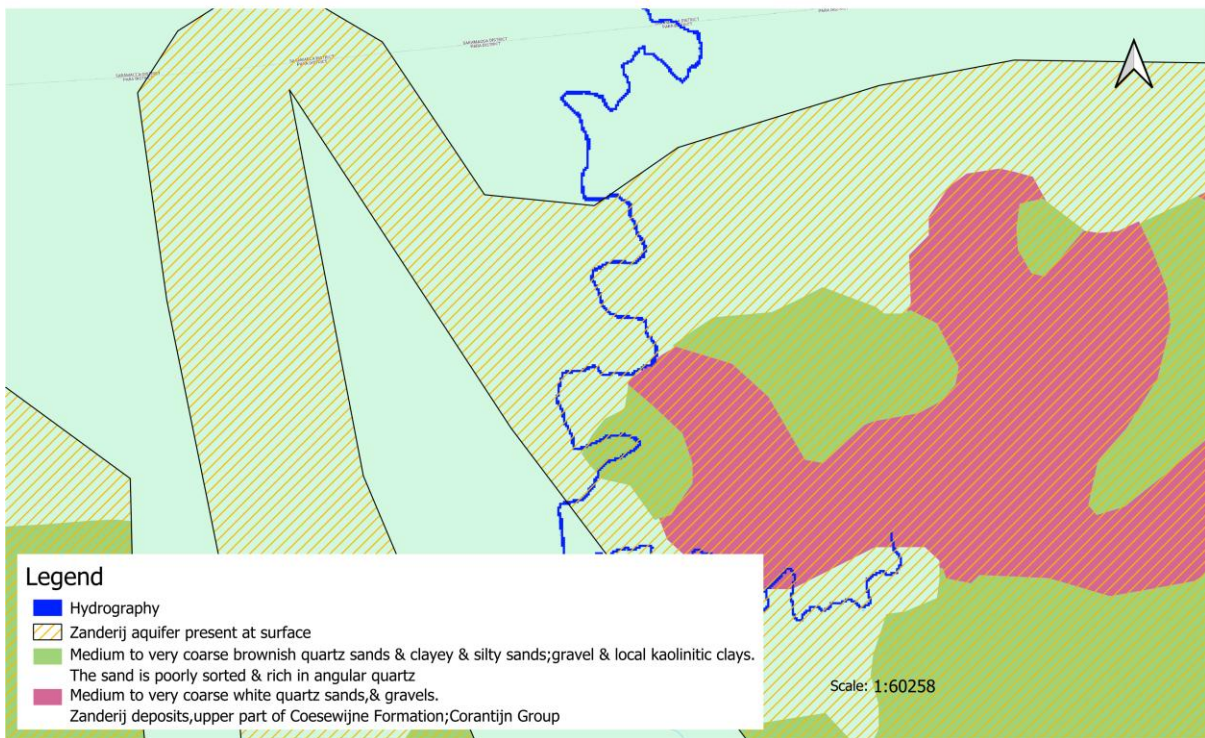
Creeks and rivers incised in Zanderij aquifer

Zoom-in at Cassipora creek,



Creeks and rivers incised in Zanderij aquifer

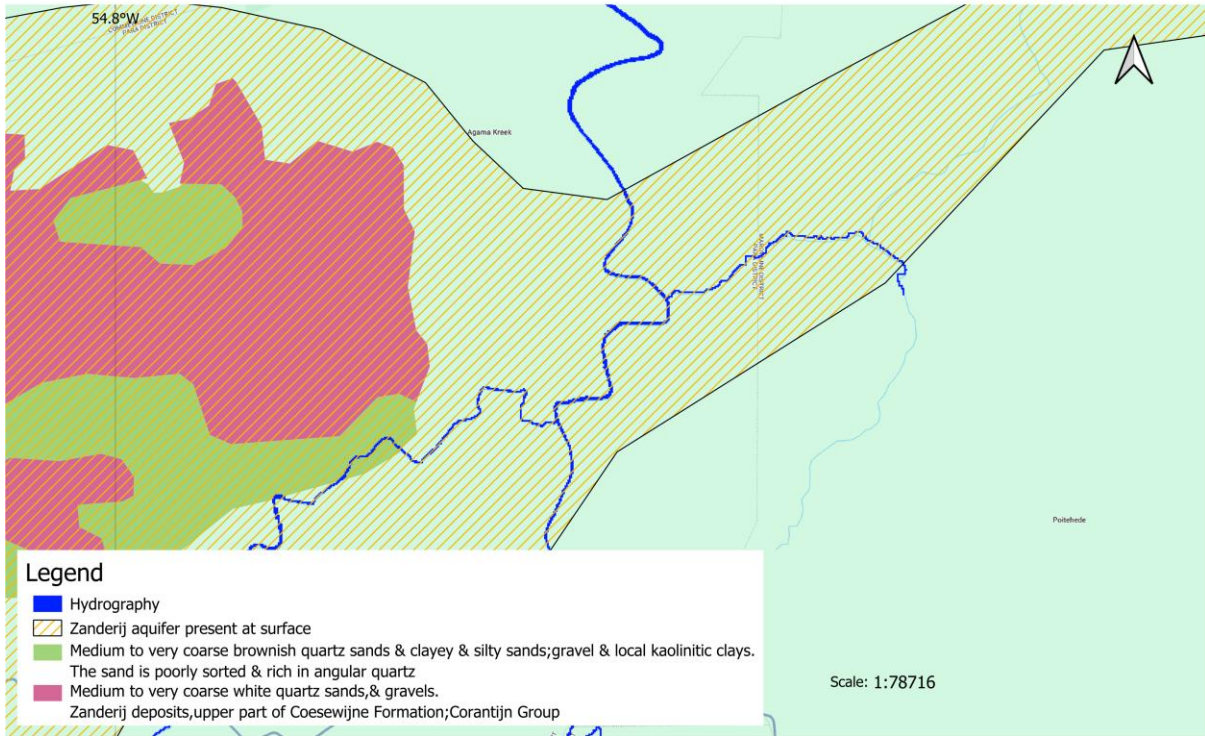
Zoom-in at Coesewijne rivier,





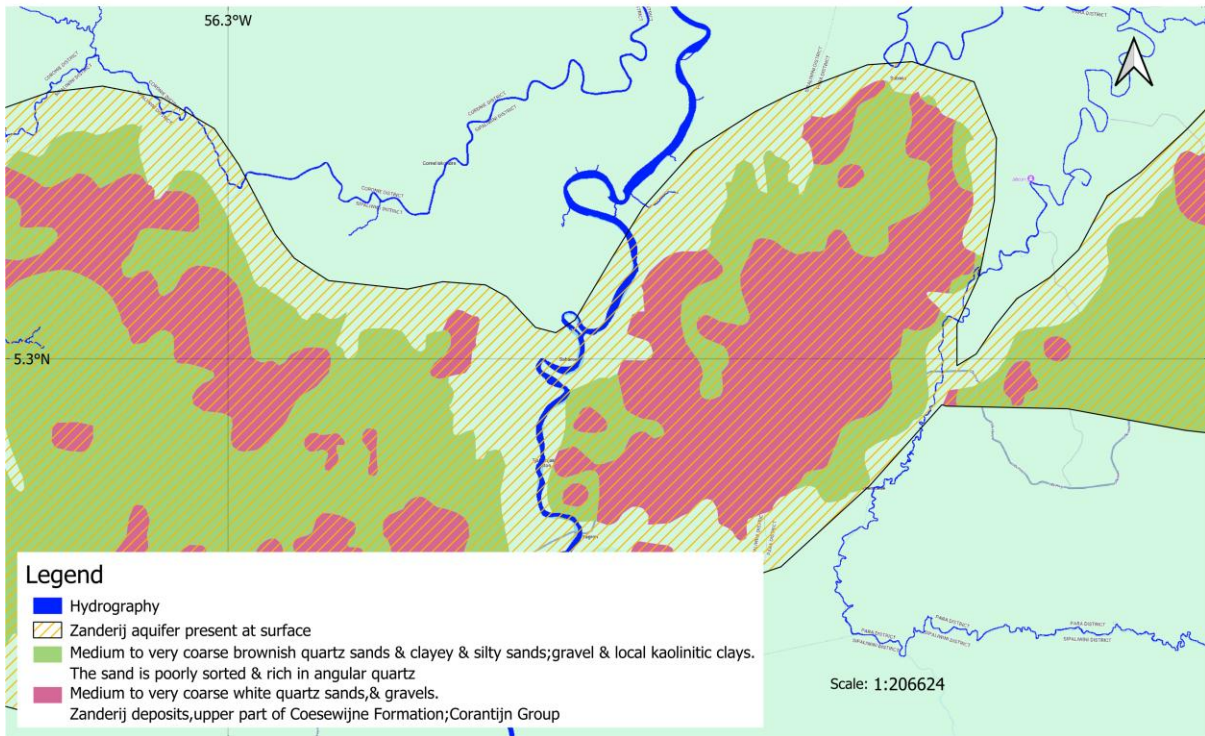
Creeks and rivers incised in Zanderij aquifer

