Groundwater basin recovery in urban areas and implications for engineering projects

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Abstract: In urban environments around the world, groundwater levels previously lowered by groundwater abstraction have begun to rise as a result of increased groundwater use controls, reduced abstraction by industry, and artificial recharge. These rising groundwater levels are a potential source of problems for existing civil engineering structures and create added complexity for projects that are now being planned. A well-known example of this issue is the London Basin in the United Kingdom. For the past two centuries, groundwater levels beneath central London were drawn down due to heavy groundwater use. Today, groundwater levels are rising due to reduced groundwater abstraction within industry. These rising levels are causing potential problems for existing engineering structures within central London. A groundwater management plan has been implemented to control the groundwater levels beneath the City.

The phenomenon of variable groundwater levels over time can also be found within urban environments in other parts of the world. An awareness of the historical hydrogeologic regime is important for projects located within these urban areas. There are many factors that can affect the hydrogeologic regime of an area. The purpose of this paper is to highlight the importance of developing “maximum credible water levels” for engineering projects with the help of three groundwater basins. This paper also provides some suggestions on how to develop this “maximum credible water level”. The selection of a “maximum credible water level” would result in a selection of groundwater levels to be expected throughout the design life of the project, reducing long-term risk associated with rising groundwater levels. This paper will address the importance of carefully evaluating the hydrogeology for major engineering projects in urban areas.

Résumé: Dans les environnements urbains autour du monde, les niveaux d'eaux souterraines précédemment abaissés par abstraction d'eaux souterraines ont commencé à monter en raison de l’augmentation des controles d'utilisation d'eaux souterraines et de la réduction d’abstraction par l’industrie. Ces niveaux de montée d'eaux souterraines sont une source potentielle de problèmes pour les structures existantes (bâtiments and structures de génie civil) et créent une complexité supplémentaire pour les futurs projets. Le bassin de Londres au Royaume-Uni est un exemple bien connu de ce problème. Pendant les deux derniers siècles, les niveaux d'eaux souterraines du coeur de Londres ont été baissés en raison de l'importante utilisation d’eaux souterraines. Aujourd'hui, les niveaux d'eaux souterraines sont en train de monter due à la réduction d’abstraction par l’industrie. Ces haut niveaux d'eaux souterraines posent des problèmes potentiels pour les structures existantes dans le coeur de Londres. Les responsables de la gestion d'eaux souterraines de la ville ont commencé à travailler pour controler les niveaux d'eaux souterraines.

Le phénomène de niveaux variables d'eaux souterraines peut également être trouvé dans les environnements urbains aux Etats-Unis. La connaissance du régime hydrogéologique historique est importante pour les projets situés dans ces secteurs urbains. De nombreux facteurs peuvent affecter le régime hydrogéologique d'un projet. Le but de cet article est de décrire une méthodologie pour le choix de la construction et “des niveaux maximum possible des eaux souterraines” pour un projet de construction. Le choix “d’un niveau maximum possible des eaux souterraines” a l’avantage que le niveau d'eaux souterraines peut être estimé durant toute la durée de conception du projet, réduisant le risque à long terme lié a la montée du niveau d'eaux souterraines. Cet article adressera l'importance d'évaluer soigneusement l'hydrogéologie pour les grands projets dans des secteurs urbains.

Keywords: aquifers, hydrogeology, urban geosciences, rising groundwater.

INTRODUCTION

The phenomenon of variable groundwater levels over a typical project’s lifetime can be found within urban environments around the world. Rising groundwater levels have recently been encountered on major projects in the United Kingdom, Saudi Arabia, and the United States. Within Construction Industry Research and Information Association (CIRIA) Special Publication 69 that discusses specifically the rising ground water beneath London, evidence of rising ground water was also noted within Birmingham, Nottingham and Liverpool. This publication also mentions the occurrence in cities throughout the world, such as Paris, France, New York, USA, Doha, Qatar, Tokyo, Japan and in areas of West Germany. Rising groundwater regimes are geographically widespread and should be evaluated for projects around the world.

An awareness of the phenomenon and development of a “maximum credible water level” during the design phase of the project will result in risk reduction for civil engineering projects of all scales. The purpose of this paper is to discuss three examples of basins experiencing groundwater level rise, emphasising the impact on engineering structures, highlighting the need for the development of two design water levels; a construction groundwater level and a "maximum credible water level". The three basins discussed in this paper are the London Basin in the United Kingdom, the Las Vegas Basin in the United States, and the Santa Clara Valley Basin in the United States. This paper will highlight the importance of carefully evaluating the hydrogeology for engineering projects in urban areas as well as providing suggestions for how this can be accomplished and a summary of potential mitigation measures to be considered.

It is important to understand both past usage (abstraction) of ground water and precipitation as well as current and future trends due to recharge, increasing or decreasing precipitation patterns, and other factors when developing design groundwater levels.

LONDON BASIN

Basin Structure and Hydrostatigraphy

A synclinal fold that opens to the east forms the London Basin. The oldest rocks are found at the edges of the syncline and the rocks become progressively younger toward the centre (BGS, 1996). The oldest rock formation of interest for the study of London's rising ground water is the Chalk. The Chalk outcrops at the surface in the Chilterns and the North Downs but is 120 metres below ground surface near the axis of the syncline in central London. Sands and then clay including the blue "London Clay" overlie the Chalk. These clays are overlain by a sequence of alluvial sands, gravels and clays of relatively recent origin.

