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**GROUNDWATER CONTROL FOR CONSTRUCTION: LESSONS FROM THE PAST AND
CHALLENGES FOR THE FUTURE**

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Abstract

Groundwater control encompasses the range of techniques used to allow construction projects such as tunnels or basement excavations to be carried out in dry and stable conditions. Two principal approaches can be used: groundwater control by pumping, which lowers groundwater levels in the vicinity of an excavation; or groundwater control by exclusion, which relies on low permeability cut-off walls around the excavation. Existing groundwater control technologies have been developed pragmatically, often on an empirical basis, in response to groundwater problems encountered on construction projects in the past. In the future, it is unlikely that there will be significant changes in groundwater control technology. The real challenge for the future of groundwater control methods will be the need to better predict, monitor and mitigate the impacts on the groundwater environment. The greater focus on environmental impacts from groundwater control is partly due to increasing regulation of groundwater control works, and partly because of the increasing importance of environmental management in the planning of construction projects.

Introduction

Groundwater control is the process of controlling groundwater levels and flows, typically on a temporary basis, to allow excavations to be made below groundwater level in dry and stable conditions. Established temporary works construction techniques have been developed¹ to allow groundwater control to be routinely achieved in a wide range of geological conditions, for diverse projects from small shallow excavations to very large and deep tunnels and underground caverns.

Dealing with groundwater during construction, however, has not always been routine. Modern practice has evolved, like many engineering processes, based partly on advances in theoretical understanding, and partly on empirical rules developed from past experience (both successes and failures). In fact, possibly because of the significant empirical element, the traditional view of groundwater control is that it is an art best left to the cognoscenti.

Future improvements in practice are likely to be derived similarly in an empirical fashion, in response to changing requirements for the execution of construction projects. This paper will consider the factors driving change in construction (such as the need to limit environmental impacts and the increased re-use of brownfield sites), and challenges for the future development of groundwater control technology will be identified.

The need for groundwater control

When sub-surface engineering works such as tunnels or basements penetrate below groundwater level, the presence of groundwater has the potential to cause significant problems. Groundwater inflows, and the associated excess pore water pressures, can have a dramatic destabilising effect on soils in and around an excavation. The shear strength of a soil is directly related a parameter known as effective stress σ' , defined in Terzaghi's equation of effective stress²

$$\sigma' = \sigma - u \quad (1)$$

where σ is the total stress resulting from the self weight of the soil and any external loads, and u is the pore water pressure in the soil. Shear strength τ is related to effective stress by the Mohr-Coulomb failure criterion:

$$\tau = \sigma' \tan \phi' \quad (2)$$

where ϕ' is the angle of effective friction of the soil.

Applying equations (1) and (2) to the excavation in Figure 1 shows that for a soil element immediately below the base of the excavation, removal of the soil will reduce total stress σ . If pore water pressure u is not reduced by artificial means, then effective stress will reduce, resulting in a corresponding reduction in the soil's shear strength. This will reduce the ability of the soil immediately around the excavation to sustain loads, and is likely to result in instability of the sides and base of the excavation. There are numerous examples of excavations that have experienced severe instability as a result of inadequate control of groundwater^{3,4}.

Consideration of equations (1) and (2) presents a simple solution to avoid groundwater-induced instability in excavations – control of groundwater locally around the excavation in such a way as to manage pore water pressures and prevent effective stresses falling to unacceptably low levels. This is the basis of the group of construction techniques collectively known as groundwater control.

There are two principal types of groundwater control: pumping and exclusion. Each takes a radically different approach to attaining the same objective, avoidance of groundwater-induced instability.

Groundwater control by pumping (Figure 2a) involves installing an array of sumps or wells in or around an excavation, and pumping from those wells to temporarily lower groundwater levels to below the base of the excavation. The lowering (or 'drawdown') of groundwater levels will reduce pore water pressures around the excavation, and prevent effective stresses falling to unacceptable levels. This approach is known as dewatering or construction dewatering.

The alternative approach of groundwater control by exclusion (Figure 2b) involves installing a notionally impermeable physical barrier or cut-off wall around the excavation. If the barrier can be driven deep enough to intersect a very low permeability geological stratum below the excavation, the net result is to effectively isolate the excavation from the surrounding groundwater regime. Once any water trapped within the area enclosed by the cut-off wall has been pumped out, pore water pressures within the excavation should be very low, ensuring that effective stresses do not fall to unacceptable levels.

Table 1 presents a summary of the most commonly used methods of groundwater control. Figure 3 summarises the range of performance of pumped groundwater control systems, in relation to two key parameters, drawdown of groundwater level, and soil permeability.

Early technology

During the first half of the 19th century, steam driven pumps were introduced into civil engineering practice and were used by, among others, Telford and I K Brunel. Perhaps the first use of pumping technology as part of a rational plan to control groundwater for an

engineering project was in the 1830s by Robert Stephenson for the Kilsby Tunnel on the London to Birmingham railway⁶.

Following repeated inundation of the tunnel by groundwater during construction, Stephenson established a line of pumping wells, drained by steam pumps, alongside the line of the tunnel. Many months of pumping (at up to 490 m³/hour), directed using Stephenson's close observations of the changes in groundwater levels resulting from pumping, successfully controlled groundwater and allowed the tunnel to be completed. The approach of using an array of groundwater abstraction points, located outside the excavation itself was radical at the time, but set a template for groundwater control by pumping that is still used today.

