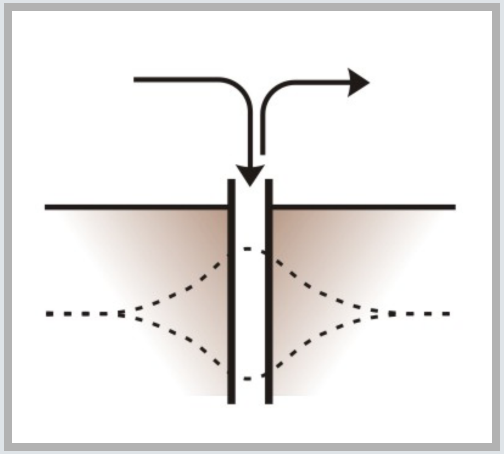
Artificial Recharge

The intentional banking and treating water in aquifers



Lecture prepared by DWAF for students of Integrated Water Resource Management, Hydrology, Hydrogeology and Water Supply Engineering

water & forestry

Department:
Water Affairs & Forestry
REPUBLIC OF SOUTH AFRICA

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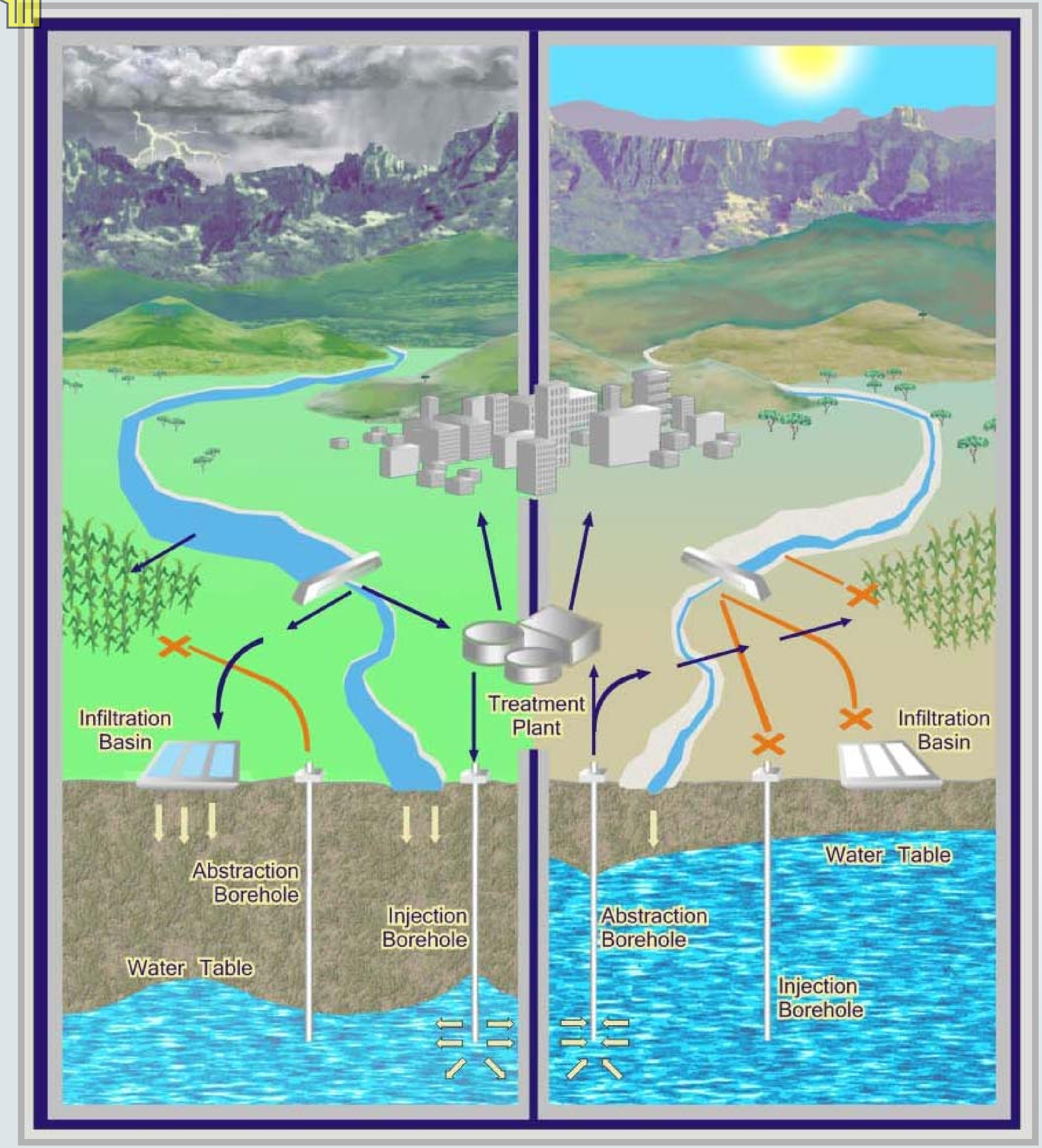


The concept

Store water underground when available and recover it when needed

Left hand part of diagram: Water is diverted to infiltration basins and recharge boreholes while water is available and the aquifer is not pumped.

Right hand part of diagram: Water is then abstracted when the aquifer is full. The recharge facilities are now rested.

Contents

- Applications of artificial recharge
- Types of artificial recharge schemes
- International examples
- Southern African examples
- Criteria for success
- Conclusions

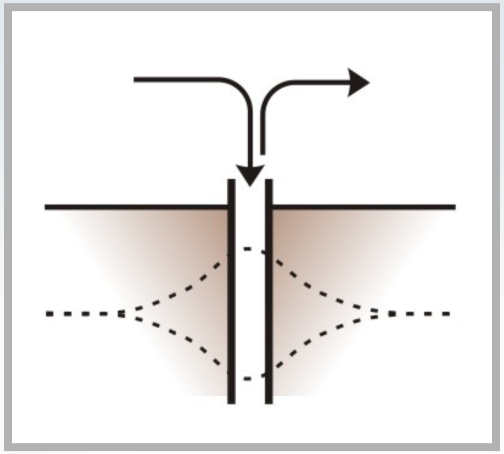
Applications of artificial recharge

- Maximise natural storage
  - Seasonal storage
  - Long-term storage (water banking)
- Physical management of the aquifer
  - Restore groundwater levels
  - Prevent salt water intrusion
  - Control contaminant plumes
- Water quality management
  - Water quality improvement
- Ecological benefits
  - Reduce abstraction from rivers
  - Maintain the Reserve (maintain groundwater levels and in-stream flow requirements)
  - Minor environmental imprint (when compared to dams)

Other benefits

- Defer expansion of water facilities (this can lead to huge financial savings)
- Store reclaimed water
- Utilise saline aquifers (create a fresh water “bubble” in a saline aquifer)
- Store huge volumes of water
- Rapid implementation and staged development (ie expand as needed; this can lead to significant financial savings)
- Low capital cost in comparison to dams
- Mitigate effects of climate change (ie store surplus water during wet periods for use during dry periods)
- Save on evaporation (if the alternative is storage in a shallow dam with high evaporation losses)

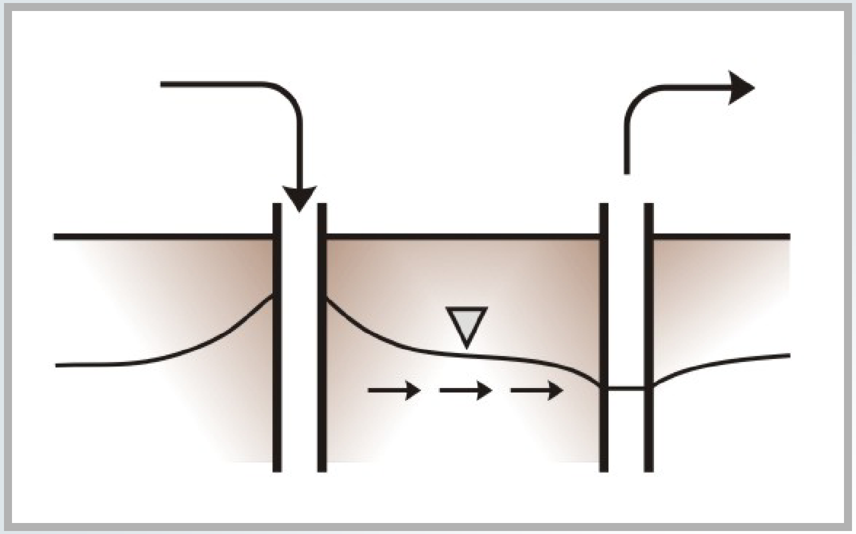
Types of artificial recharge schemes



ASR

Aquifer Storage and Recovery:
Injection and abstraction from the same borehole

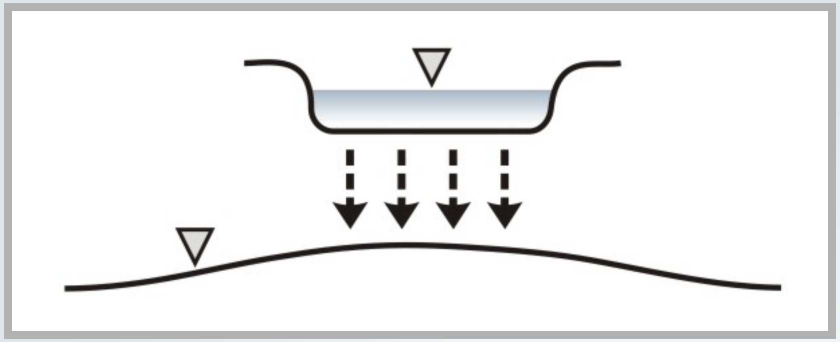
ASR borehole, Adelaide, Australia. Urban runoff is diverted into a constructed wetland for treatment and then injected into a limestone aquifer.



Aquifer Storage, Transfer and Recovery:
Injection and abstraction from different boreholes

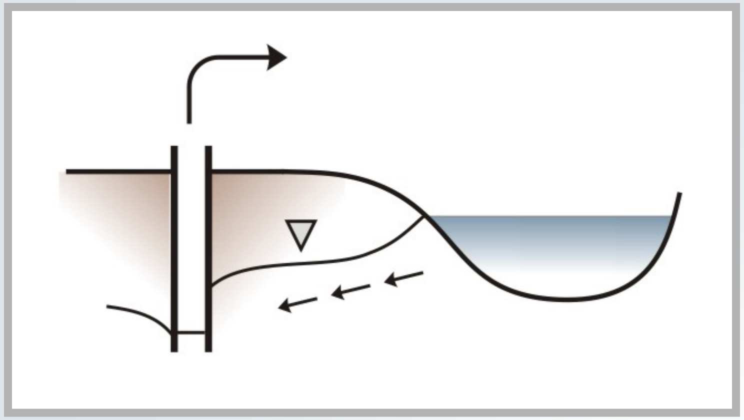
ASTR

Injection borehole, Windhoek, Namibia. Treated surface water is injected into into a quartzite aquifer and recovered from nearby boreholes.



Infiltration basin

Infiltration basin, Phoenix, Arizona, USA. Water from the Colordo River is diverted into a number of shallow infiltration basins.



Bank Filtration

Maximising river bank storage and filtration

South Korea. River water is induced to flow through the alluvium to wells located alongside the river.

