Impact of urbanization on groundwater recharge: The case study of Dübendorf, Switzerland

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Groundwater recharge

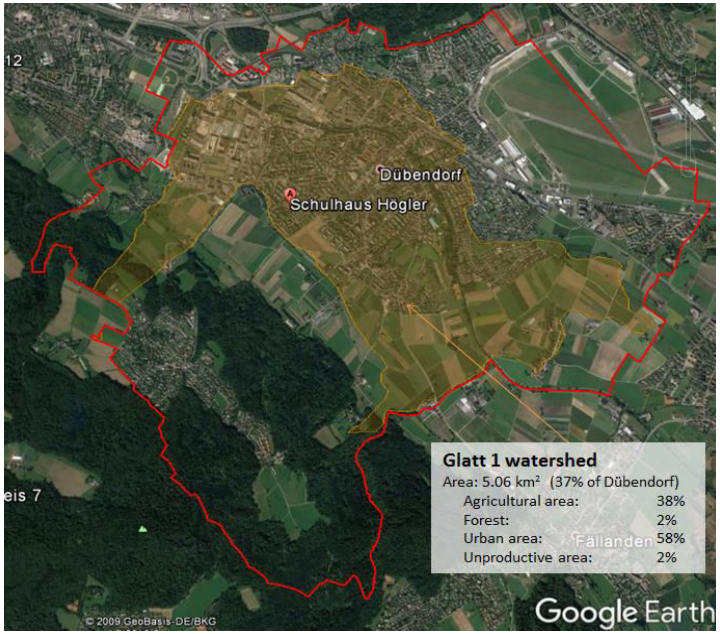
Urbanization effects

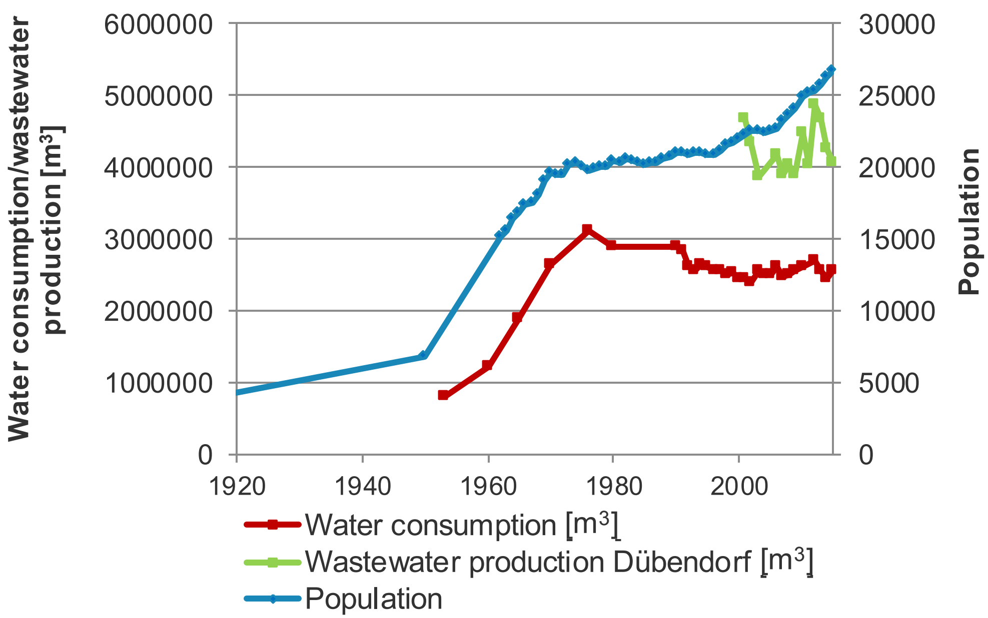
- Urban groundwater recharge affected by land use changes, subsurface infrastructure and meteorological conditions → very variable
- Human influence on the water cycle since centuries, but increase in amplitude since ~1850:
  - Need of additional water
  - Increased impervious surfaces
  - New recharge sources and new contaminants into the water cycle
  - Regulation or damming of river courses and drainage of wetlands
- In cities, water does not follow a cycle anymore

Methods

General methodology

Approach	Investigation period	Area of study	Climatic data	Land use repartition
1. Influence of climatic conditions	2006-2015	Glatt 1 watershed	Time dependent	Fixed; data of the year 2009
2. Influence of urbanization	1880, 1955, 1980 and 2009	Municipality of Dübendorf, each of the 17 watersheds	Fixed; data of the year 2009	Time dependent





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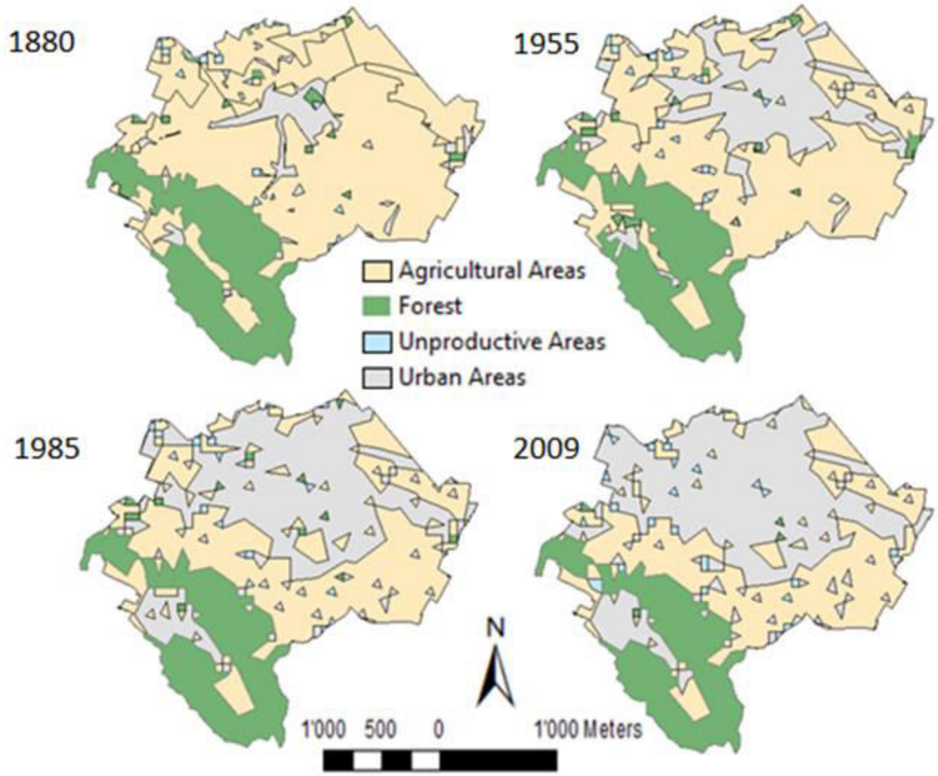
Methods