During the 19th century early generations of groundwater exclusion methods were developed in the mining industry in the form of close fitting 'tubbing' used to line shafts and keep water out. These tubbings were initially made from timber, and later from cast iron. In the very early years of the 20th century British mines made the first use of artificial ground freezing (where chilled brines were used to freeze groundwater) and the 'cementation' method where cement-based grouts were used to prevent groundwater flow through pores and fissures in soils and rocks⁷. These techniques were soon added to the repertoire of civil engineers.

During the first half of the 20th century there were notable developments in practical groundwater control technology, often resulting when improved equipment fell into the hands of engineers faced with the need to work below the water table. In North America, in 1925 Thomas Moore introduced improvements to the small diameter wellpoints used for shallow dewatering. His system, which allowed the wellpoints to be jetted into the ground using high pressure water, continues to form the basis of wellpoint systems around the world, more than 80 years later⁸.

In Britain, H. J. B Harding (later Sir Harold) was involved, through his work for the contractor Mowlem, in the introduction of the deep well method to Britain. Deep wells using submersible pumps had been used for groundwater lowering in Germany from 1896 onwards, but were not a method recognised in Britain. In the 1930s Mowlem took up licence agreements with Siemens Bau-Union to use their geotechnology patents for, among other things, groundwater lowering by deep wells. Harding used ten deep wells, each equipped with a Siemens Submersible pump, during construction of the King George V graving dock at Southampton^{9, 10}. This groundwater control system was based on exactly the same physical principles as Stephenson's Kilsby Tunnel a century earlier, but with the technology updated to contemporary levels.

Into the modern era

In the years from the immediate post war period to the end of the 20th century, there was little change in the equipment used for wellpoint and deep well dewatering, other than incremental improvements resulting from the availability of new and better materials from which to construct pumps and pipework. Occasionally, new techniques were introduced, such as the ejector well system first used in the United States in the 1960s, which had its first large-scale application in Britain on the A55 Conwy crossing project in the late 1980s¹¹.

The real advances in groundwater control resulted from the accumulation of collective experience of the application of the various techniques. Because many of the techniques were developed from a practical rather than a theoretical basis, much of the experience

became concentrated in specialist contracting companies, instead of consulting engineers or academic bodies. Companies such as Soil Mechanics Limited carried out numerous large scale groundwater control projects in Britain in the 1950s and 1960s, and many of their staff ultimately moved on and spread their experience around several successful groundwater control contractors in the 1970s, 1980s and beyond.

The improvements in groundwater control practice were supported by some publications that selflessly shared some of the hard won experience acquired by contractors. First in 1981, J P Powers, then of the Moretrench American Corporation, produced his book *Construction Dewatering* which outlined North American Practice. Now in its third edition⁸, this remains a thorough and readable book. In the United Kingdom, in 1986 CIRIA produced Report 113 *Control of Groundwater for Temporary Works*¹², largely based on the experience of Pat Cashman from his work with Soil Mechanics Limited, Sykes and other organisations. In the late 1990s CIRIA produced Report C515 *Groundwater Control Design and Practice*¹, again based on the experience of a specialist contractor, this time WJ Groundwater Limited.

Current groundwater control practice

Beyond the 1990s and into the 21st century, there were no radical changes in the way that groundwater control works were executed. More subtle changes were apparent in the way that groundwater control became better integrated into the planning of construction projects, as a result of the cultural changes implemented in many parts of the construction industry following the publication of the Latham¹³ and Egan¹⁴ reports.

Latham and Egan reviewed the then performance of the UK construction industry and recommended specific improvements to planning and execution, and promoted increased efficiency and integration between the different parties involved in projects. With hindsight, the concept of having more integrated planning on projects has often improved the way that groundwater control has been carried out.

Under the old, often adversarial, contractual system, the need to control groundwater was often left as a last minute temporary works fix for the contractor (after many other aspects of the project had been finalised), and was procured as a cost driven 'distress purchase'. If the integrated approach of Latham and Egan is followed, it is more likely that key constraints, such as the need to control groundwater, will be identified as risks early on in planning. This can allow rational assessment, and open discussion between the various parties to construction, of the potential risks and the way they could be managed. This opens up a wide range of options to control groundwater including, for example, redesign of the permanent works to reduce (or avoid completely) the need for groundwater control. The Channel Tunnel Rail Link, constructed in the UK from the mid 1990s onward is a good example of how the need to control groundwater was one of the key factors considered throughout the design process when assessing options for structures below ground level¹⁵.

Another subtle change is the increased ability to gather and manage geotechnical data¹⁶ via electronic datalogging systems, often accessed remotely via GSM modems, with data disseminated via web-based platforms. Such technology opens up the opportunity of providing some degree of automation or 'self regulation' of pumped groundwater control systems. The operation of pumps could be regulated automatically, in real time, based purely on groundwater level readings monitored in boreholes and piezometers around the excavations. This is of particular interest where there is a need to use mitigation measures, such as artificial recharge, to limit any detrimental impacts of drawdown of groundwater levels on the surrounding area¹⁷.

Challenges for the future

It is likely that the future challenges for those involved in controlling groundwater for engineering projects will not be primarily technological. The performance of the technologies used for groundwater control are governed by the laws of physics. For example, the range of application of pumped well groundwater control methods shown in Figure 3 are unlikely to significantly change in the future. Any improvements in technology are most likely to come from incremental refinements in methods, or by technology transfers from other industries.

The real challenges in the future are likely to be in relation to the way that the potential environmental impacts of groundwater control are managed. Until relatively recently, little attention was paid to assessing the potential environmental impacts associated with groundwater control, either as the result of abstraction of groundwater, or as a result of the installation of physical barriers to groundwater flow.