Photo: R Murray

International examples

- **Peace River, Florida, USA**: 21 ASR boreholes, ~ 68 000 m^3/day in a limestone aquifer
- **Kerrville, Texas, USA**: The implementation cost for the ASR project is ~US $3M, compared with $30M for off-stream reservoir construction
- **The Netherlands**: Amsterdam receives 60 % of its drinking water from artificial recharge in dune fields
- **Australia**: Mt Gambier - over 100 years of operation
- **Germany**: 15 % of the country’s drinking water is from artificial recharge
- **Israel**: 400 Mm^3 off treated waste water was recharged over 5 years
- **Sweden**: artificial recharge provides about 50 % of total groundwater use

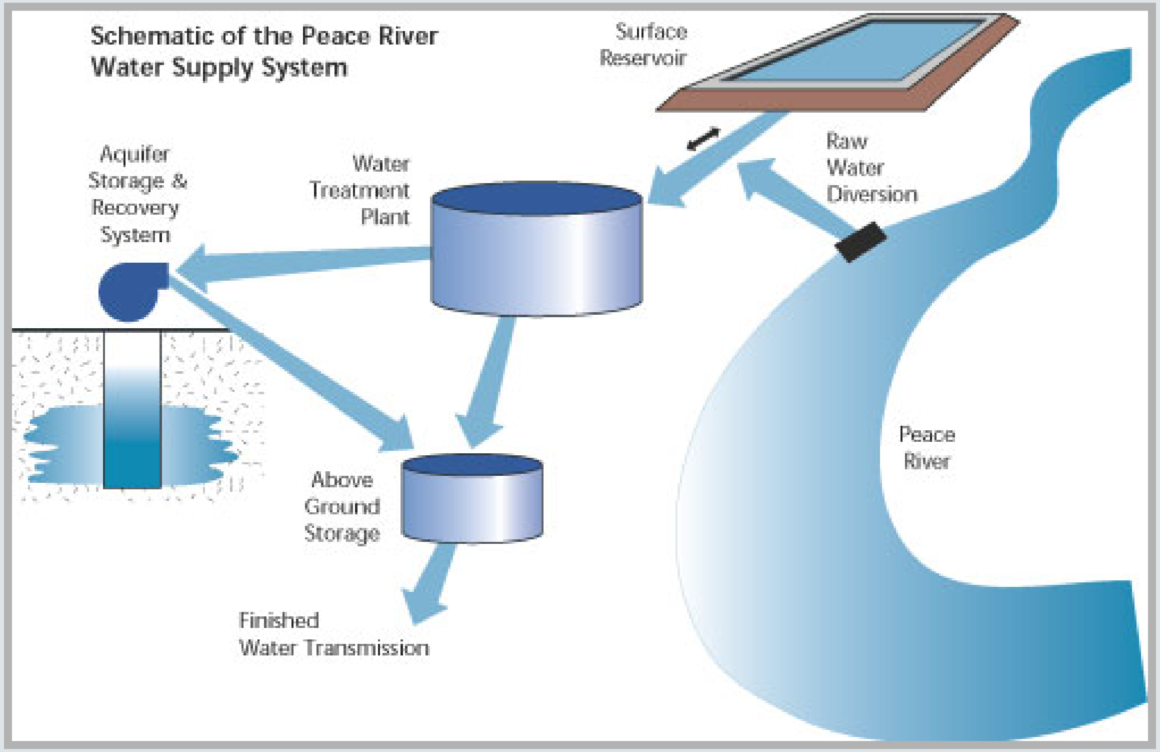
ASR schemes in the USA

1985: 3 ASR wellfields
2005: 72 ASR wellfields and about 100 in various stages of development

Peace River

Large-scale Borehole Injection

- Large-scale artificial recharge in a brackish limestone aquifer
- Aquifer has some similarities to South Africa's dolomites
- Injection and recovery from the same boreholes (ie ASR scheme)
- Purpose:
  - Primary goal: Seasonal storage
  - Secondary goal: Water banking



Water is treated to domestic standards prior to injection

Peace River continued…

- Aquifer: Two limestone aquifers confined by overlying low-permeability formations:
  - Upper: 122 – 152 m deep (30 m thick)
    - Transmissivity: 450 m^2/day; storativity: 0.0004
  - Lower: 174 – 274 m deep (100 m thick)
    - Transmissivity: 560 m^2/day; storativity: 0.0001
- Water quality:
  - Recharge water (average):
    - Conductivity: 47 mS/m
    - Alkalinity (as $CaCO_3$, mg/L): 50
  - Groundwater:
    - Conductivity: 122 mS/m
    - Alkalinity (as $CaCO_3$, mg/L): 143

Peace River continued…

- Injection and recovery capacities per borehole:

  2000 – 4000 m^3/day (23 – 36 L/s)

- In the main ASR area, a storage volume of 6 400 Mm^3 has been developed over 19 years of operation
- History:
  - 1985: 2 ASR boreholes ~6 000 m^3/day (70 L/s)
  - 1988: Additional 4 ASR boreholes ~18 000 m^3/day (210 L/s)
  - 2005: 21 ASR boreholes ~ 68 000 m^3/day (790 L/s)
- Maintenance: Seasonal back-flushing of boreholes

Peace River continued…

By deferring or eliminating the need for surface reservoir expansion and relying instead on sub-surface storage, this system is expected to meet regional water demands at less than half the capital cost of other water supply alternatives.

Elevated arsenic concentrations in some areas have led to post treatment and research into assessing ways of minimising these concentrations. In other areas, the arsenic concentrations have decreased.

Typical ASR borehole (Las Vegas)

Photo: R Murray


Photo: R Murray

Kerrville, Texas, USA

Medium-scale ASR

- Aquifer: Sandstone and conglomerate comparable to South African hard-rock aquifers (although Kerville's sandstones do have primary porosity)
- Transmissivity: 90 m^2/day; storativity: 0.0007
- Water is treated to domestic standards prior to injection
- Groundwater and injectant are of similar quality
- Purpose:
  - Primary goal: Seasonal storage
  - Secondary goal: Water banking

Kerrville continued…

- Injection and recovery capacities per borehole: 3000 – 6000 m^3/day (35 – 70 L/s)
- Storage:
  - Currently the ASR wellfield has 1.6 Mm^3 in storage
  - Target storage volume is 5.7 Mm^3 to achieve drought security and to meet the projected 2040 demand.
- The implementation cost of the scheme to meet this target is ~US $3M, compared with $30M for off-stream reservoir construction

The Netherlands

A history of successful implementation

- Artificial recharge started on a small scale in 1940
- Surface water infiltration unconfined primary aquifers to counteract declining water levels and prevent sea water intrusion
- The volume of artificial recharge water in 1990 was 180 Mm^3
- This is 22 % of the country's total water demand
- Amsterdam receives 60 % of its drinking water from artificial recharge in dune fields
  - 40 recharge ponds covering 86 ha
  - infiltration rates are in the order of 20 cm/day
  - average travel time in the sub-surface is 90 days
  - the water is recaptured through drains and open canals located about 60 m from the infiltration basins
  - borehole injection is also being used to transfer water to the deeper aquifers.

Australia

Leading research into the use of poor quality source water

- Mt Gambier in Southern Australia
  - over 100 years of opertion
  - more than 300 drainage wells
  - artificial recharge of 3.6 - 6.2 Mm^3/a
- Leading research in the use of poorer quality water such as stormwater, stream water and reclaimed water
- In 2002, 25 ASR projects were in operation, under development or being investigated
- Burdekin Delta infiltration scheme: artificial channels and recharge pits
  - operating since the mid 1960s
  - purpose: sugarcane irrigation & prevent salt water intrusion
  - 2 000 production boreholes abstracting 210 to 530 Mm^3/a

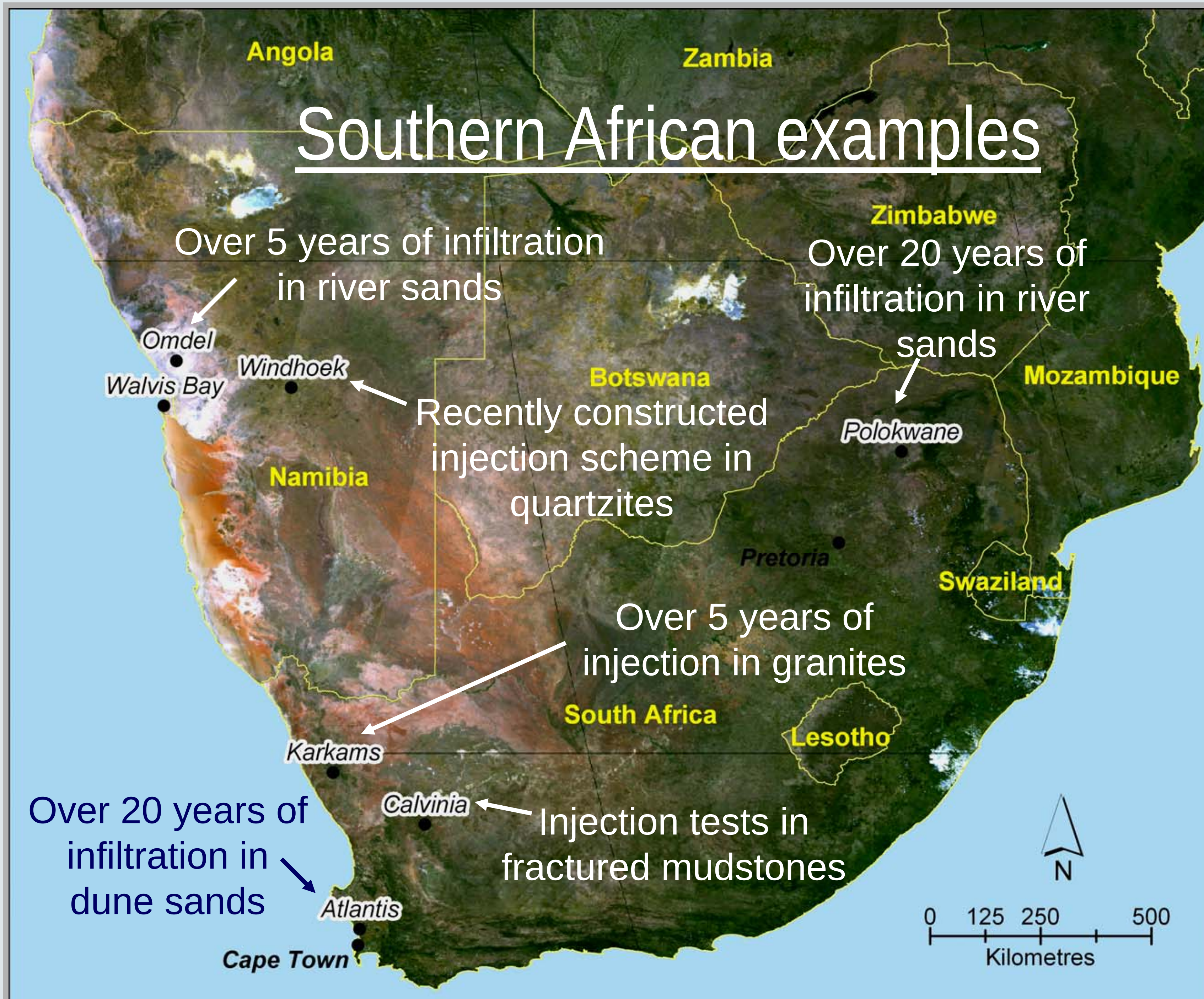
ASR borehole, Adelaide, Australia

Treated waste water is injected into a confined limestone (non-karstic) and sand aquifer and later used for irrigation

