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Water in the GCC…Towards Efficient Management

Water well design and groundwater development in the Gulf region

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THE WORLDWIDE GROUNDWATER ORGANISATION

Wells have been around for a long time

- The earliest use of groundwater was presumably from springs, with hand-dug wells along river valleys following later
- A well in Cyprus may be between 9,000 and 11,500 old (Fagan, 2011)
- The shallow Hemudu well in the lower Yangtze coastal plain in China has been dated at around 5,600 years (C14 age for the wooden piles around the well; Zhou et al. 2011)
- The origins of the aflaj in the Gulf region go back 3,000 years
- **Good well design is still important in the 21st century for efficient management of groundwater abstractions**
  - **Increasing demands for good quality drinking water**
  - **Additional irrigation supplies for food production**
  - **Increasing industrial uses, etc**

(Photos BM)

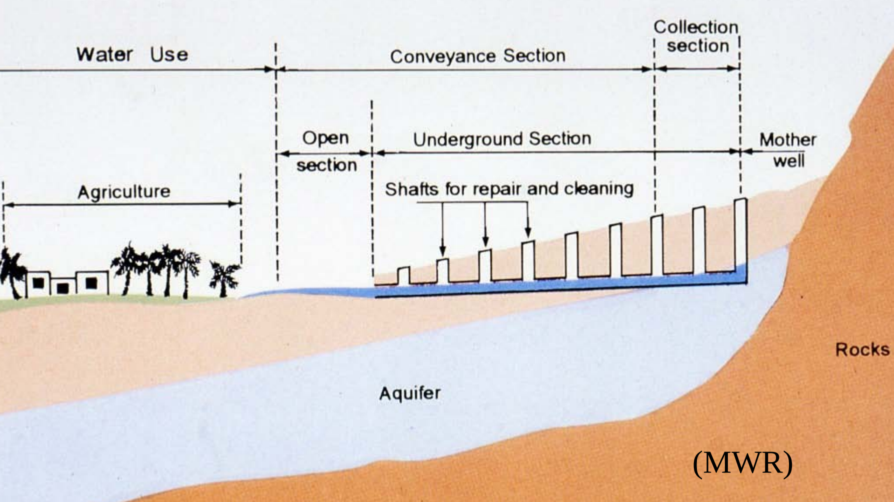
Ireland: St Moling’s well, Co. Carlow

Many thousands of pilgrims visited this well in the plague year 1348

Ireland: St Brigid's well, Kildare

Celebrations take place around the 1st February, the traditional first day of spring (feast of Imbolc in Celtic Ireland)

(Photos BM)



4,000 aflaj in Oman, of which 3,000 still flowing

Huge cultural significance

ENVIRONMENTAL ATLAS OF ABU DHABI EMIRATE

For more information go to **www.environmentalatlas.ae**

Explore the Environmental Atlas of Abu Dhabi Emirate and discover the unique and amazing environment of the Emirate.

IRON AGE TO PRE-ISLAM

DEVELOPMENT OF AFLAJ

As aridity gradually became a permanent feature of the Emirati environment, accessing groundwater increasingly became a challenge. Around Al Ain, *falaj* (plural *aflaj*) were dug to tap and distribute water using tunnels excavated underground to tap into subterranean aquifers. This unique and innovative method has been used in the Eastern Region of Abu Dhabi for 3,000 years. It precedes, by several centuries, similar water distribution systems known as *qanat* in Persia (Iran). The use of *aflaj* during the Iron Age some 3,000 years ago allowed the development of productive oases and the large-scale cultivation of date palms as a valuable commodity. The Iron Age itself lasted from 1250-300 BC.

Some of the Iron Age *aflaj* in Al Ain seem to have been abandoned by around 300 BC as aridity intensified across the region and, presumably, groundwater became more scarce or harder to extract. Some of the settlements, at Al Jabeeb, north of Al Ain, for example, were abandoned and covered by the advancing dunes. The use of *falaj* systems did not revive until the subsequent Islamic period.

Along with the domestication of the camel, which took place around the beginning of the Iron Age, the *falaj* system made an enduring cultural imprint across the Emirate. As the climate become more arid and agriculture could no longer depend upon seasonal rainfall, the *aflaj* made it possible for the oasis settlements to survive.

Wild or Domestic? ▶

When approximately 200 bones of young camels were recovered from excavations on the island of Umm al-Nar it was thought that this might provide evidence that the camel was domesticated in Arabia as early as 4,700 years ago. Discovery of a carving of a single-humped camel etched into stone in one of the tombs supported this theory.

However, it now appears the camels were not domesticated until much later. Recently excavated camel bones from Bronze and Iron Age levels at Tell Abraq (on the Sharjah-Umm al-Qaiwain border) and the Iron Age fortified settlement of Muweilah (in Sharjah Emirate) have revealed the presence of both wild and domesticated dromedaries at both sites.

Bones from the sites were analysed using a combination of biometric techniques and demographic data to distinguish wild from domesticated camels, which are smaller. It is now thought that domesticated camels did not appear in the Emirates until the Iron Age, perhaps 3,000 years ago.

Christianity ▶

The monastery settlement discovered on Sir Bani Yas – the only known physical evidence of early Christianity in south-eastern Arabia – is an archaeological site of international significance. A comparison of the finely decorated plaster fragments found at the site with other examples found in Kuwait and elsewhere suggests that the monastery was part of the Nestorian Church, otherwise known as the Church of the East. Named after Nestorius, bishop of Constantinople (modern day Istanbul) from AD 428 to 431, the Nestorians were expelled from the Greek Orthodox church for heresy although their teachings proved popular in Iraq and Iran and spread as far east as India and China.

Nestorian missionaries appear first to have reached the southern Gulf by the mid-5th century AD, although the Sir Bani Yas monastery appears to have been founded after that, perhaps in the late 6th century AD.

Studies of the pottery from the site suggest that it was occupied until around the early or mid-8th century AD, when it was abandoned. By this stage, the revelation of Islam to the Prophet Mohammed had already taken place, and in AD 630, the population of what is now Abu Dhabi and the rest of the Emirates had accepted the new faith. The apparent survival of the monastery for another century after the arrival of Islam is evidence of the tolerance of the area's early Muslim leaders, a tradition that continues today.

Since that time, the history and culture of the people of Abu Dhabi and of the broader region can be placed firmly into the Islamic context.

Anatomy of a Falaj ▶

A falaj has five basic components:

- Mother well(s)
- Tunnels
- 'Cut-and-cover' section
- Shari'a
- Surface channels leading to the irrigated fields

A suitable aquifer is essential for a falaj and a test well is usually sunk to determine if there is sufficient groundwater. Once the mother well has been excavated and ample water discovered, additional wells are excavated nearby which are connected by tunnels to the area of the main well to increase the overall water supply.

The tunnels are pierced with vertical shaft holes known as thuqba (plural thuqab) and are excavated at regular distances between the mother well and the irrigated fields.

The thuqab allow ventilation, the removal of debris and provide access to the tunnel whenever maintenance is necessary.

The 'cut-and-cover' section starts where the top of the underground tunnel comes close to the surface while the shari'a is where water flows to the surface to be distributed.

Aflaj in Abu Dhabi ▲

At least 5 Iron Age *aflaj* have been found in the Al Ain area. At Hili 15, a *falaj* dating from around 1000 BC has been excavated, revealing surface channels, a shari'a with sluice gates still in situ, a cut-and-cover section and 2 shafts. A nearby, fortified site was also found that might have been the administrative centre for controlling the *falaj* system, which was a communal infrastructure.

At Bida Bint Saud, north of Al Ain, 2 more Iron Age *aflaj* were discovered and an area of previously irrigated land has been identified. The shari'a of the first *falaj* was found at a depth of 3.8 metres below the present ground surface with steps descending from the northern side. While excavating the steps, fragments of Iron Age pottery were also discovered. 2 further examples have been identified at Nahil and Al Jabeeb, also to the north of Al Ain.