Traditionally, groundwater has been viewed quite differently by civil engineers working on construction projects, and water resources managers (such as hydrogeologists). To the civil engineer groundwater is a potential *problem* requiring a solution. Engineers know that projects which require working below groundwater level are inherently more difficult than those that do not. Their response has been to pragmatically develop the groundwater control technologies outlined in this paper, to allow such works to be successfully executed. In contrast, to the hydrogeologist, groundwater is a potential *resource*, valuable when abstracted for use as drinking or process water, and also when contributing to natural features such as springs, streamflow, wetlands, etc.

It has long been recognised that if there is no system by which national, regional or local bodies can regulate the abstraction of groundwater, there is a risk that aquifers (geological strata of soil and rock that can yield groundwater) may be over exploited. Typically, this occurs where the volumes abstracted from an aquifer significantly exceed the long term average inflows from infiltration, inter-aquifer flow and other sources. There are numerous examples from around the world of urban areas where, due to the local concentration of abstraction, groundwater levels fell significantly in the time from the industrial revolution to the present day¹⁸. A well known example is the Chalk aquifer beneath central London, where excessive abstraction in the late 19th and early 20th century caused groundwater levels in the deep Chalk aquifer to fall from close to ground level, to between 50 and 90m depth¹⁹. Changes in water use, and the relocation of industry away from central London have resulted in significant reductions in annual abstractions, allowing groundwater levels to slowly recover toward their original levels (Figure 4). Perversely, the rise in groundwater levels may cause its own problems for existing below ground engineering infrastructure, and may require additional abstraction to be implemented to prevent groundwater levels from rising further.

In many countries the need to regulate abstraction has been recognised, and legislation implemented that requires the all significant groundwater abstractions be controlled by a system of licensing which sets limits on abstraction volumes. Licensing systems are intended to set a balance between the need for water of individual abstractors, and the need for rational overall management of groundwater resources. In England and Wales a licensing system has been in place since the 1960s, and has latterly been administered by the Environment Agency via the Water Resources Act 1991.

Interestingly, under the system in England and Wales, abstractions for groundwater control (so called dewatering abstractions) were exempted from the requirement for licensing. Hence dewatering was not directly regulated in relation to the rate of abstraction, and the potential impact on the groundwater environment. In practice, for the great majority of dewatering systems any impacts outside the immediate area of the works were minimal. This is probably because the rate of abstraction from dewatering pumping was a tiny fraction of the recharge available to the aquifer, or the area of aquifer dammed by a cut-off wall was small in relation to the extent of the aquifer. However, in a small number of cases, often involving large scale abstractions from highly permeable aquifers such as the Chalk, significant lowering of groundwater levels has occurred over a very wide area, perhaps 1 km or more from the site being dewatered.

When such significant impacts have occurred, engineering mitigation measures (such as artificial recharge of groundwater to reduce net abstraction from the aquifer) have been implemented to manage impacts. However, in many cases these mitigation measures are adopted after the event, instead of being planned from the start, based on a rational assessment of the potential groundwater impacts. In essence, assessment of groundwater impacts was often not high on the agenda when projects were planned.

However, changes in European legislation will move groundwater impacts from engineering projects up the agenda. The EU Water Framework Directive (WFD), adopted by the European Union in 2000 is intended to establish a Framework for the protection of surface and groundwater. In relation to groundwater, the WFD should promote long term protection of groundwater quality (by preventing and remediating groundwater pollution) and groundwater quantity (by controlling abstraction volumes to prevent over-exploitation of aquifers).

Cumulatively, it is possible that, on a local level, abstractions for groundwater control may form a significant proportion of total groundwater abstractions. The management of water resources in line with the WFD will be much easier if dewatering abstractions are licensed in a similar way to other groundwater abstractions, and recent changes in legislation have facilitated this. From 2007, in England and Wales, dewatering abstractions of greater than 20 m³/day will require licensing as set out the Water Act 2003. In Scotland, since April 2006, abstractions of greater than 10 m³/day have required consenting under the Water Environment (Controlled Activities) (Scotland) Regulations 2005, and this includes dewatering abstractions. An abstraction licensing system is planned for Northern Ireland in 2008²⁰.

As part of the process to obtain a license from the regulatory bodies, there will be a likely requirement to assess the groundwater impacts (a process sometimes known as a hydrogeological impact appraisal or HIA²¹). The wide range of impacts on the groundwater environment that can result from groundwater control have been recognised²². Often, the primary focus is on the impacts associated with abstraction, such as drawdown of groundwater levels resulting in reduction of yield from nearby water supply boreholes, the drying out of groundwater-dependent natural features such as wetlands or other surface water features, and the reduction of baseflow to rivers. With the increased requirement to protect of groundwater resources, other impacts have become recognised, including changes in groundwater flow paths caused by construction works, and the impact of discharge of the water arising from dewatering pumping. Table 2 summarises the types of impacts on groundwater that can potentially arise from below ground construction works.

One case worth considering further is when groundwater control is carried out on or near a brownfield site, where there is existing groundwater contamination. The effect of pumping or of installing a cut-off wall will change the groundwater flow regime and will alter the way that groundwater contamination migrates beneath the site. It is possible that the changes in hydraulic gradient and direction of groundwater flow can cause groundwater contamination to migrate much more quickly, or even in a radically different direction than under natural conditions (Figure 5).