Other international examples

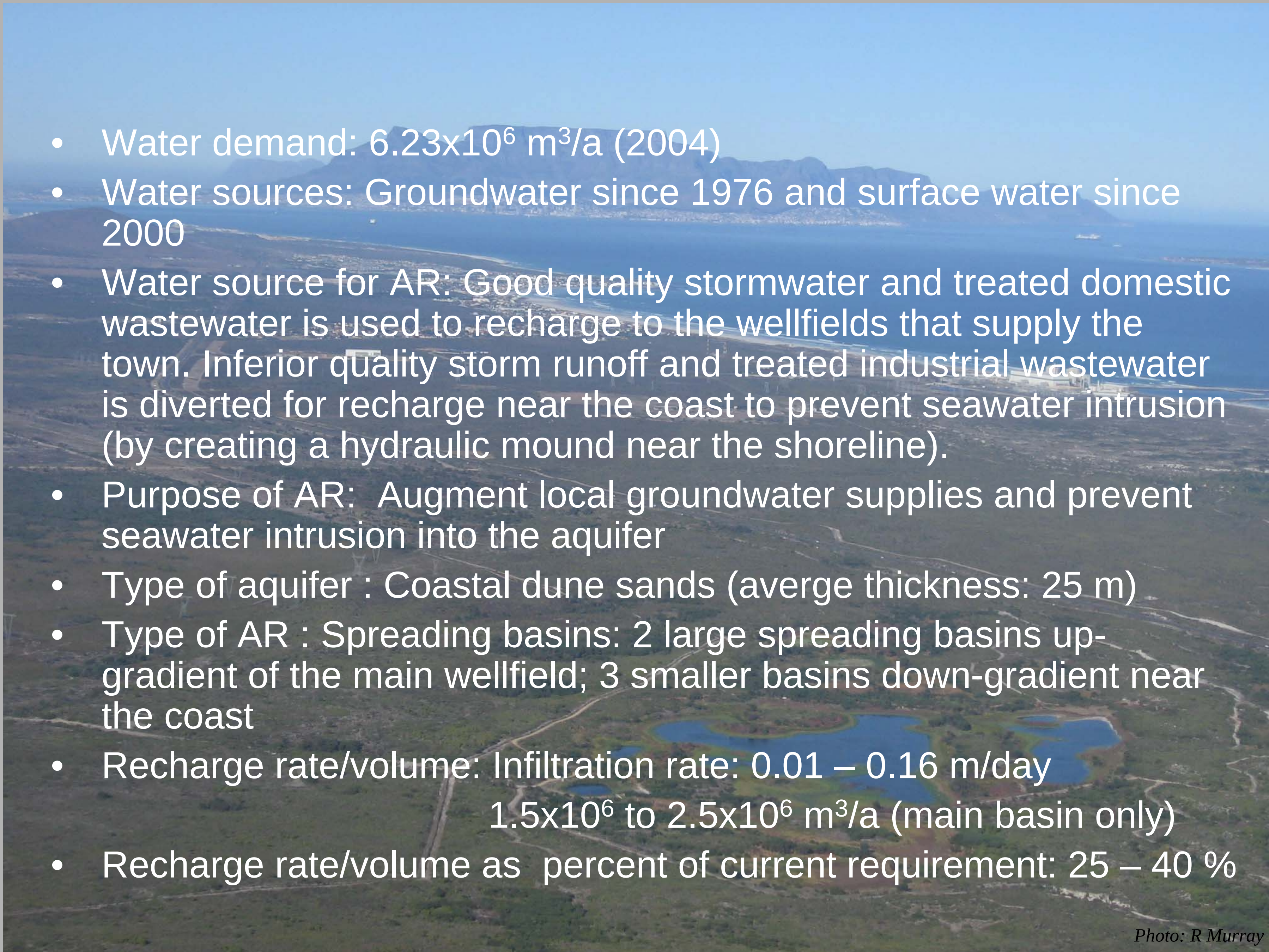
- **Germany**:
  - about 15 % of Germany's drinking water is produced through artificial recharge
  - mostly bank filtration along major rivers
  - artificial recharge has been in operation in Berlin since 1916 and Hamburg since 1928
- **Israel**:
  - Dan Region Project uses the aquifer media for treating reclaimed wastewater from Tel Aviv
  - over five years a total of 400 Mm^3 was supplied for this purpose
- **Sweden**:
  - infiltration basins have been operational since 1898
  - 1 800 artificial recharge schemes
  - artificial recharge provides about 50 % of total groundwater use

Southern African examples



Atlantis

Infiltration in dune sands



- Water demand: 6.23x10^{6} m^{3}/a (2004)
- Water sources: Groundwater since 1976 and surface water since 2000
- Water source for AR: Good quality stormwater and treated domestic wastewater is used to recharge to the wellfields that supply the town. Inferior quality storm runoff and treated industrial wastewater is diverted for recharge near the coast to prevent seawater intrusion (by creating a hydraulic mound near the shoreline).
- Purpose of AR: Augment local groundwater supplies and prevent seawater intrusion into the aquifer
- Type of aquifer : Coastal dune sands (averge thickness: 25 m)
- Type of AR : Spreading basins: 2 large spreading basins up-gradient of the main wellfield; 3 smaller basins down-gradient near the coast
- Recharge rate/volume: Infiltration rate: 0.01 – 0.16 m/day

  1.5x10^{6} to 2.5x10^{6} m^{3}/a (main basin only)
- Recharge rate/volume as percent of current requirement: 25 – 40 %

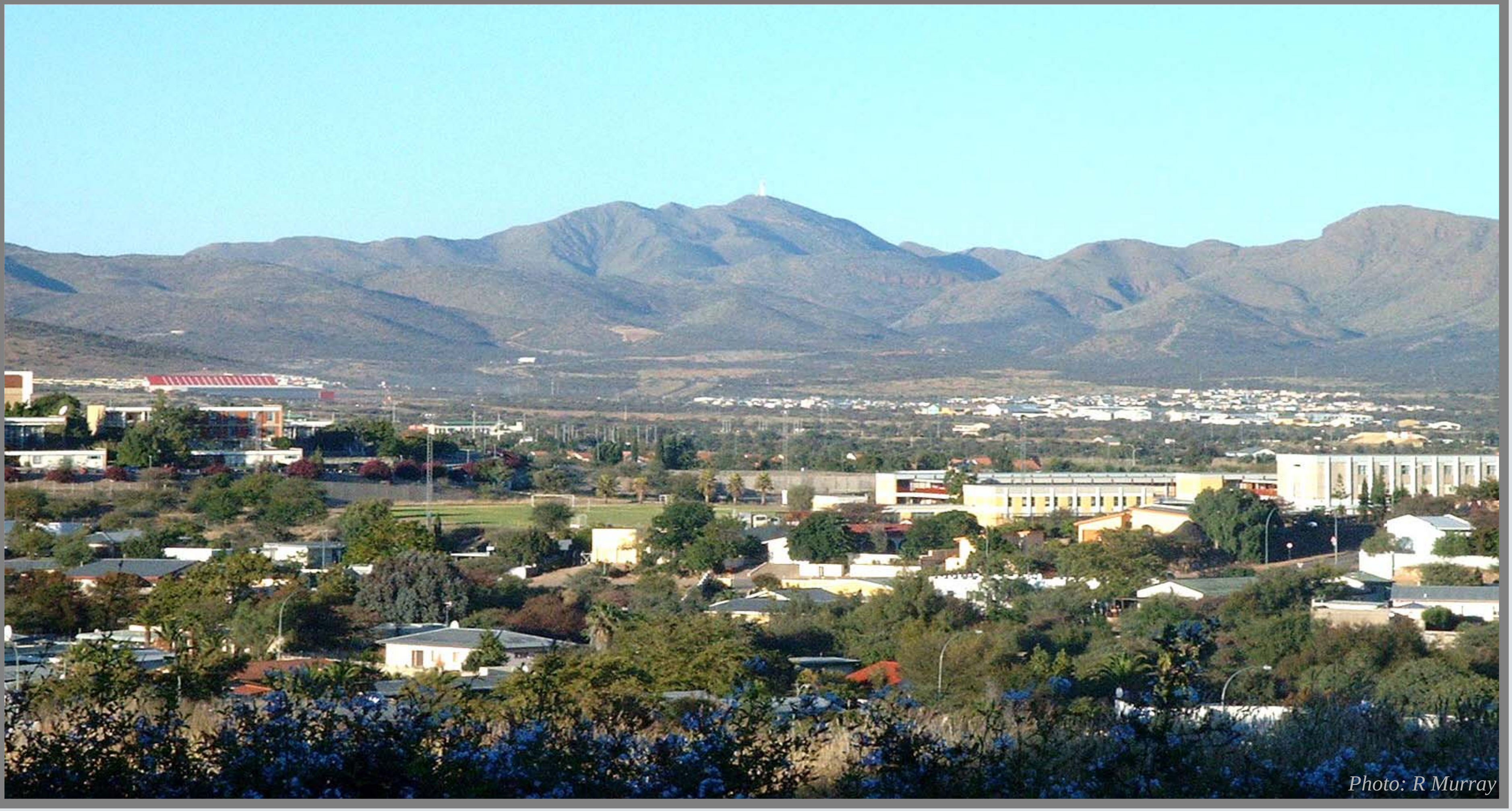
Photo: R Murray

Atlantis continued…

- Quality of water source:
  - Source for main basins: EC 60 – 95 mS/m; DOC 8 – 10 mg/L
  - Source for coastal basin: EC 100 – 150 mS/m; DOC > 10 mg/L
- Quality of recovered water: EC 60 – 100 mS/m; DOC 2 – 7 mg/L
- Key lessons:
  - Artificial recharge is a reliable water augmentation option when coupled with appropriate engineering design and control
  - For optimal artificial recharge implementation, infrastructure planning for urban stormwater runoff and wastewater collection should form part of urban planning design
  - Separation of domestic and industrial wastewater is essential as domestic wastewater can be treated and recycled indirectly
  - Environmental protection of the recharge zone and general catchment management is needed to maintain water quality
  - Regular and scheme-specific monitoring must be undertaken for effective artificial recharge management

Windhoek

Borehole injection in quartzites



The mountains in the background form the prime aquifer unit – the Auas Formation quartzites


Abstraction borehole converted to an injection and abstraction site
Photo: R Murray

Windhoek continued…

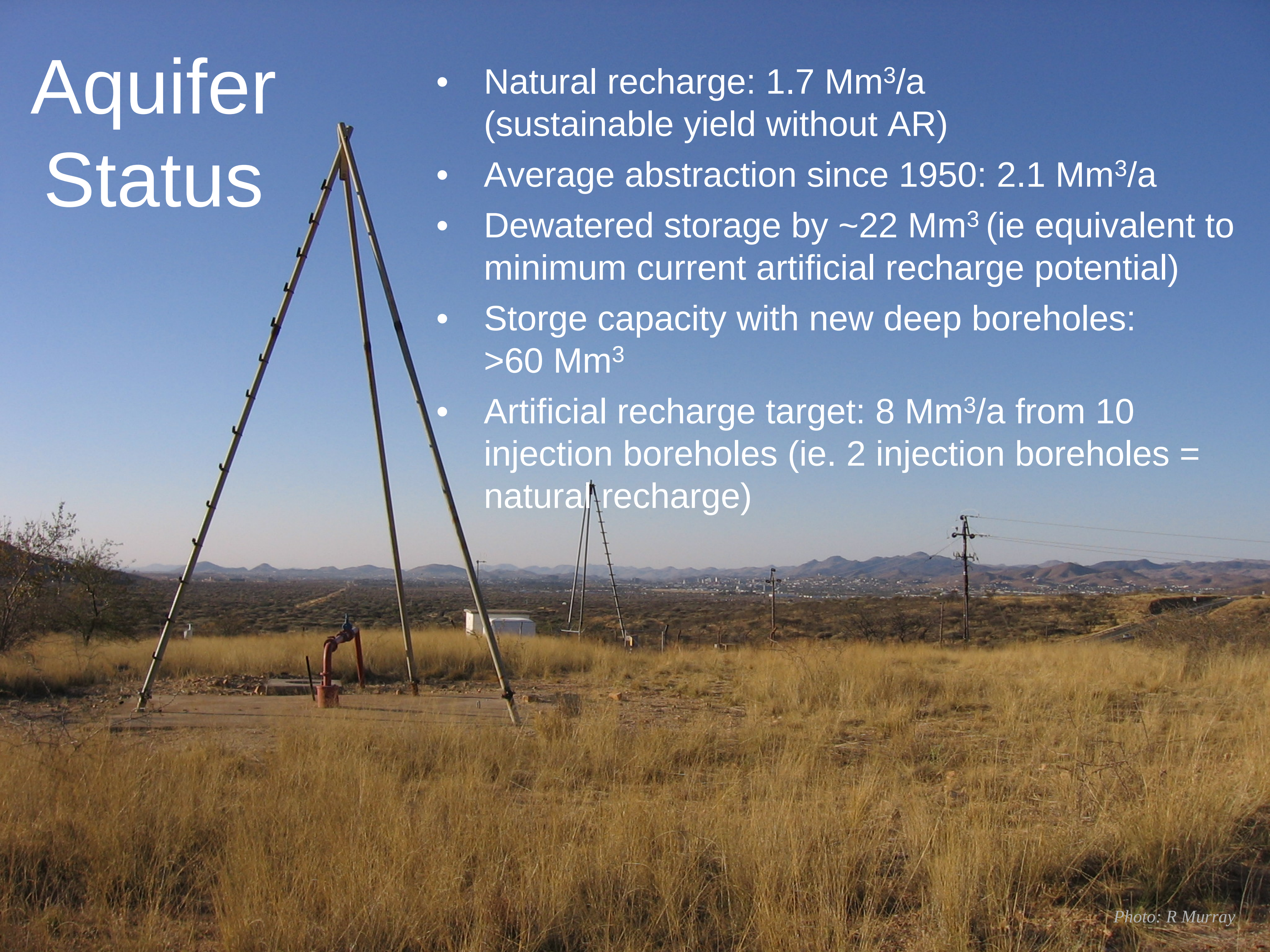
- Water demand: 21 Mm^3/a (2007)
- Water sources: Dams (main source); reclaimed water; groundwater from the Karst area in northern Namibia and the Windhoek aquifer
- Water source for AR: Mainly dam water
- Purpose of AR:
  - Main purpose: Water banking to provide security of supply during droughts
  - Secondary aims: Meet seasonal peak demands and provide emergency supplies in case of problems with the other bulk supplies or the treatment works (recharged water can be supplied directly into the distribution system without treatment).
- First AR activity: 1st injection test in 1996
- Recharge rate/volume:
  - 2009: 2 Mm^3/a (9.5% of current reuirements)
  - Planned: 8 Mm^3/a (38% of current requirements)