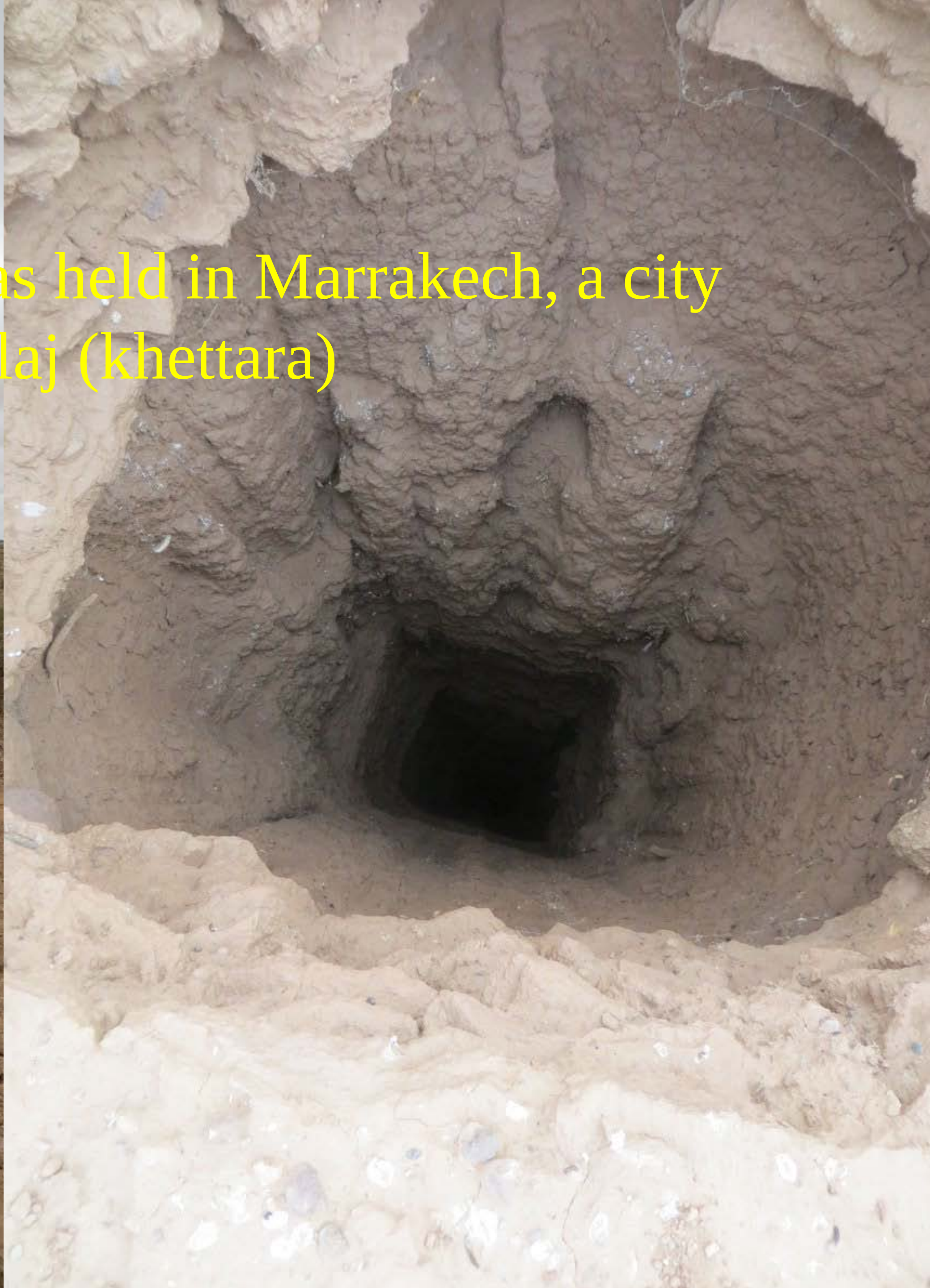
Pre-Islamic Civilisations

The Iron Age was followed by a period when Abu Dhabi came under the influence of major empires that emerged across Europe and Western Asia. These certainly controlled the maritime trading routes of the Gulf, although there is little evidence they exerted extensive political control on the mainland.

AGEDI

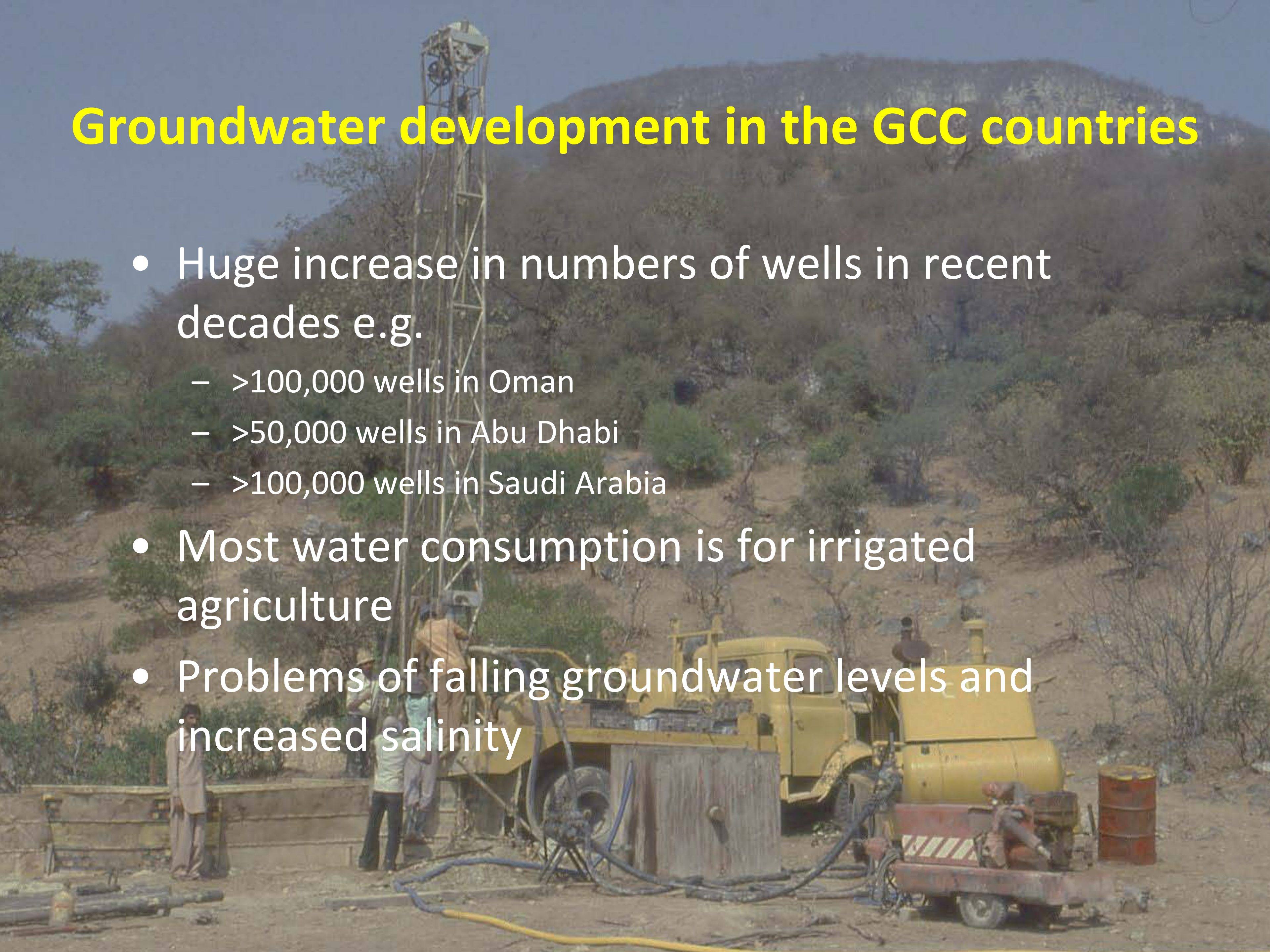
هيئة البيئة - أبوظبي
Environment Agency-ABU DHABI

The 2014 IAH congress was held in Marrakech, a city originally supplied from aflaj (khettara)