This is a potential problem that affects groundwater control works in areas where there is a legacy of existing ground contamination, for example from industrial land uses. But conversely, the fact that groundwater control systems can affect the movement of plumes of contaminated groundwater can, with a little ingenuity, be turned to advantage. Pumped groundwater control systems have been modified to deliberately extract contaminated groundwater and treat it to reduce contamination to acceptable levels – an approach known as pump and treat²³ (Figure 6). The concept of cut-off walls conventionally used to block groundwater flow has been adapted by forming all or part of the wall from a permeable material that can react with groundwater, removing contamination as groundwater flows through it (Figure 7). This concept is known as a permeable reactive barrier or PRB²⁴. A key factor affecting the future use of these systems is that since traditional groundwater control systems have been largely optimised through many years use, and there is little expectation of significant improvement in performance. However, remediation techniques derived from some of the groundwater control technologies are at a relatively early stage in their development, and significant improvements in performance may be anticipated in the future.

The foregoing sections have concentrated on the water-based impacts of groundwater control. There is an inevitability about impacting, to a lesser or greater degree, on groundwater. However, it may be that in the future geotechnical processes such as groundwater control will be selected partly on an assessment of the overall environmental impact of processes. Pumps used in dewatering systems probably use natural resources in the form of fossil fuels (either directly as diesel fuel, or indirectly via mains electricity) and correspondingly produce carbon emissions. Groundwater exclusion methods can involve the use of toxic chemicals (grouts) or use large amounts of energy (refrigeration plants used for artificial ground freezing). A range of sustainability appraisal tools that could be used to allow some degree of comparison between different engineering processes that interact with groundwater²⁵, but thus far they have not been widely applied to geotechnical engineering processes. Perhaps in the future measures of natural resource utilisation and carbon footprint will be a fundamental part of the design and specification of groundwater control works.

Conclusions

The traditional view of groundwater control may be that it is a black art, but that should not obscure that fact that it has a firm rational foundation. The existing technologies have evolved to meet the pragmatic requirements of construction projects. There is now a wide range of established and proven techniques available to control groundwater. The principal challenges for the future are unlikely to be technological, but are likely to involve a change in focus to recognise the environmental impacts that can result when groundwater is controlled. Changes in regulation, and the increasing importance of environmental management when planning construction projects, result in the need to better predict, monitor and mitigate the impacts on the groundwater environment that can result when groundwater control is carried out.

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Table 1: Commonly used methods of groundwater control

Method	Principal of operation	Key advantages	Key disadvantages
Groundwater control by pumping			
Sump pumping	Groundwater is allowed to seep into the excavation, where it is collected in pits or sumps, to be pumped away by robust pumps	Simple and cheap, equipment widely available	The pumped water may contain suspended fine particles removed from the soil; this can result in instability of the excavation and environmental problems when the water is discharged
Wellpoints	A line or ring or small diameter shallow wells (wellpoints) are installed around the excavation, and pumped by a suction pump located at ground level	Uses widely available equipment, flexible in application	Suction lift limitations mean that drawdowns of greater than 5–6 m below pump level cannot be achieved by a single stage of wellpoints
Deep wells	An array of boreholes (deep wells) are drilled around the excavation, fitted with appropriate wellscreens. Each deep well is pumped by a submersible pump within the borehole	Depth of is drawdown not limited by suction lift (drawdown limited only by soil stratification and depth of borehole)	Less flexible in use than some other methods
Ejector wells	High pressure water is circulated through nozzle and venturi systems (ejectors) located within a series of boreholes. The ejectors act as jet pumps to remove water and create a vacuum	Depth of drawdown is not limited by suction lift. Can be highly effective in depressurising and stabilising low permeability soils such as silts	Drawdown typically limited to a maximum depth of 30–50 m. Cannot handle large groundwater flow rates. Low energy efficiency
Groundwater control by exclusion			
Steel sheet-piling	Interlocking steel piles are driven, pushed or vibrated into the ground to form a cut-off wall around the excavation	Uses widely available equipment. Can be used to form temporary cut-offs (where the piles are extracted following completion of the works), avoiding any long term obstruction of natural groundwater flow	Boulders, buried obstructions or bedrock can make installation of piles difficult or limit penetration that can be achieved
Concrete diaphragm walls and bored pile walls	Continuous concrete cut-off wall formed from interlocking concrete panels (diaphragm walls) or interlocking bored piles	Produces a structure that can be used to form part of the permanent works. Can penetrate hard soils and weak rocks	Permanent, may cause long term obstruction of natural groundwater flow
Slurry trench	Continuous trench is excavated and filled with a slurry of bentonite or bentonite-cement	Relatively quick and cheap to install	Permanent, may cause long term obstruction of natural groundwater flow.
Injection grouting	Cement-based or synthetic chemical fluids are injected into the ground via an array of closely-spaced boreholes. The grout permeates into the soil or rock, infilling the pores or fissures	Relatively flexible in application. Can be used to great depths.	Permanent, may cause long term obstruction of natural groundwater flow. Multiple stages of treatment may be required to achieve sufficiently low permeability
Jet grouting	An aggressive jetting method is used to form overlapping columns of soil/grout mixture	Can penetrate hard soils and weak rocks	Permanent, may cause long term obstruction of natural groundwater flow. Can be messy and create large volumes of waste slurry
Artificial ground freezing	A wall of frozen ground (a freezeway) is formed around the excavation by circulating a low temperature fluid (calcium chloride or liquid nitrogen) through an array of closely-spaced freezetubes drilled around the excavation	Effective in a wide range of ground conditions. Ground freezing is temporary, so the freezeway will slowly dissipate following completion of the works, avoiding any long term	Relatively expensive and specialised technique. Can be difficult to achieve a complete freezeway if groundwater velocities are significant

obstruction of natural groundwater flow

Table 2: Impacts on groundwater conditions from civil engineering works (from Preene and Brassington, 2003²²)