The Chalk and overlying sands form the major aquifer beneath London. Recharge to this aquifer is from the rainfall on outcrops in the Chilterns and North Downs. The overlying clays act as an aquitard between the primary aquifer and the near surface alluvial materials that also form an aquifer. The near surface alluvial materials are in direct contact with the river systems and are recharged by rainfall (GARDIT, 1996). Figure 1 shows a cross section beneath central London of the London Basin (modified from CIRIA, 1989). Included on the cross sections are water levels beneath central London in 1965, 1985 and the original groundwater levels.

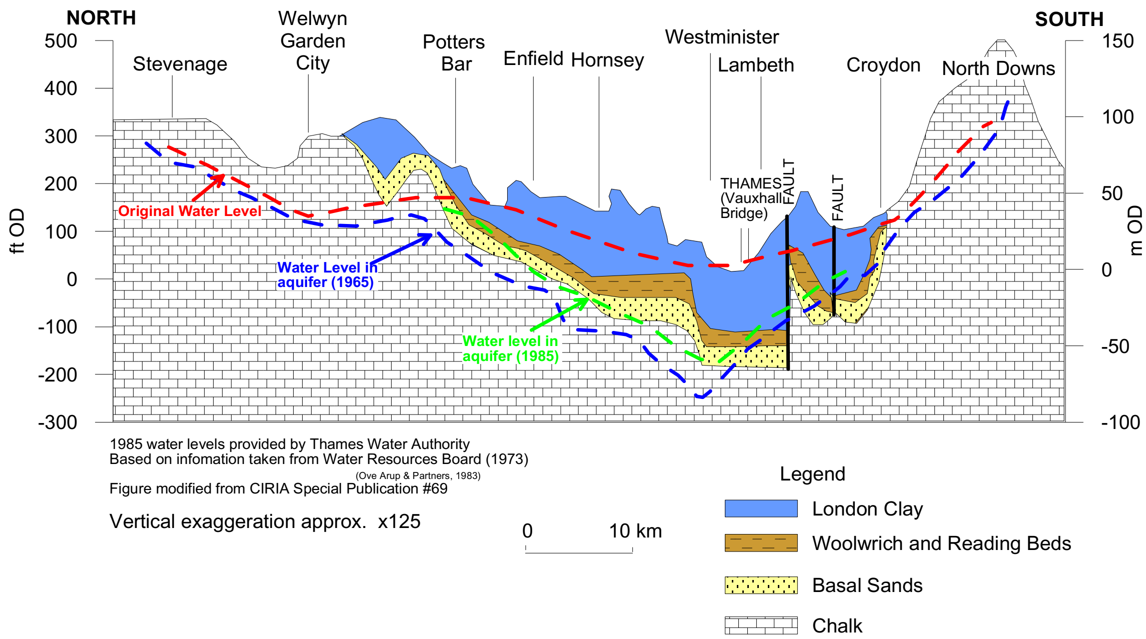

Figure 1. Cross Section Beneath Central London (modified from CIRIA, 1989)

Groundwater Levels

Two centuries of groundwater abstraction by industry lowered the water table within the upper chalk within the London basin by as much as 70 metres (Ciria, 1989). Since the late 1960's the amount of pumping beneath central London has declined. Abstraction by industry has been drastically reduced as industry moves away from central London. This has resulted in steadily rising groundwater levels beneath the city.

Figure 1 shows the rise in groundwater levels since 1965 beneath central London as well as indicating the original groundwater levels. The level is rising in many areas by as much as 3 metres per year. Figure 2 shows the Trafalgar Square hydrograph of the groundwater level. This hydrograph illustrates the pattern of groundwater level rise beneath much of central London (GARDIT, 1996).