Zoom-in at Commewijne rivier,



Creeks and rivers incised in Zanderij aquifer

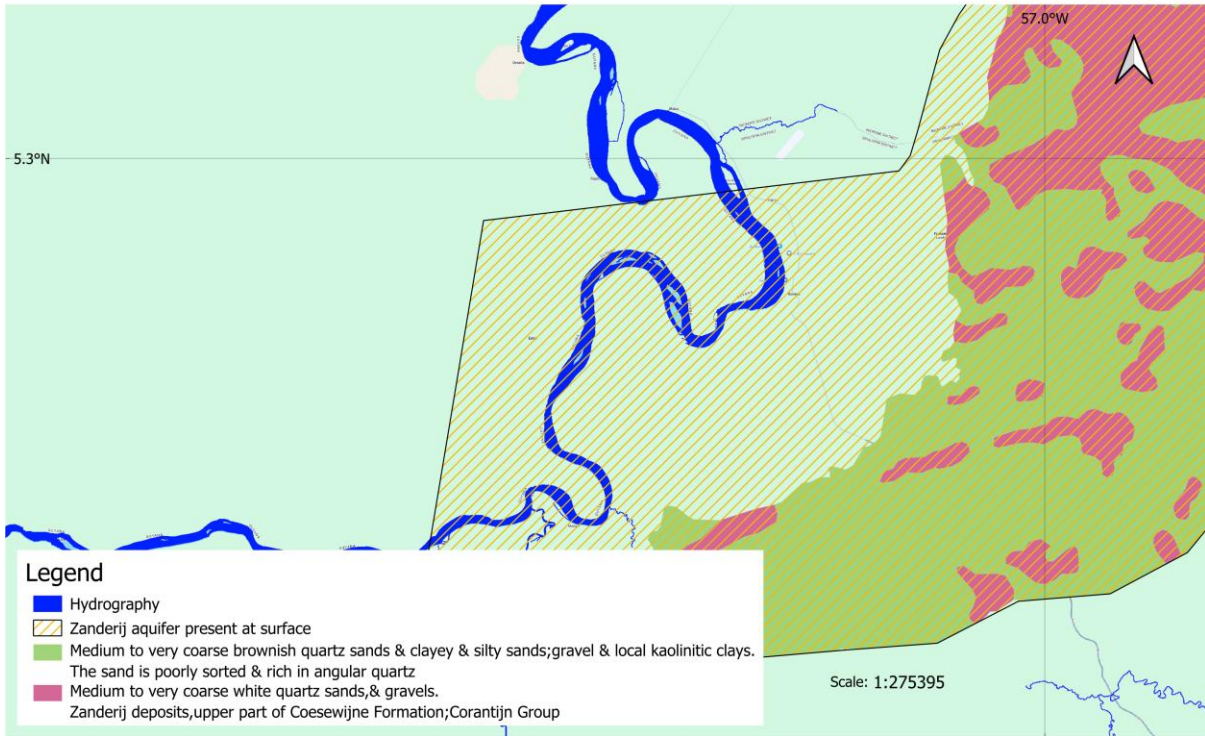
Zoom-in at Coppename rivier,





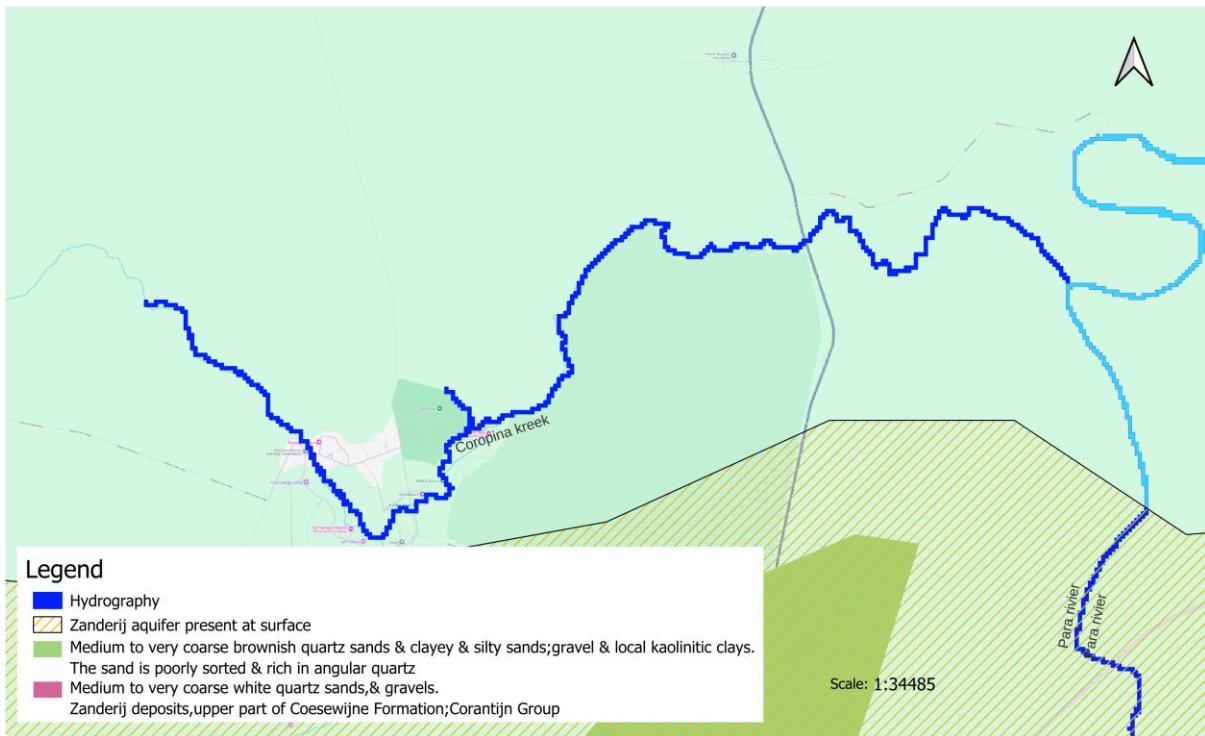
Creeks and rivers incised in Zanderij aquifer