	Category	Potential impacts	Duration	Relevant construction activities
1	Abstraction	Ground settlement Derogation of individual sources Effect on aquifer – groundwater levels Effect on aquifer – groundwater quality Depletion of groundwater dependent features	Temporary Permanent	Dewatering of excavations and tunnels using wells, wellpoints and sumps Drainage of shallow excavations or waterlogged land by gravity flow Permanent drainage of basements, tunnels, road and rail cuttings, both from pumping and from gravity flow
2	Pathways for groundwater flow	Risk of pollution from near surface activities Change in groundwater levels and quality	Temporary Permanent	Vertical pathways created by site investigation and dewatering boreholes, open excavations, trench drains, etc. Horizontal pathways created by trenches, tunnels and excavations Vertical pathways created by inadequate backfilling and sealing of site investigation and dewatering boreholes and excavations and by permanent foundations, piles and ground improvement processes Horizontal pathways created by trenches, tunnels and excavations
3	Barriers to groundwater flow	Change in groundwater levels and quality	Temporary Permanent	Barriers created by temporary or removable physical cut-off walls such as sheet-piles or artificial ground freezing Barriers created by permanent physical cut-off walls or groups of piles forming part of the foundation or structure or by linear constructions such as tunnels and pipelines Barriers created by reduction in aquifer hydraulic conductivity (e.g. by grouting or compaction)
4	Discharge to groundwaters	Discharge of polluting substances from construction activities	Temporary Permanent	Leakage and run-off from construction activities (e.g. fuelling of plant) Artificial recharge (if used as part of the dewatering works) Leakage and run-off from permanent structures Discharge via drainage soakaways
5	Discharge to surface waters	Effect on surface waters due to discharge water chemistry, temperature or sediment load	Temporary Permanent	Discharge from dewatering systems Discharge from permanent drainage systems