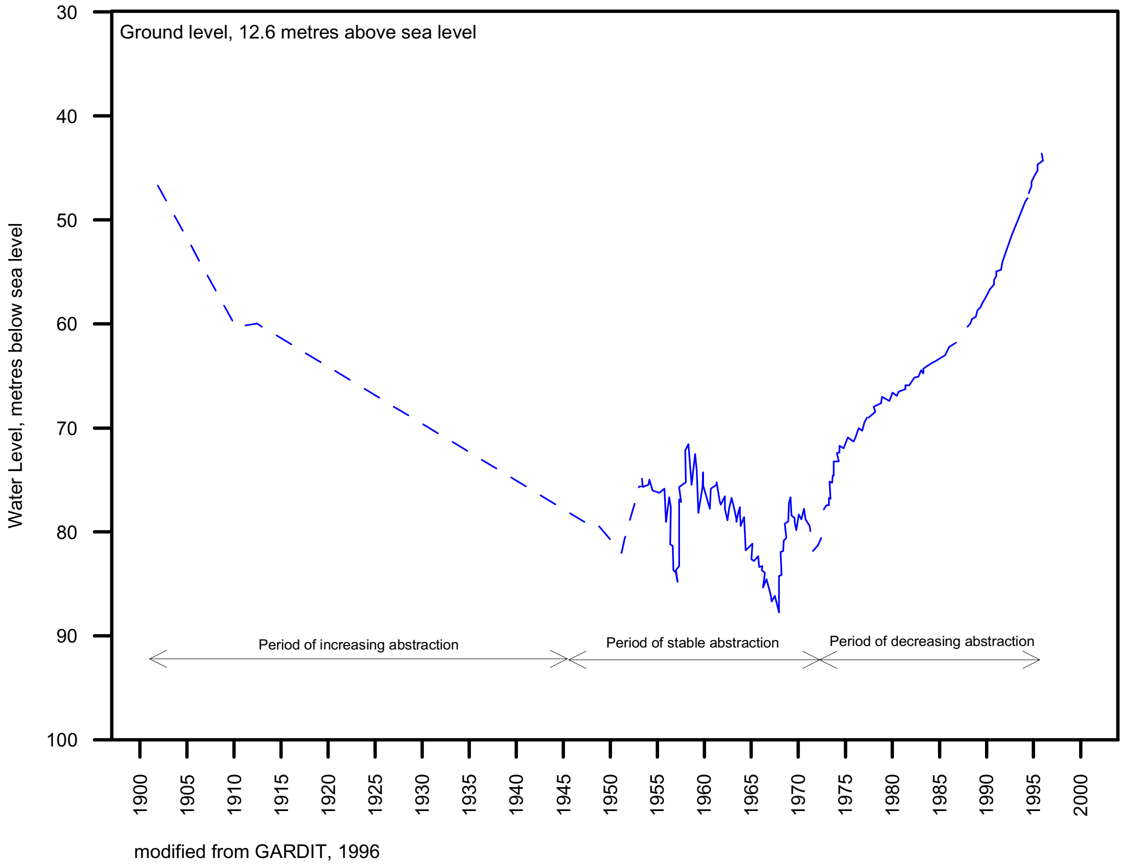

Figure 2. Hydrograph at Trafalgar Square (modified from GARDIT, 1996)

Engineering Implications

Engineering Implications of rising ground water beneath London were researched extensively in CIRIA Special Publication #69. This publication described the rising groundwater levels in the deep aquifer (the Chalk), which extended into the overlying Clay, and the resultant lowering of strength of the Clay within which many foundations are located. Some of the potential engineering effects outlined in this report and by (Simpson et. al, 1987) included:

- A reduction in bearing capacity of both deep and shallow foundations
- The development of uplift water pressures under foundations and floor slabs
- Swelling and heave of clays
- Increased loads on retaining walls
- Leakage into basements and service ducts
- Solution of minerals and an increased potential for chemical attack on buried structures
- The confinement of hazardous gases
- Increased drainage requirements and potential instability of excavations and temporary works

Mitigation Controls

Subsequent to the issuance of CIRIA Special Publication #69 the General Aquifer Research and Investigation Team (GARDIT) was formed in 1992. This is an informal group of parties interested in the rising groundwater levels beneath London. GARDIT produced a five-phase strategy to control London's rising ground water that was published in March of 1999. In the early 1990's the Environment Agency (formerly National Rivers Authority (NRA)) began producing annual reports on groundwater levels in the Chalk-Basal Sands aquifer beneath London. In their fourteenth annual report (Environment Agency, May 2005) the Environment Agency stated that the GARDIT five-phase strategy for controlling London's rising ground water is "very nearly completed and has significantly increased the abstraction from ground water beneath London." This implies that London is well on its way to mitigating problems associated with the rising groundwater table in response to reduction in industrial abstraction since 1965. The solution that was adopted was essentially a permanent dewatering program orchestrated primarily by Thames Water.

LAS VEGAS VALLEY BASIN

Basin Structure and Hydrostatigraphy

The Las Vegas Valley Basin in the United States is composed of Pliocene-Pleistocene basin fill deposits, which are cut by a series of primarily north-south trending faults. These faults form escarpments with displacement down to the east and many occur in steps. The Escarpments are up to 30 metres (100 feet) high and as long as 16 kilometres (50 miles) (Bechtel Nevada, 2000). These faults are typically referred to as "compaction faults", however, more recent studies suggest that these faults are of tectonic origin, or of both tectonic and compaction origin (Bell, 1981, and Bell and DePolo, 1996). The faults sometimes act as barriers to horizontal groundwater flow and in some cases provide preferential pathways toward the ground surface.

The hydrogeology of the Las Vegas Valley basin consists of recharge in the mountains surrounding the basin and discharge in the basin floor. Flow within the basin is downward in the recharge areas, horizontal around the margins of the valley toward the central part of the valley and upward within the central part of the basin.

There are two major aquifers in the basin, the principal aquifer and the shallow aquifer. The principal aquifer is located between 30 and 300 metres (100 and 1000 feet) below land surface. The bottom of the shallow aquifer is located 15 metres (50 feet) or less below land surface and is found mostly in the central and southern parts of the valley. (LVVWD, 2005) The shallow perched aquifer has developed as a result of excess irrigation due to rapid urbanization and is very salty. It is often referred to as "nuisance water". The U.S. Geological Survey first identified the shallow aquifer in 1976 (LVVWD, 1991).

Las Vegas, Nevada is one of the fastest growing metropolitan areas in the United States and one of the hottest and most arid regions of the southwest. The rapid population growth has increased demand for water supplies. Las Vegas Valley relied almost entirely on ground water until the 1970's.

Groundwater Levels

Several major hydrologic changes in the groundwater basin have influenced regional water levels over several decades:

- Overdraft of the groundwater basin beginning in the 1950's (Malmberg, 1965), which by 1980, resulted in water-level declines in the principal aquifer of more than 90 m (300 ft) from predevelopment conditions in some areas of Las Vegas Valley (Burbey, 1995)
- Importation of Colorado River water since 1971, and corresponding reduction in groundwater extraction. (By 2000, ground water accounted for less than 20 percent of water used in the valley (Coach, 2000)).
- Artificial recharge of the aquifer using injection wells (By LVVWD) since 1987, and by the City of North Las Vegas (CNLV) since 1990. Since about 1988, water levels in some areas have stabilized or risen by as much as 30 m (100) ft (Wood, 2000).
- An increase in irrigation as the Southern Nevada population continues to grow rapidly. Residents use as much as 90 percent of the drinking water supply to irrigate their lawns, contributing to an increase in thickness of the shallow aquifer. The shallow aquifer holds low-quality water and is still present in the valley today.

Figure 3 shows the change in groundwater level in the Principal Aquifer during the fall season between 1990 and 1998. The increase is centered in areas of the Las Vegas Valley Water District's artificial recharge operations.