Zoom-in at Corantijn rivier,



Creeks and rivers incised in Zanderij aquifer

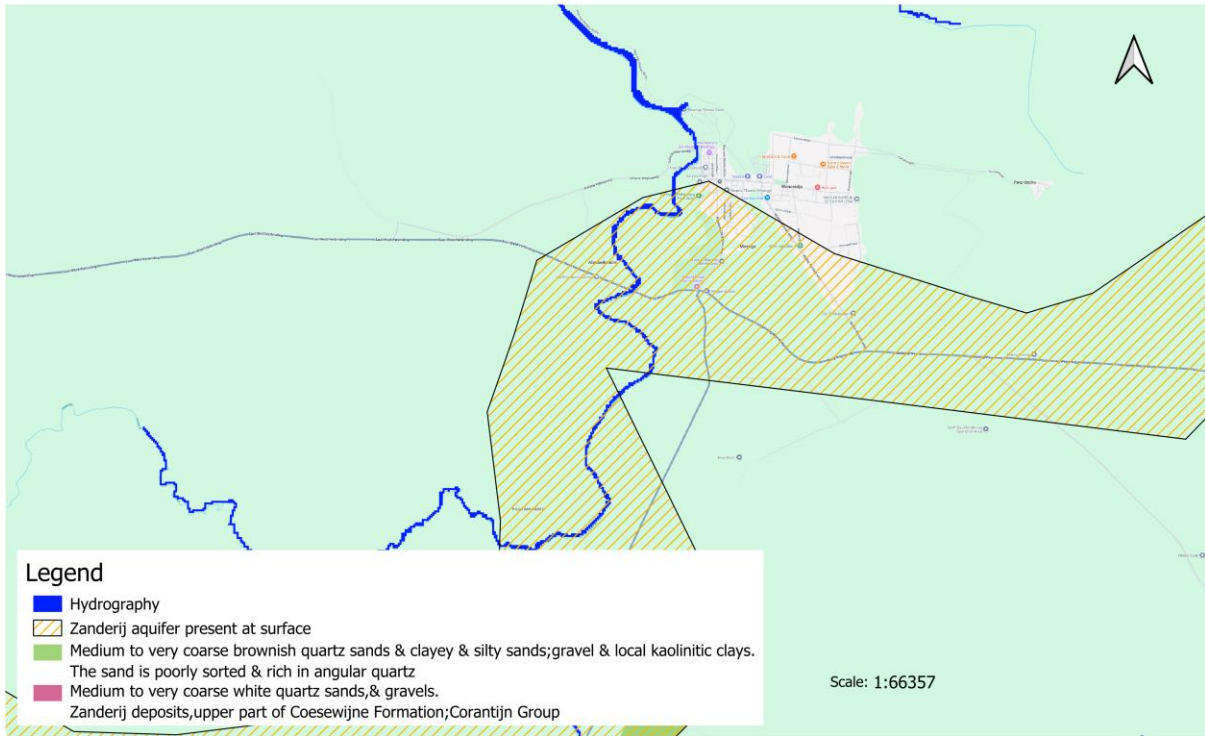
Zoom-in at Coropina creek,





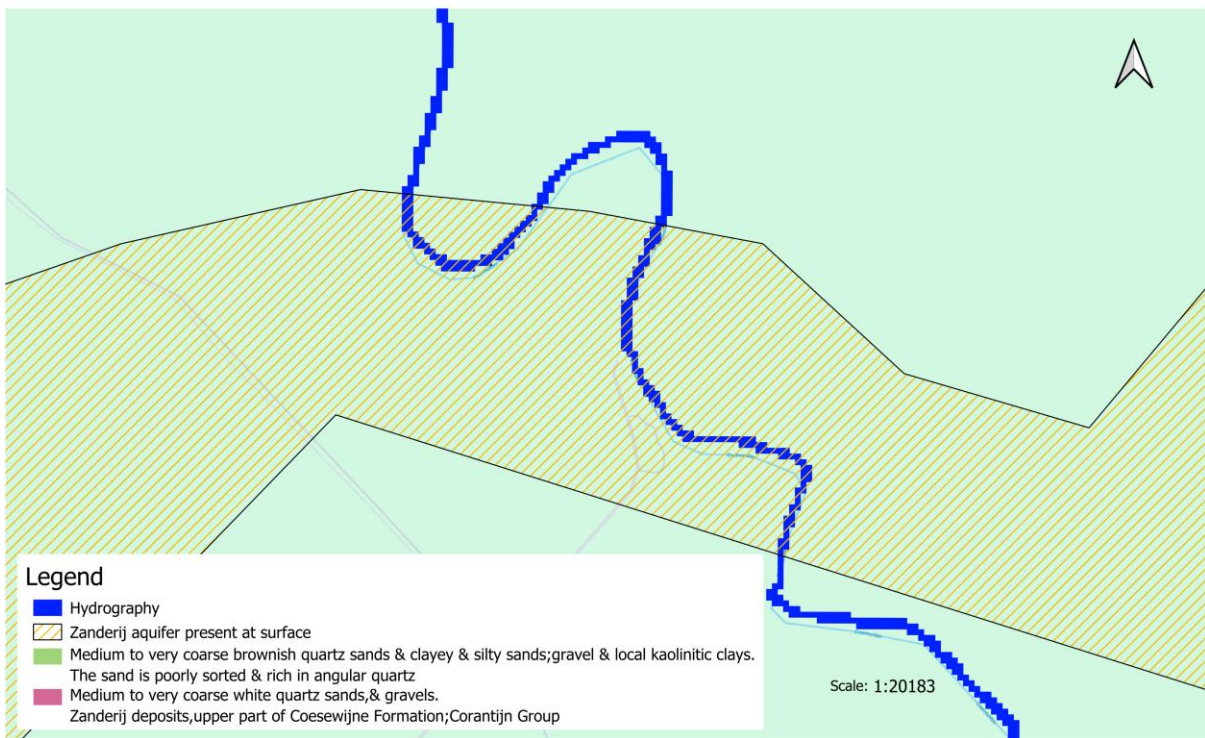
Creeks and rivers incised in Zanderij aquifer