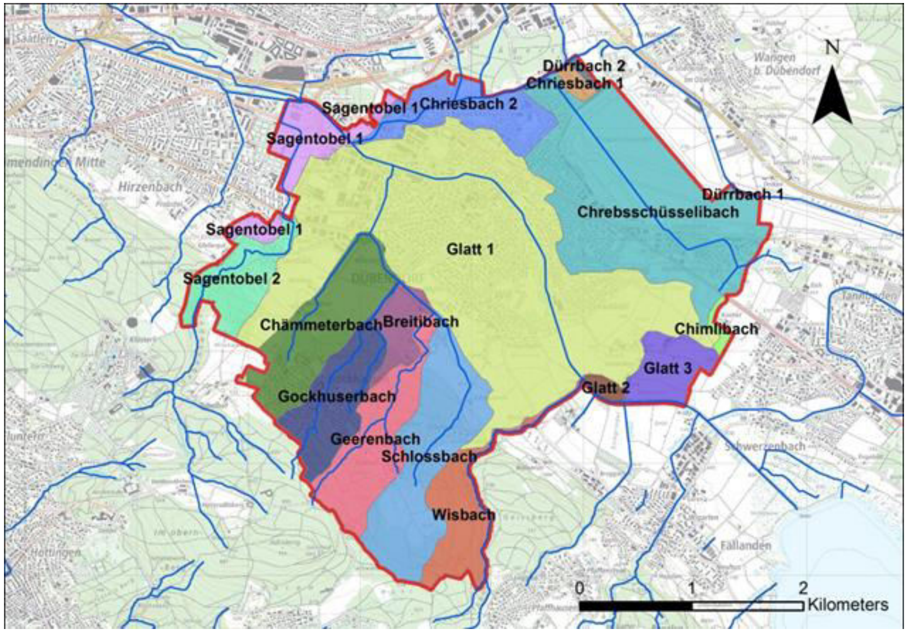
Study area: Dübendorf

Location	Glatt valley, canton Zurich, Switzerland
Population (2015)	26,700
Area	13.6 km^2
Topology and geology	Mostly flat in urban area, some relief in the forest Soil types: sandy loam, loam, clayey loam and sandy gravel Presence of a porous aquifer
Climatology	Temperate climate Average temperature (2006-2015): 9.9°C Average rainfall (2006-2015): 1004 mm
Water network	Drinking water: since 1894 Wastewater: since 1920, mostly combined sewer systems
Irrigation	Can be neglected

Methods

Study area: Dübendorf





Urban area: 1880: 6%; 2009: 44%

17 watersheds in Dübendorf

Methods

Calculation background - General

- Water budget: “accounting of water movement into and out of, and storage change within, some control volume” (Healy, 2010)
- Assumptions:
  - Annual storage nil
  - Recharge instantaneous
  - Subsurface runoff neglected

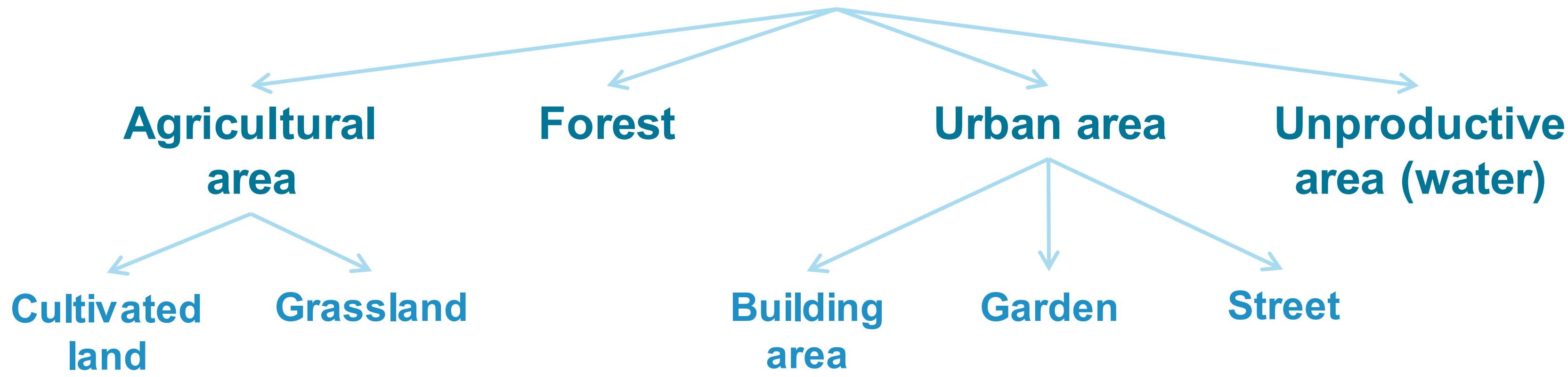
$$GWR = P - ET_a - R_{off} + L$$

GWR=	Groundwater recharge
P=	Precipitation
ET_a=	Actual evapotranspiration
R_{off}=	Runoff
L=	Leakages from wastewater and drinking water mains

Methods

Calculation background – Land use

Land use classes



Time period	Source
1880	Digitalization by hand of historical map (Swisstopo)
1955	Digitalization by hand of historical map (Swisstopo)
1980	Land use statistics 1985 (BFS)
2009	Land use statistics 2009 (BFS)

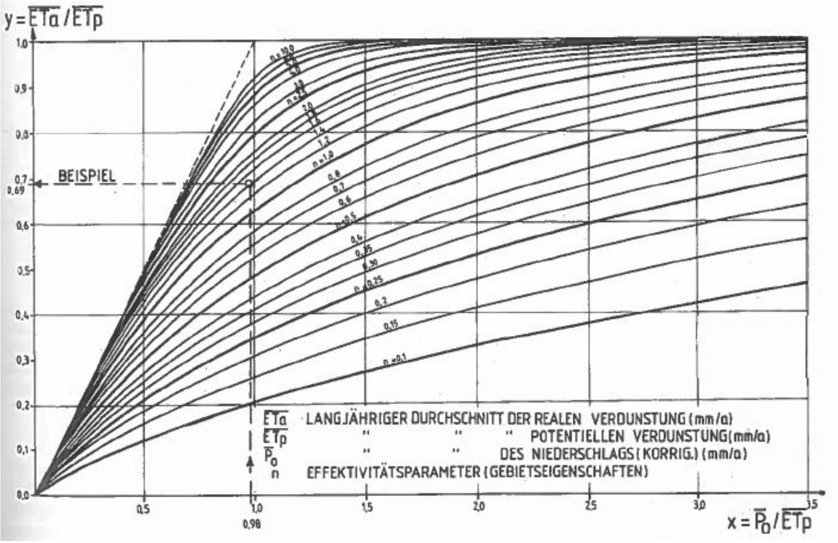
Methods

Calculation background - Evapotranspiration

- Potential evapotranspiration
  - Calculation with various formulas (Turc-Wendling, Turc, Hargreave, Haude)
  - Comparison with estimation of MeteoSwiss (Primault formula)
- Actual evapotranspiration:
  - Water surfaces: Dalton law $\mathrm{ET}_{\mathrm{a\ water}} = f(v) \cdot e_s(T_{w0}) \cdot (1 - \frac{RH}{100})$
  - Land surfaces: Bagrov method using $\mathrm{ET}_{\mathrm{pot}}$ from Turc:

$$ET_{pot,Turc} = 0.0031 \cdot C \cdot (R_G + 209) \cdot \frac{T}{T+15} \text{ if T} \geq 0;$$

$$C = 1 + \frac{50-RH}{70}\ if\ RH < 50\%, C = 1\ if\ RH \geq 50\%$$



Source: DVWK, 1996

Methods

Calculation background – Runoff and Leakages

- Runoff: SCS-CN method $$Q = \begin{cases} 0 \; for \; P \leq I_a \\ \frac{(P-I_a)^2}{(P-I_a+S)} \; for \; P > I_a \end{cases}$$