Windhoek continued…

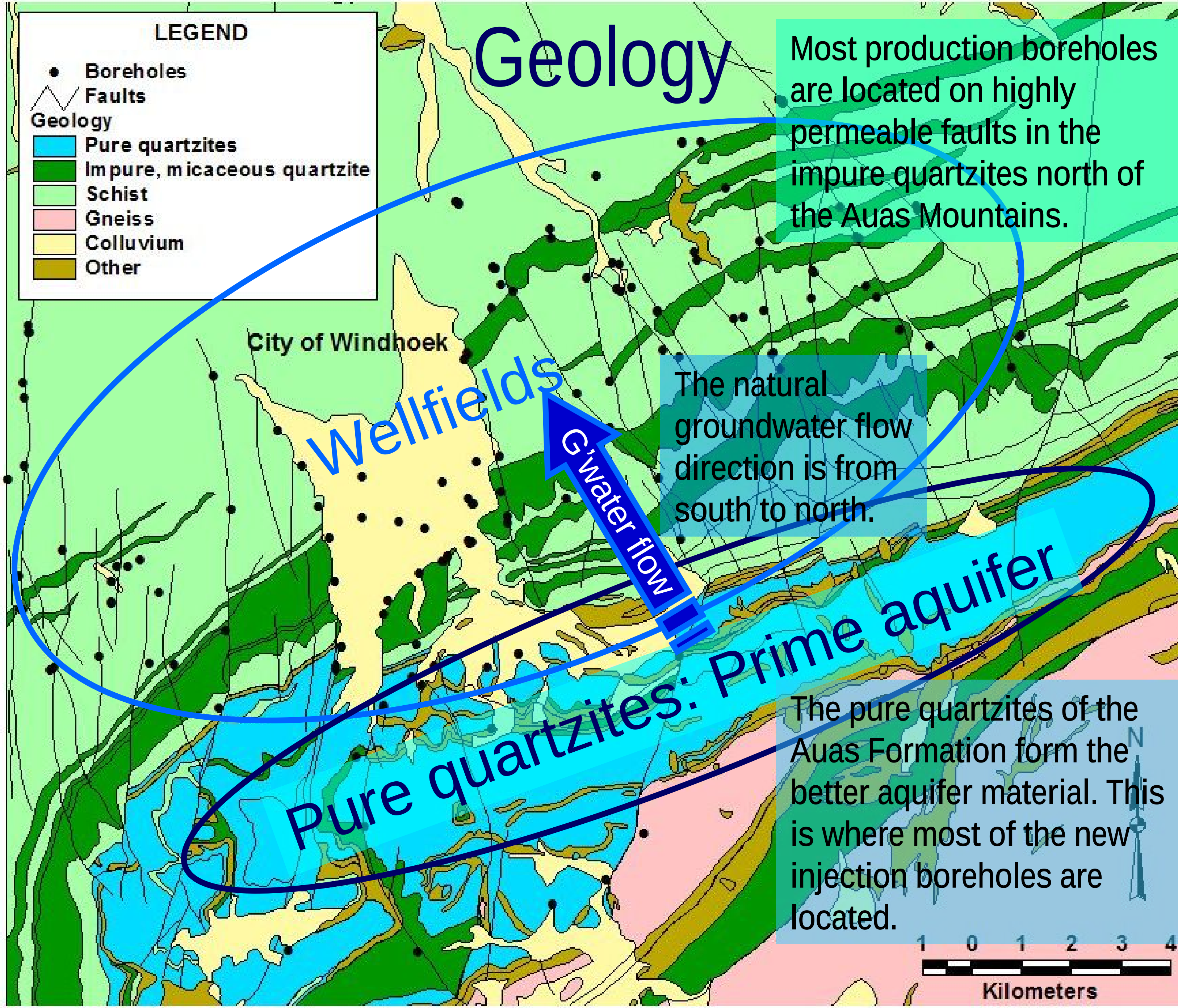
- Quality of water source: EC: ~50 mS/m; Dissolved Organic Carbon (DOC): ~4 mg/L
- Quality of water abstracted from the aquifer:
  - Without AR: EC: ~60 mS/m; DOC: <2 mg/L
  - With AR: Long-term, large-scale sub-surface storage has not yet taken place; water quality should improve as injectant is drinking quality water
- Comments: The City of Windhoek has opted to implement artificial recharge prior to other options, such as transferring water from the Kavango River. This is because artificial recharge is the most cost-effective option for the city, and it will provide the water supply security needed. It is the first of its kind in the world – large-scale injection in a fractured aquifer, and it should pave the way for similar schemes in highly complex geological settings.

Aquifer Status

- Natural recharge: 1.7 Mm^3/a (sustainable yield without AR)
- Average abstraction since 1950: 2.1 Mm^3/a
- Dewatered storage by ~22 Mm^3 (ie equivalent to minimum current artificial recharge potential)
- Storge capacity with new deep boreholes: >60 Mm^3
- Artificial recharge target: 8 Mm^3/a from 10 injection boreholes (ie. 2 injection boreholes = natural recharge)



Geology

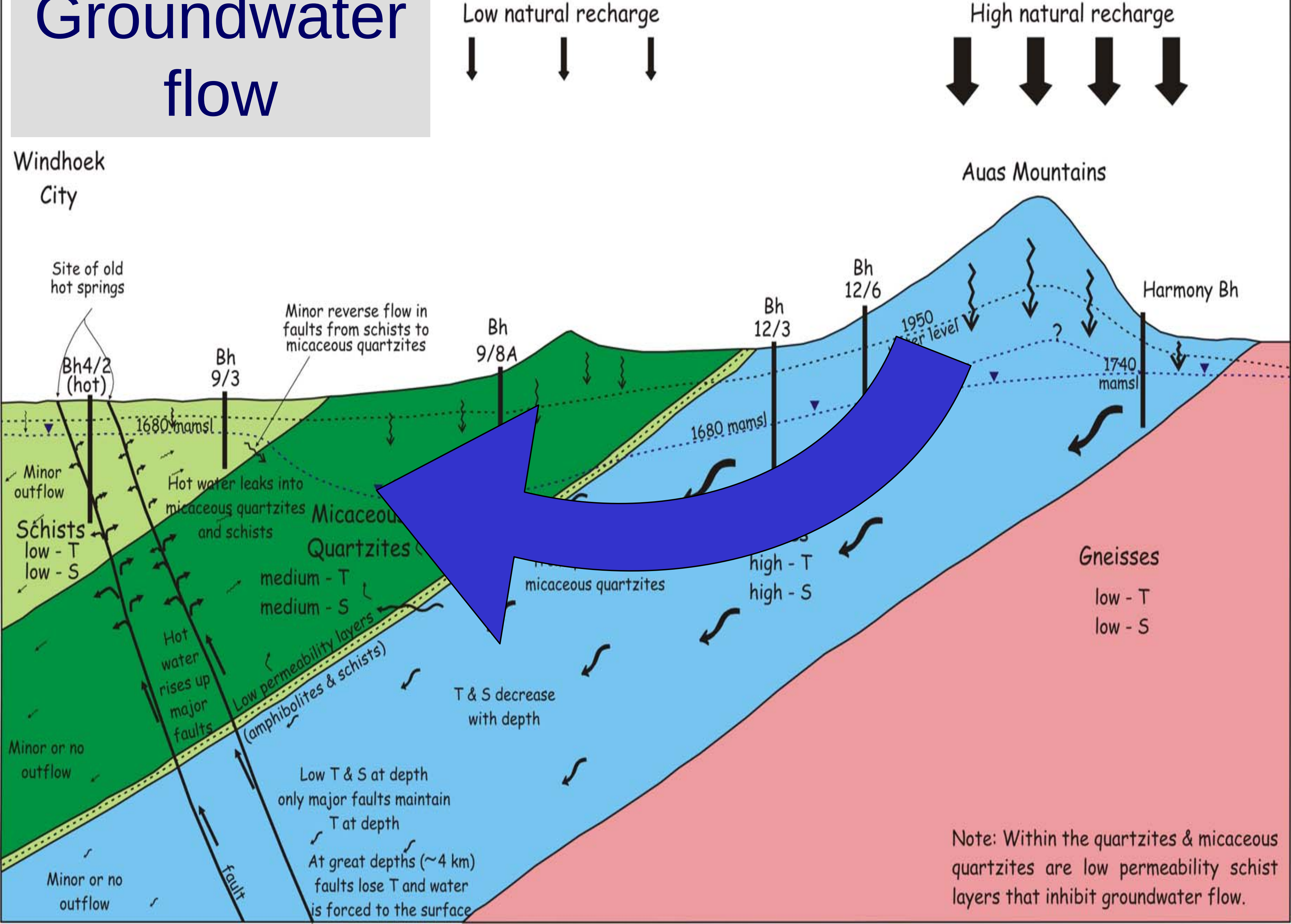


Most production boreholes are located on highly permeable faults in the impure quartzites north of the Auas Mountains.

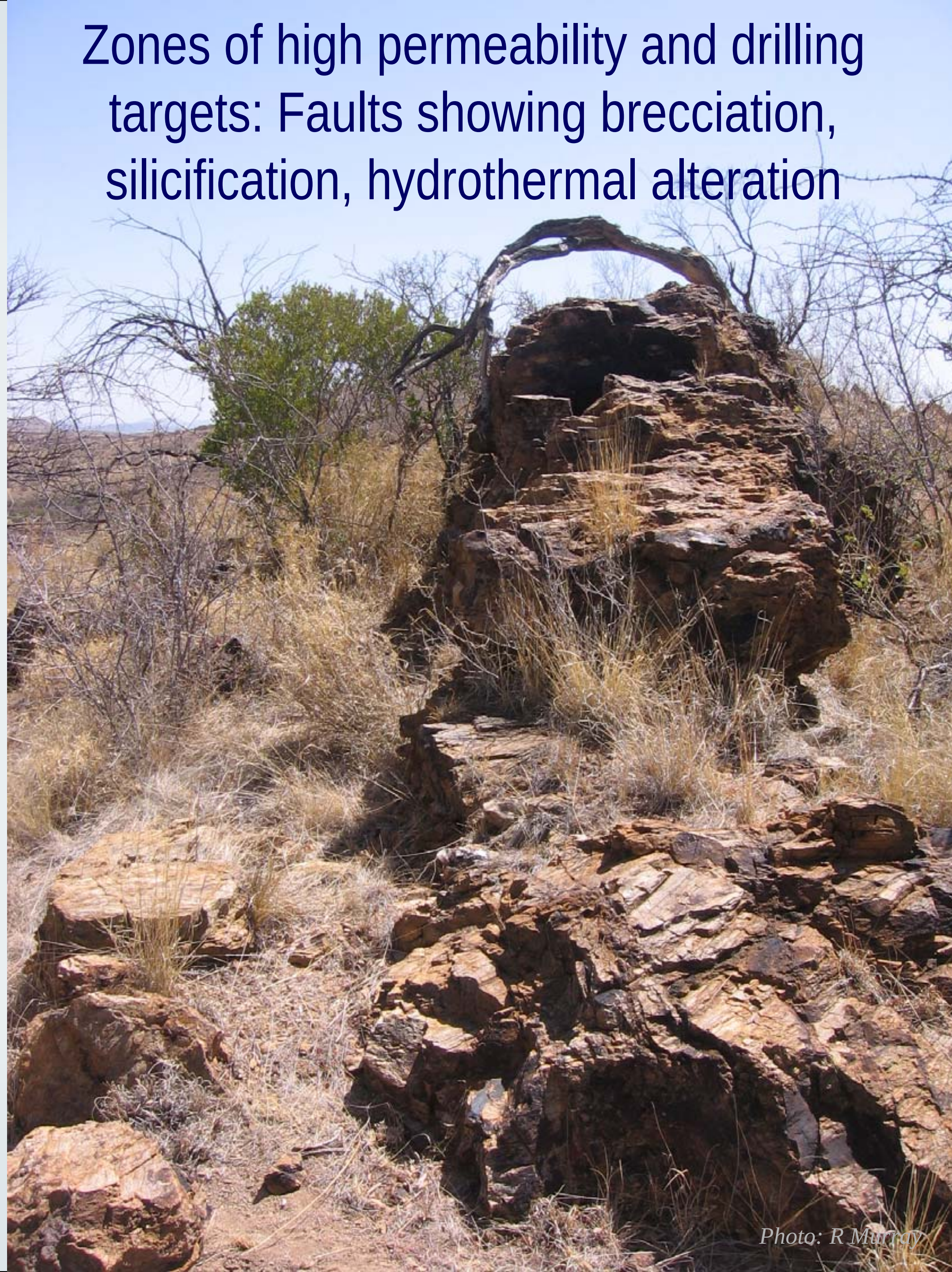
The natural groundwater flow direction is from south to north.