Zoom-in at Cottica rivier,



Creeks and rivers incised in Zanderij aquifer

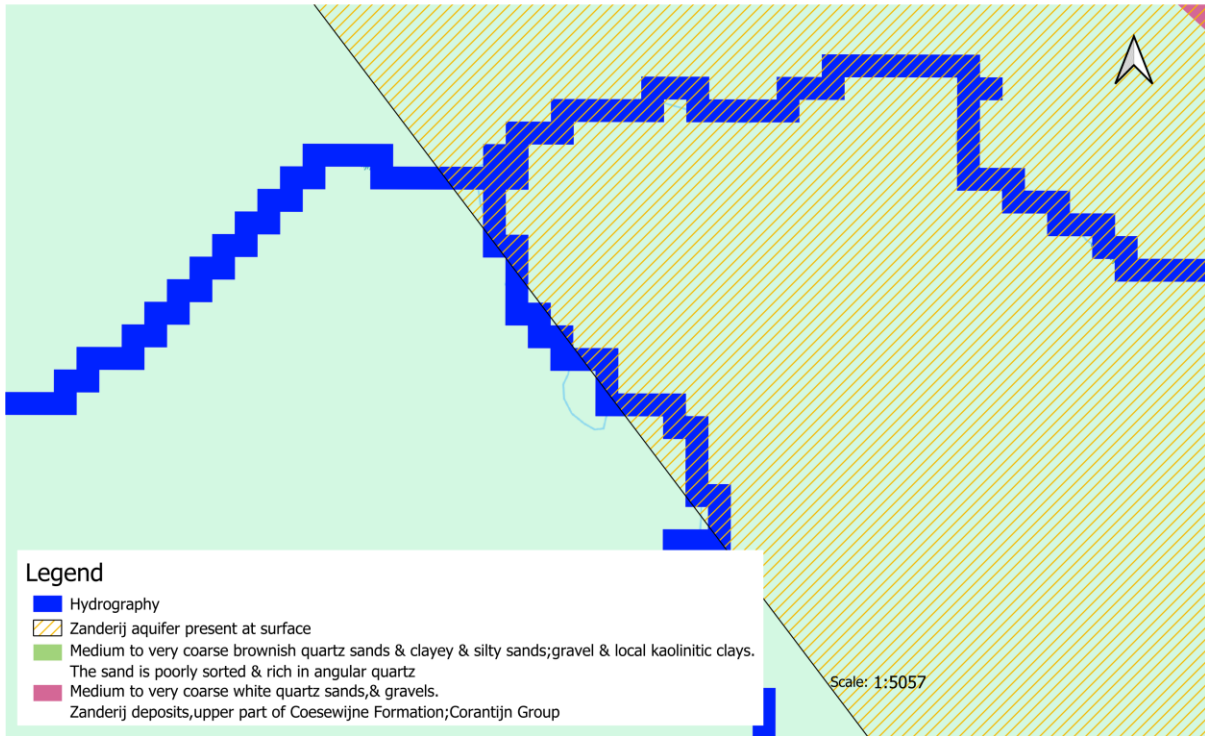
Zoom-in at Curmotibo rivier,





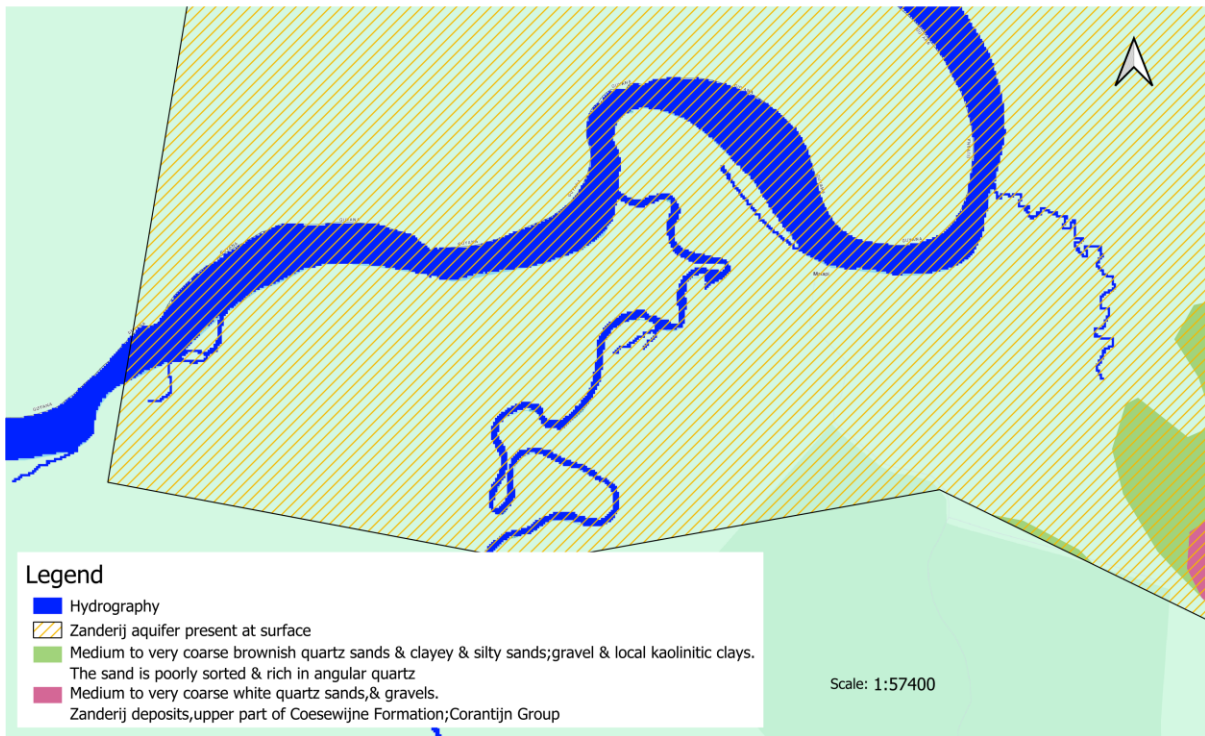
Creeks and rivers incised in Zanderij aquifer