Hand-dug wells common in Gulf region

Modern drilled wells

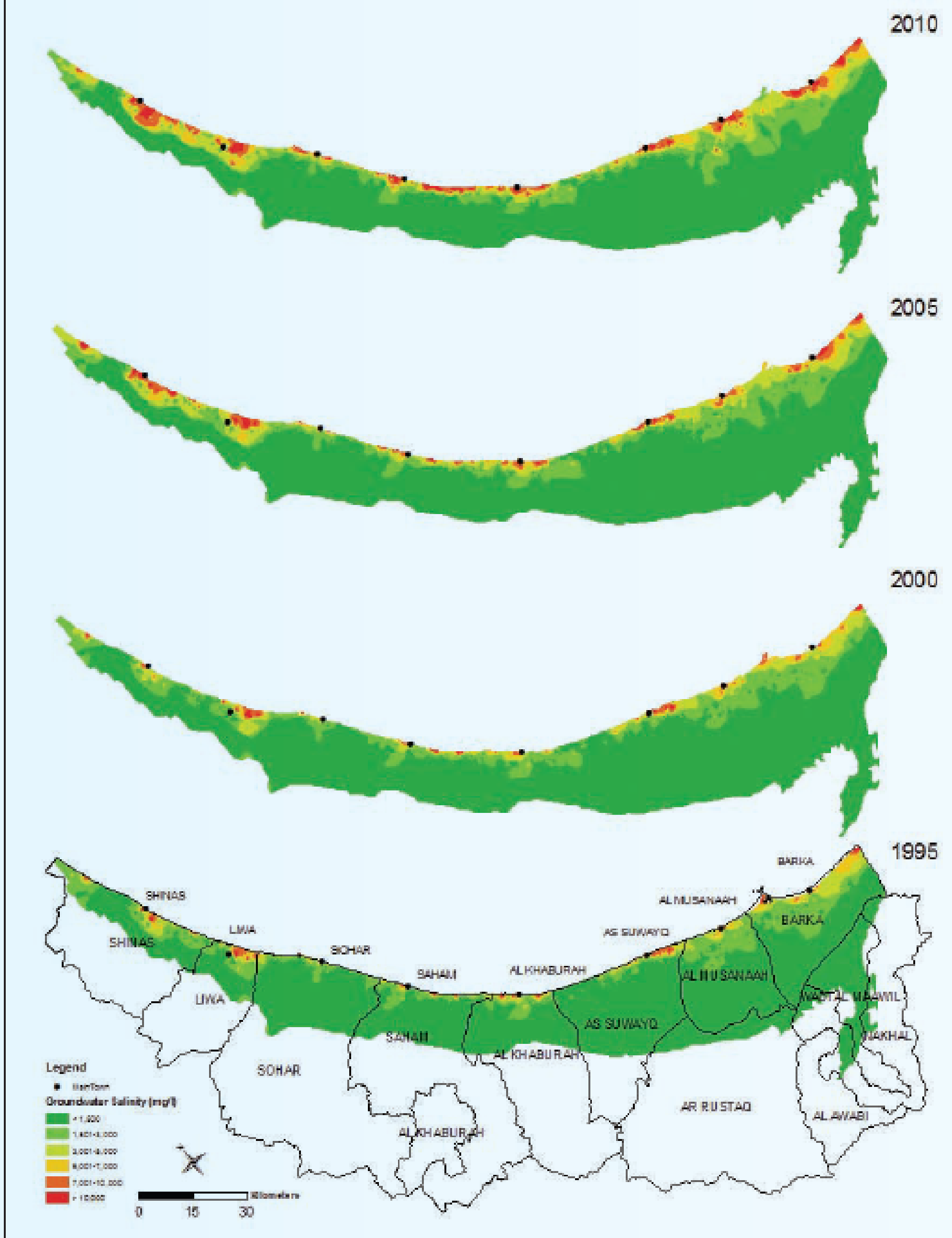


Groundwater development in the GCC countries

- Huge increase in numbers of wells in recent decades e.g.
  - >100,000 wells in Oman
  - >50,000 wells in Abu Dhabi
  - >100,000 wells in Saudi Arabia
- Most water consumption is for irrigated agriculture
- Problems of falling groundwater levels and increased salinity

Groundwater salinity, Al-Batinah Oman

Figure 27. The growth of sea water intrusion in Al-Batinah 1995-2010



Source: ICBA, 2011.

(Ministry of Agriculture and Fisheries Oman, and International Centre for Biosaline Agriculture, Dubai, 2012)

Groundwater salinity, Abu Dhabi

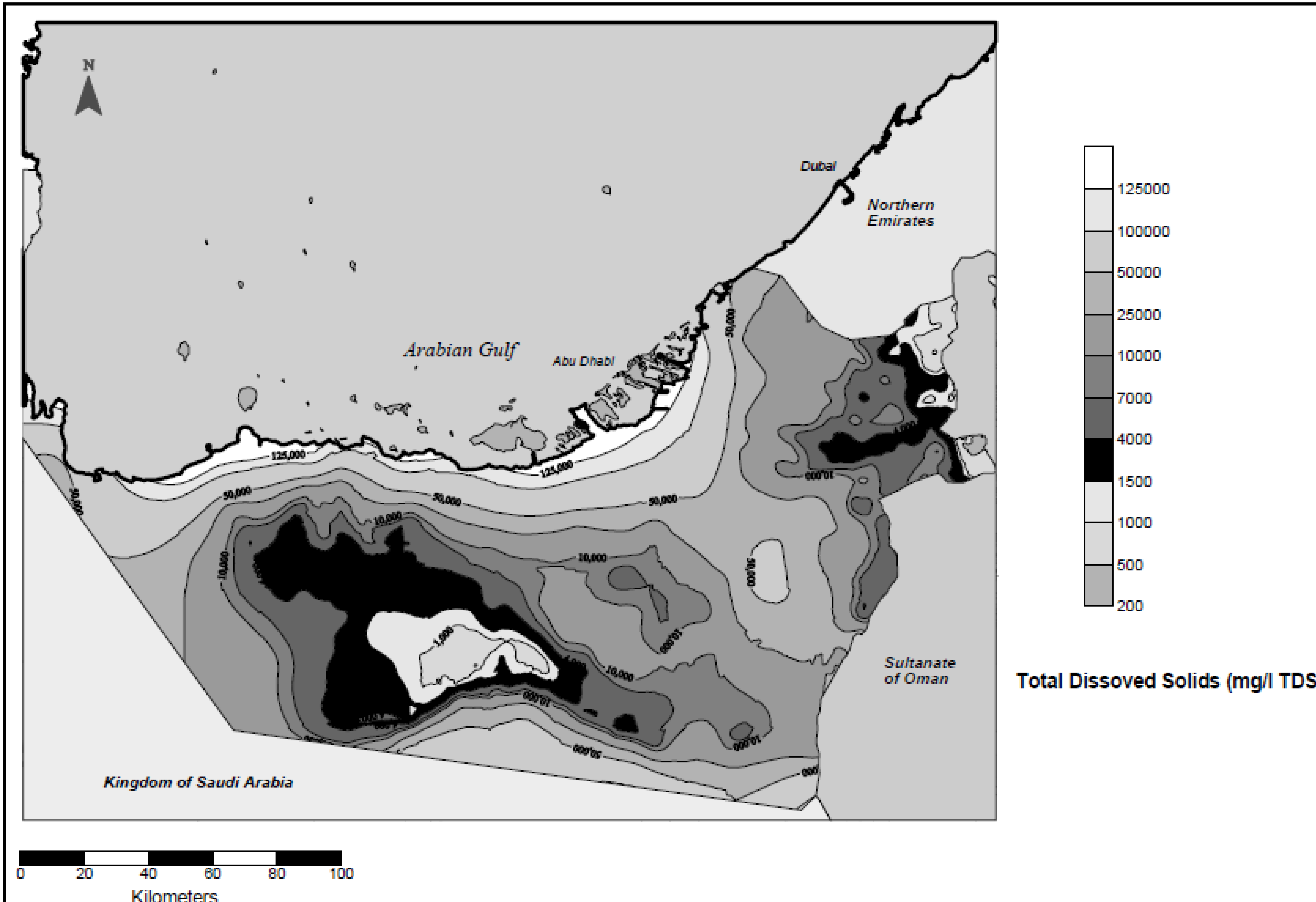


Figure 5 Groundwater Salinity of the Upper Aquifer (adapted from GTZ el al, 2005

(Brook et al., 2006)

Main aquifers in the Gulf region

- Shallow wadi gravel aquifers
- Deeper bedrock aquifers e.g.
  - Palaeozoic Saq and Wajid formations (sandstones)
  - Mesozoic Minjur and Wasia formations (sandstones)
  - Tertiary Umm er Radhuma, Damman and Fars formations (carbonates)

Groundwater recharge

- Wadi gravel aquifers receive modern recharge from flood infiltration (especially near mountains)
- The deeper bedrock aquifers receive little or no recharge

Groundwater management options which are being implemented across the region include:

- Restricting new wells and the deepening of existing wells through permitting
- More efficient water use
  - Modern irrigation systems
  - Domestic water metering
  - Leakage control
- Re-prioritisation of groundwater use
- Use of brackish groundwater
- Replacement of groundwater with wastewater recycling
- Construction of recharge dams

