



Freshwater storage in brackish-saline aquifers for irrigation water supply: a bottomless pit or a fountain of gold?

SubSol
Subsurface Water Solutions

Toward Sustainable Groundwater in Agriculture: 2nd International Conference Linking Science and Policy

June 28, 2016

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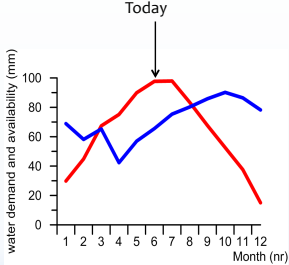



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Introduction

Why storage?

- Mismatch freshwater availability and demand
 - Coastal areas: freshwater shortage and salinization
 - Mainly problem for high-end agriculture
- Traditionally
 - expensive aboveground solutions (rainwater storage)
 - unsustainable solutions (desalination + brine disposal)
- Aquifer storage and recovery (ASR) would be more elegant...



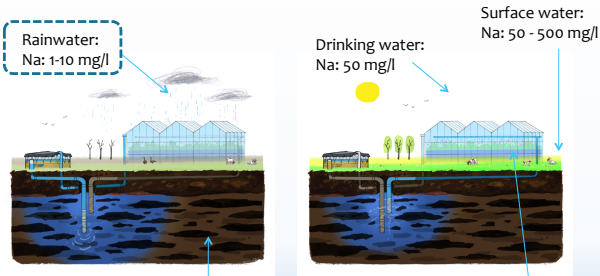
Horticulture Greenport Eastland – Westland (NL): rainwater availability and demand

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Introduction

The Netherlands, '80s

ASR introduced to bridge the mismatch...



Rainwater: Na: 1-10 mg/l

Drinking water: Na: 50 mg/l

Surface water: Na: 50 - 500 mg/l

Water demand: Na: < 11 mg/l

Na: 50 - 3000 mg/l

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Introduction

Known problem of ASR in brackish-saline aquifers

- $\rho(\text{freshwater}) < \rho(\text{saltwater})$
- Recovery is hampered by buoyancy effects
- Too little water is recovered practically unmixed

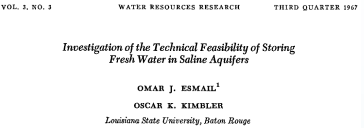
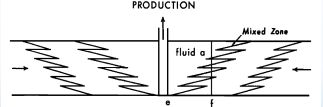



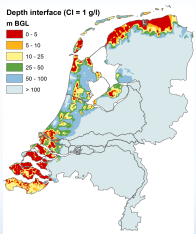
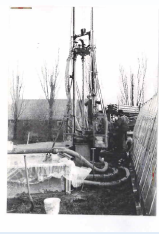
Fig. 1. Schematic representation of gravity segregation and mixing occurring simultaneously.

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Introduction

The Netherlands, '80s

- Many 'small-scale' ASR-systems failed in the coastal zone

zoetwaterinfiltratieproef
kapelle

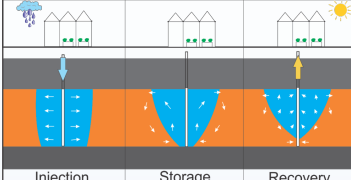
kort verslag van een onderzoek naar de mogelijkheden voor horizontale infiltratie van zoetwater in een kreekrug

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Introduction

The Netherlands, '80s

- Many 'small-scale' ASR-systems failed in the coastal zone
- Mainly by buoyancy effects
- >100 small-scale systems realized in freshwater aquifers, though

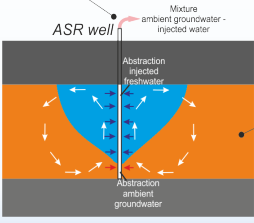


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Introduction

Recent ASR-studies to understand...