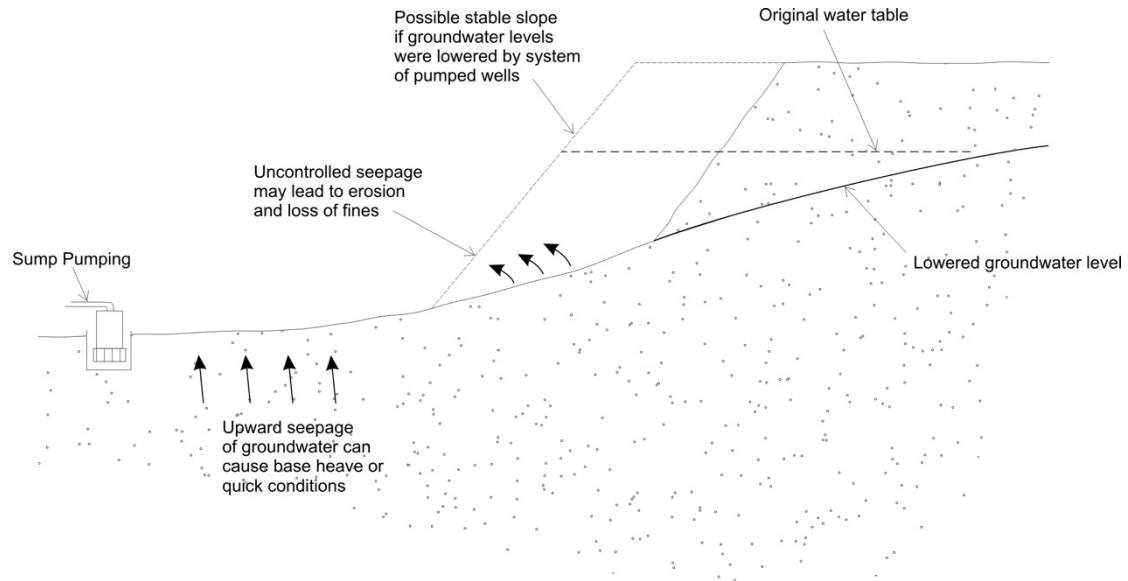
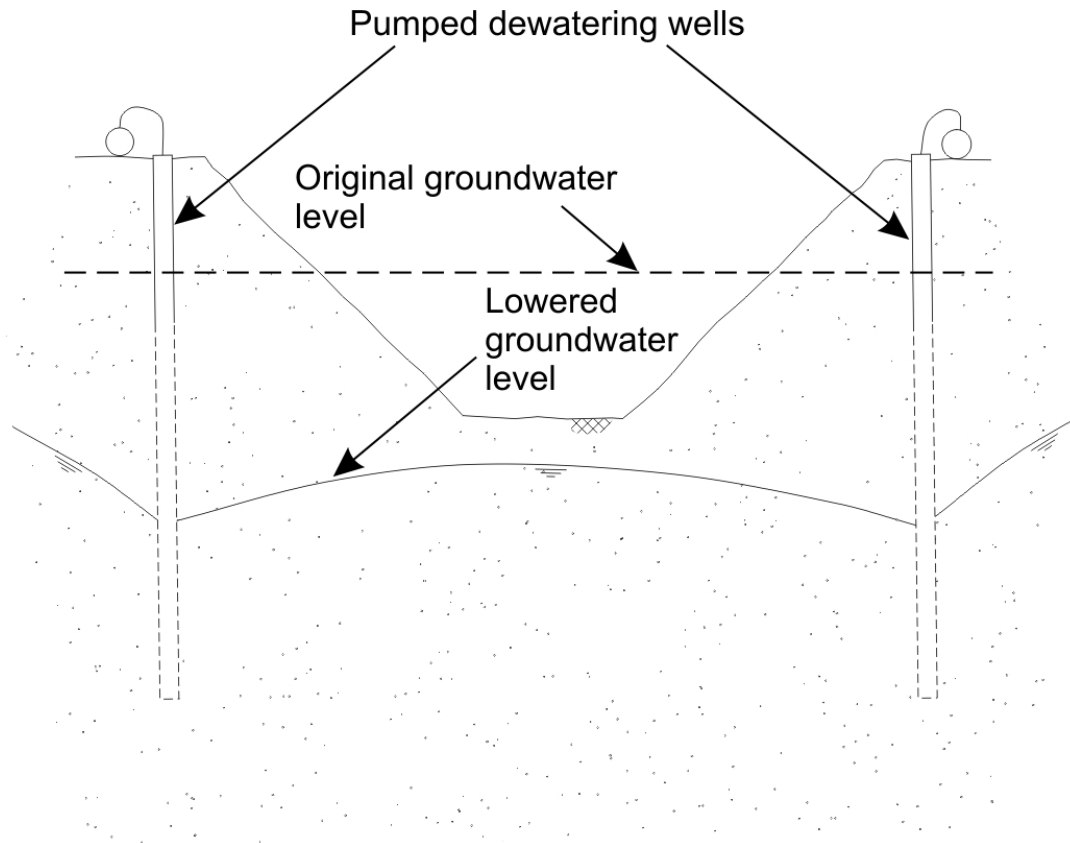
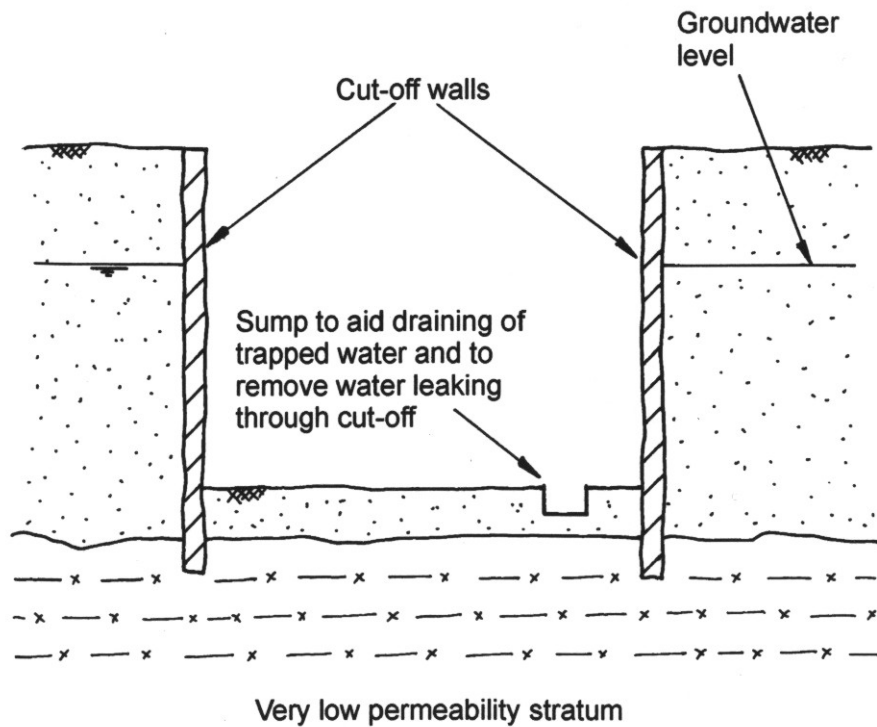


Figure 1: Instability of excavation due to inadequate control of groundwater



a) Groundwater control by pumping (from Cashman and Preene, 2001⁵, reproduced by kind permission of Spon Press)

Figure 2: Approaches to control of groundwater



- b) Groundwater control by exclusion (from Cashman and Preene, 2001⁵, reproduced by kind permission of Spon Press)