The pure quartzites of the Auas Formation form the better aquifer material. This is where most of the new injection boreholes are located.

Groundwater flow

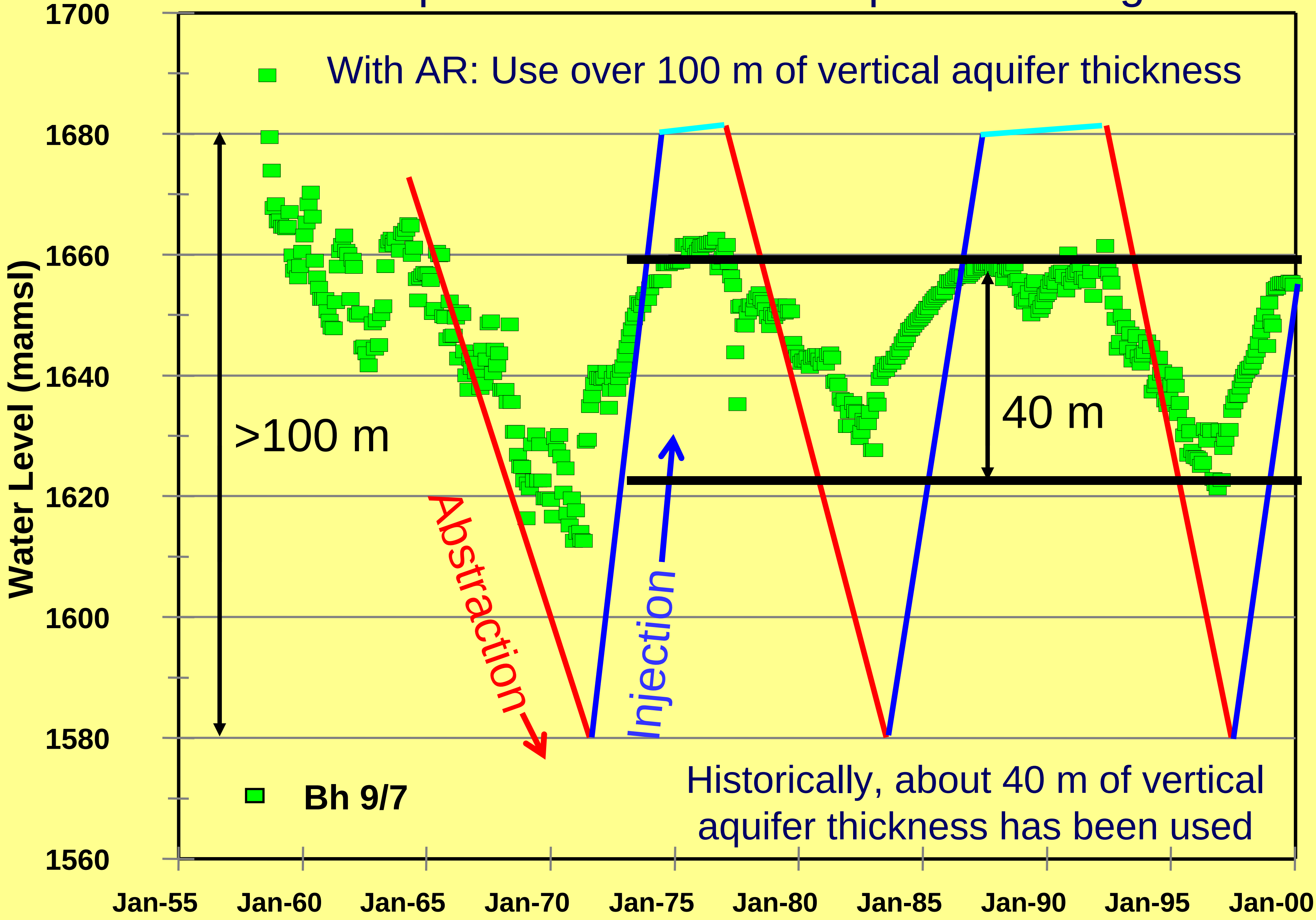


Zones of high permeability and drilling targets: Faults showing brecciation, silicification, hydrothermal alteration




Fault breccia
Photo: R Murray

Concept: Use more of the aquifer's storage



Deep drilling programme: 2005 - 2008

Aim: To abstract from greater depth (use more of the aquifer's storage) and to rapidly replenish the aquifer after large-scale abstraction

- Drilled 10 new deep recharge & abstraction boreholes
- Average depth: 350 m
- Average yield: 45 L/s

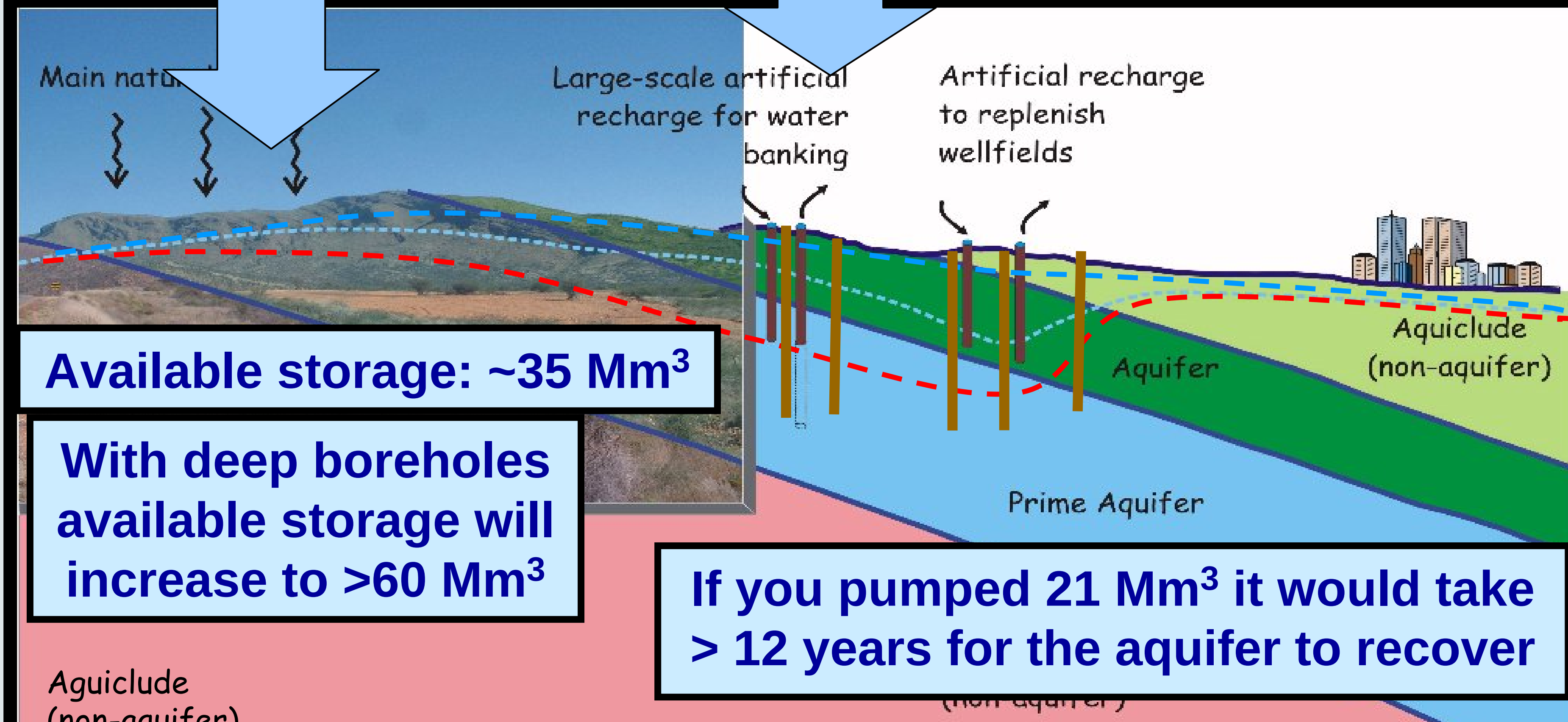
New deep abstraction borehole with existing injection borehole in the background

Value with AR

City's water use:
~ 21 Mm^3/year

Natural replenishment
1.7 Mm^3/year
(~ 8% of demand)

Borehole injection
8 Mm^3/year
(~ 38%)



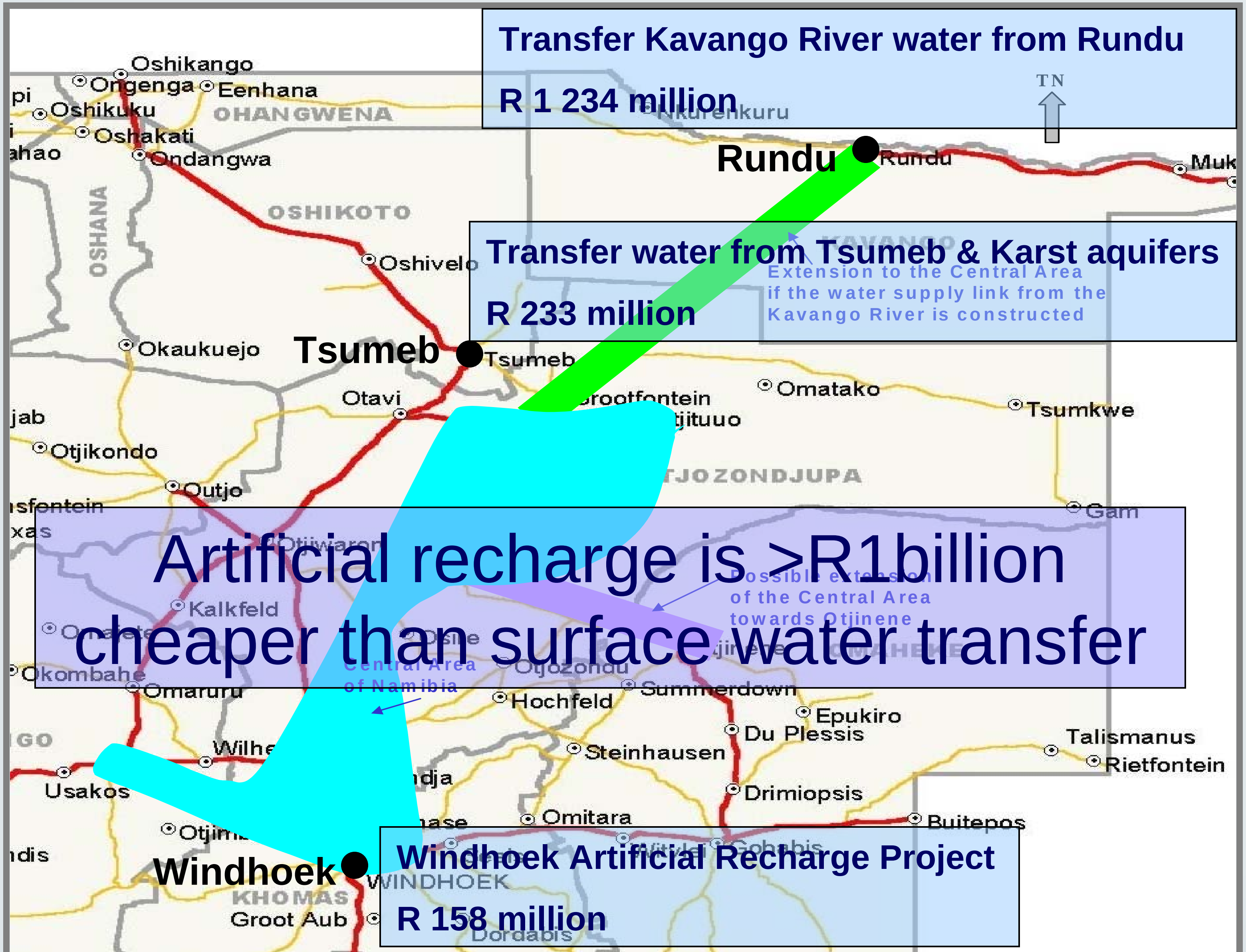
Available storage: ~35 Mm^3

With deep boreholes available storage will increase to >60 Mm^3

If you pumped 21 Mm^3 it would take > 12 years for the aquifer to recover

With AR it should take 2.2 years for the aquifer to be replenished

Capital cost of water supply options



Cost Comparison - 2004

Options costed in the same way taking capital and operational costs into account

Scheme	URV (R/m^3)
Groundwater	1.25
WDM	1.26
Surface sources (bulk)	4.11
Reclaimed water	5.55
Windhoek AR	6.72
Tsumeb & Karst III	16.88
Kavango River	141.27