Photo Geoff Wright

Well design and operation can contribute to more efficient management of groundwater resources

We will now consider:

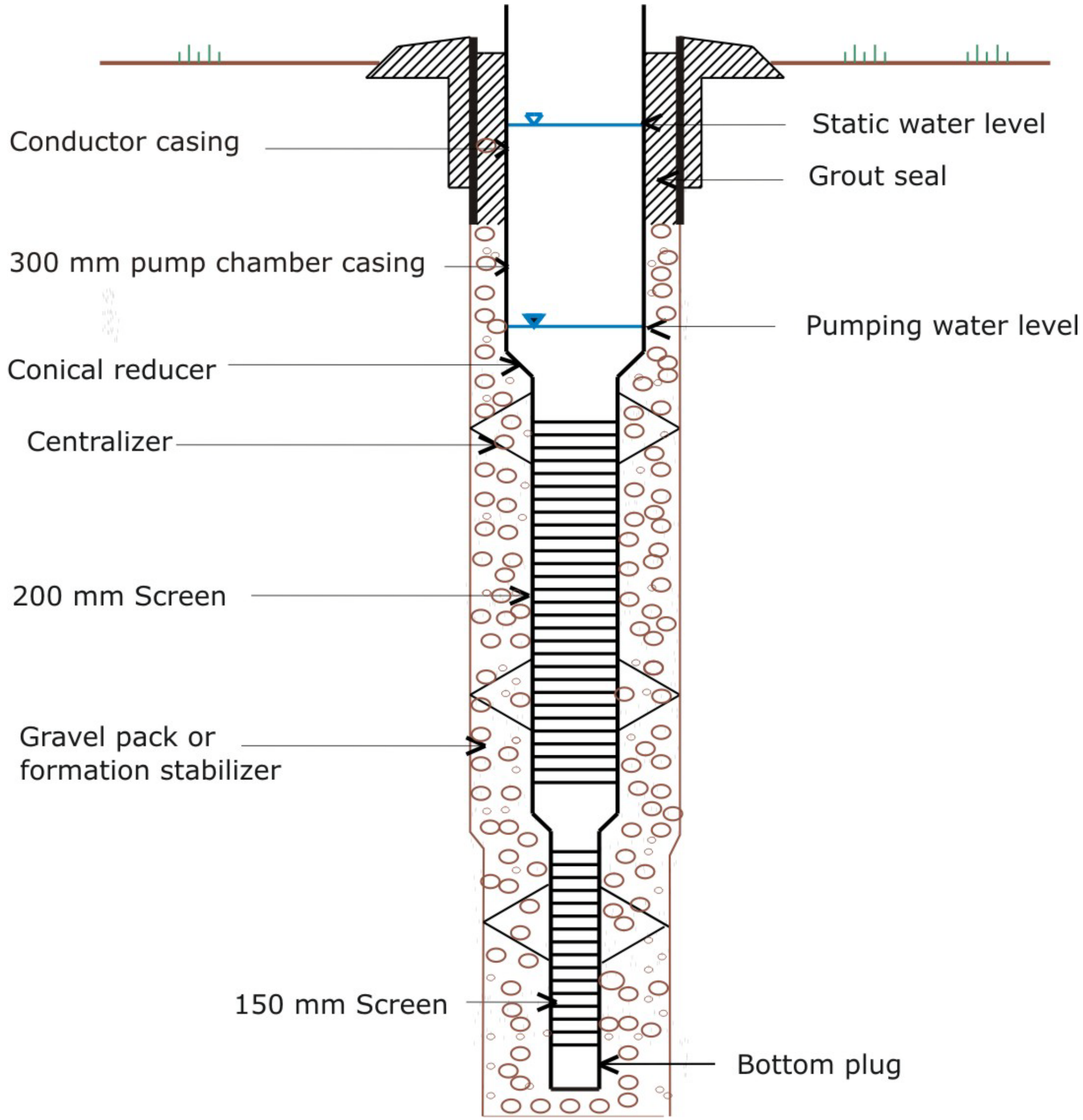
- Hydraulic design to avoid unnecessary energy losses in a well
- Proper sealing of the upper section of a well to minimise pollution risks, and securing the well structure against flooding
- Effects of declining water levels on well performance
- Assessing the reliable yields of wells using operational data

We will focus on wells in **sand and gravel** and **sedimentary rock** aquifers

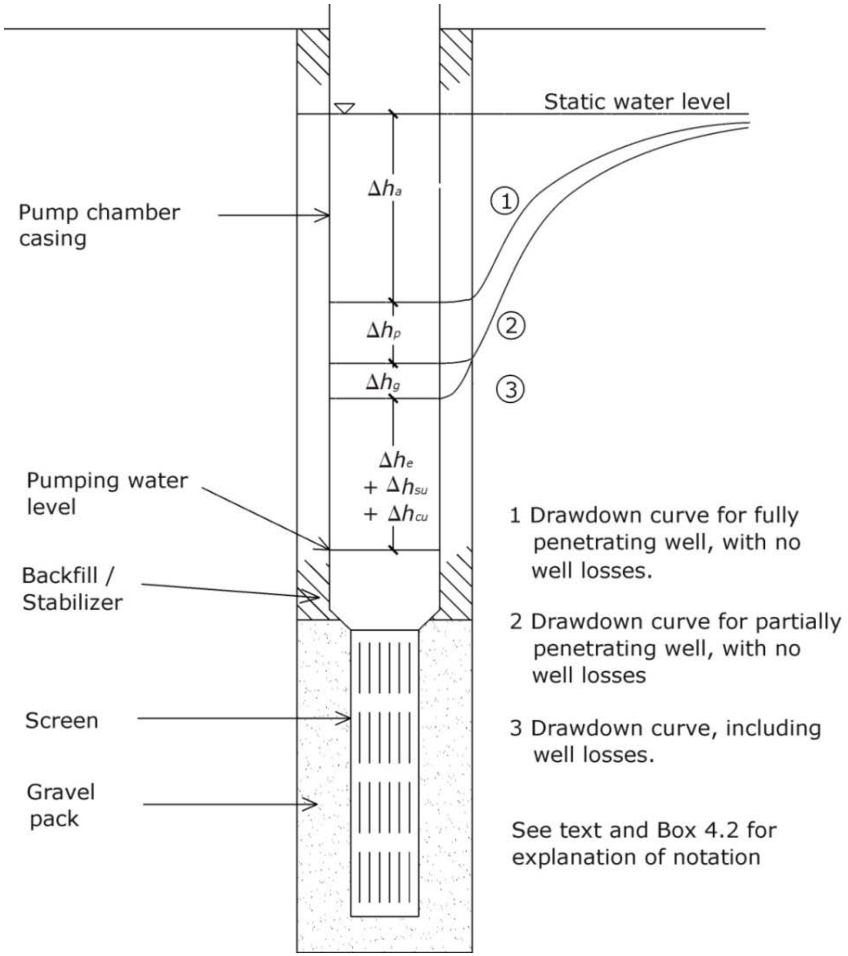
Wells in sand and gravel aquifers

- Lining of the full well is necessary for stability, even though the wadi gravels are often cemented
- The design of the screen and casing affects the hydraulic performance of the well
- Corrosion-resistant materials are essential (especially because of often high salinities)

Schematic well design in a sand and gravel aquifer



Head loss at a well



$$\Delta H = \Delta h_a + \Delta h_p + \Delta h_g + \boxed{\Delta h_e + \Delta h_{su}} + \Delta h_{cu}$$

(Misstear B, Banks D & Clark L (2006) *Water wells and boreholes*. J Wiley & Sons)

Screen entrance velocity

$$v_e = \frac{Q}{\pi D L_s A_{eo}}$$

where Q is the discharge rate, D and L_s are the diameter and length of the screen, respectively, and A_{eo} is the effective open area of the screen

Much debate about maximum permissible entrance velocity.

Many people have advocated maximum v_e of 0.03 m/s.

Others suggest maximum of 0.6-1.2 m/s is OK.

Limit not included in current AWWA standard (ANSI/AWWA A100-06) - previous edition had limit of 0.46 m/s - nor in new NGWA water well construction standard (ANSI/NGWA-01-14).