Engineering Implications

The shallow aquifer or "nuisance water" is very salty due primarily to the dissolution of naturally occurring salts within the fine-grained formations near the surface. Because this salty water (shallow aquifer) is close to the land surface, it can impact the integrity of concrete foundations exposed to sulfate attack. Additionally, the shallow ground water creates added complexities for construction excavations. Construction excavations will experience added expense due to necessary dewatering activities.

Mitigation Controls

The Southern Nevada Water Authority (SNWA) has developed an incentive program for residential property as well as multifamily and business property owners serviced by the SNWA. This program includes a "Water Smart Landscapes" rebate that helps property owners convert water-thirsty grass to something called xeriscape that is described as a lush, yet water-efficient landscape. They offer to rebate $1 per square foot of grass removed and replaced with xeriscape up to $300,000 USD (SNWA, 2005).

SANTA CLARA VALLEY BASIN

Basin Structure and Hydrostatigraphy

The Santa Clara Valley Basin (SCVB) is situated at the southern end of San Francisco Bay in the State of California. The San Francisco Bay lies within a structural trough bounded by the Coast Range to the west and the Diablo Range to the east. The SCVB fills the southern end of this structural trough. At its southern end, the SCVB narrows to 0.8 kilometres (1.2 mile) in width at Coyote Narrows, then extends 11.5 kilometres (7 miles) south through Coyote Valley to the boundary with the Llagas ground-water basin at Morgan Hill. At its northern end, the Basin is approximately 35 kilometres (22 miles) long and 24 kilometres (15 miles) wide, with a surface area of 583 square kilometers (225 square miles) (RWQCB 2003). See figure 4.

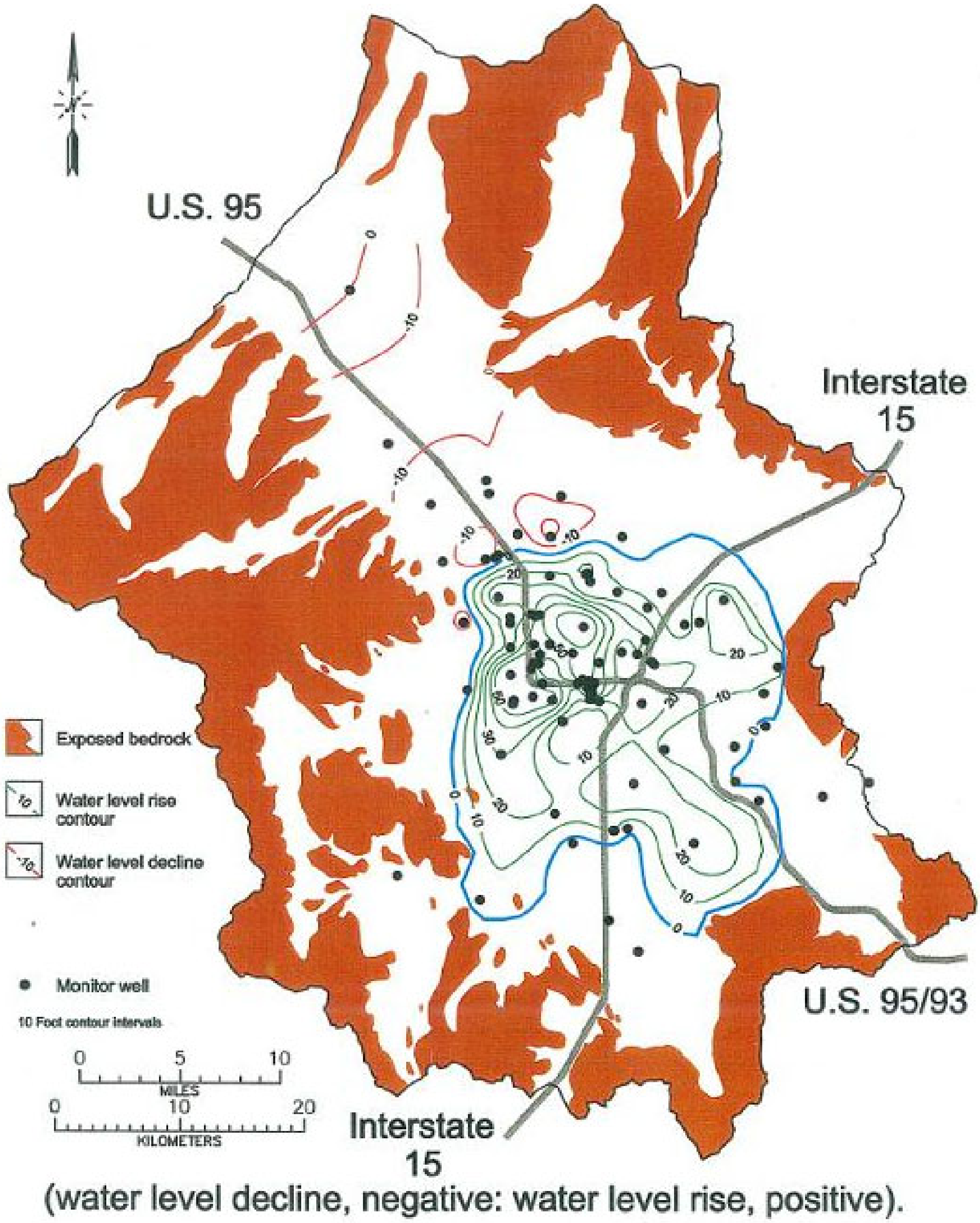

Figure 3. Water Level Change in Principal Aquifer Fall 1990 to Fall 1998, in feet (Source: LVVWD, 1999 figure 4)

The hydrogeologic units of the Santa Clara Valley Basin are summarized below.