URV : Unit Reference Value
WDM: Water Demand Management

The AR scheme is >20 times cheaper than taking water from the Kavango River which flows into the Okavango Delta

Injection borehole

Source water is fully treated drinking water – mostly from the 3 supply dams plus a small portion of reclaimed water

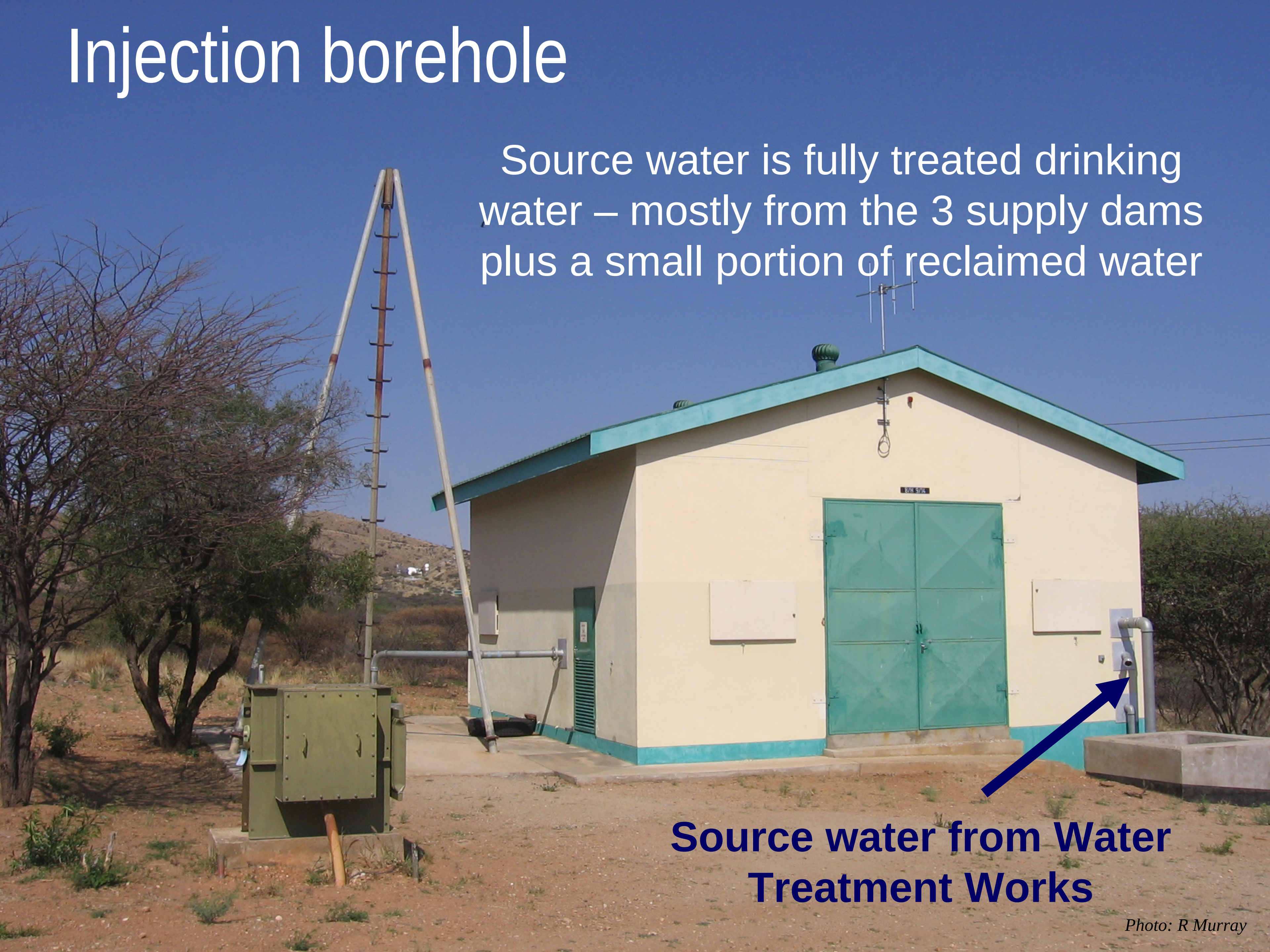


Photo: R Murray


The water is further treated to ensure the Dissolved Organic Carbon (DOC) is less than 4 mg/L. This is to minimise the potential for bacterial growth in the aquifer. The chlorination is to disinfect against the bacteria in the carbon column prior to injection.
Granular Activated Carbon, Filtration & Chlorination
Photo: R Murray

Injected into the borehole

Success criteria

1. The need for an artificial recharge scheme
2. The source water
3. Aquifer hydraulics
4. Water quality (including clogging)
5. The artificial recharge method and engineering issues
6. Environmental issues
7. Legal and regulatory issues
8. Economics
9. Management and technical capacity
10. Institutional arrangements

1. The need for an artificial recharge scheme

Sometimes people think AR will solve their problem whereas what's needed is better aquifer management

Usually this means :

- decrease pumping rate (L/s) of existing boreholes and increase pumping hours (hrs/day) to get the required daily volumes
- …and monitor the water levels in pumping and nearby non-equipped boreholes

Only after existing boreholes, wellfields and aquifers are being managed properly is it possible to establish whether AR is really needed

AR is needed when….

- Abstraction already exceeds recharge and lateral inflows to the aquifer/ wellfield
- You plan to increase abstraction to be greater than recharge and lateral inflows
- You want to treat water by filtering it in the aquifer or by storing it (increasing the residence time) in the aquifer

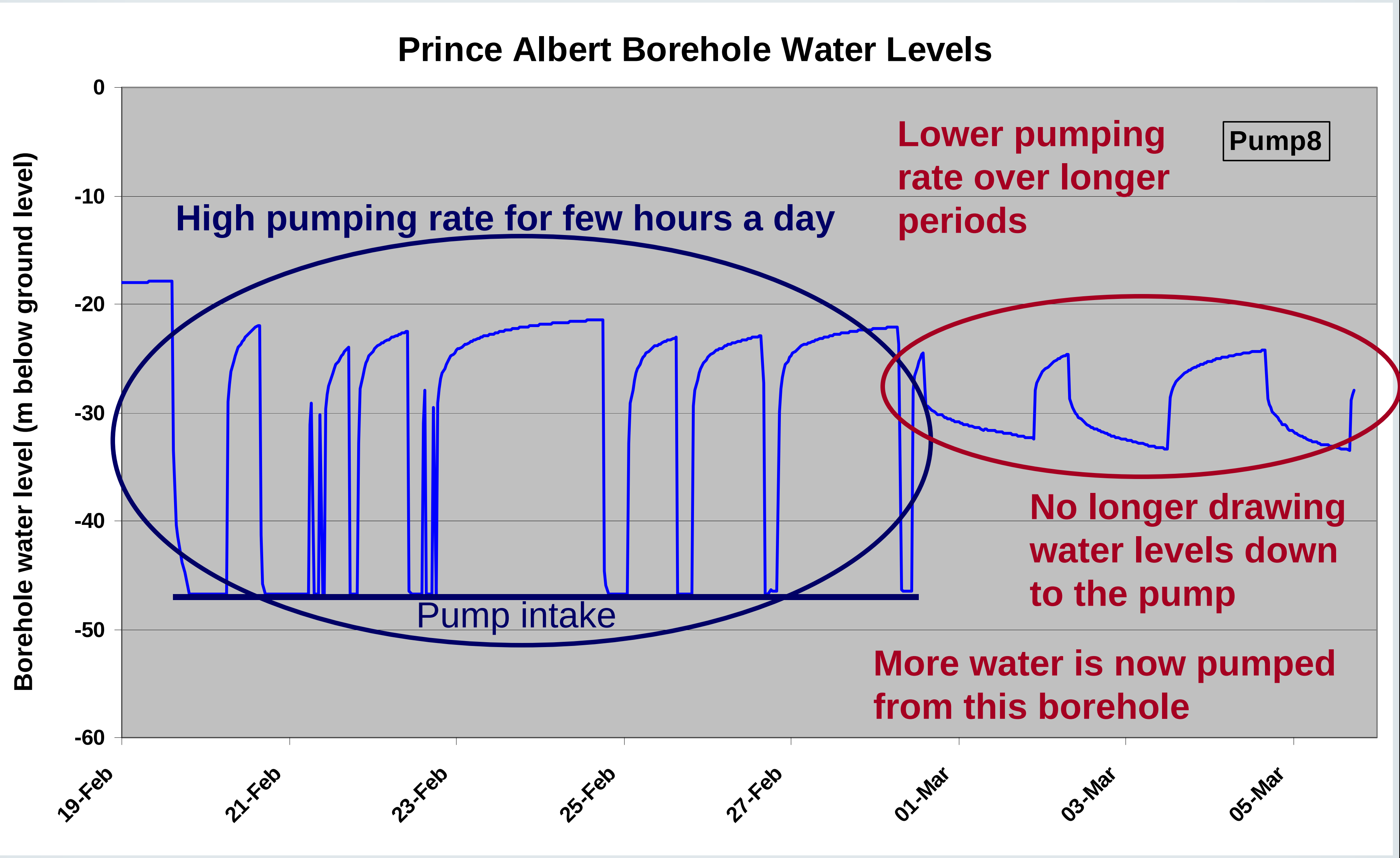
Some key questions:

- When water is available for AR (usually in the rainy season) is the aquifer not already full?
- If you reduced borehole pumping rates and increased the pumping hours to get a more even drawdown in the aquifer would you need artificial recharge?
- If you used more of the aquifer’s storage by drawing water levels down deeper prior to artificial recharge, would there be any negative environmental impacts such as the drying up of springs?

Example: Prince Albert

- Until 2005, Price Albert, a town in the southern Karoo, always had water shortages and restrictions in summer
- Since modifying their 9 production boreholes to pump at the correct rates (lower pumping rates and longer hours) they have not experienced water shortages
- Artificial recharge may still be needed to provide security against droughts. The aim is to be able to rapidly replenish the aquifers (to “full” levels) prior to each summer if the groundwater levels have not naturally recovered by the onset of summer (then they will fill the aquifers using borehole injection).

Prince Albert: The water level in Pump 8 was regularly drawn down to pump intake until it was set at the correct pumping rate



2. The source water quantity & reliability

- Ensure that the volumes of water available for recharge will meet the aims of the scheme
- Examples:
  - **Atlantis** – ongoing supply of treated waste water for recharge purposes
  - **Kharkams** – Aim: opportunistic AR whenever water is available (ie when the ephemeral river flows water is diverted to the injection boreholes)
  - **Windhoek**: Water is safer in the aquifer than in the dams (lower water losses), ie aim to keep the aquifer full by recharging it whenever it is not being used

3. Aquifer hydraulics

Key questions:

1. Will the recharge water be able to flow into the aquifer (ie is it sufficiently permeable)?
2. Will the aquifer have sufficient space to accept the water? If it’s a confined aquifer, is the pressure system such that it will accept and store the water?
3. Will the water be recoverable? Can you recover it from the point of recharge; can you intercept it down the hydraulic gradient? How long can it be stored and still be recoverable?

Examples:

- Windhoek
  - Shist rocks form a hydraulic barrier against which recharged water “dams up”. The losses from the aquifer are negligible.
- Plettenberg Bay
  - There is potential to recharge the Table Mountain Group sandstones
  - The unsaturated zone is about 100 m thick (ie very high storage potential)
  - The concern is that the recharged water will be lost to the sea
  - AR needs to be tested to establish losses.

Examples continued…

High injection rate and high storage potential

Calvinia, Northern Cape

- Breccia plug in Karoo shales
- Injection potential of over 20 L/s per borehole
- Porosity:
  - 20 % up to 182 m
  - 10 % from 182 – 220 m
  - 6 % from 220 – 255 m
  - Ie better than many sand aquifers

AR potential sufficient to supply the town's needs for 3 months/year

Low injection rate and low storage potential

Kharkams, Northern Cape

- Fractured granites
- Injection rate of ~ 0.7 L/s
- Aquifer has low storage capacity and can be filled at this injection rate if the river flows for a few months of the year.
- With AR, the borehole's annual yield increased three-fold.