Zoom-in at Goliath kreek,



Creeks and rivers incised in Zanderij aquifer

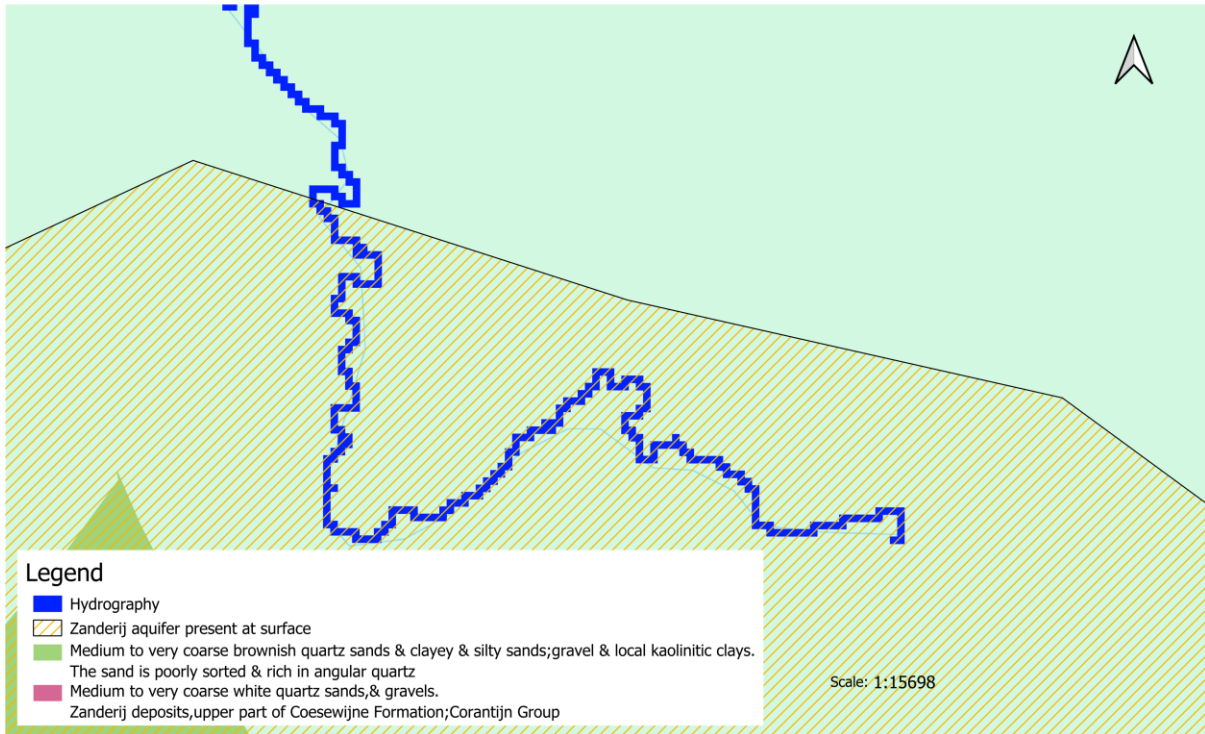
Zoom-in at Kabalebo rivier,





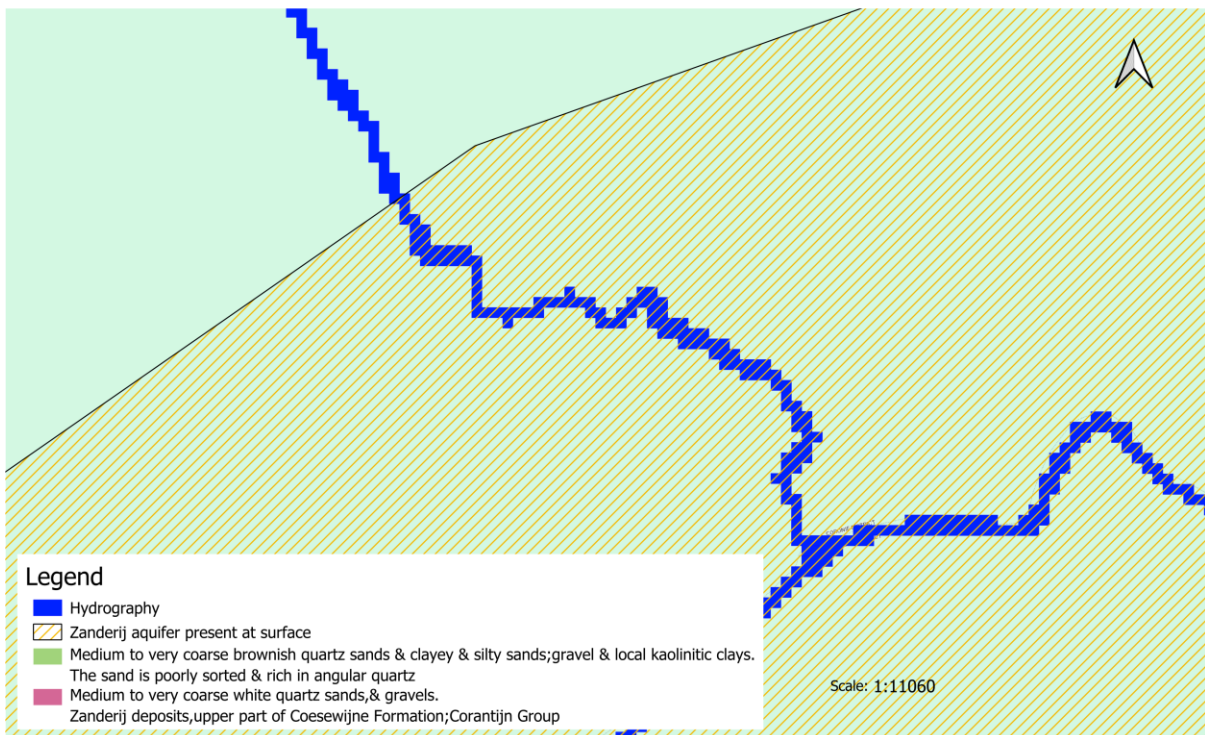
Creeks and rivers incised in Zanderij aquifer

Zoom-in at Kabo kriki,



Creeks and rivers incised in Zanderij aquifer

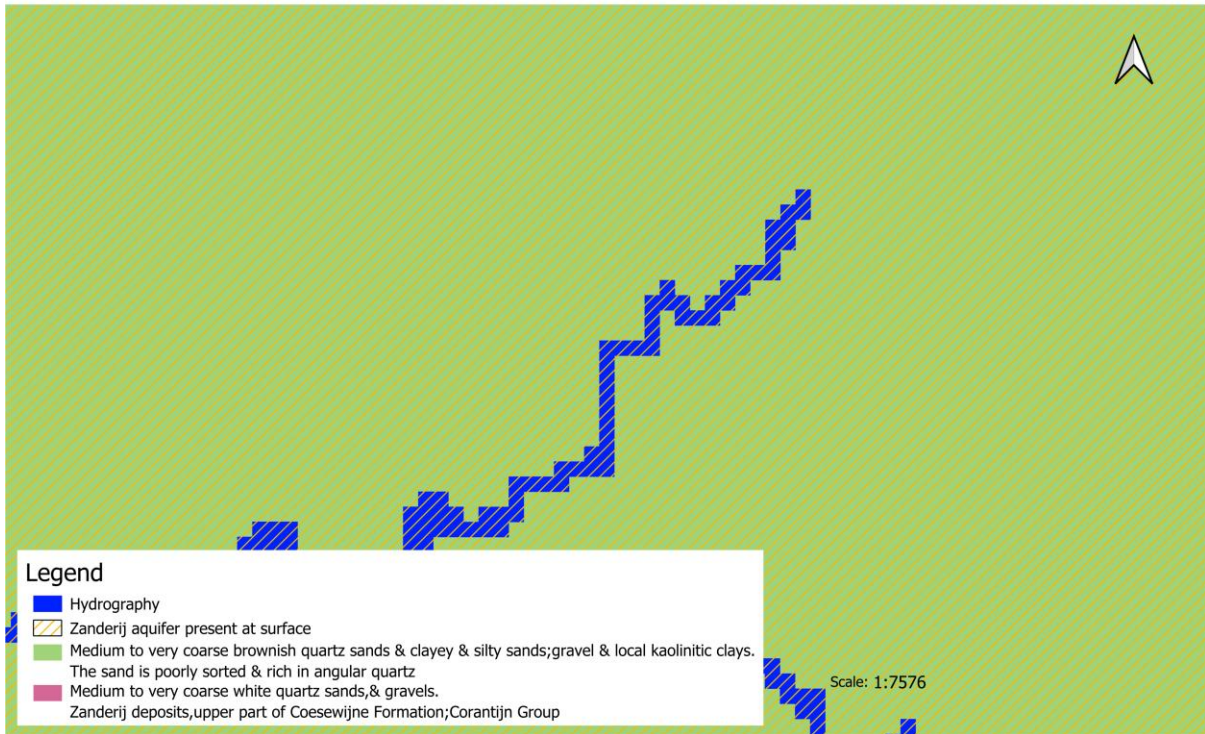
Zoom-in at Kaijwando kriki,





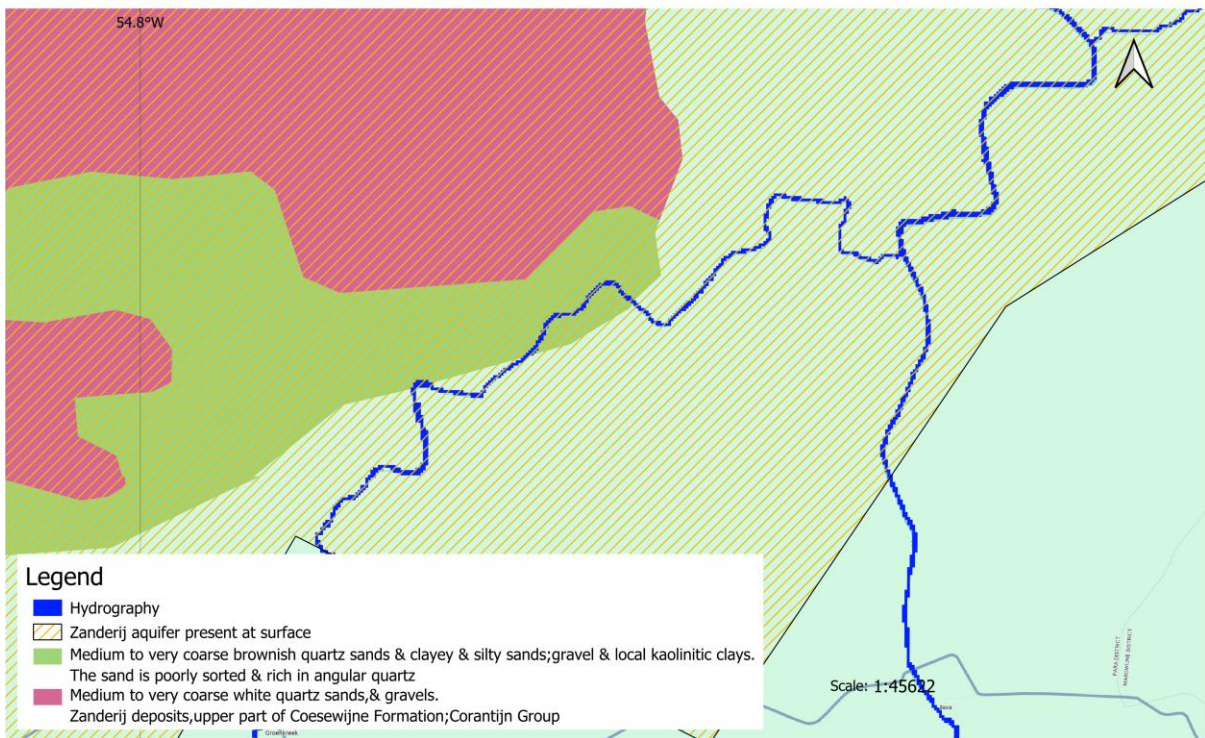
Creeks and rivers incised in Zanderij aquifer