- Confining Layer. Composed of clays and silts, with channels of sand.
- Upper Aquifer. Composed of mixtures of silty sand, sand, gravelly sand, and sandy gravel. Includes intersecting and coalescing channels of varying thickness and differing hydraulic conductivity. This unit is comprised of Holocene age and possibly late Pleistocene age alluvial deposits.
- Major Aquitard. This zone is primarily clays and silts, but can include deposits of sand and silty sand.
- Lower Aquifer. Zone of major ground-water withdrawals, composed of sand and gravel zones, with intervening clay and silt layers. This unit is made of Pleistocene and Pliocene age sediments.

- Bedrock. The underlying non-water-bearing stratigraphy consists of portions of the Santa Clara Formation and the Mesozoic age Franciscan Complex.

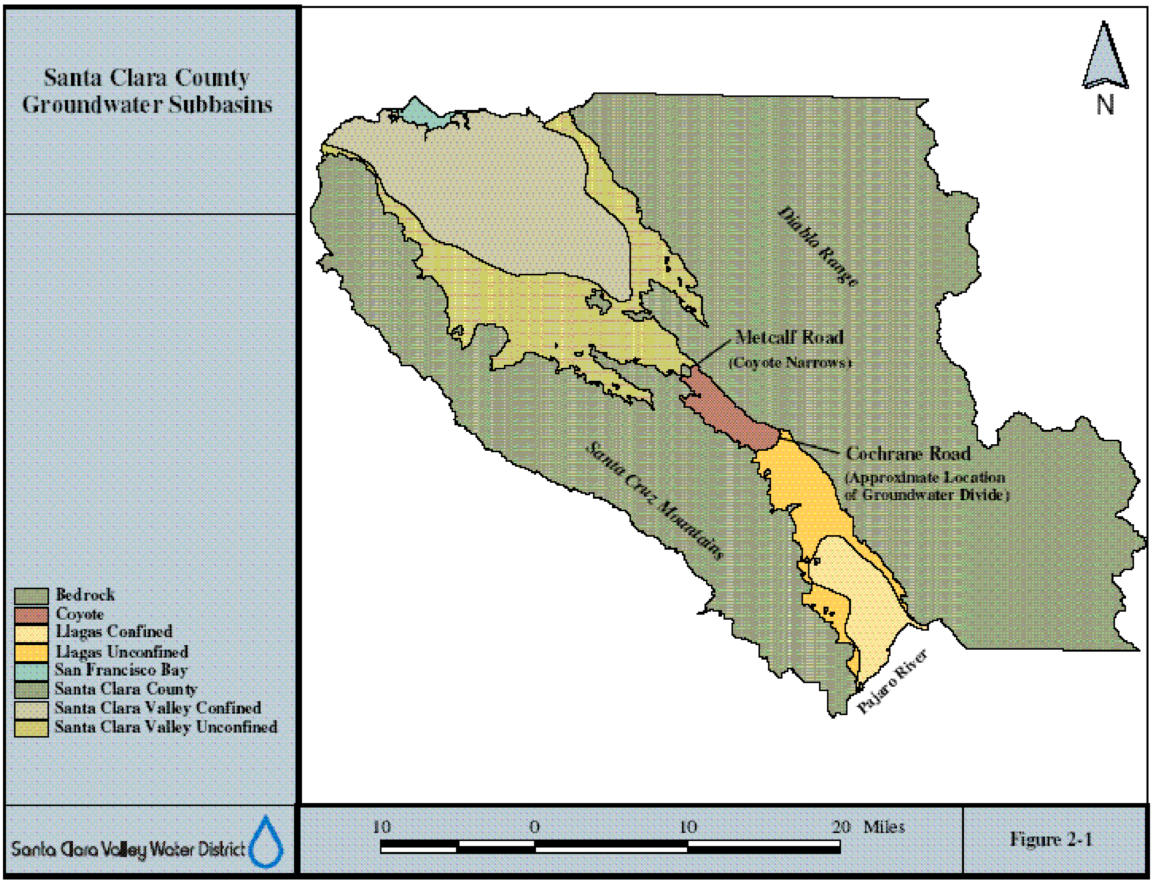

Figure 4. Santa Clara Valley Groundwater Subbasins (SCVWD, 2002)

Figure 5 is a general cross section summarizing the hydrostratigraphy across the Santa Clara Valley Groundwater Basin.