Even though it is not a high-yielding aquifer, with AR it can be used to its maximum potential.

4. Water quality

The following key factors need to be considered:

- Groundwater quality
- Blending of source water and groundwater
- Water-rock interactions
- Clogging
- Pre-treatment prior to AR

• *Groundwater quality*

- Recharged water should generally be better quality than natural groundwater (ie AR should maintain or improve natural groundwater)
- Converting saline aquifers to useable water resources is becoming increasingly popular – "brack" aquifers in South Africa could be recharged with "fresh" water to make them useable
- Critical to obtain a comprehensive assessment of natural groundwater quality

• *Blending of source water and groundwater*

- Unlike groundwater, surface water used for recharge is usually saturated with oxygen
- The quality of blended water will be influenced by the quality of the two wates and the blending ratios
- Key *in situ* measurements:
  - Oxidation-reduction potential (Eh) of groundwater (especially when iron and mangnese are >0.1 mg/L)
  - Dissolved oxygen of both waters
- An assessment of the final water quality needs to be made

• *Water-rock interactions*

- The aquifer media (sands or rocks) may contain species that are vulnerable to change with the introduction of “new” water and oxygen
- Examples:
  - the oxidation of pyrite increases the sulphate concentration and brings iron into solution
  - Calvinia (Northern Cape): Aresnic is present in the pyrite minerals in the aquifer media. Once oxidised after lowering the water table and injecting with surface water the arsenic entered into solution

Calvinia

Potential for sub-surface storage in a mineralised breccia pipe

Groundwater in the breccia is not fit for drinking:
- high pH (pH 10)
- fluoride (11 mg/L)
- arsenic (0.3 mg/L)

Key question: Will the introduction of surface water dilute the groundwater and bring it to drinking standards? What will the water quality be like after artificial recharge & storage?