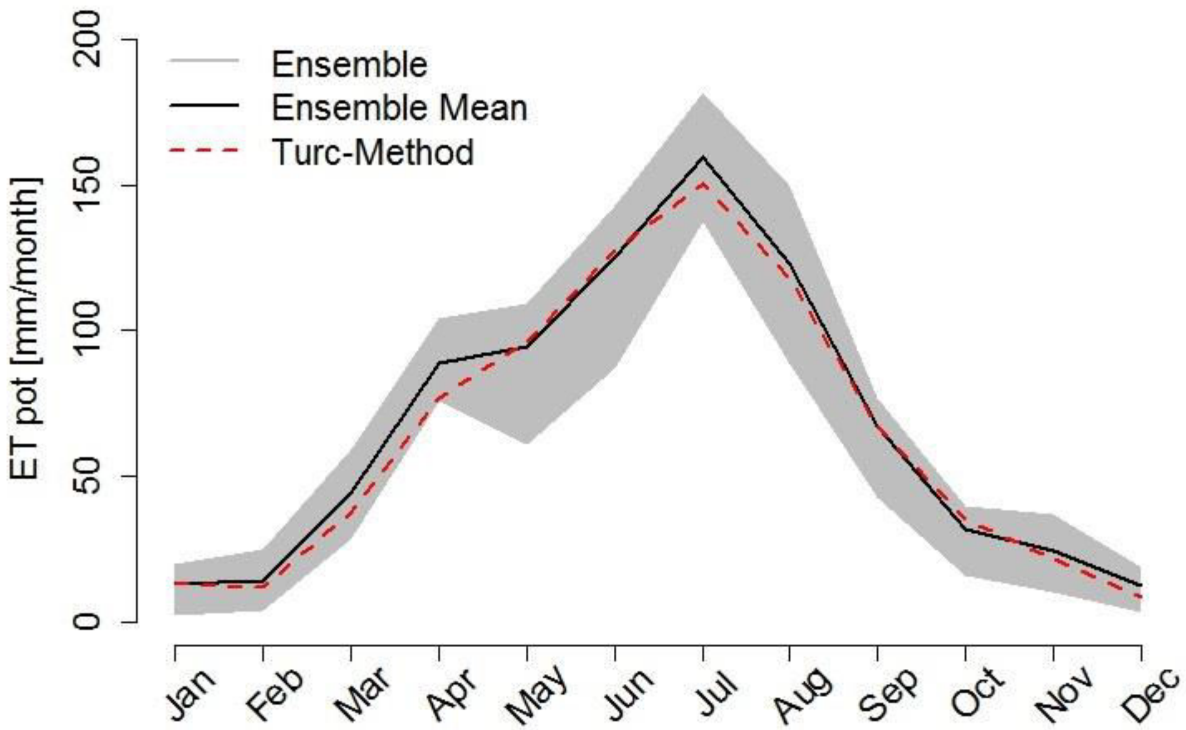
- Leakages: $L\ [m^3] = 0.07 \cdot Q_{DW}\ [m^3] + 0.1 \cdot Q_{WW}\ [m^3]$

$$Q_{WW}\,[m^3] = Q_{DW}\,[m^3] + 0.281 \cdot P\ [mm]/1000 \cdot impervious\ area\ [\%] \cdot A_{\text{Dübendorf}}\ [m^2]$$

[Soil Conservation Service Curve Number method (SCS-CN method)]

Results and discussion

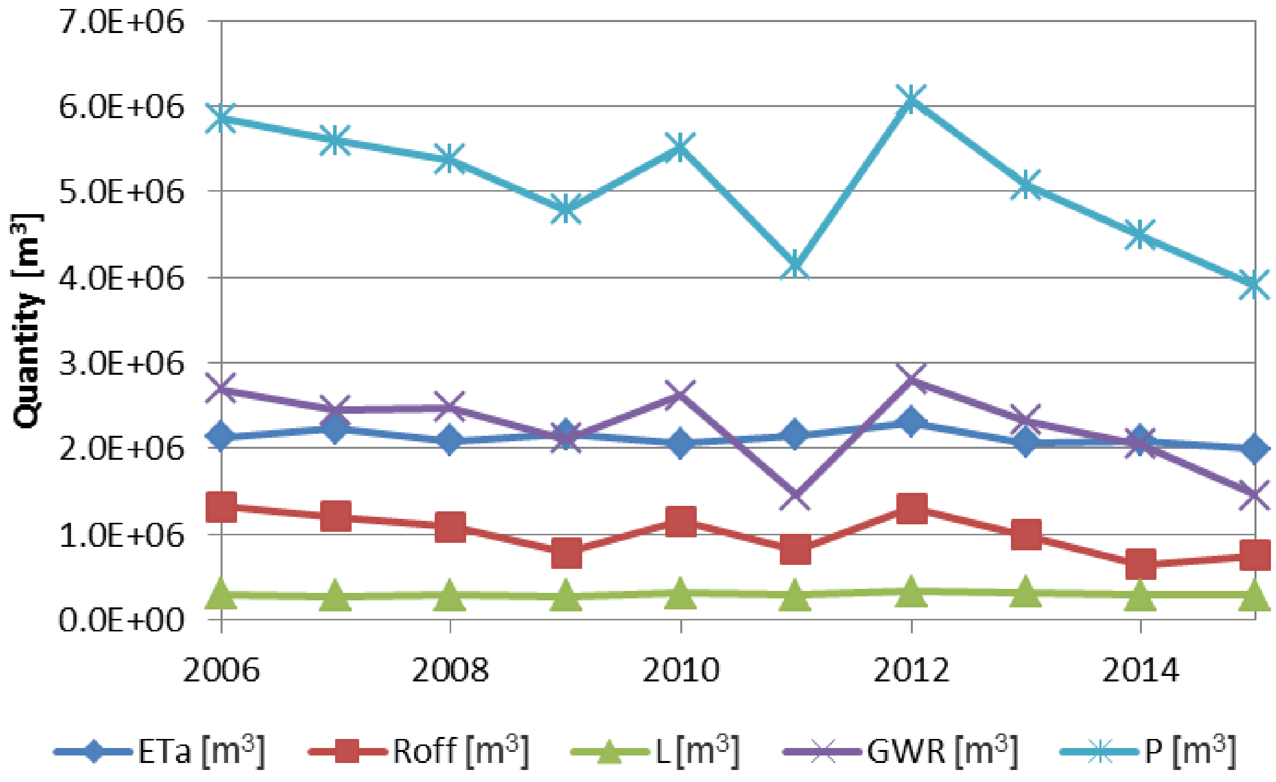
Influence of climatic conditions – Potential evapotranspiration



- Trend: high ET_{pot} in summer, low in winter
- High variability between the formulas
- ET_{pot} calculation with empirical formulas associated with high uncertainties

Results and discussion

Influence of climatic conditions – Groundwater recharge



- GWR varies significantly, high correlation with precipitation
- GWR 2x higher in years with a lot of precipitation than in dry years
- R_{off} responds strongly to climatic conditions, ET_a and L almost steady
- ET_a significantly higher than R_{off} or L