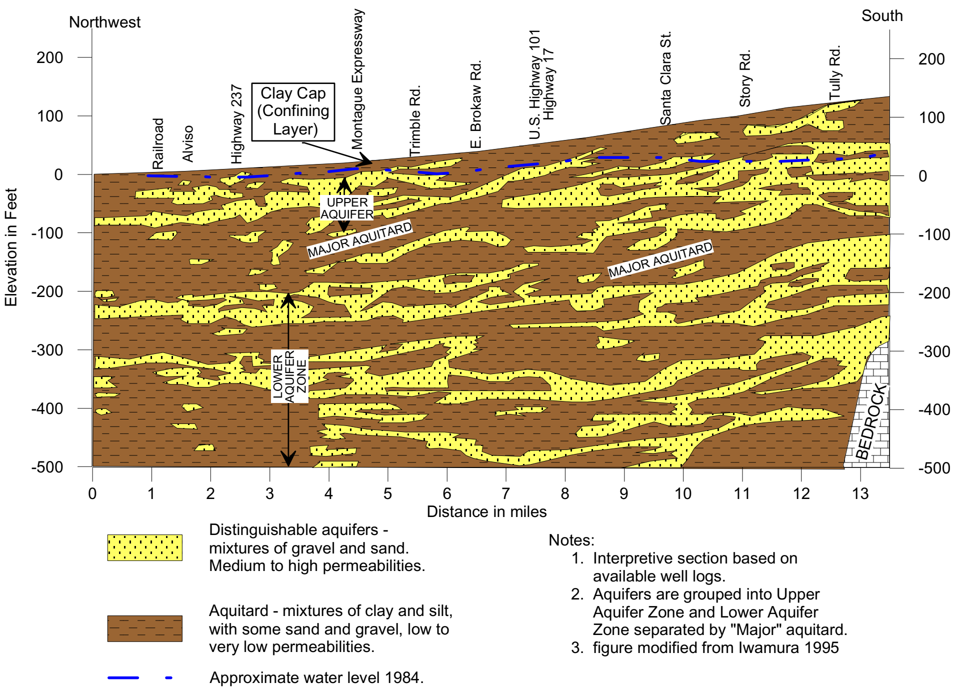

Figure 5. Hydrogeologic Cross Section across the Santa Clara Valley Groundwater Basin (modified from Iwamura, 1995)

Ground-water Levels

The Santa Clara Valley Basin was over-pumped for decades, which induced land subsidence in San Jose by as much as 14 feet. Land subsidence likely began in the 1920's and continued until the late 1960's.

Regional initiatives to counteract over-pumping and land subsidence included expanding the existing supply by erecting 11 local dams and using the stored water for ground-water recharge; building the infrastructure and securing the rights to import water from state and federal projects, as well as the City of San Francisco's Hetch Hetchy water supply; operating numerous ground-water recharge ponds and in-stream recharge with spreader dams; and aggressively sealing abandoned wells. These measures have succeeded in curtailing land subsidence since 1968.

The San Jose "Index Well" is located in Downtown San Jose. The hydrograph for this well appears in numerous publications on the ground water of Santa Clara Valley (Iwamura 1995; USGS 1999; SCVWD 2002) because it dramatically shows the long-term subsidence and water level decline resulting from overdraft of the Lower Aquifer during a period of below-normal precipitation, and then water level recovery associated with artificial recharge, water importation, and a period of above-normal precipitation, and subsequent cessation of subsidence. Figure 6 is a modification of this figure produced by Iwamura.

As shown in Figure 6, the "maximum annual depth" (lowest of each year's monthly readings) decreased to an historic low of 235 feet below ground surface at Santa Clara Street and Delmas Avenue in 1964. The long-term water level recovery (rise) of 195 feet from 1963 to 1993 corresponds to above-average precipitation since 1970 with simultaneous importation of water for artificial recharge and decline in per capita ground-water usage.

This graph indicates that water levels beneath San Jose have been rising and are continuing to rise. It is important for engineering projects being designed in this area to be designed in accordance with this phenomenon. From this graph it is apparent that the water levels rise with increases in precipitation. Annual precipitation cumulative departure hit a low in 1977. Since this time precipitation levels have been rising. If the precipitation levels increase following the trend seen between 1889 and 1916 it would appear that precipitation levels and subsequently groundwater levels will continue to rise in the future.

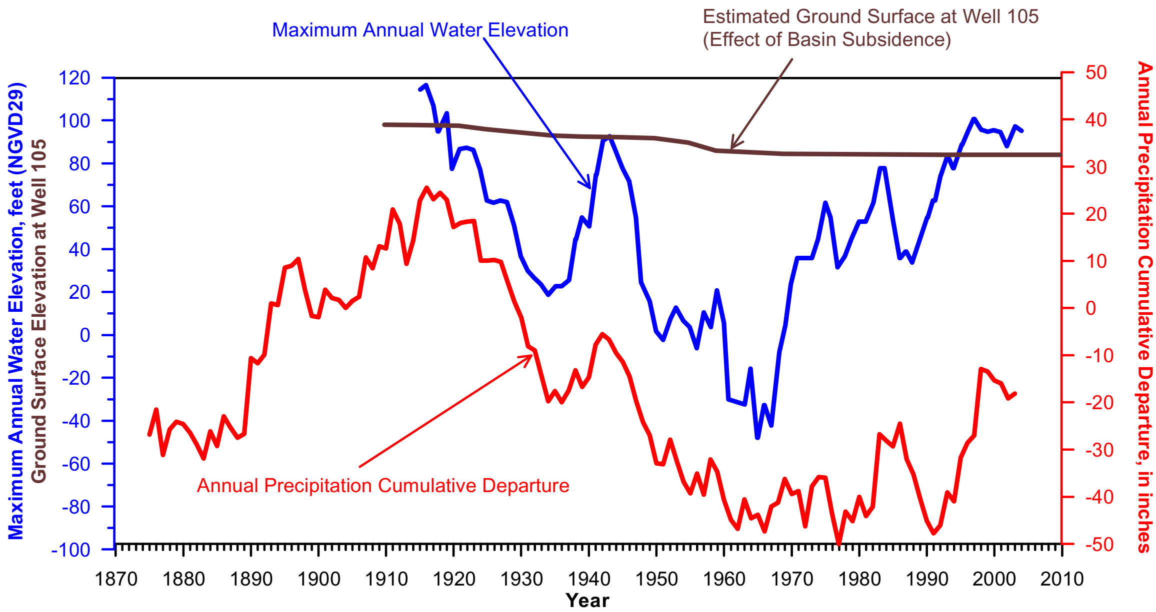

Figure 6. Groundwater Levels at San Jose "Index" Well, Subsidence of the Ground Surface and Annual Precipitation Cumulative Departure (modified from Iwamura, 1995)

Engineering Implications

Projects that are currently being designed within downtown San Jose, and the Santa Clara Valley need to be designed in accordance with the existing rising groundwater regime. The rising groundwater level has resulted in artesian conditions in the lower aquifer that may cause problems during construction of new projects. Below is a list of problems reportedly experienced by structures as a result of rising groundwater levels are listed below:

- The San Jose Airport had to fix many of its runways after improperly abandoned groundwater wells that had been paved over flooded the surface through cracks in the runway as the lower aquifer returned to artesian conditions.
- Santa Clara University Library basement was flooded that contained many of the libraries references. This was due to the groundwater level rising significantly in the years following the design. This is an excellent reminder of how an accurate prediction of groundwater level to be expected throughout the design life of a project can mitigate risks for the civil engineering company.
- A City Hall Offsite Parking Garage site in San Jose was claimed by a contractor to be "flooded by an underground river" due to a failure of the pumps that had been installed in the lower aquifer.