Well upflow velocity

Less discussion in the literature about well upflow velocity (v_u), which can be calculated from:

$$v_u = \frac{Q}{\pi\left(\frac{D}{2}\right)^2}$$

where D is the diameter of the screen or casing

Max v_u generally given as 1.5 m/s

Example of an equation for calculating screen upflow head losses:

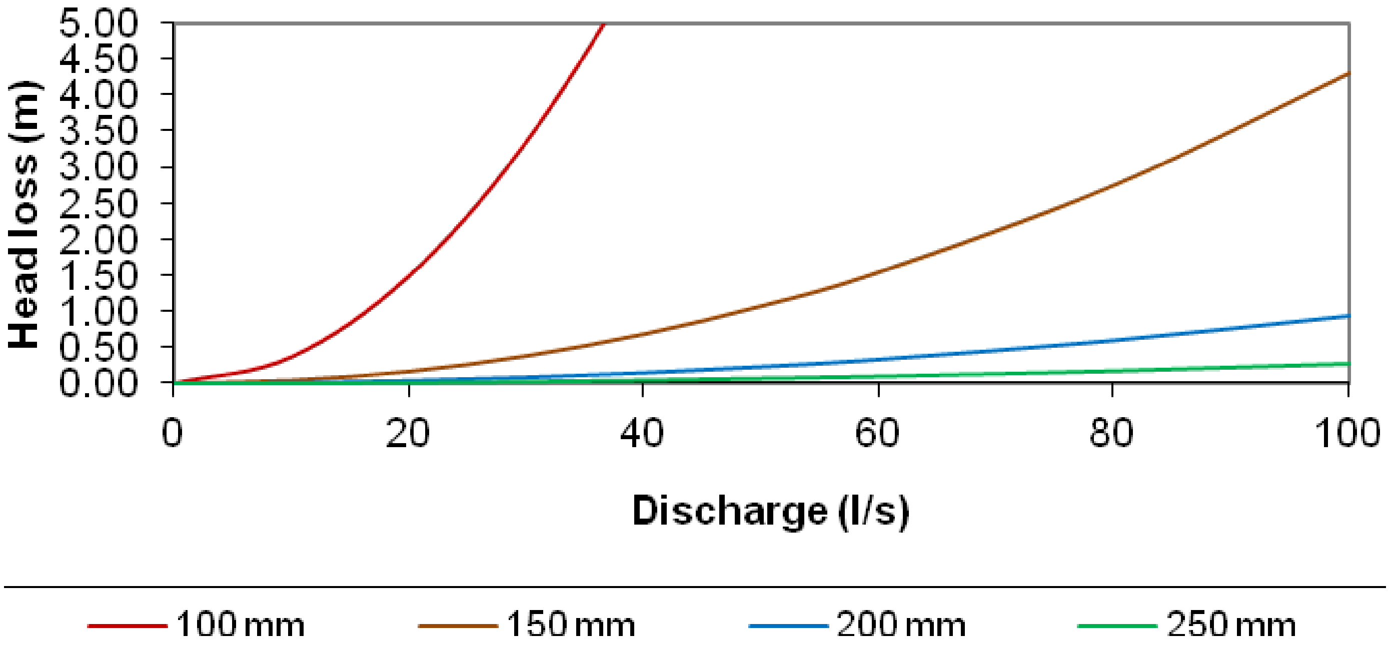
$$\Delta h_{su} = 3.428 q^2 n^2 L_s^3 D^{-\frac{16}{3}}$$

(Manning-type equation: Bakiewicz *et al*., 1985)

where Δh_u is the upflow head loss (in m), q the flow rate into the screen per unit length of screen ($m^3\ s^{-1}\ m^{-1}$), n the Manning roughness coefficient, and L_s and D are the length and diameter of the screen (m)

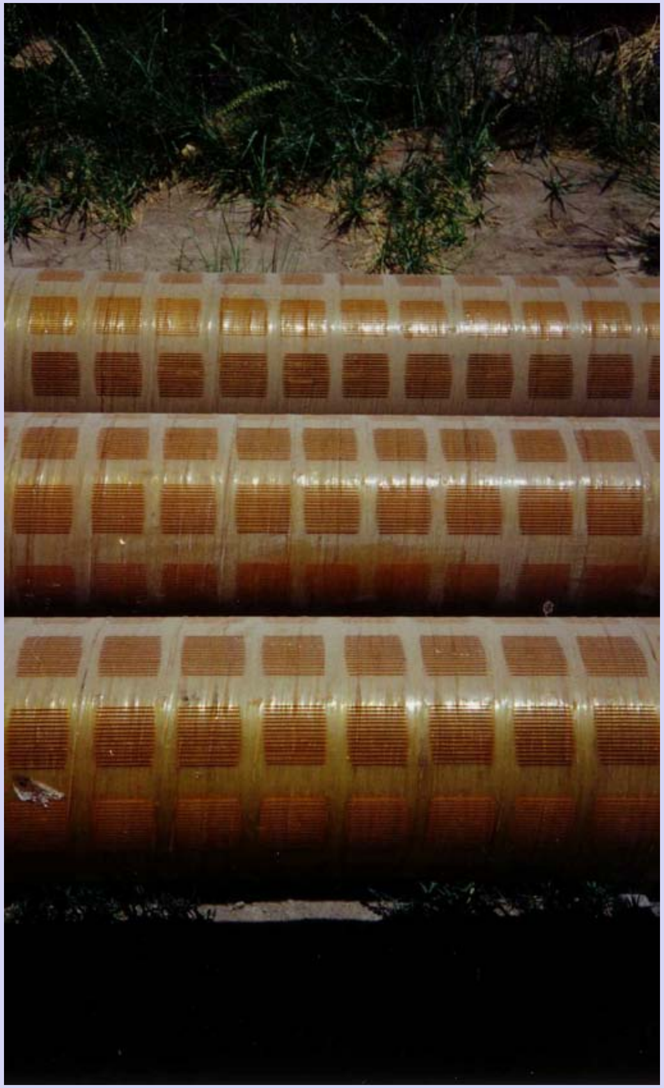
Calculated screen upflow head losses

(calculated using Manning-type formula; 30 m slotted pipe)



(Misstear B, Banks D & Clark L (2006) *Water wells and boreholes*. J Wiley & Sons)

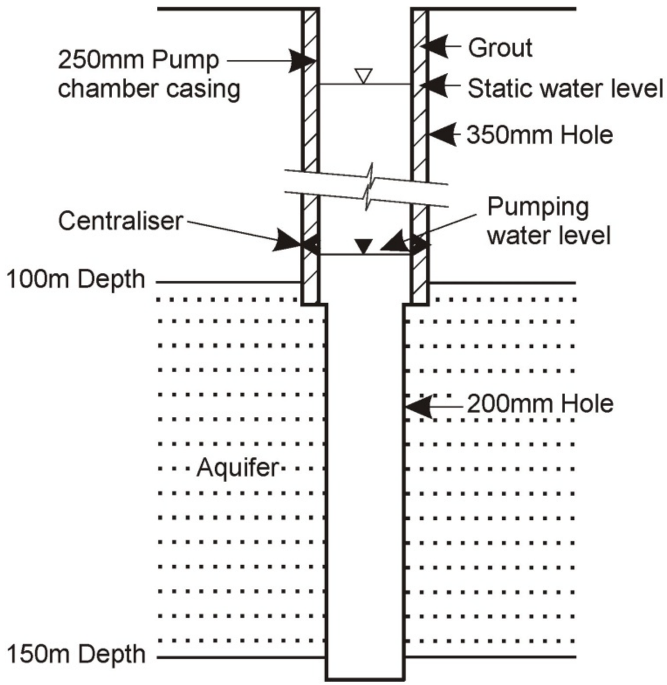
Need to choose corrosion-resistant materials