Results and discussion

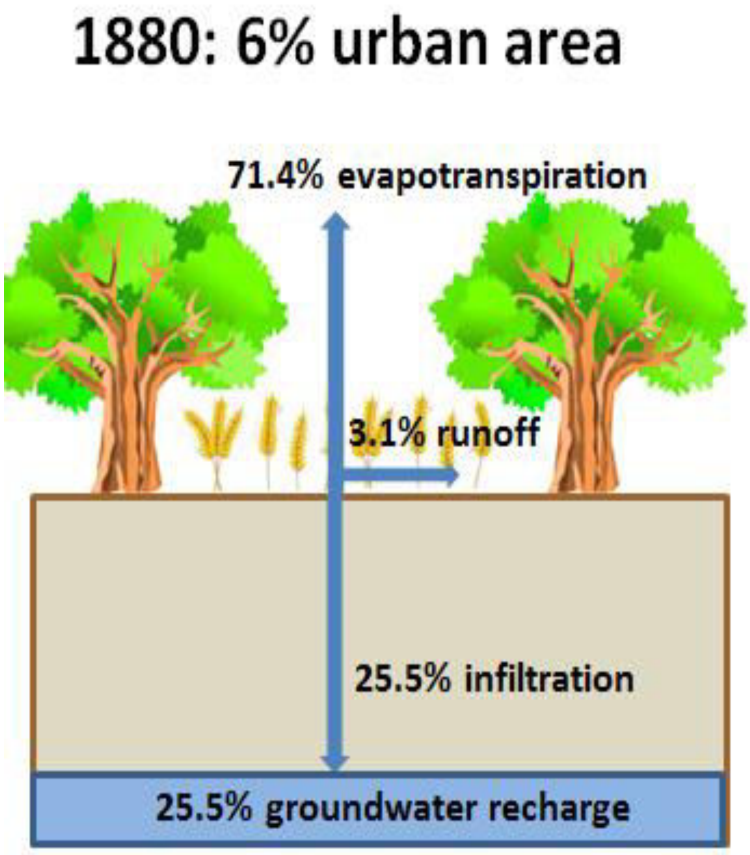
Influence of urbanization – Evapotranspiration, runoff and leakages (L)

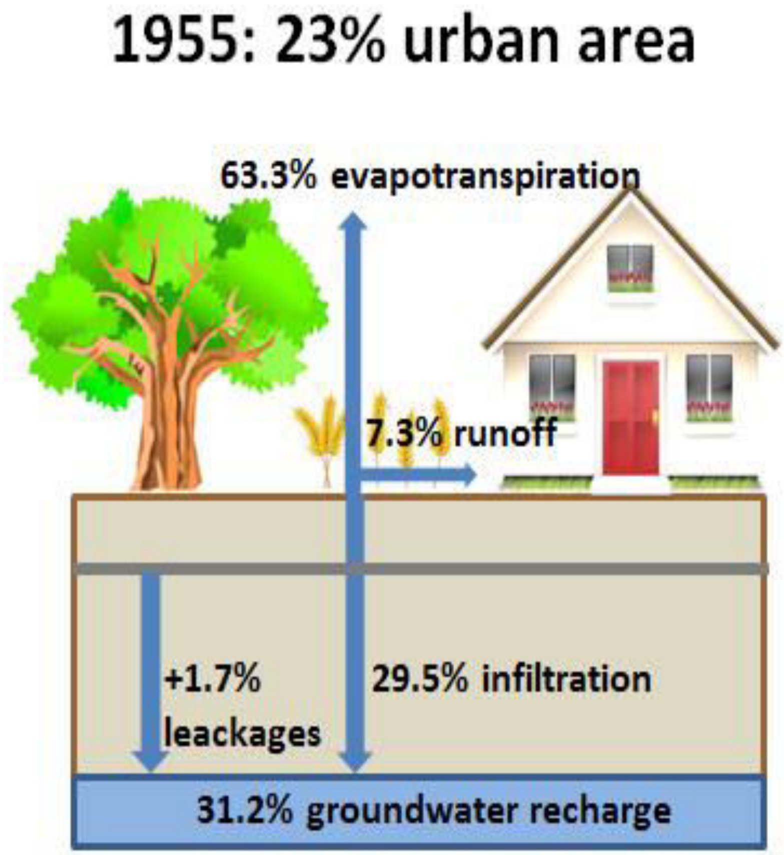
	ET_a [mm/year]	R_{off} [mm/year]	L [mm/year]			
			1880	1955	1980	2009
Agricultural areas	678	16	0	0	0	0
Forests	776	6	0	0	0	0
Urban areas	252	258	0	70	122	95
Unproductive areas	462	0	0	0	0	0

- ET_a high in agricultural areas and forests, low in urban areas. Opposite behavior for R_{off}.
- Leakages assumed distributed evenly over the urban area
- No leakages in 1880 as no water mains existed. Highest leakages in 1980 as highest water consumption

Results and discussion

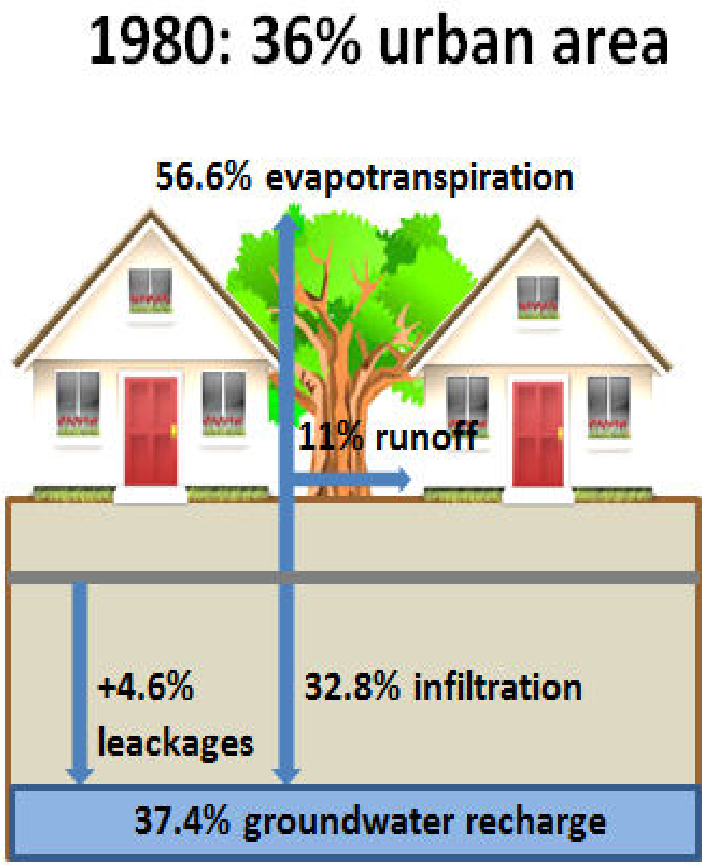
Influence of urbanization – Groundwater recharge