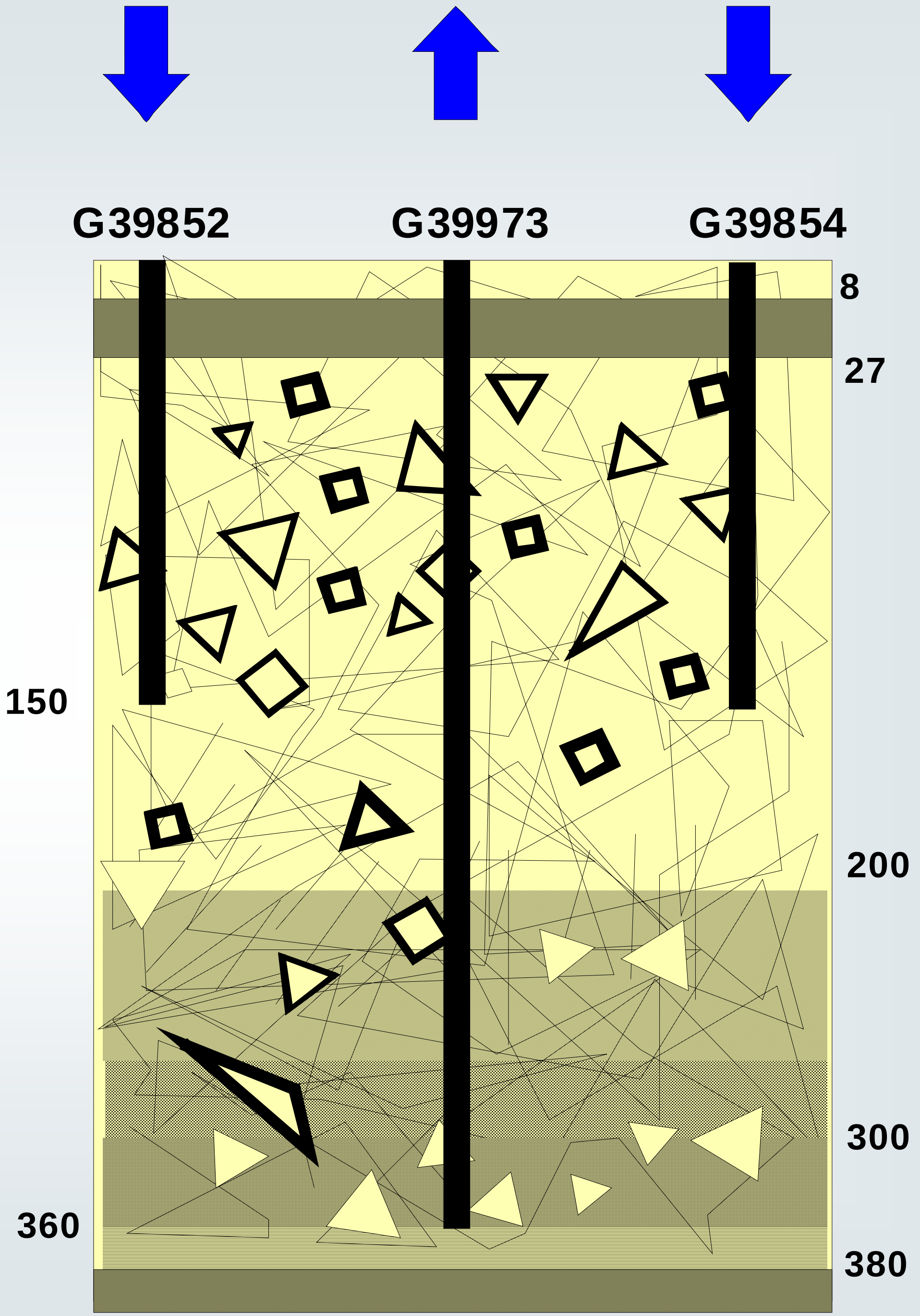
Volumes

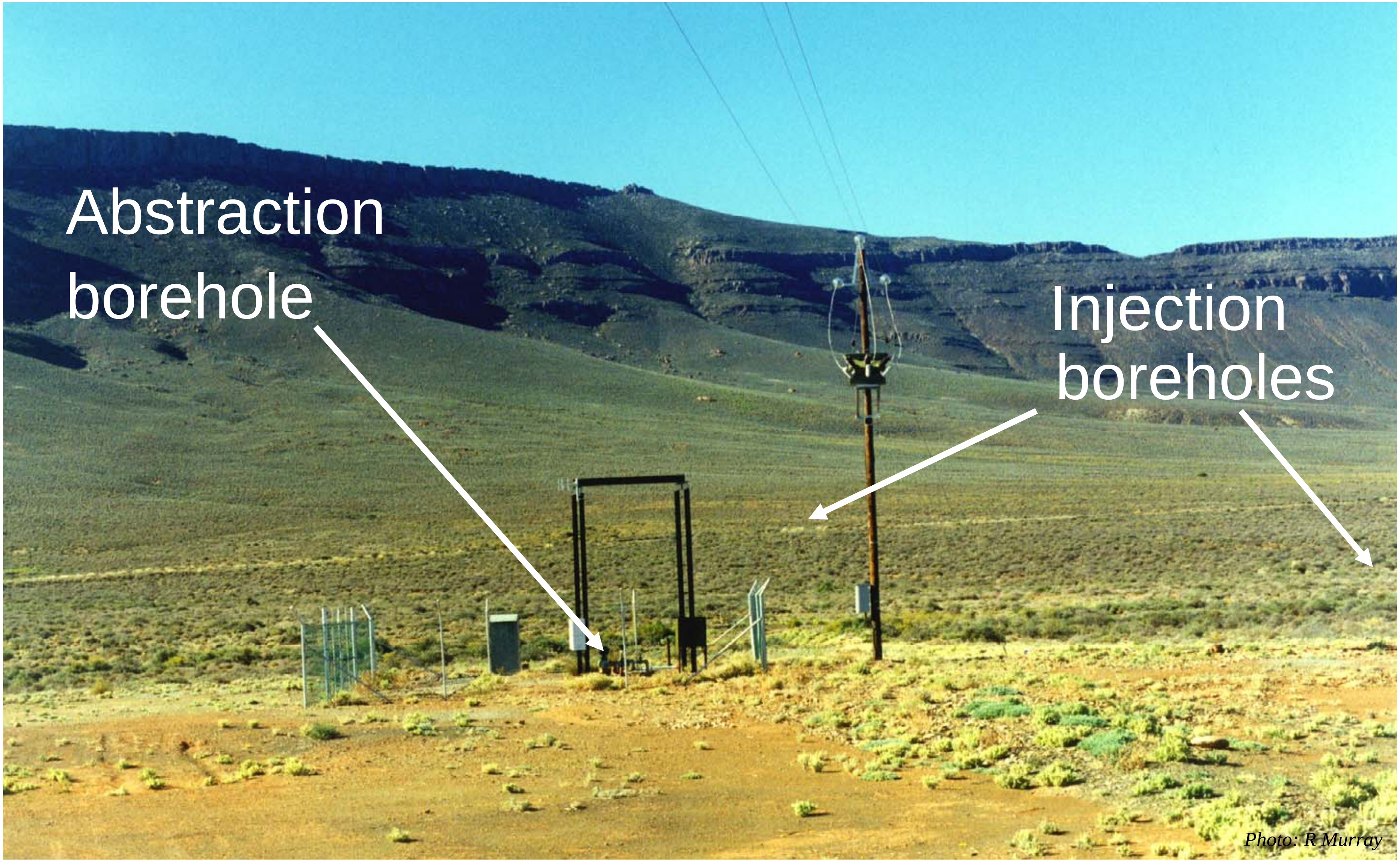
O – 142 m:
48 000 m^3

O – 182 m:
78 – 108 000 m^3

O – 220 m:
94 – 138 000 m^3

Potential to store enough water to supply the town for 3 months



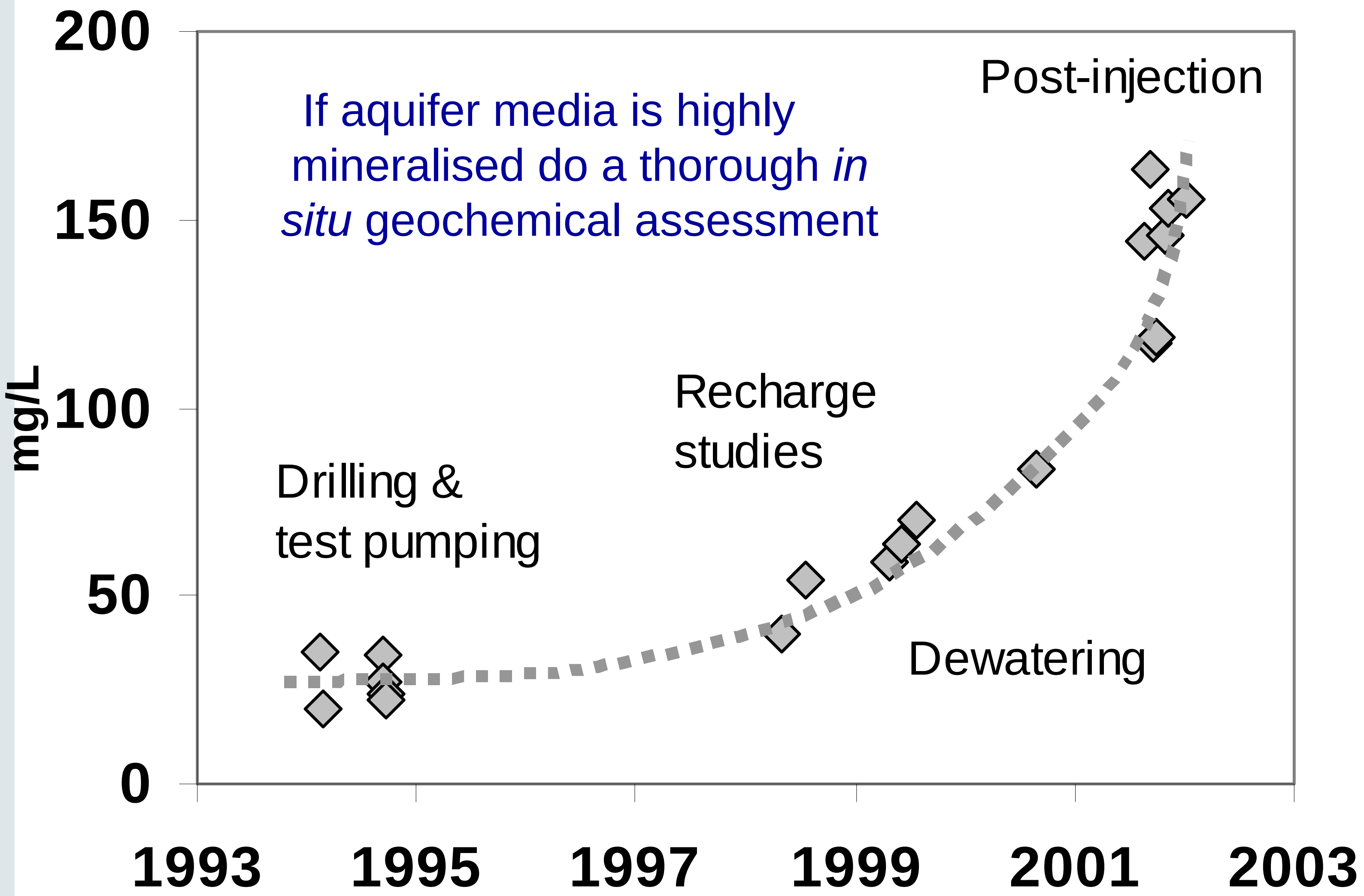

Abstraction borehole
Injection boreholes
Photo: R Murray

- The breccia groundwater is very old (probably over 10 000 years) and has taken a long time to develop this chemistry. It was hoped that, if the poor quality water could be removed and replaced with fresh water, the storage time would not be long enough for the quality to deteriorate.
- Water was pumped out the breccia (48 000 m^3) and replaced with good quality dam water.
- The pH, fluoride and ammonium decreased. Fluoride concentrations in the water can be lowered, since the natural fluoride is predominantly in the groundwater and will be diluted by fresh water over each injection cycle.
- The electrical conductivity, sulphate and arsenic concentrations increased over the short time that the water was stored. This provided a warning that sulphide minerals are being converted to sulphate, dissolving and releasing arsenic and other potentially toxic substances.
- The effect is partly caused by atmospheric oxygen entering the breccia and is very difficult to prevent. Oxygen enters the subsurface when the water table drops each time the breccia pipe is pumped out. Sulphate concentrations have risen since the drilling and test pumping first allowed oxygen into the subsurface and the effect escalated after the injection trials further disturbed the geochemical system.
- Arsenic is released simultaneously with the sulphate, since it comes from the same sulphide minerals.

Water quality – before & after

Units: mg/L	Breccia (pre-AR)	Dam (source water)	Recovery (post-AR)	SABS 241 Class 0 – I
pH	9.8	7.1	9.1	5 – 9.5
EC (mS/m)	89	19	95	<150
Ammonium	1.3	<0.1	0.7	<1.0
Fluoride	10.6	0.1	7.0	<1.0
Arsenic	0.26	<0.001	0.40	<0.05
Sulphate	64	20	157	<400

Sulphate in breccia water



• Clogging

The reduction in permeability of the filtration surface of the recharge facility or the reduction in available pore volume and permeability in the aquifer

There are various forms of clogging, each of which could be a combination of physical, biological and chemical processes:

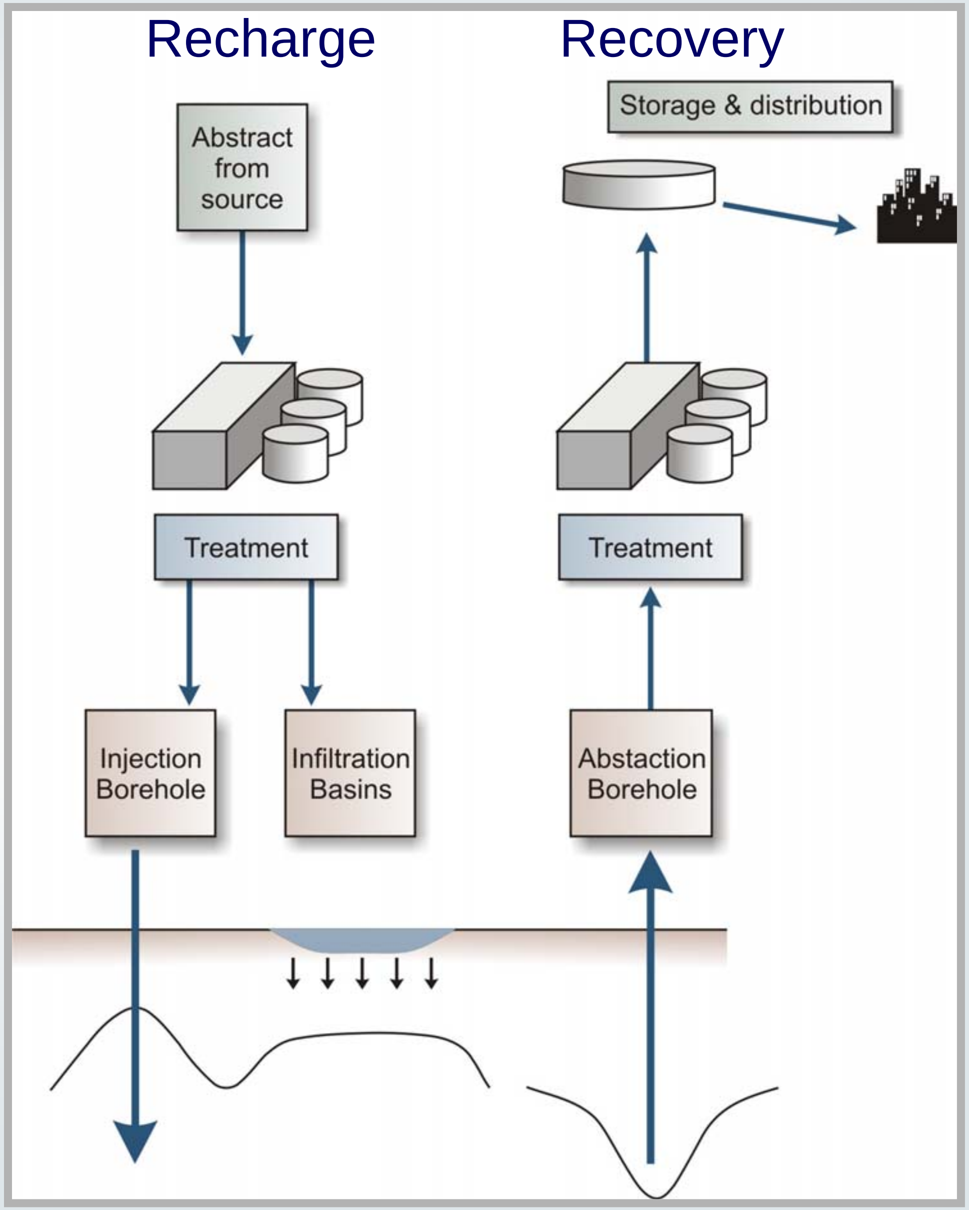
- Filtration of suspended solids
- Microbial growth
- Chemical precipitation
- Clay swelling and dispersion
- Air entrapment (or entrainment)
- Gas binding (release of dissolved or generated gases
- Mechanical jamming and mobilization of aquifer sediments

Clogging continued…

- Clogging is an operational problem largely related to the quality of the recharge water
- Site-specific conditions also influence the clogging process:
  - groundwater characteristics
  - borehole construction
  - recharge facility design
- Adequate and timely identification of clogging generally leads to the opportunity to restore the initial capacity of the scheme by using a suitable redevelopment method
- Best to design the scheme to minimise clogging. Key to this is the quality of the source water.

5. The artificial recharge method and engineering issues

Infrastructure



Key issues

- Which artificial recharge method is most efficient and cost-effective?
- Are the engineering logistics practical and cost-effective regarding the transfer of source water to the point of recharge and from the point of abstraction to the point of consumption?
- How can the scheme be designed to minimise clogging?
- The design must be appropriate for the operation and maintenance skills levels

Kharkams

- Remote, rural
- Low maintenance

In-stream sand filter and gravity flow to injection boreholes

Windhoek

- Urban
- Sophisticated pre-treatment

Pre-treatment: City's drinking water further treated with Granular Activated Carbon & chlorination

6. Environmental issues

- Artificially recharging groundwater can have both detrimental and positive impacts on the environment.
- Ecosystem enhancement is the prime objective of some AR projects
  - Comprehensive Everglades Restoration Plan, Florida, USA: Plans for 330 ASR wells with a capacity of 19 Ml/day to restore the Everglades wetlands
  - Squaw Valley, California, USA: Aim to use ASR to provide perennial stream flow to maintain trout populations

Environmental advantages & disadvantages

Advantages

- Reduce abstraction from rivers: water stored in wet months means lower stream diversions in dry months
- Maintain the Reserve by maintaining groundwater levels & in-stream flow requirements
- Minor environmental imprint: Where confined aquifers are used, there is minimal impact on surface water cources
- Minimal land use: Very small land area as opposed to dams

Disadvantages

- Raised water table: Vegetation die-back, discharge of foreign water into wetlands & flooding
- Lowered water table: impact on vegetation, land subsidence, drying up of boreholes
- Water quality issues: clogging, mobilisation of undesirable chemical constituents (eg arsenic)
- Aquifer organisms: Affected by foreign water

7. Legal and regulatory issues

Artificial recharge schemes need to be licensed because storing water underground is defined as a "water use" in the National Water Act

The key legal issues regarding the assessment and operation of artificial recharge schemes include:

- Water use licensing for artificial recharge schemes
- Environmental authorisation requirements for both testing and implementing the scheme (i.e. Basic Assessment or Environmental Impact Assessment)
- Environmental Management Plans (EMPs)
- Compliance with regulations (e.g. relating to water reuse)
- Rights associated with the use of artificially recharged water
- Compliance with the conditions and reporting requirements of the water use licence and environmental authorisation

8. Economics

"Unused aquifer storage capacity can often be developed at a significantly lower cost than surface storage facilities, and without the adverse environmental consequences frequently associated with surface storage" Pyne, 2005

An economic study should compare the cost per cubic meter of water supplied for each alternative supply option. It is important that the same method be used to price water. This is particularly important when water is purchased from a bulk water provider such as a water board or when compared with existing schemes, as the price of water may be subsidized.

Example: Windhoek

- Present worth cost including the following costs and revenues:
  - Initial capital investment cost
  - Annual depreciation and residual value (discounted to present value)
  - Average incremental annual pumping cost
  - Average incremental annual operation and maintenance cost
- The incremental security of supply (ISS). The study modeled the supply for each scenario as well as a baseline “do nothing” scenario. The ISS is the difference between the expected annual shortfall of the particular scheme scenario and the “do nothing” scenario during a 10 year planning period.
- Water Saving (or scheme efficiency) based on evaporation losses for each alternative scheme
- Ratio of cost to ISS (in R/annual volume).
- Other factors that could be assigned an economic value include:
  - The strategic value of drought mitigation measures
  - The efficient use of local resources compared with developing sources in other distant areas

9. Management and technical capacity

The successful operation of an artificial recharge facility depends largely on an effective management strategy and on the availability of sufficiently skilled or competent staff to carry out the necessary tasks.

Commonly needed skills:

- Hydrogeology
- Recharge and recovery technology
- Groundwater level monitoring
- Water treatment and water quality management
- Water supply engineering

10. Institutional arrangements

Eight out of ten of the most significant impediments to implementing a cost-effective conjunctive management program in California related to institutional issues
(Utah State Water Plan, July 2005)

The key issues relate to:

- Licensing
- Monitoring
- Water quality control
- Financial arrangements
- Rights to the use of recharged water
- Reporting
- Support

Responsible authorities

The responsible authorities for authorizing, licensing and operating artificial recharge schemes could include:

- DWAF/CMA
- Water Services Authority (WSA)
- Water Services Provider (WSP), including Water Boards
- Water User Association (WUA)
- Dept. Environmental Affairs & Tourism (DEAT)

Conclusions

*Where the conditions are favourable for implementing artificial recharge, it would be foolish not to do so. It would be like choosing **not** to divert water into a dam to keep it as full as possible even if the conditions are favourable for doing so. The key question is not whether artificial recharge should be practiced, but rather, when is it appropriate to do so. This depends on a number of factors, the key ones being the availability of a suitable water source, the ability of the aquifer to receive the water, the cost of implementation and operation, and management / skills requirements. In some cases water quality is a problem, but this usually translates to an economic factor.*

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All photos are by Dr Murray except for the close up of the Atlantis infiltration basin which was taken by Dr G Tredoux. No photos may be taken from the presentation without approval by Dr Murray or Dr Tredoux.