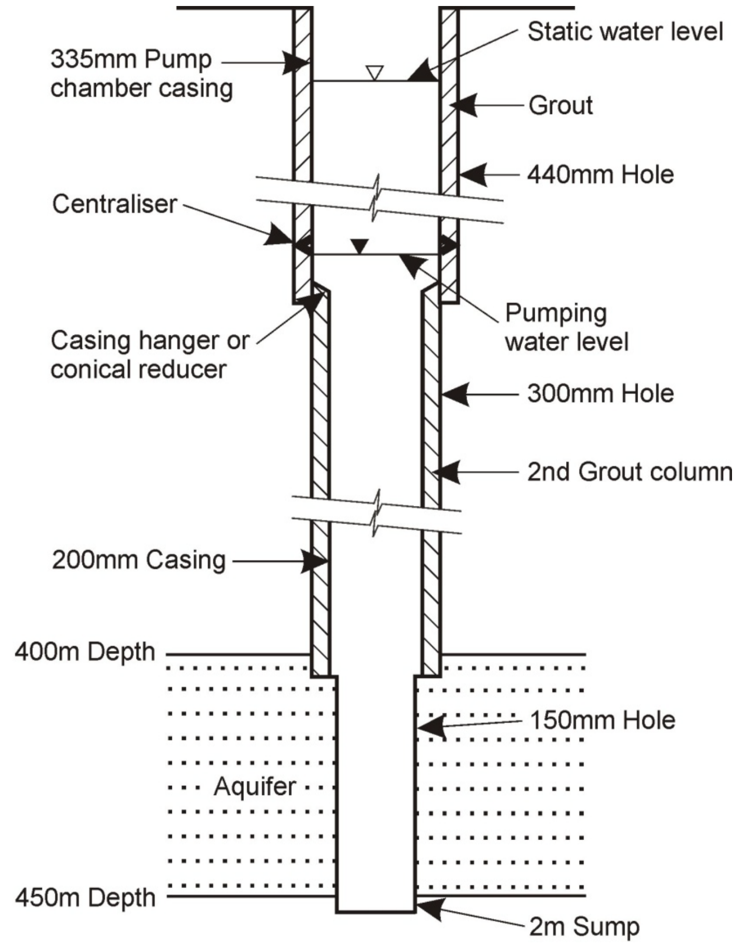
Well design in sedimentary rock aquifers

- Many of the aquifers in GCC countries occur in sedimentary rocks such as limestones and sandstones
- Many of these aquifers are characterised by fracture-flow

Well designs for sedimentary rock aquifers



(a) Shallow aquifer

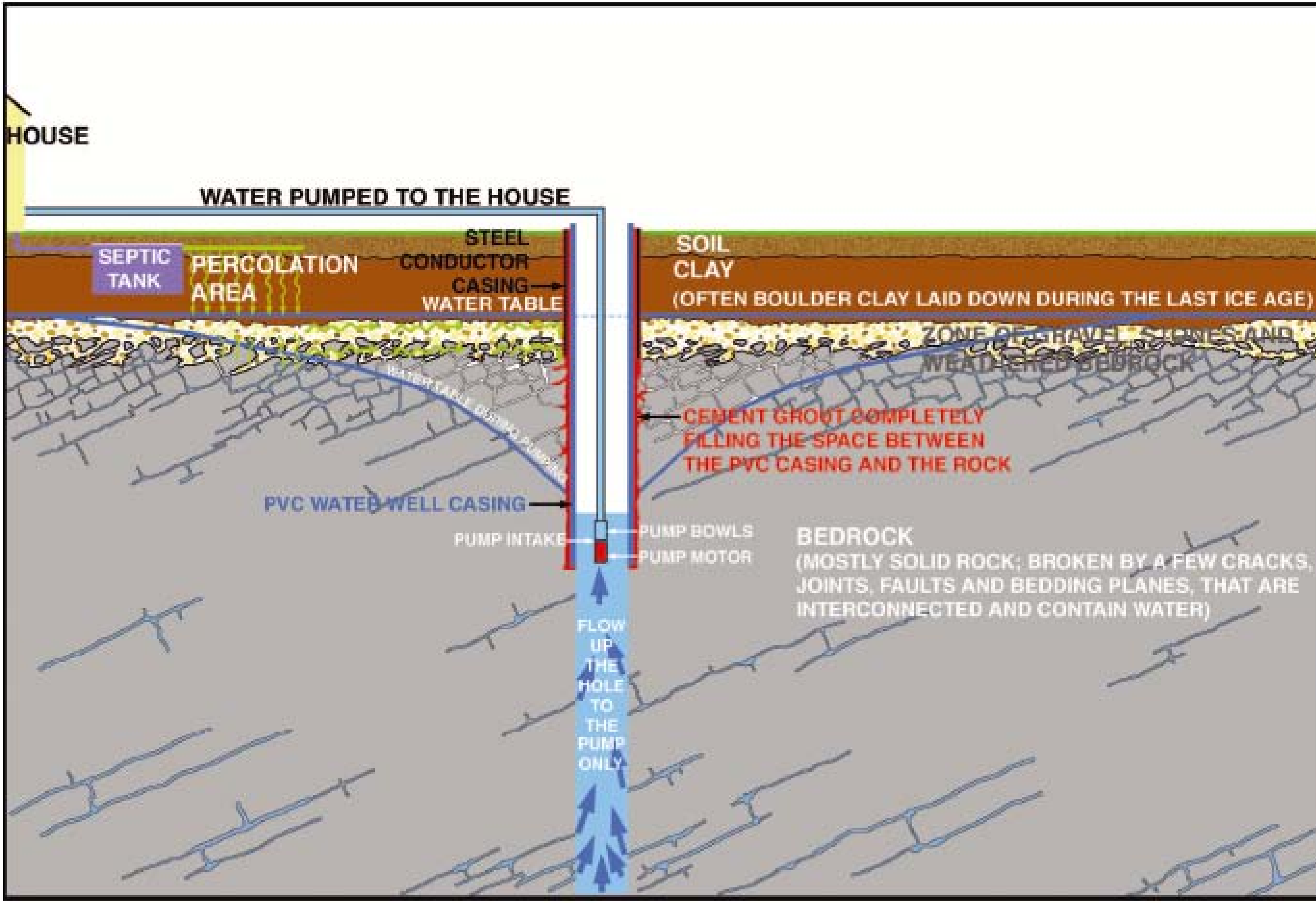


(b) Deep aquifer

Note:
Pump chamber diameter should be sized to fit pump diameter. Bottom of chamber must be below lowest forecast water level. A final 200mm hole diameter allows a 150mm screen to be fitted if necessary.

(Misstear B, Banks D & Clark L (2006) *Water wells and boreholes*. J Wiley & Sons)

Key issue in fractured-rock wells is grouting of upper casing



(Institute of Geologists of Ireland (2007) *Water well guidelines*)

Borehole in Co. Offaly, Ireland

Awareness surveys amongst private well owners in Ireland

	Total % aware	Hand-dug well % aware	Borehole % aware
Well Diameter	49	64	44
Well Depth	63	71	61
Liner Presence	61	68	60
Seal Presence	22	39	17
Pump Type	59	61	60

Very low levels of awareness about the presence of a sanitary seal

(Hynds P, Misstear B & Gill L (2013) Unregulated private wells in the Republic of Ireland: Consumer awareness, source susceptibility and protective actions. *Journal of Environmental Management*, 127: 278-288)

Well grouting operation in Nejd to block off saline aquifer

Where there is a reduction in the number of fractures with depth, a long section of grouted upper well casing will reduce the yield