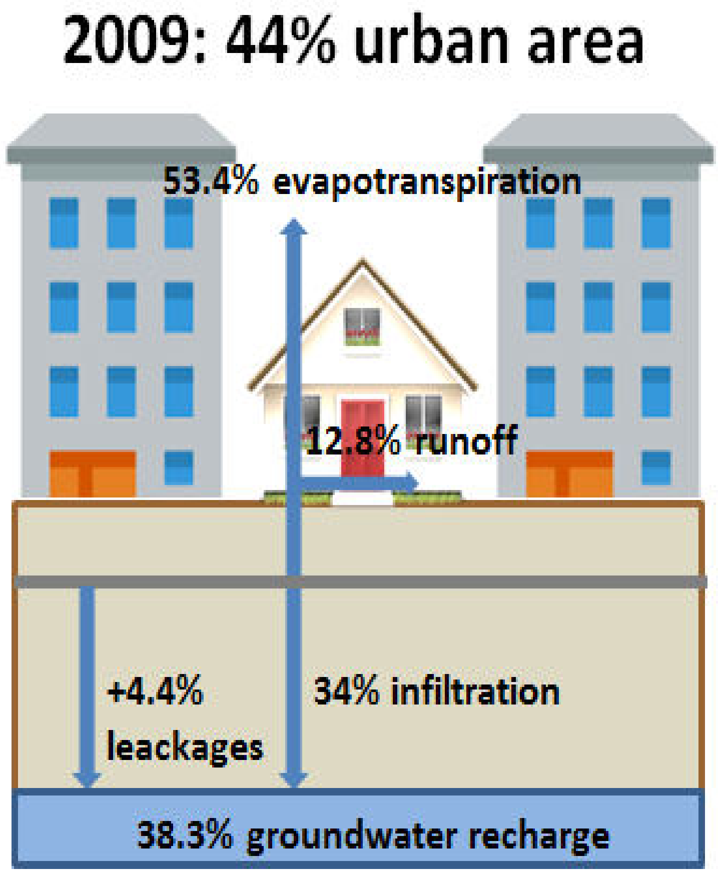




Results and discussion

Influence of urbanization – Groundwater recharge

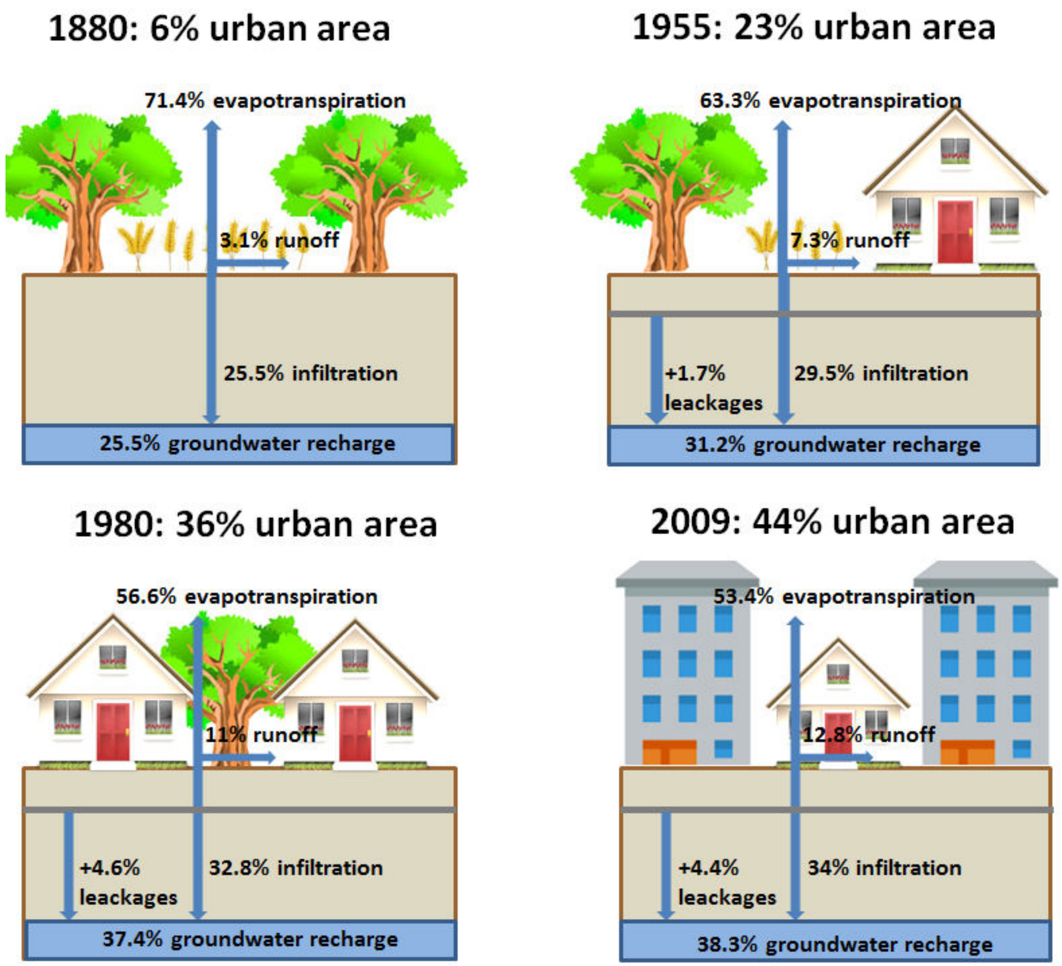




Minnig et al., JofH, 2018

Results and discussion

Influence of urbanization – Groundwater recharge

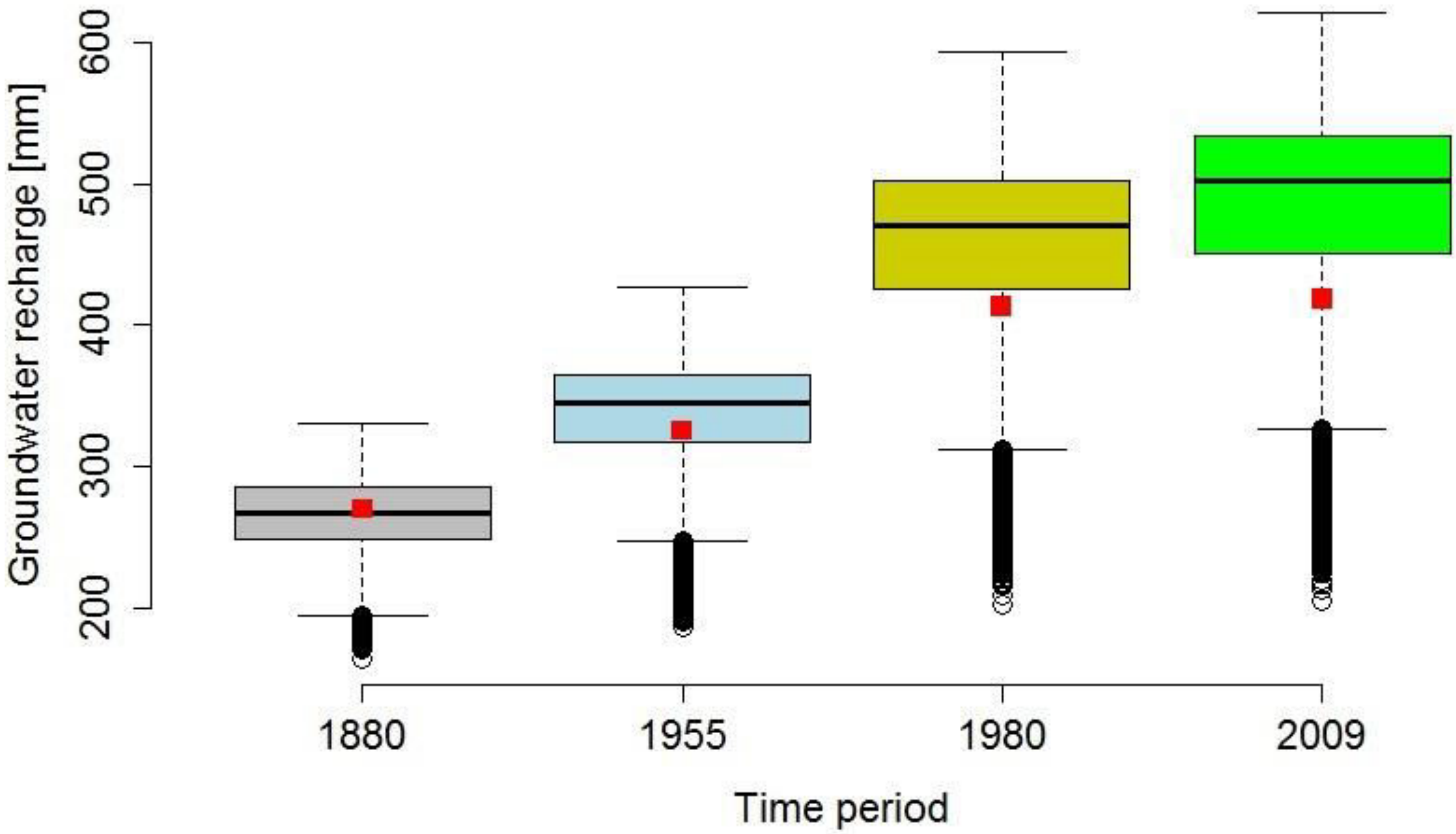


→ 50% increase in groundwater recharge from 1880 (242 mm) to 2009 (363 mm)

Uncertainty analysis using Monte-Carlo-Approach

- To explore parameter space of uncertain parameters
- most uncertain parameters are related to ET_a (3 parameters) and leakage fluxes (2 parameters: drinking water and waste water)
- 100,000 random parameter values within realistic parameter range generated
- Calculation of the corresponding fluxes for all land use classes and subclasses (for 1880, 1955, 1980 and 2009) for different parameter combinations

Uncertainty analysis using Monte-Carlo-Approach



Results and discussion

Comparison with literature

Few case studies on urban groundwater recharge

- Hooker (1999), Wolverhampton (UK):
  - Pre-urban rate: 120-250 mm (Dübendorf, 1880: GWR= 242 mm)
  - Current rate: 220-300 mm (Dübendorf, 2009: GWR= 363 mm)
- Appleyard (1995), Perth:
  - Non-urban areas: GWR=15-25% of P (Dübendorf, 1880: GWR= 26% of P)
  - Residential areas: GWR= 37% of P (Dübendorf, 2009: GWR= 38% of P)

→ The values obtained for Dübendorf seem plausible

Conclusion

- Urban groundwater recharge highly variable in time and space