Mitigation Controls

None are in place for rising ground water. The focus by the water agency has been to recharge the aquifer that had been overdrafted for years and was causing settlement. Recharge ponds were located in the unconfined portions of the aquifer and water was imported. This has resulted in water levels returning to their previous levels, however, the rising ground water may prove to be a problem in the future.

SUMMARY AND CONCLUSIONS

Three examples of rising ground-water levels have been discussed. These examples highlight the importance of a thorough investigation for developing design water levels for an engineering project. It is recommended that two water levels be developed for projects; a design water level expected at the time of construction and a maximum water level to be expected throughout the design life of structures. The term "Maximum Credible Water Level" is proposed for the maximum water level and "Construction water level" for the period of time during which the project is expected to be built. The term "Maximum Credible Water Level" was selected because of the familiarity within the engineering community with the term "Maximum Credible Earthquake". The term should aid those using it in understanding that the maximum credible water level is not the water level at the present time, however, there is a credible risk that the water level could reach this maximum level during the design life of the structure. This is similar to the concept of the "Maximum Credible Earthquake. The purpose of developing a Maximum Credible Water Level is to minimize long term risk to the integrity of projects that are built in areas that may experience rising ground water during the lifetime of the project. Suggestions for the steps for data collection and data evaluation to be considered are listed below.

To achieve the objective of developing a "construction" water level and a maximum credible water level, a borehole exploration and testing programme should be developed to examine subsurface characteristics and to estimate the geologic, hydrogeologic and engineering properties of the subsurface materials underlying the project area. Monitoring wells should be installed beneath the project site to determine short-term (or seasonal) fluctuations of the water levels in each of the identified aquifers. These data should be collected on a regular basis and compared with previously collected data by others, if available, to achieve a better understanding of how the present ground-water conditions at the site compare with the long-term ground-water conditions.

Sources of existing data

The following sources are suggested:

- Existing reports for the project site, and for other projects in the vicinity.
- Reports by environmental agencies and utilities regarding ground water.
- Reports by other governmental agencies, research institutes, and universities, including state-sponsored geological agencies and water supply agencies.

Suggested steps for data evaluation

The following steps are suggested:

- Identify existing wells in proximity to the project.
- Compile available water level data and information on well construction. Make an interpretation of the hydrostratigraphic zone that each well monitors.
- Create water level hydrographs for wells in the vicinity of the engineering project.
- Create water level contours and/or profiles at the project location.
- Identify the maximum historical water levels measured within each hydrostratigraphic zone identified at the project location.
- Consider factors that affect the water levels, such as depths of incised streams and stream-aquifer interaction, response to seasonal precipitation and long-term precipitation trends, response to seasonal pumping and long-term trends in pumping, recharge from lakes and ponds, localized effects from permanent and temporary dewatering systems, injection wells, and ground-water remediation systems.
- Perform statistical analyses and/or modeling to evaluate trends and uncertainties.
- Estimate the "maximum credible water level" (for the design life of the project), considering uncertainties in the data and possible future trends as well as a construction water level to be expected during construction.

"Maximum Credible Water Level" for Risk Reduction on Engineering Projects

A clear understanding of the groundwater conditions at a project site can allow for the mitigation of problems associated with rising ground water during the design phase of a project, rather than implementing recovery measures after the structure is built. This will result in a reduction of long-term risk to projects. Table 1 includes a summary of engineering problems associated with rising groundwater levels and potential mitigation controls that could be implemented. This table is included to illustrate the point that development of a "Maximum Credible Water Level" (MCWL) can be used as a risk mitigation tool associated with rising ground water. The cost of implementing mitigation controls at the onset of design is significantly cheaper than costs that would be associated with implementing these mitigation controls during or after construction.

Table 1. Mitigation Controls for Rising Ground water

Effects of Rising Ground water	Applicable Mitigations	Mitigations	
Leakage into Basements and Service Ducts	1,2,3,4,5,7,8,9	1	Regional Pumping Policy
		2	Local Pumping Adjacent to Structure
Swelling and Heave of Clays	1,2,4,7,10	3	Permeable basement and drain to sump
		4	Relief wells draining to a sump
Reduction in Bearing Capacity causing differential settlement	1,2,4,7,9	5	Waterproof structure
		6	anchor or ballast foundation
Hydrostatic Uplift	1,2,4,6,7,9	7	drainage channels
Chemical Attack on buried structures	1,2,4,7,8,11	8	Water Efficient Landscaping
Difficulties During Construction (increased drainage requirements and potential instability of excavations and temporary works	1,2,4,7,9	9	Use "MCWL" when developing geotechnical parameters
increased active pressures on walls and decreased passive pressures	1,2,4,7,9	10	Removal or treatment of Clays that would swell if the "MCWL" were reached.
Liquefaction of saturated materials	1,2,4,7,9	11	Use "MCWL" when selecting concrete design

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REFERENCES

BELL, JOHN W., 1981. "*Subsidence in Las Vegas Valley*." Nevada Bureau of Mines and Geology Bulletin 95.