Zoom-in at Kopi krika,



Creeks and rivers incised in Zanderij aquifer

Zoom-in at Mapane creek,





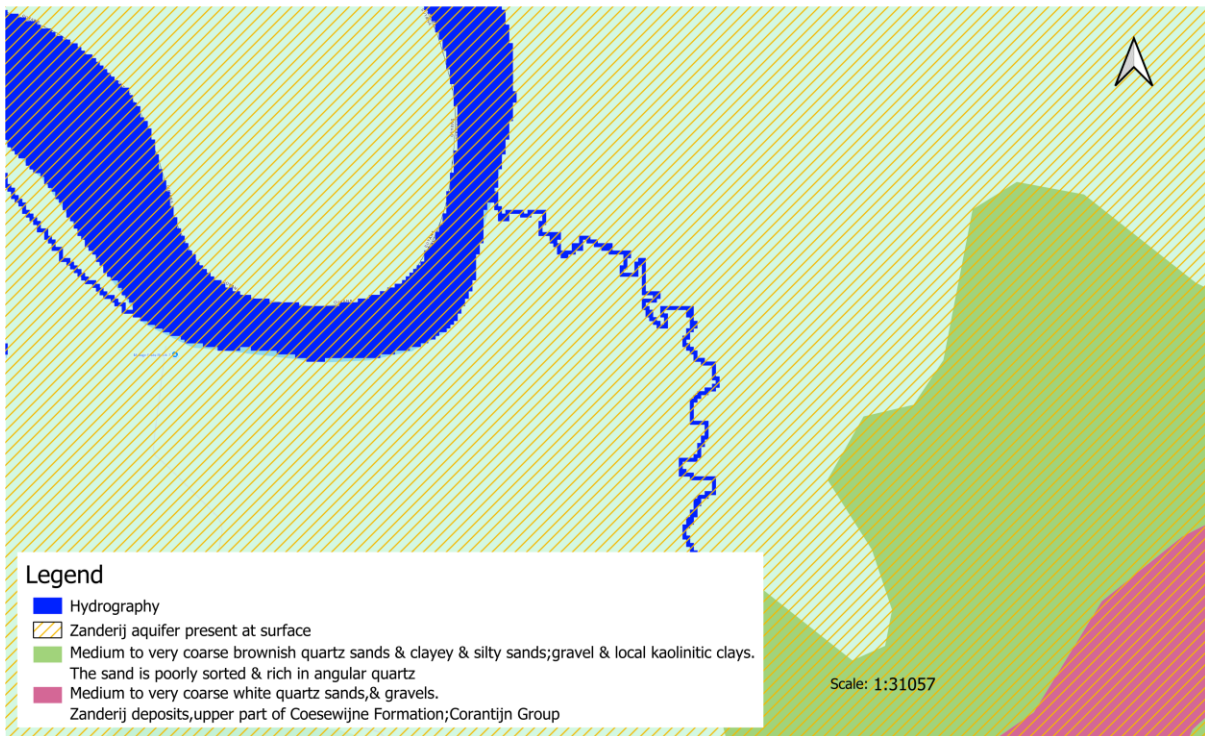
Creeks and rivers incised in Zanderij aquifer