- Urban groundwater recharge remains an under-researched topic
- High positive correlation between GWR and P
- R_{off} is the component of GWR which responds the most to climatic conditions
- High positive correlation between GWR and the extent of urban area
- Dübendorf: GWR increase of 50% between 1880 and 2009:
  - ET_a reduction that more than compensate for R_{off} increase
  - Contribution of water main leakages
- A better understanding of urban groundwater recharge critical for sound water management
- Challenge: groundwater recharge and water quality (for example leakages of sewer system)

Thank you for your attention!

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Urban recharge investigations in Dübendorf

- Groundwater recharge
  - Groundwater recharge under natural conditions
  - Urbanization effects on groundwater recharge
- Results / Comparison with literature

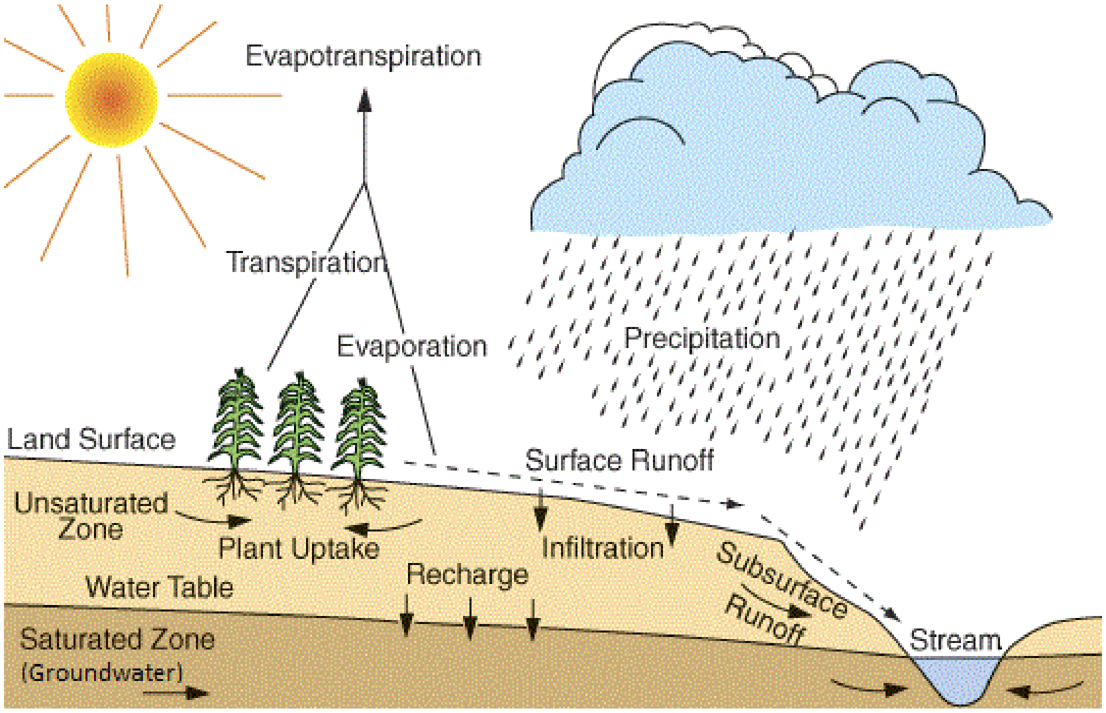
Introduction

- Groundwater: largest source of fresh available water, good quality and modest cost
- Land use and anthropogenic activities can lead to groundwater resources deterioration
- Issues: groundwater contamination, land subsidence, saline intrusion, flooding of underground infrastructure
- Two urbanization-related processes affect groundwater recharge:
  - Increase of impervious surfaces
  - Extension/building of water supply and sewer network
- Net effect of urbanization on groundwater recharge difficult to predict as each city has different settings