Figure 2: Approaches to control of groundwater

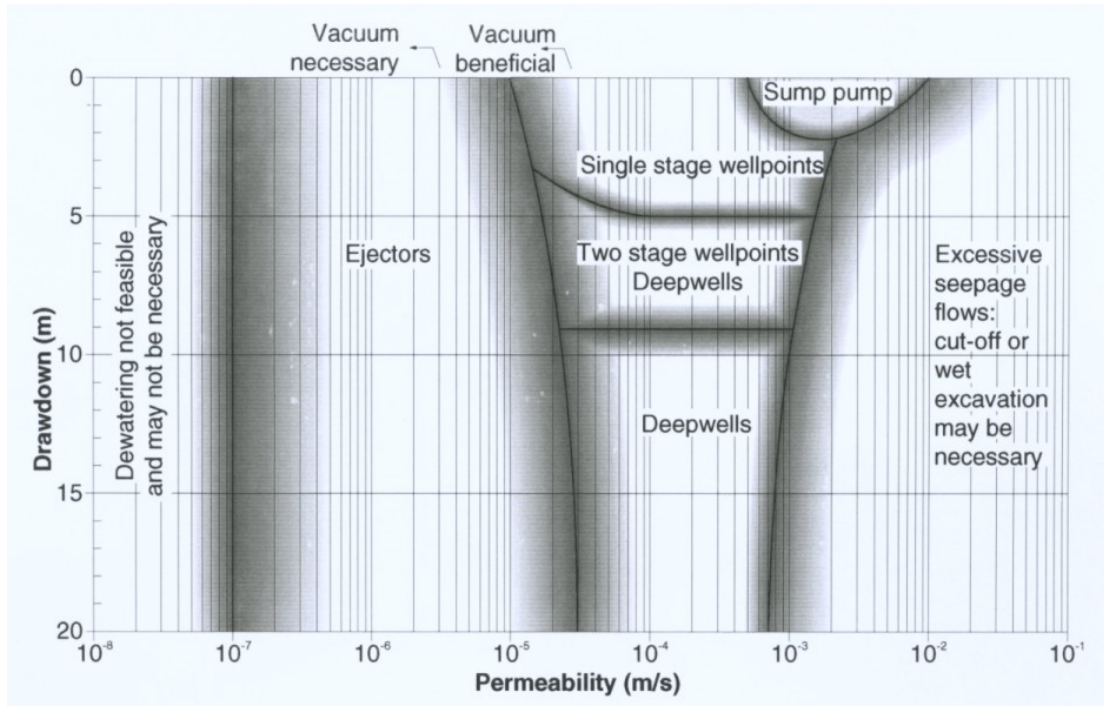


Figure 3: Range of application of pumped well groundwater control techniques – adapted from Roberts and Preene (1994), and modified after Cashman (1994) (from Preene *et al.* 2000¹: reproduced by kind permission of CIRIA)

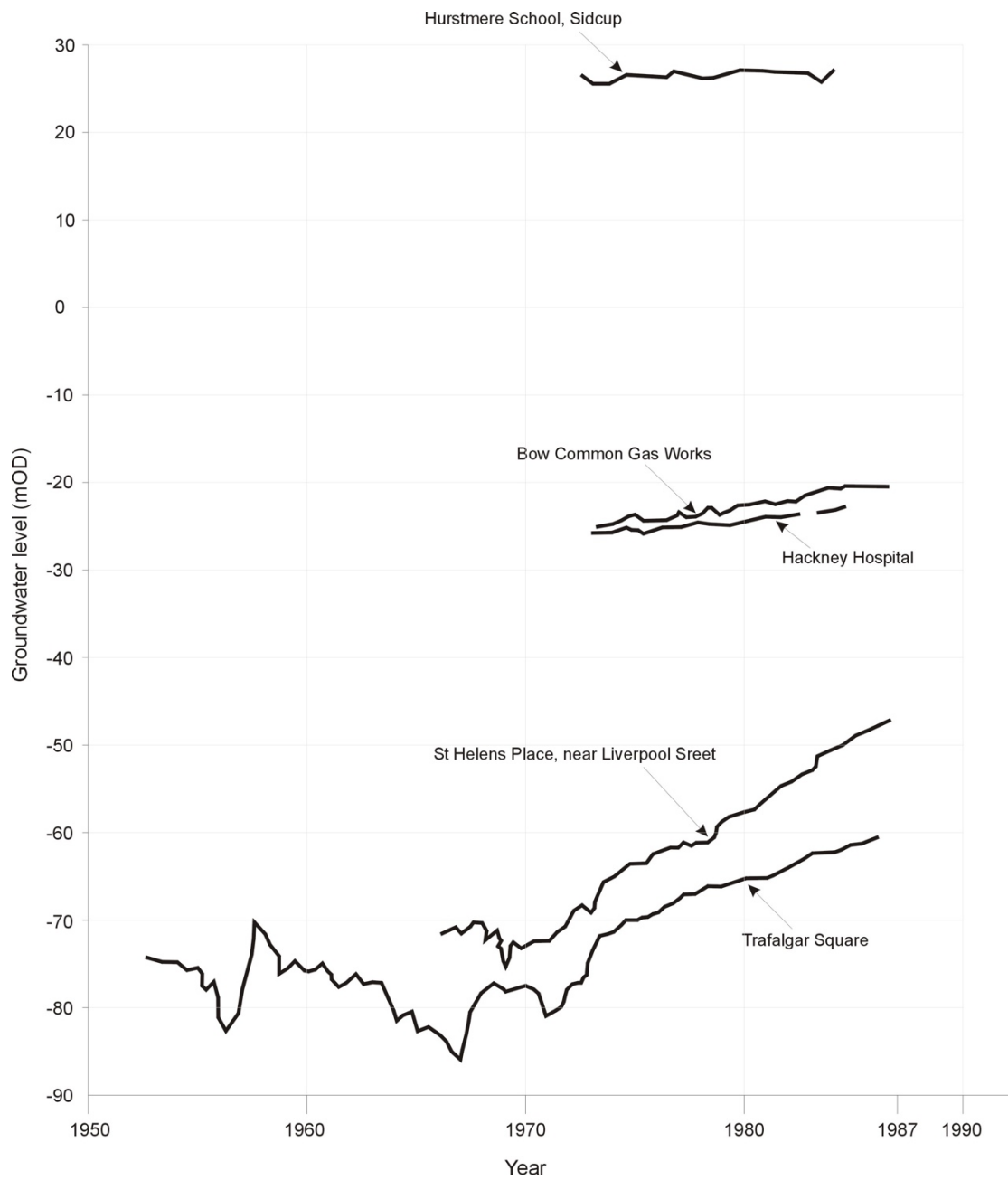


Figure 4: Rising groundwater levels beneath central London (redrawn from Simpson *et al.* 1989¹⁹)