Zoom-in at Marataka rivier,



Creeks and rivers incised in Zanderij aquifer

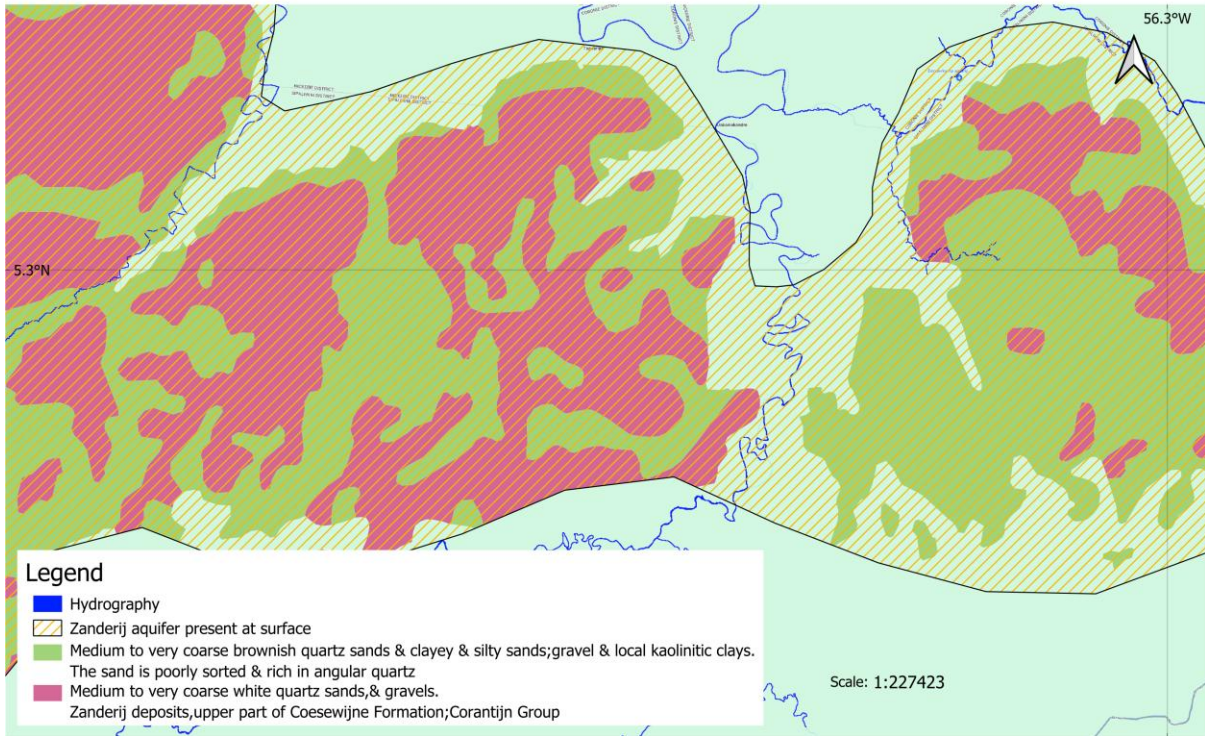
Zoom-in at Matapi krika,





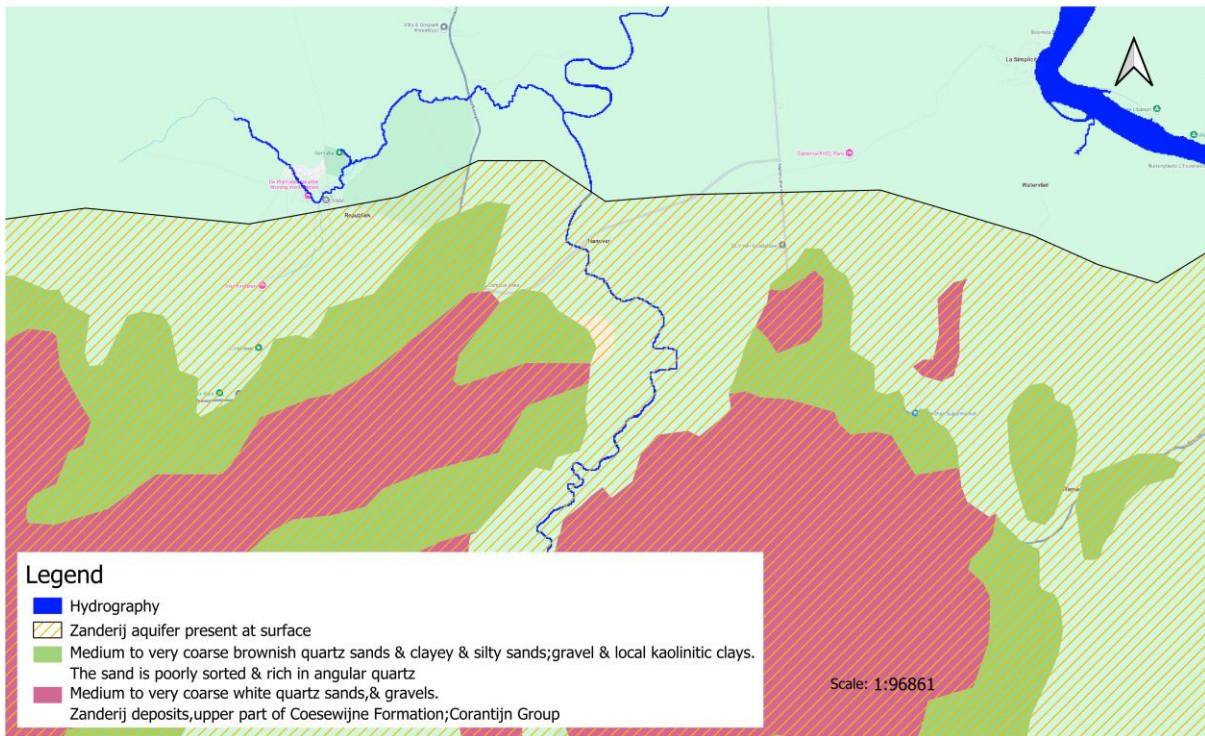
Creeks and rivers incised in Zanderij aquifer

Zoom-in at Nickerie rivier,



Creeks and rivers incised in Zanderij aquifer

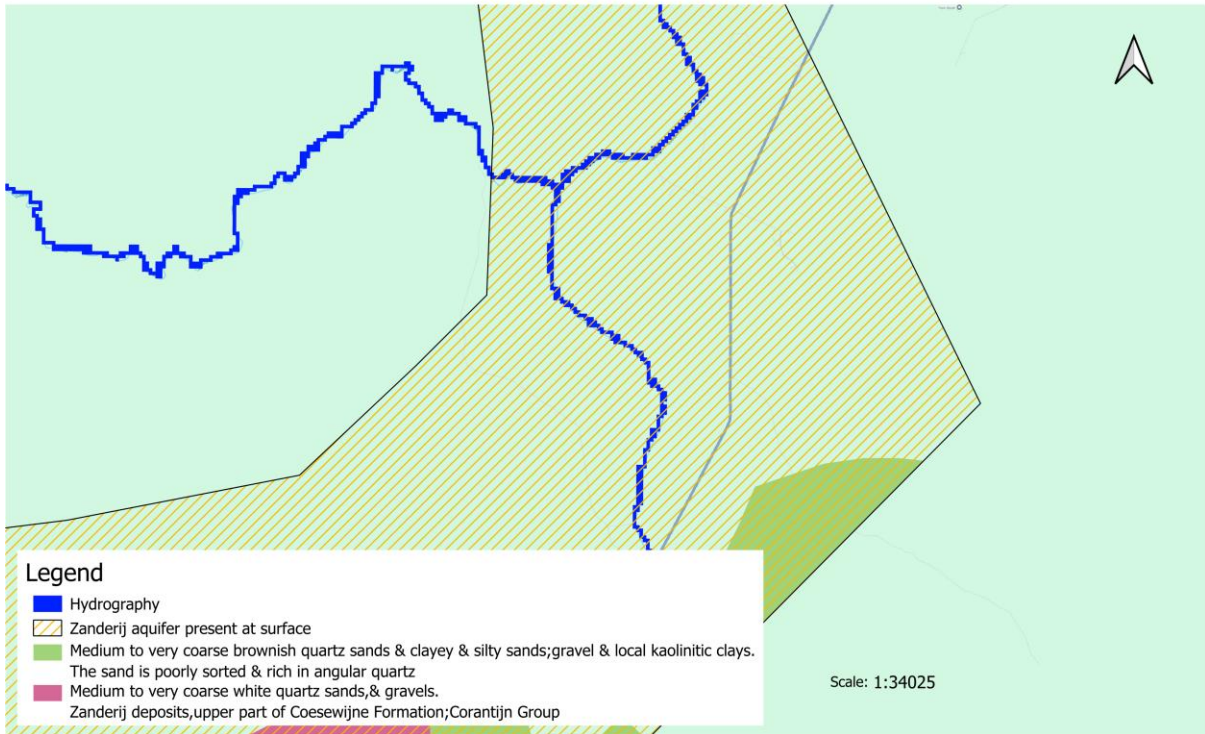
Zoom-in at Para rivier,





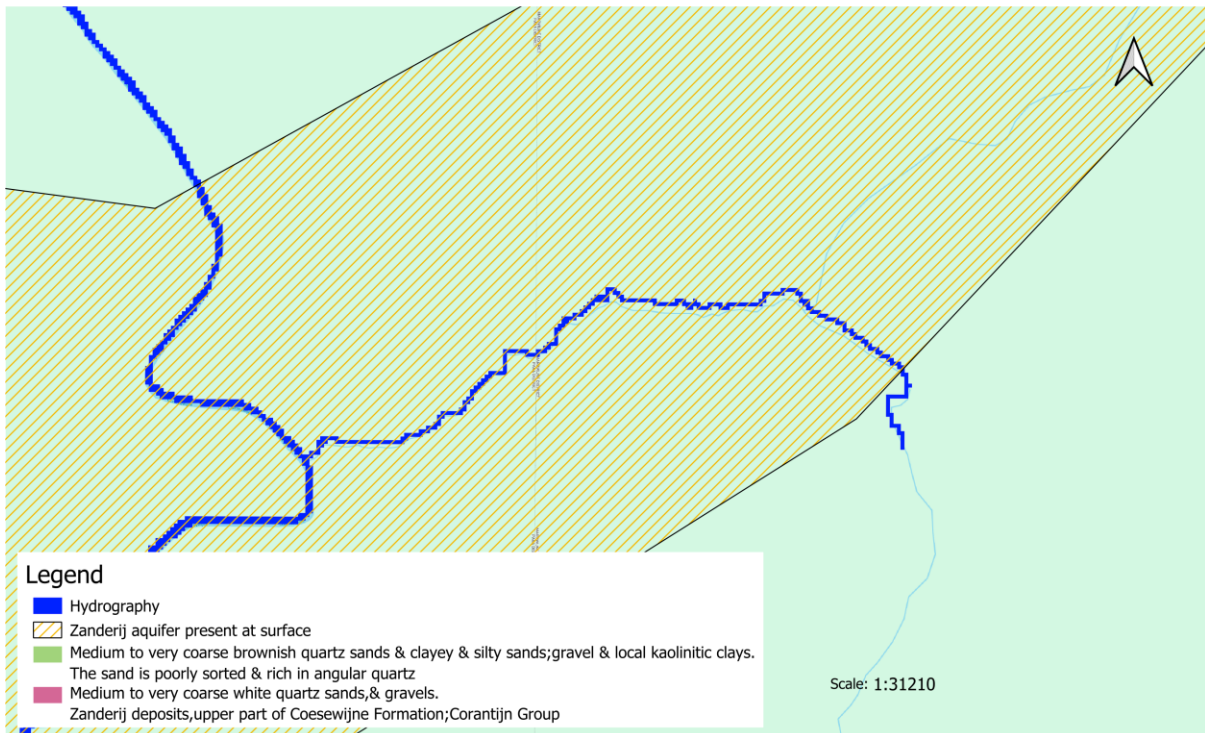
Creeks and rivers incised in Zanderij aquifer