Groundwater recharge

Under natural conditions

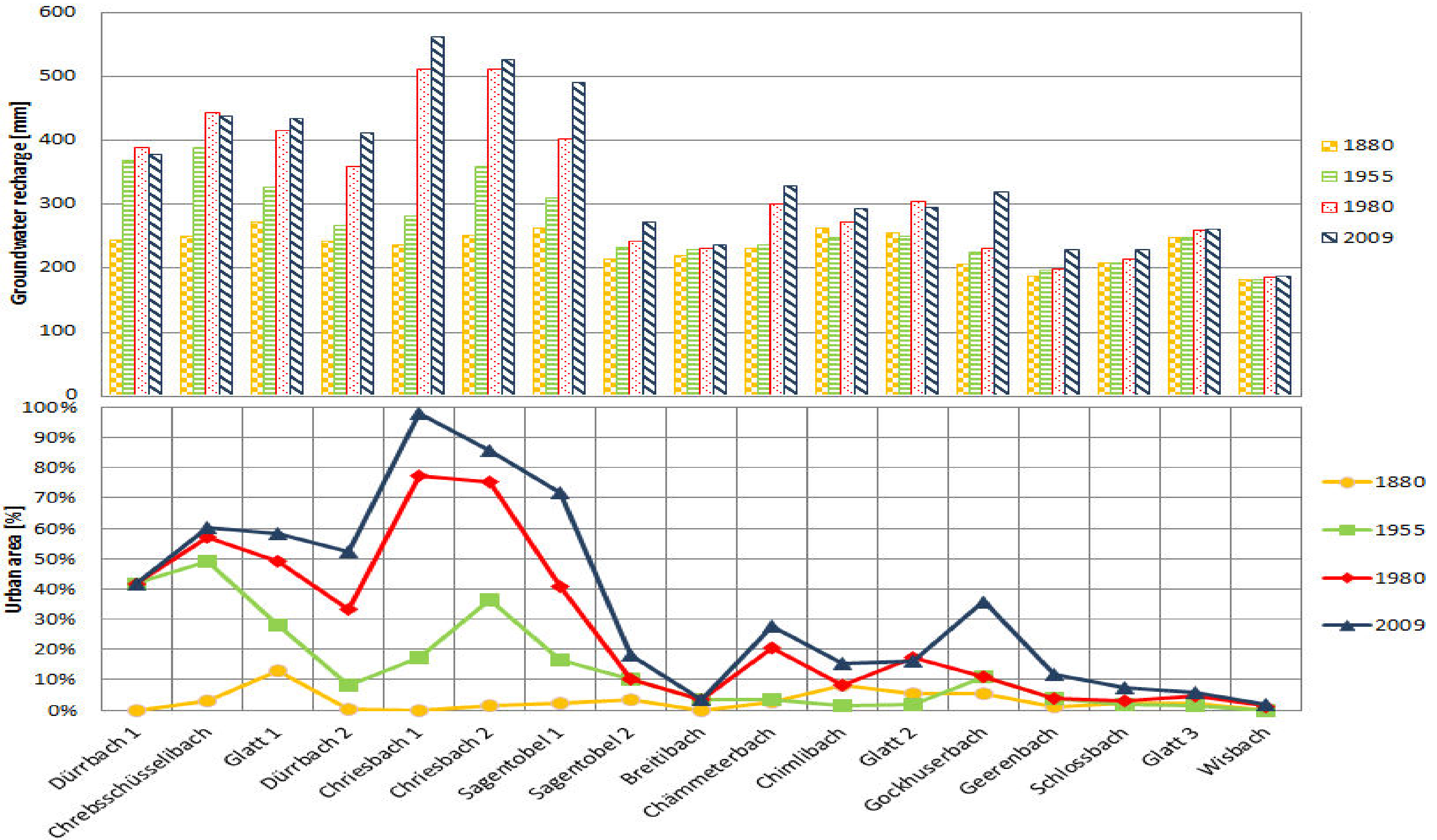
- Groundwater recharge: downward flow of water into an aquifer (Healy and Scanlon, 2012), occurs naturally or through anthropogenic processes



Source: KGS, 2003

Results and discussion

Influence of urbanization – Groundwater recharge



Results and discussion

Influence of climatic conditions – Potential evapotranspiration

ET_{pot} [mm]	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sep.	Oct.	Nov.	Dec.	Total
Turc-Wendling	17.3	24.9	59.1	99.6	106.1	143.2	161.3	124.3	77.1	39.9	28.4	18.8	**900.0**
Turc	12.8	11.8	37.4	77.0	96.0	127.7	150.5	118.0	67.4	35.0	21.3	8.4	**763.3**
Hargreave	-	-	-	86.7	109.5	135.5	167.2	133.0	73.6	-	-	-	**-**
Haude	19.7	16.3	51.6	104.3	101.3	132.3	182.1	150.1	74.0	37.5	36.9	18.2	**924.3**
Primault	1.9	4.0	28.1	75.7	60.6	87.2	137.4	89.0	42.4	15.7	9.9	3.1	**554.8**
Average	**12.9**	**14.2**	**44.0**	**88.7**	**94.7**	**125.2**	**159.7**	**122.9**	**66.9**	**32.0**	**24.1**	**12.1**	**785.6**
RSD	61%	61%	32%	15%	21%	18%	11%	18%	21%	35%	47%	63%	**22%**

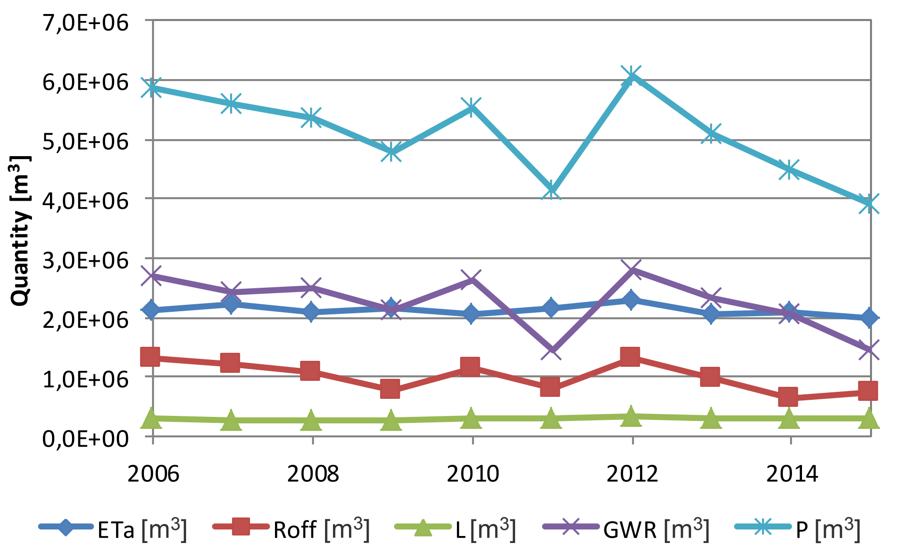
- Trend: high ET_{pot} in summer, low in winter
- High variability between the formulas
- ET_{pot} calculation with empirical formulas associated with high uncertainties

Results and discussion

Influence of climatic conditions – Groundwater recharge

	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	Average	RSD
P [m³]	5.9E+06	5.6E+06	5.4E+06	4.8E+06	5.5E+06	4.1E+06	6.1E+06	5.1E+06	4.5E+06	3.9E+06	**5.1E+06**	14%
ET_a [m³]	2.1E+06	2.2E+06	2.1E+06	2.2E+06	2.1E+06	2.2E+06	2.3E+06	2.1E+06	2.1E+06	2.0E+06	**2.1E+06**	4%
R_{off} [m³]	1.3E+06	1.2E+06	1.1E+06	7.9E+05	1.1E+06	8.2E+05	1.3E+06	9.9E+05	6.4E+05	7.5E+05	**1.0E+06**	24%
L [m³]	3.0E+05	2.8E+05	2.8E+05	2.8E+05	3.1E+05	2.9E+05	3.3E+05	3.2E+05	2.9E+05	2.9E+05	**3.0E+05**	6%
GWR [m³]	2.7E+06	2.4E+06	2.5E+06	2.1E+06	2.6E+06	1.5E+06	2.8E+06	2.3E+06	2.0E+06	1.4E+06	**2.2E+06**	21%
GWR [mm]	**532**	**483**	**490**	**418**	**517**	**287**	**555**	**460**	**404**	**286**	**443**	**21%**