- Ranked the controlling factors
 - Pumping rate (m³/d)
 - Operational scheme
 - Density injection water (g/l)
- Unfavourable:
 - High density difference
 - High hydraulic conductivity (K)
 - Small volumes, long storage
 - Large thickness



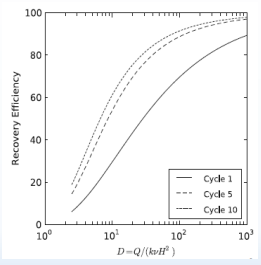
- Density ambient groundwater (g/l)
- Aquifer thickness (m)
- Aquifer hydraulic conductivity (m/s)
- Anisotropy (-)

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Introduction

Recent ASR-studies to understand...

- Ranked the controlling factors
- Possibility to estimate performance (based on a single, fully penetrating ASR-well)

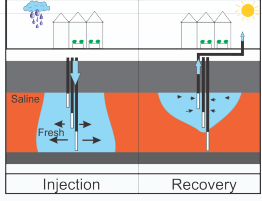



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Introduction

... recent hydrogeological engineering to counteract

- Multiple partially penetrating wells in one borehole (MPPW)






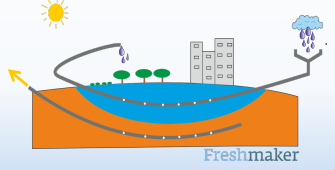
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Introduction

... recent hydrogeological engineering to counteract

- Multiple partially penetrating wells in one borehole (MPPW)
- Horizontal directional drilled wells (HDDWs)





Freshmaker

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Introduction

ASR is only effective if you can recover the water upon storage...

Bottomless pit, or fountain of gold?




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Introduction

Bottomless pit, or fountain of gold?





INCREASING FRESHWATER RECOVERY UPON AQUIFER STORAGE



Koen C. Daalder

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Methods

2010-2014:

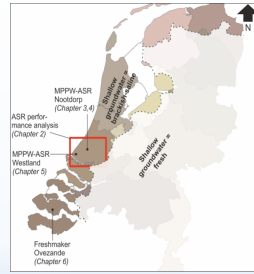
1. Mapping of spatial ASR - performance

3. Three field pilots testing optimizations

- Nootdorp (MPPW)
- Westland (MPPW + RO)
- Ovezande (HDDW)

5. Transport modelling (SEAWAT)

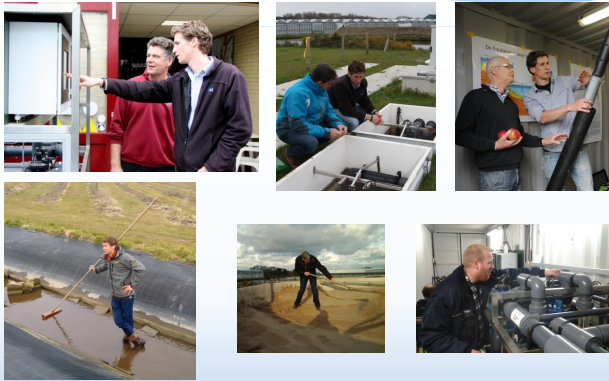
- Compare well configurations
- Predict future performance



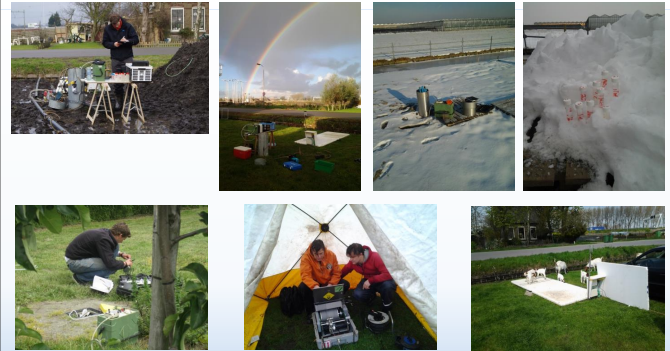
Methods



Methods

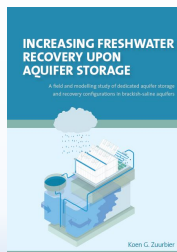


Methods



Lessons learned

Bottomless pit, or fountain of gold?