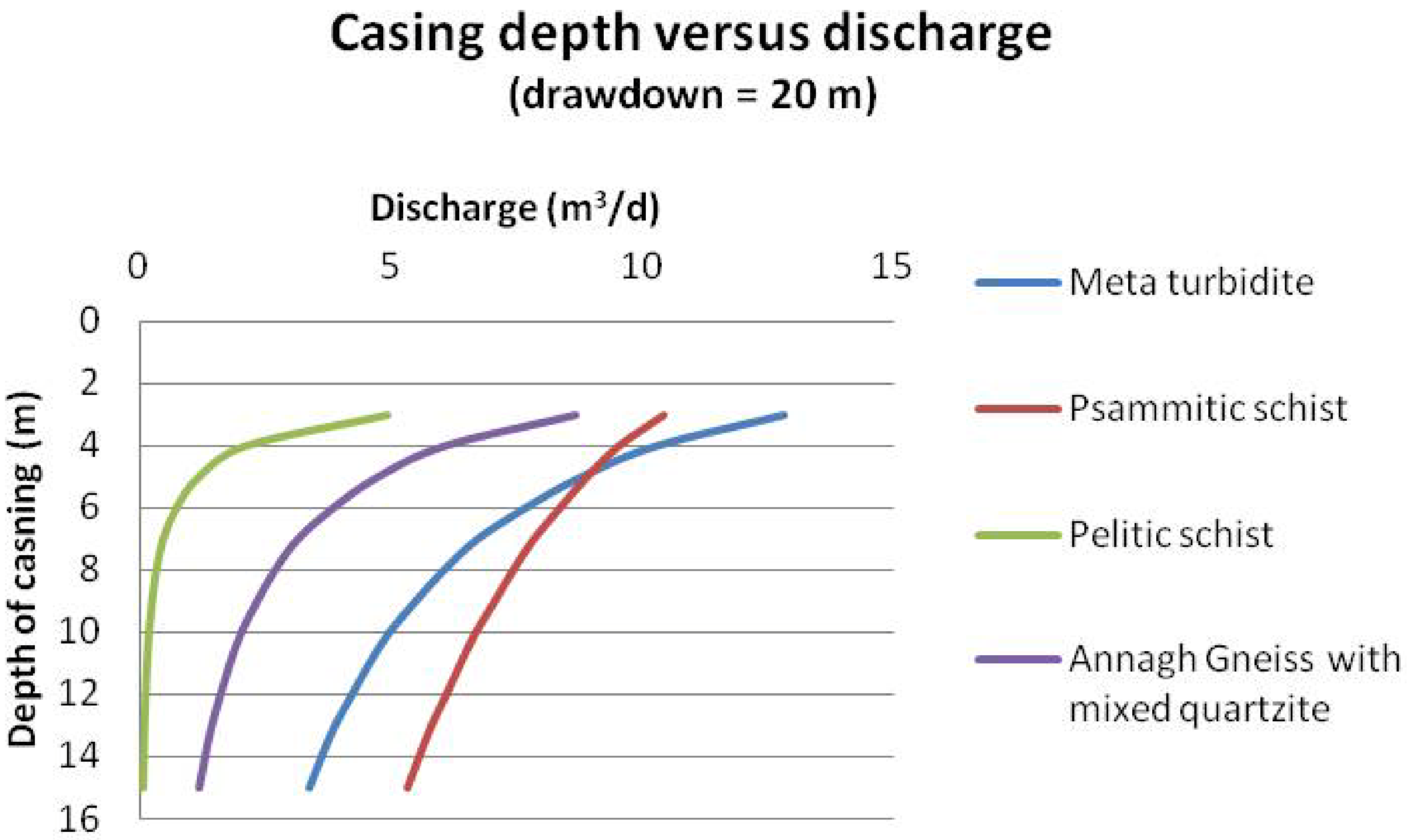
Recent study of crystalline rock aquifers in Ireland expressed relationship as an inverse power law:

$$K = Ad^{-B}$$

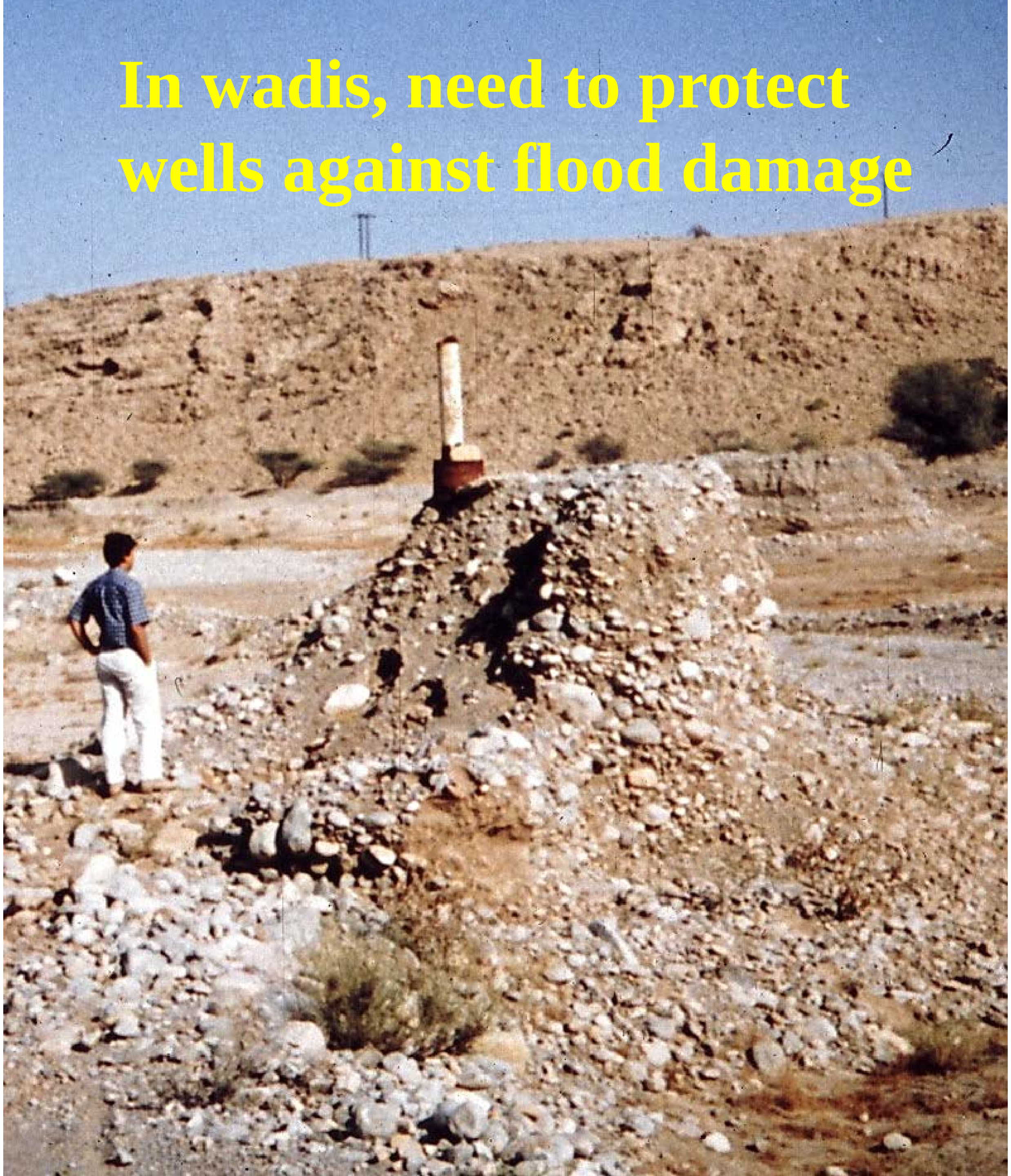
where *d* is depth below top of bedrock and *A* and *B* are coefficients relating to the particular rock units

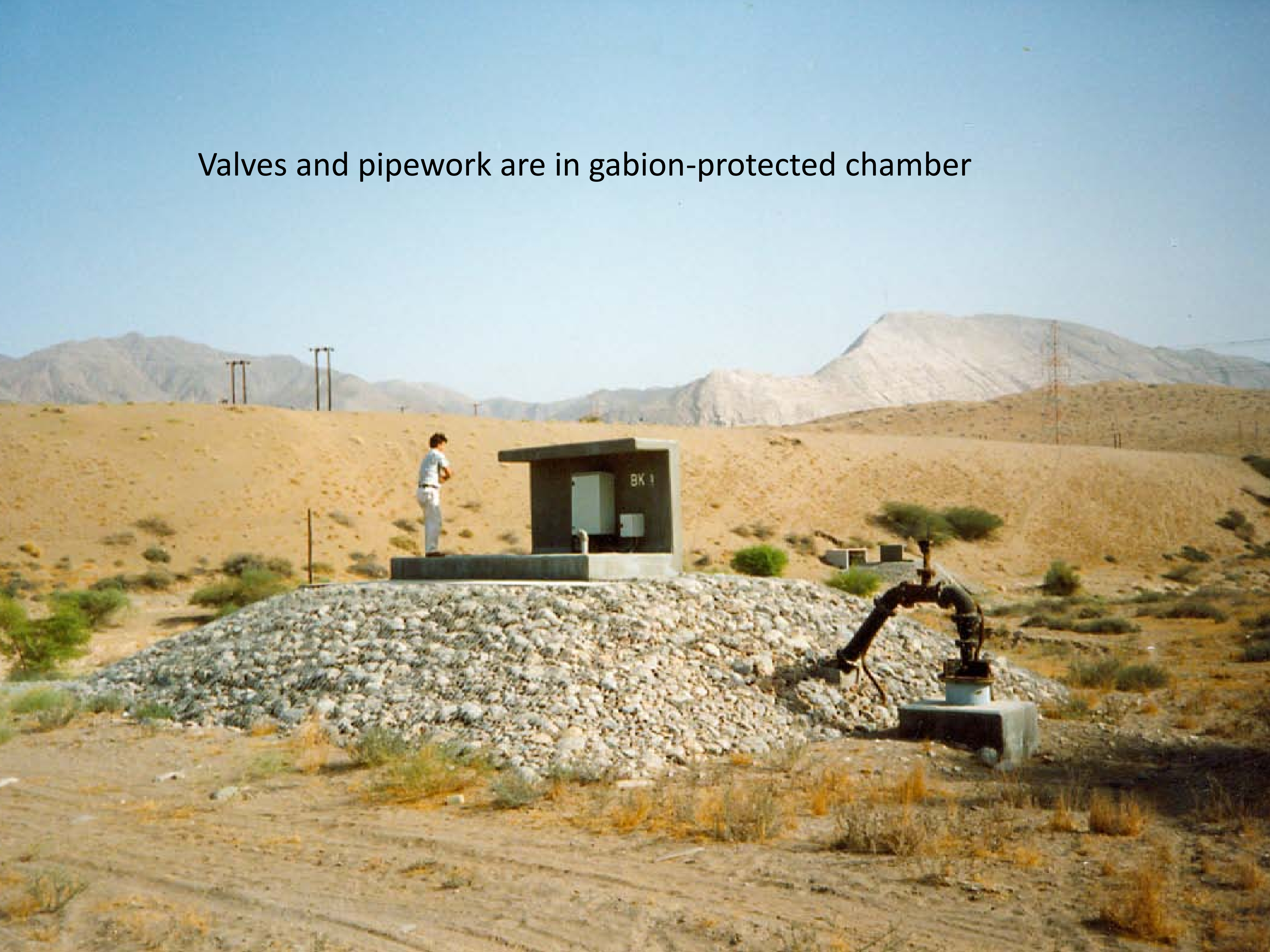
There may be a compromise required between using a longer section of grouted upper casing to provide good sanitary protection, or using a shorter length to maximise well yield