- GWR varies significantly, high correlation with precipitation
- GWR 2x higher in years with a lot of precipitation (e.g. 2012) than in dry years (e.g. 2015)
- R_{off} responds strongly to climatic conditions, ET_a and L almost steady
- ET_a significantly higher than R_{off} or L



Results and discussion

Influence of urbanization – Evapotranspiration, runoff and leakages (L)

	Relative area in the class [%]	ET_a [mm/year]	R_{off} [mm/year]	L [mm/year]			
				1880	1955	1980	2009
Agricultural areas	**100%**	**678.5**	**16.1**	**0**	**0**	**0**	**0**
Cultivated lands	24.0%	672.4	17.4	0	0	0	0
Grasslands	76.0%	680.4	15.7	0	0	0	0
Forests	**100%**	**776.4**	**6.2**	**0**	**0**	**0**	**0**
Urban areas	**100%**	**252.5**	**257.6**	**0**	**70.4**	**121.7**	**94.7**
Building areas	68.2%	216.1	163.8	0	70.4	121.7	94.7
Gardens	7.0%	736.4	7.0	0	70.4	121.7	94.7
Streets	24.8%	216.1	586.4	0	70.4	121.7	94.7
Unproductive areas	**100%**	**461.8**	**0**	**0**	**0**	**0**	**0**

- ET_a high in agricultural areas and forests, low in urban areas. Opposite behavior for R_{off}.
- Leakages assumed distributed evenly over the urban area
- No leakages in 1880 as no water mains existed. Highest leakages in 1980 as highest water consumption

Outlook

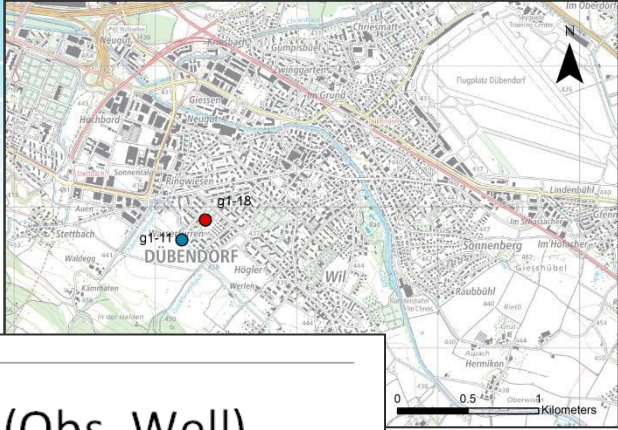
Considerable uncertainties in groundwater recharge assessment → accuracy could be increased by:

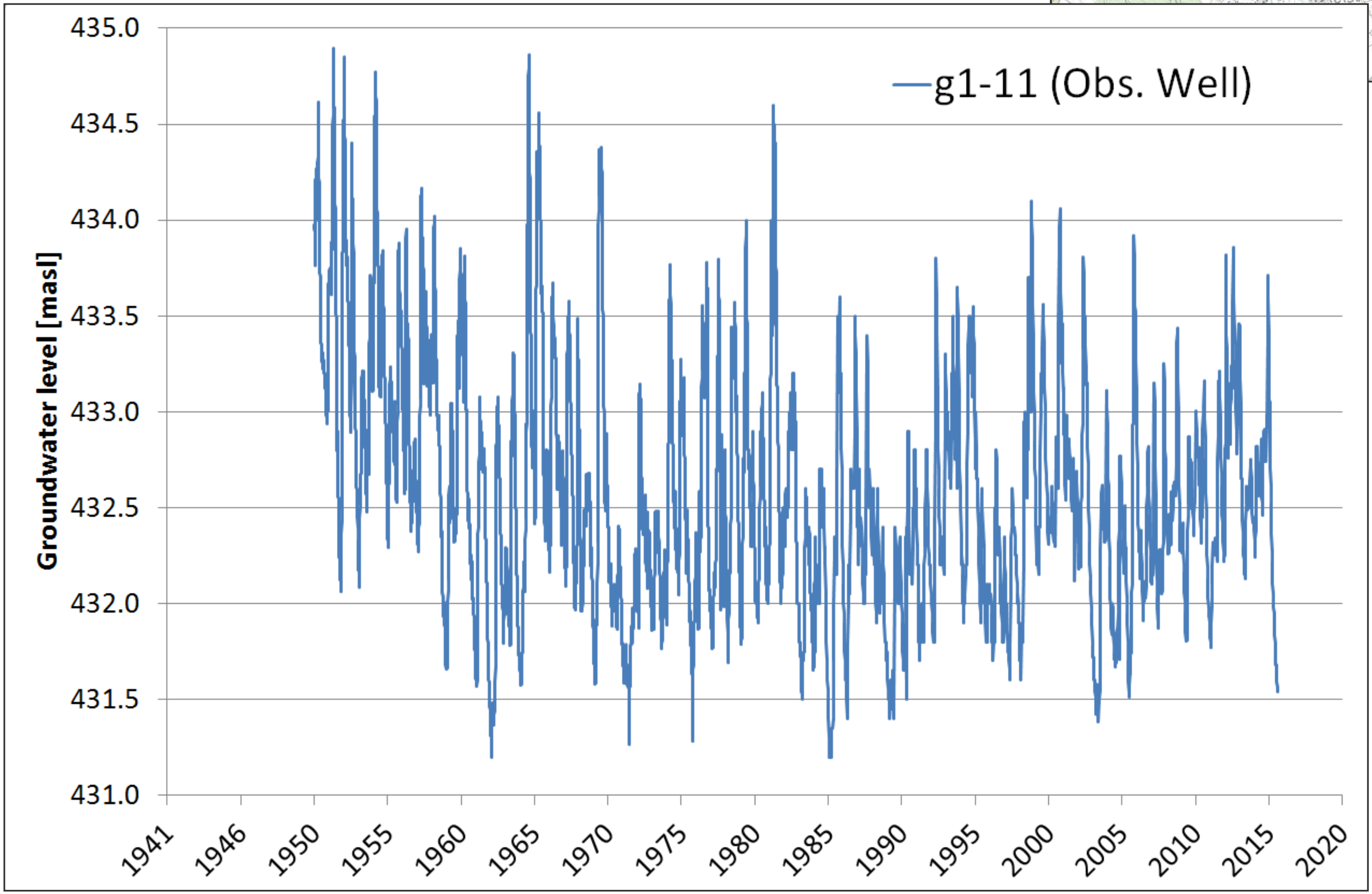
- Use of marker species to identify recharge sources
- Tracer experiments for leakages assessment
- Verify the assumption that water always exfiltrates the water mains
- Long-term measurements of groundwater level with a dense number of piezometer

Even if groundwater recharge remains poorly understood, considerable progress was made recently on the topic.

Observation well g1-11

Time series from 1951 - 2015





Observation well g1-18

Time series from 1984 - 2015