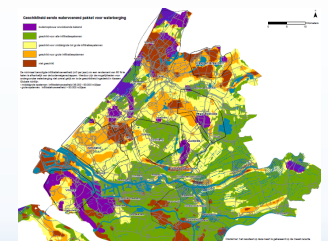
Lessons learned

Lesson 1: Large variety of ASR performance in coastal zones

We can make meaningful predictions of the ASR performance in heterogeneous coastal aquifers

The Dutch delta shows:

- A lot of variation
- Very suitable areas
- Unsuitable areas
- and a lot in between...



Zuurbier, K., Bakker, M., Zaadnoordijk, W., Stuyfzand, P., 2013. Identification of potential sites for aquifer storage and recovery (ASR) in coastal areas using ASR performance estimation methods. Hydrogeology Journal, 21(6): 1373-1383.

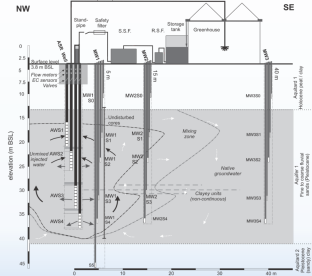
Lessons learned

Lesson 2: Control the aquifer sections used for infiltration and recovery

Flexibility in infiltration and recovery will increase your recovery

As evidenced for:

- MPPW (Nootdorp)



Zuurbier, K.G., Zaadnoordijk, W.J., Stuyfzand, P.J., 2014. How multiple partially penetrating wells improve the freshwater recovery of coastal aquifer storage and recovery (ASR) systems: A field and modeling study. *Journal of Hydrology*, 509(0): 430-441.

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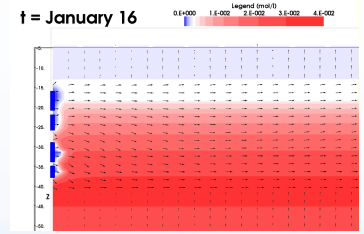
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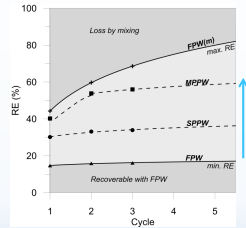
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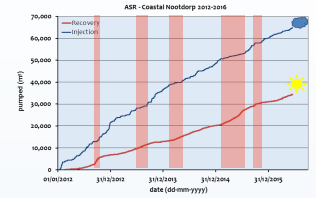
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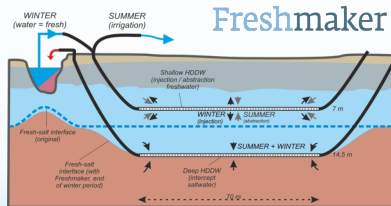
Lessons learned

Lesson 2: Control the aquifer sections used for infiltration and recovery

Flexibility in infiltration and recovery will increase your recovery

As evidenced for:

- MPPW (Nootdorp)
- HDDW (Ovezande)



Zuurbier, K.G., Kooiman, J.W., Groen, M.M.A., Maas, B., Stuyfzand, P.J., 2015. Enabling Successful Aquifer Storage and Recovery of Freshwater Using Horizontal Directional Drilled Wells in Coastal Aquifers. *Journal of Hydrologic Engineering*, 20(3): B4014003.

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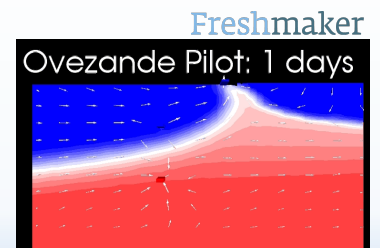
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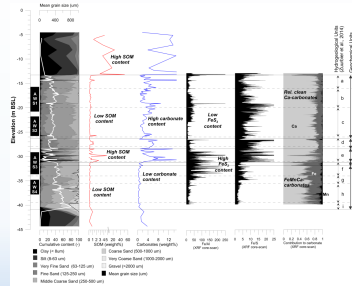


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Lessons learned

Lesson 3: Take geochemical reactivity into account

Long-lasting geochemical impact on the recovered water quality during MPPW-ASR



Zuurbier, K.G., Hartog, N., Stuyfzand, P.J., 2016. Reactive transport impacts on recovered freshwater quality during multiple partially penetrating wells (MPPW-)ASR in a brackish heterogeneous aquifer. *Applied Geochemistry*, 71: 35-47.