Can use Logan relationship and assumptions on available drawdown to calculate effect on yield of increasing the upper casing



(Misstear B (2012) Some key issues in the design of water wells in unconsolidated and fractured rock aquifers. *Acque Sotternanee*, *Italian Journal of Groundwater*, AS0206: 009-017)

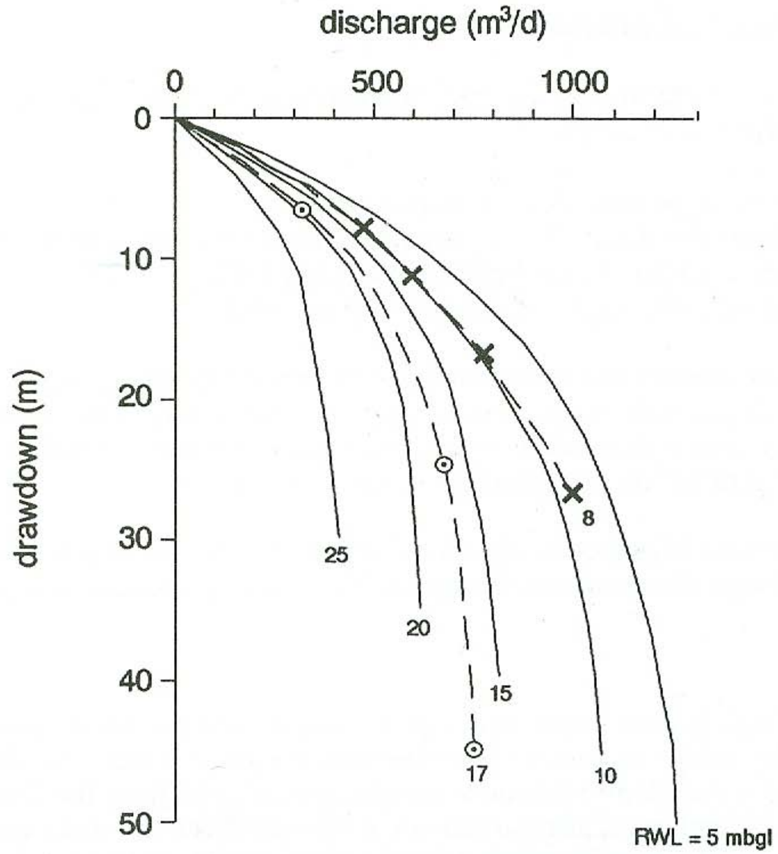

In wadis, need to protect
wells against flood damage



Valves and pipework are in gabion-protected chamber

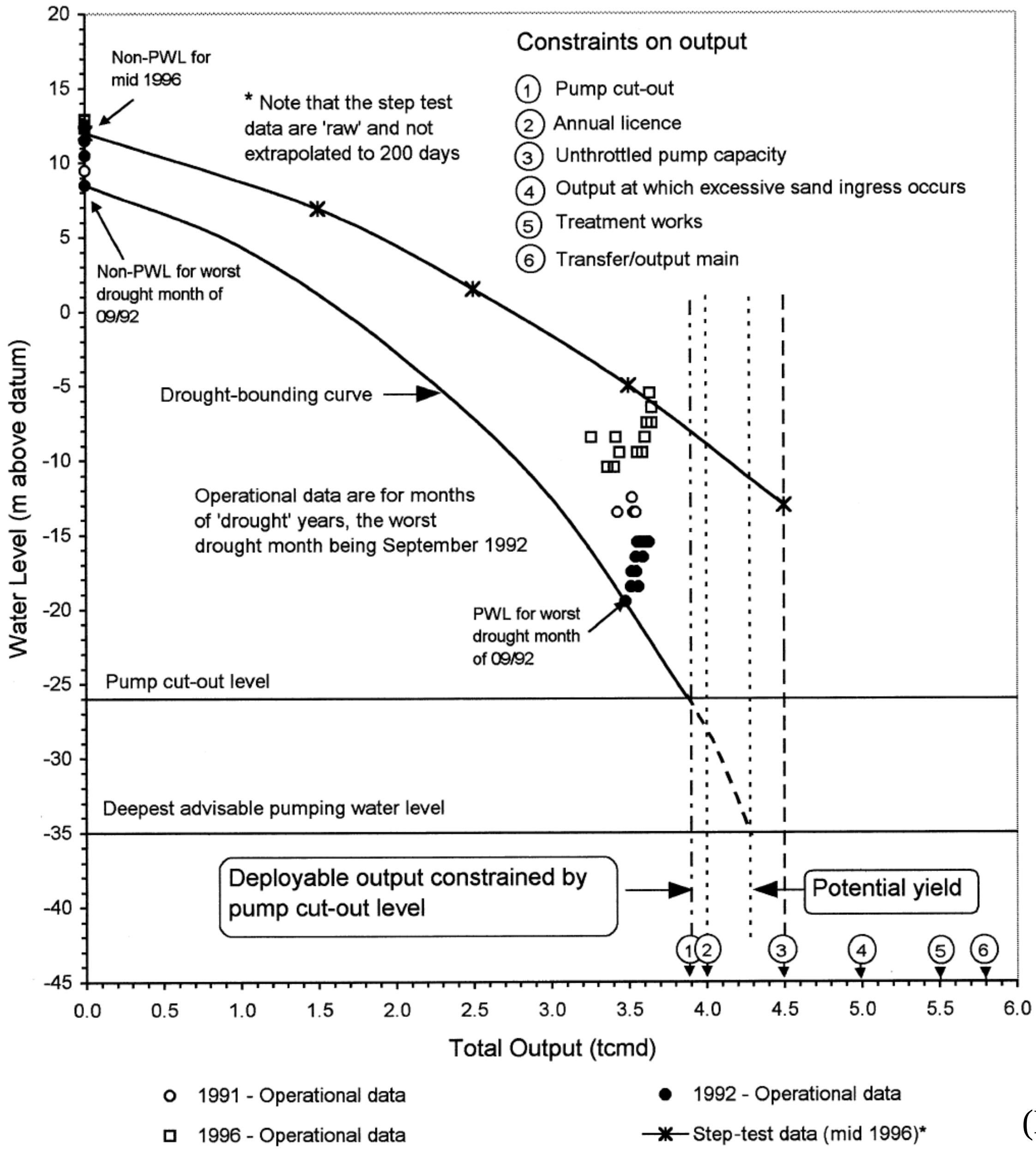
Monitoring and evaluating the performance of operational wells:

Effect of falling water levels on well yield



(Howsam et al., 1996)

Using well operational data to estimate reliable well yield (UK example)



(Misstear & Beeson, 2000)

Conclusions

- In the GCC region, extensive groundwater pumping has lead to falling groundwater levels and increased water quality problems in some areas
- Improved well design and operation can contribute to more efficient management of natural resources
- Good well design can avoid unnecessary head losses and hence lead to reduced pumping costs
- Proper headworks, including grout seals, can reduce the risks of well pollution and improve well security
- Collecting operational data is important for predicting reliable well yields