Zoom-in at Patamacca,



Creeks and rivers incised in Zanderij aquifer

Zoom-in at Penninica,





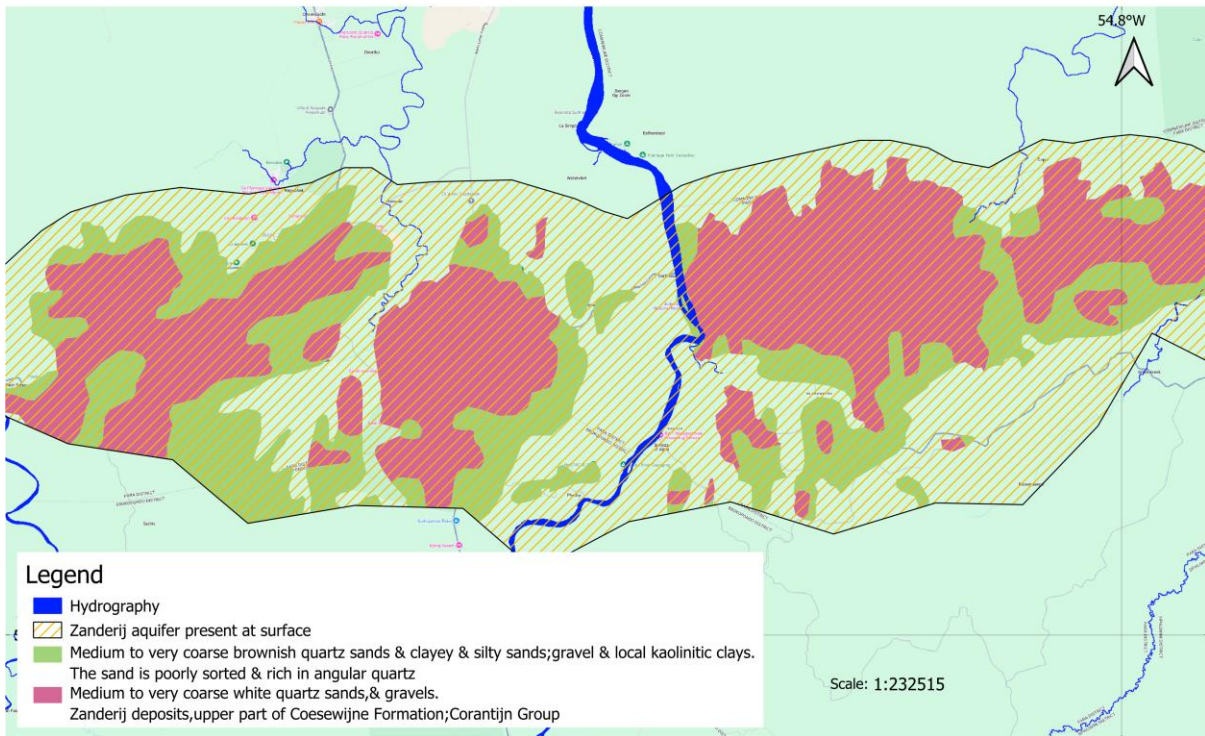
Creeks and rivers incised in Zanderij aquifer

Zoom-in at Saramacca river,



Creeks and rivers incised in Zanderij aquifer

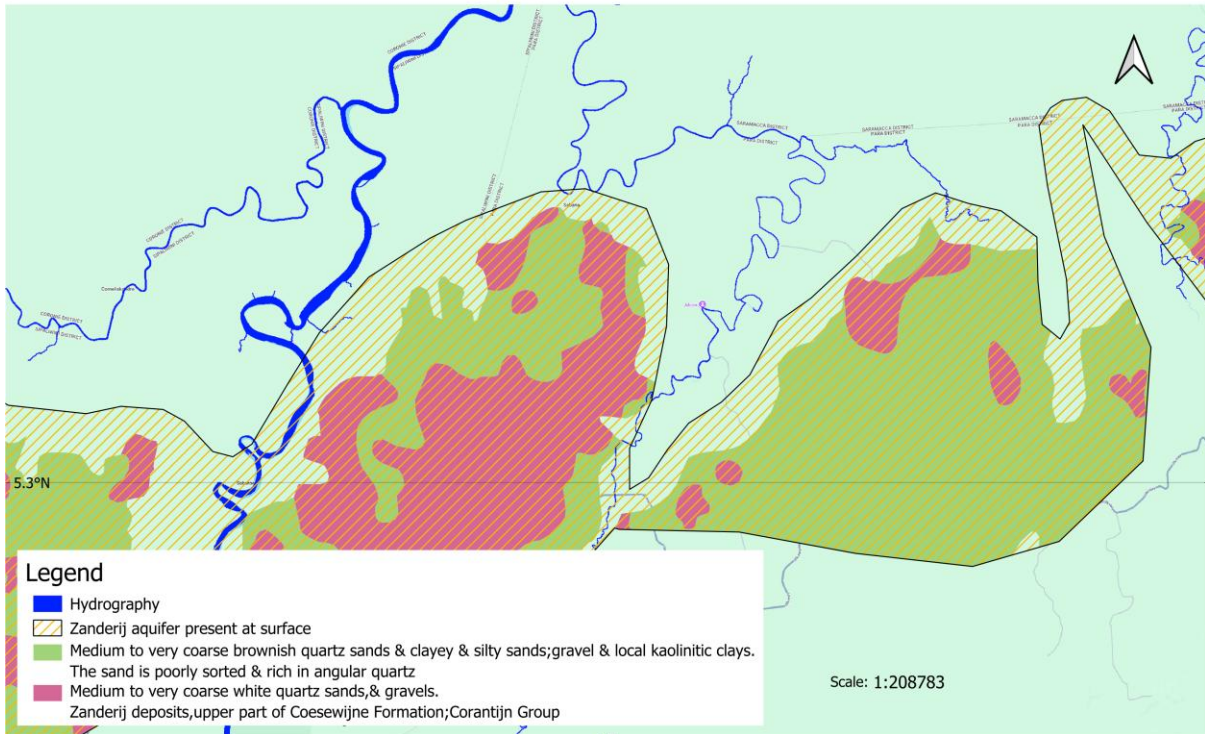
Zoom-in at Suriname rivier,





Creeks and rivers incised in Zanderij aquifer

Zoom-in at Tibiti river,



Creeks and rivers incised in Zanderij aquifer

Zoom-in at Wayambo river,