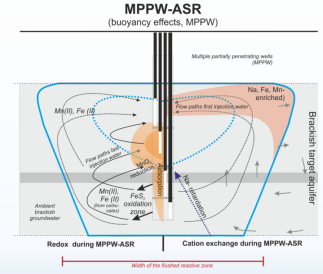
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Lessons learned

Lesson 3: Take geochemical reactivity into account

Long-lasting geochemical impact on the recovered water quality as a consequence of:

- Freshening/salinization (lower half of the aquifer)
 - Cation exchange: mainly Na
- Flushing of reactive units
 - Pyrite oxidation (SO_4 , As)
 - Carbonate dissolution (Fe, Mn)
- Subsurface iron removal (SIR) at recovery well to counteract Fe, Mn



Zuurbier, K.G., Hartog, N., Stuyfzand, P.J., 2016. Reactive transport impacts on recovered freshwater quality during multiple partially penetrating wells (MPPW-)ASR in a brackish heterogeneous aquifer. *Applied Geochemistry*, 71: 35-47.

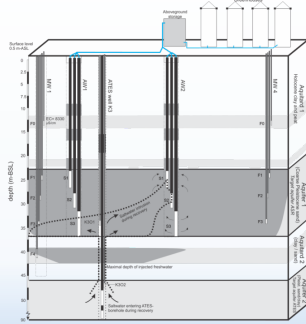
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Lessons learned

Lesson 4: chances can be ruined...

We can exploit and ruin the subsurface...

- Careless installation / operation of former injection wells led to short-circuiting
- Intrusion saltwater from deeper aquifer precluded successful recovery



Zuurbier, K.G., Stuyfzand, P.J., In press. Consequences and mitigation of saltwater intrusion induced by short-circuiting during aquifer storage and recovery (ASR) in a coastal subsurface. *Hydrology and Earth System Sciences*.

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Lessons learned

Lesson 6: out of sight, out of mind.

- NL: 2-D freshwater management rules
- ASR can be a technically viable solution, also on a small scale, also in coastal areas
- Cost price: 0.3 to 1.5 US \$/m³ (competitive)
- Communicate!

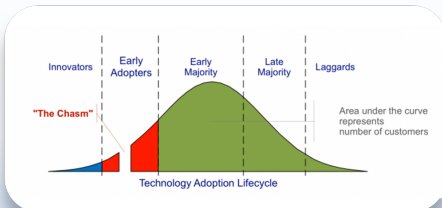


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Current projects, follow-up

- Pilots show that ASR can be feasible in the coastal zone thanks to hydrogeological engineering
- Now: enable market breakthrough
 - Reference sites
 - Replication sites
 - Economics, market scans

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Current projects, follow-up

Automation of the dedicated ASR-concept

End users ≠ hydrogeologist

- Prevent 'mistakes'
- Limits labour during operation
- Enhance recovery
- Enables anticipation to weather predictions



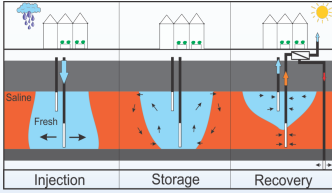
Zuurbier, K.G., Raat, K.J., Paalman, M., Oosterhof, A.T., Stuyfzand, P.J., 2016. How Subsurface Water Technologies (SWT) can Provide Robust, Effective, and Cost-Efficient Solutions for Freshwater Management in Coastal Zones. *Water resources Management*: 1-17.