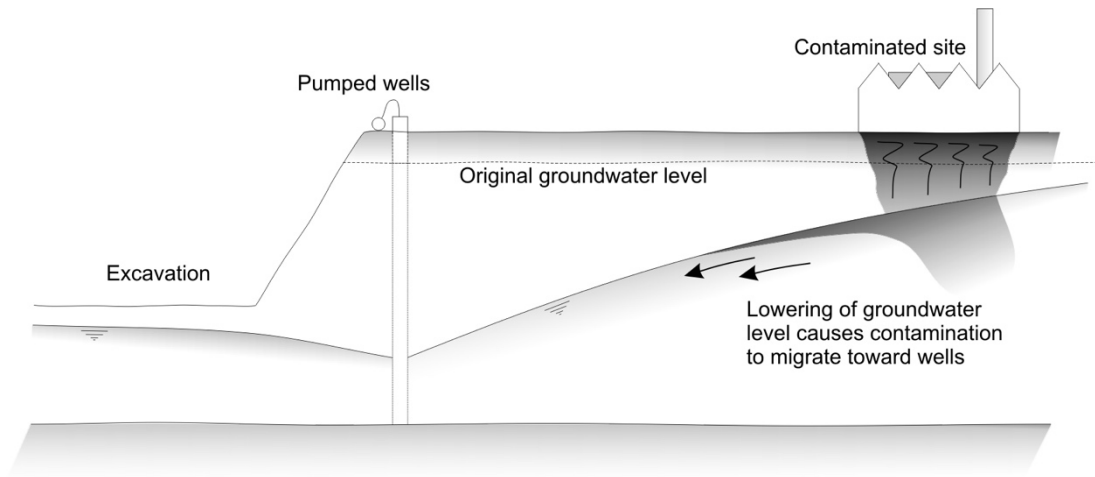


Figure 5: Interaction between groundwater control by pumping and groundwater contamination beneath a brownfield site

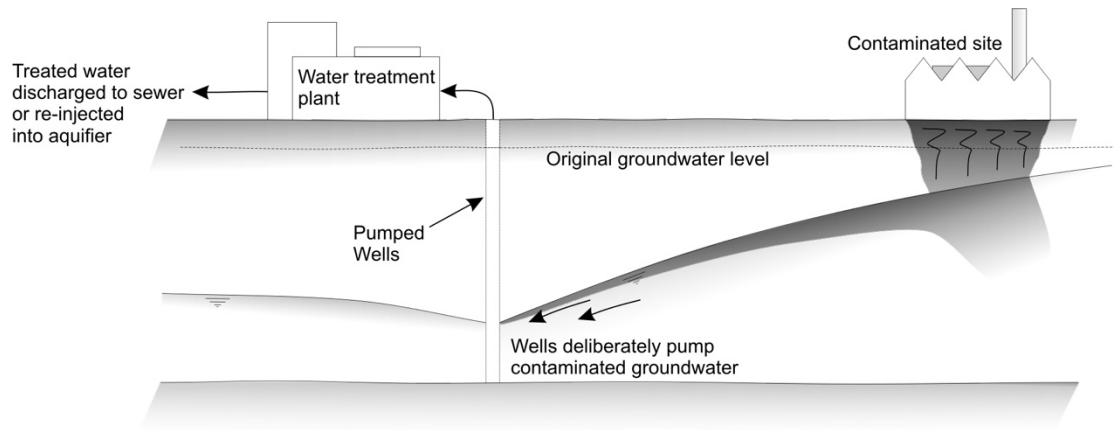


Figure 6: Pump and treat system to control groundwater pollution

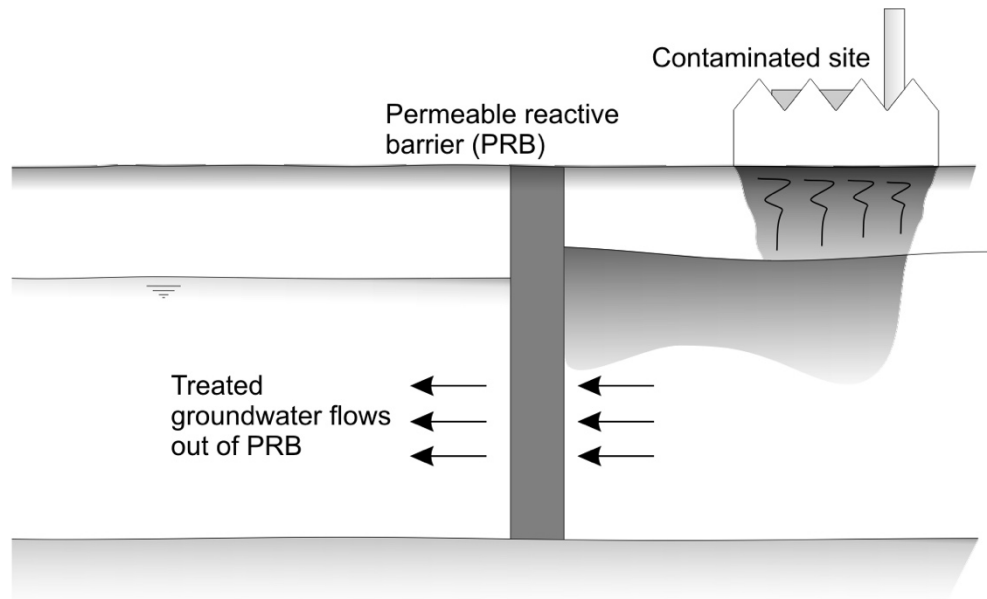


Figure 7: Permeable reactive barrier (PRB) to control groundwater pollution