BELL, J.W., and DePOLO, C.M., 1996. On the origin of Quaternary fault scarps in Las Vegas Valley; *Seismic Hazards of the Las Vegas region, Program and abstracts*. University of Nevada, Las Vegas, November 14-15, 1996.

BGS. See British Geological Survey.

BRITISH GEOLOGICAL SURVEY (BGS), 1996. *London and the Thames Valley, Fourth Edition*, British Regional Geology, London HMSO, 173p.

BURBEY, 1995.

CALIFORNIA DEPARTMENT OF WATER RESOURCES. 1967. Evaluation of Ground Water Resources, South Bay, Appendix A: Geology. Bulletin No. 118-1, August 1967.

CALIFORNIA REGIONAL WATER QUALITY CONTROL BOARD, San Francisco Region. 2003. "*A Comprehensive Groundwater Protection Evaluation for the South San Francisco Bay Basins,*" May 2003. URL: http://www.swrcb.ca.gov/rwqcb2/sobayground.htm, accessed July 2004.

CNLV, 1998. City of North Las Vegas, ground-water recharge program 1998 annual report, Department of Public Works.

CONSTRUCTION INDUSTRY RESEARCH AND INFORMATION ASSOCIATION (CIRIA), 1989 SIMPSON, B., BLOWER, T., CRAIG, R.N., WILKINSON, W.B., 1989. *The Engineering Implications of Rising Groundwater Levels in the Deep Aquifer Beneath London*, Special Publication 69, CIRIA, 115 p.

CIRIA. See Construction Industry Research and Information Association.

DWR. *See* California Department of Water Resources

ENVIRONMENT AGENCY, 2005. Groundwater Levels in the Chalk-Basal Sands Aquifer of the Central London Basin, May 2005 14th Annual Report.

GARDIT. *See* Groundwater Aquifer Research and Development Team

GOLDEN SOFTWARE, INC., 2002. GRAPHER, Version 4.

GENERAL AQUIFER RESEARCH AND INVESTIGATION TEAM, 1996 "Rising Groundwater Under London, G.A.R.D.I.T. Update, July 1996.

IWAMURA, T. I. 1995. "Hydrogeology of the Santa Clara and Coyote Valleys Groundwater Basins, California." In Sangines, Eugenia M., David W. Anderson, and Anna V. Buising, eds., 1995, *Recent Geologic Studies in the San Francisco Bay Area, Pacific Section of the Society of Economic Paleontologists and Mineralogists*, v. 76, p. 173-192.

LAJOIE, K.R., and HELLEY, E.J.. 1975. "Differentiation of Sedimentary Deposits for Purposes of Seismic Zonation." *In* Borcherdt, R.D. (ed.), "*Studies for Seismic Zonation of the San Francisco Bay Region*," U.S. Geological Survey Professional Paper 941-A.

LAS VEGAS VALLEY WATER DISTRICT, 1991. The shallow aquifer system in Las Vegas Valley, Nevada**.** Las Vegas Valley Groundwater Management Program, URL: http://www.lasvegasgmp.com/html/index.html, accessed October, 2005.

LAS VEGAS VALLEY WATER DISTRICT, 1999. Las Vegas Valley Water District Artificial Recharge Report, 1999 Year End Report, Nevada Division of Water Resources Permit Nos. R-001, R-003, and R-012, Nevada Division of Environmental Protection Permit UIC No. NEV 87054.

LAS VEGAS VALLEY WATER DISTRICT in cooperation with the NEVADA DIVISION OF ENVIRONMENTAL PROJECTION (Kay Brothers et al), 1988. Groundwater chemistry changes resulting from stressed aquifer systems in Las Vegas Valley, Clark County, Nevada, URL: http://www.lasvegasgmp.com/html/tech_papers.html accessed October, 2005.

LVVWD. *See* Las Vegas Valley Water District.

MALMBERG, G.T., 1961. A Summary of the Hydrology of the Las Vegas Ground-Water Basin, Nevada, with special Reference to the Available Supply. Nevada Department of Conservation and Natural Resources, Water Resources Bulletin No. 18, 23 p., four plates.

MORGAN, D. S., and DETTINGER, M.D., 1990. Ground-Water Conditions in Las Vegas Valley, Clark County, Nevada – Part II Hydrogeology and Simulation of Ground-Water Flow. U.S. Geological Survey Open-File Report 90-179, 151 p., two plates

RWQCB *See* California Regional Water Quality Control Board

SANTA CLARA VALLEY WATER DISTRICT. 2002. Groundwater Conditions 2001. July 2002.

U.S. Geological Survey. 1999. Land Subsidence in the United States. Circular 1182.

SCVWD *See* Santa Clara Valley Water District.

SIMPSON, B., LANCE, G.A., and WILKINSON, W.B., 1987. Engineering Implications of Rising Groundwater levels beneath London In Hanrahan, E.T., Orr, T.L., and Widdis, T.F., (eds), "*Groundwater Effects in Geotechnical Engineering*", Proceedings of the Ninth European Conference on Soil Mechanics and Foundation Engineering, Dublin, 31 August-3 September, 1987.

SNWA *See* Southern Nevada Water Authority.

SOUTHERN NEVADA WATER AUTHORITY (KIM ZIKMUND), 1996. Extent and potential use of the shallow aquifer and Wash flow in Las Vegas Valley, Nevada 1996. URL: http://www.lasvegasgmp.com/html/tech_papers.html accessed October, 2005.

SOUTHERN NEVADA WATER AUTHORITY WEBSITE, 2005. URL: http://www.snwa.com accessed October, 2005.