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Current project: ASR and desalination

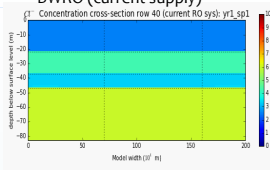
ASR + 'Freshkeeper' + RO: ASRO

- Robust recovery of freshwater
- Infiltration + production freshwater in balance, despite membrane concentrate disposal

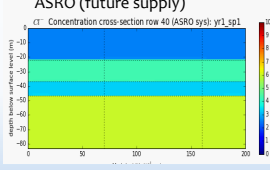


www.dessin-project.eu

BWRO (current supply)
Concentration cross-section row 40 (current RO sys: yr1_0p1)



ASRO (future supply)
Concentration cross-section row 40 (ASRO sys: yr1_0p1)

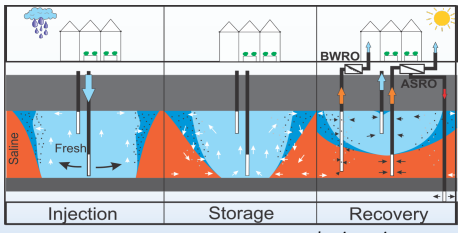


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Current project: ASR and desalination

ASR + 'Freshkeeper' + RO: ASRO

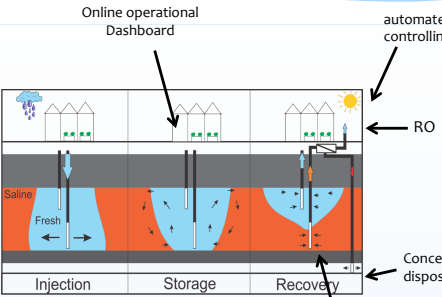
- Critical aspect for RO: particle mobilisation during infiltration
 - Clay (freshening)
 - Fe-colloids



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Future direction: ASR and desalination



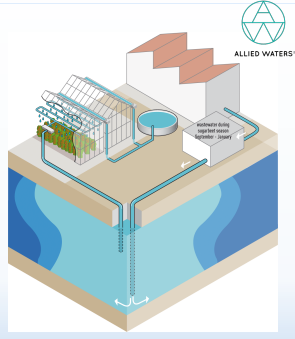
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Current project: effluent re-use for irrigation

Nieuw Prinsenland greenhouse area:

- New source water for ASR in NL (recycled effluent)
- Turning waste from the industry (sugar factory) into water resource for horticulture (220 ha)
- 220 m³/h back-up supply additional to aboveground rainwater storage

First ASR-cycle underway



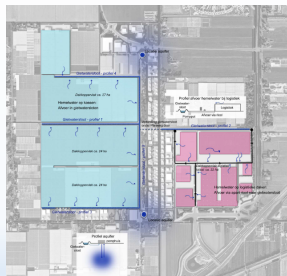
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Current project: extended rainwater harvesting and ASR

Glasparel+ greenhouse area:

- Roofwater from horticultural and nearby industrial area feed ASR systems
- Recovery upon irrigation water demand (90 ha)
- 600.000 m³/yr
- max. 5.000 m³/d

Realization: September 2016

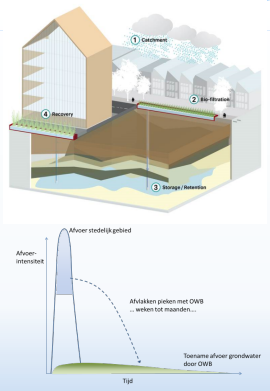


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Current project: Urban Waterbuffer

- Prevent pluvial flooding, sewage overflow and waste water dilution in urban areas by deep injection of rainwater
- Supply freshwater for ponds, irrigation, grey water, drinking water during droughts

First systems planned for 2017-2018



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Summary

1. ASR can be a very successful freshwater management strategy, even when target aquifer is brackish-saline
2. Hydrogeological engineering required for improvement in freshwater recovery
3. The increased complexity may necessitate automation and a more detailed evaluation of reactive transport
4. ASR increasingly reconsidered a freshwater management strategy again in NL



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Conclusion

Freshwater storage in brackish-saline aquifers for irrigation water supply: a bottomless pit or a fountain of gold?



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www.alliedwaters.com



download thesis 'Increasing freshwater recovery upon aquifer storage' via www.subsol.org/results



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