FACULTY OF ENGINEERING SCIENCE
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Heritage and the Environment:

Groundwater Mapping, Analysis and Management of the World Heritage Site, Rani Ki Vav, India.

Promoters: **Prof. Koen van Balen**
Prof. Mario Santana Quintero
Prof. Rohit Jigyasu

United Nations Educational, Scientific and Cultural Organization
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Thesis to obtain the degree of Master of Science in Conservation of Monuments and Sites
Presented by Johannes du Preez

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Wholeheartedly dedicated to
Caroline and Annabelle du Preez.

"By 2025 more than half of the world's nations will face significant shortages of fresh water"[1]

[1] Mithan, S. (2012), *Thirst: Water and Power in the Ancient World*, Harvard University Press: Cambridge. P296.

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1. Introduction

1.1. Problem Statement

There is limited research documentation available which makes the link between the environment and heritage. That being said, the importance of multi-disciplinary research in the relationship between water-related studies and heritage is becoming an increasingly relevant topic in the contemporary context of the heritage sector. Climate change is increasing at a faster rate than expected.[2] Antony Bigio (2013) noted at the ICOMOS Netherlands conference, '*Water and Heritage: Protecting Deltas',* that although a 2° centigrade temperature increase is already baked into the existing climate, a 3° or 4° centigrade increase by the end of the century is a possibility, and one with catastrophic yet largely non-quantifiable or mappable outcomes.[3] Although the ICOMOS Netherlands seminar discussed water relationship to heritage with respect to the risks involved to deltas, the same increase in temperature plays an important role in other scenarios, such as sustainable equilibriums between human settlements and the surrounding environment, or the relationship between old technologies and new solutions to water-related challenges.

Projects such as CFRAM (Catchment-based Flood Risk, Analysis and Management), an EU directive, seek to understand the risk that surface-water poses to human settlements. The INCBS (Irish National Committee of the Blue Shield) has endeavored to extend this risk analysis to moveable and immovable heritage through the development of a heritage risk-analysis platform based on a geographical information system (GIS).[4] Whereas strides have been taken to research and understand the relationship between surface water and heritage, the role of groundwater in relation to a heritage context is largely unexplored. Groundwater accounts for the vast majority of potable water in certain areas of the globe, and potentially

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2 U.S. Global Change Research Program, *2014 National Climate Assessment* (Washington: GlobalChange, 2014), http://nca2014.globalchange.gov/highlights/overview/overview. [accessed 11 April 2015]
3 Antony Bigio, 'Water Related Impacts In Times Of Change', in *Protecting Deltas, Heritage Helps!* (Amsterdam: ICOMOS Netherlands, 2013).
4 Deirdre McDermott, Risk Analysis of Heritage-Based Flood Data, interview by: John du Preez, in person (Dublin, Ireland, 2014).

plays an essential role in the challenges addressed at the ICOMOS Netherlands seminar as well as the ICOMOS General Assembly (Florence, November 2014).[5] Furthermore, access to mappings of these underground dynamics allow for a relationship to form between heritage structures and sites and the surrounding environment. The Rani ki Vav, a subterranean well-structure in Patan, India, and a recent World Heritage Site, is an example of the relationship-base between heritage structures and the surrounding environment.[6] To explore the potential reuse of these structures for their original purpose, and to investigate the role that ground-water pollutants have on these structures, opens a dialog of symbiotic coexistence between human settlements and nature through the medium of heritage objects and sites. Additionally, to understand the underground resources that are available to heritage sites allows for a deeper level of heritage site management with regards to the interaction of human and environmental factors which affect the sustainability of the heritage structures with which they co-exist. This approach also allows for the environmentally sustainable management of the natural environment in or on which the heritage structures exists.

It is therefore the purpose of this study to investigate the relationship between groundwater and heritage monuments and sites in order to understand both the role that heritage can offer towards environmental sustainability, as well as the effect that the environment has on heritage structures and the approach to be taken in order to prevent negative impact in to either the natural environment or the heritage structure, with the following research questions in focus:

- *In what way is groundwater mapping, analysis and management useful to the heritage sector?*
- *How does the new information integrate within the context of the heritage sector?*

[5] Howard Perlman, 'Where Is Earth's Water?', *USGS Water-Science School*, 1993, http://water.usgs.gov/edu/earthwherewater.html. [accessed 14 April 2015]
[6] The Biharprabha News, 'Gujarat's Rani Ki Vav Added To UNESCO World Heritage Site List', 2014, http://news.biharprabha.com/2014/06/gujarats-rani-ki-vav-added-to-unesco-world-heritage-site-list/. [accessed: 6-March-2015]

1.2. Research Methodology

This will be a mixed-method case study based research paper. The selected case study will be chosen in support of the research question and in exploration of the functional connection between geohydrology and heritage application. The case study will focus on a unique and specific approach and function of the relationship between these two fields, and the resulting challenges, developments and outcomes will be recorded and reflected in the overall analysis of the research question. A broader outline of the application of groundwater within heritage research and professional practice will be discussed. Qualitative research will be based on the selected case study. The secondary method would be quantitative by virtue of the technical data collection processes involved in the case study analysis. The case study research will allow for a clearer view of the application of the technology within a specific heritage environment and help to define a methodology towards the recording and analysis thereof. The selected case study is the Rani ki Vav, located in Patan, India. Information will be gathered from on-site case study research, literature and policy review, contemporary research articles and related seminars, professionals within each field of expertise, and through creative development of technological solutions in support of the research question.

1.3. Global Outline

The paper will firstly focus on the geohydrology aspects to be used within the scope of the research question and will discuss how these are applied to the heritage sector. Within this section a broad scope of groundwater/heritage applications are discussed, after which focus is given to the application within the specific case study in the preceding section. The second part of the paper introduces the heritage case study. Discussion as to the relationship between groundwater and the case study, from a heritage perspective, take place within this section. Finally, analysis of collected data is presented with recommendations based on the acquired information.

2. Geohydrology

2.1. Overview of the Role of Groundwater in Heritage

Although the relationship between groundwater and the heritage sector is one that is largely underdeveloped at this stage, the benefits of groundwater related analysis to the conservation efforts of heritage structures are potentially high. These benefits vary according to site and context, and as such appropriate application is limited based on specific case studies. Further studies are required to fully understand the role of groundwater in the heritage sector, and these potential aspects are briefly discussed below. It must be noted that the overview in the forthcoming sub-chapters give an holistic overview of the relationship of geohydrology to a heritage application, although these applications are site and context-specific. That said, the case study seeks to apply and investigate these functions as applicable to the requirements of the given site.

2.1.1. Groundwater Flooding

Flooding from groundwater as well as coastal and fluvial sources is an acknowledged risk within Europe, and EU initiatives are underway to manage the challenges involved.[7] The Netherlands, as an example, faces particular flooding challenges and the risk to heritage has been identified and prioritized by ICOMOS Netherlands.[8] The Catchment-based Flood Risk Assessment and Management programme undertaken and nearing completion in Ireland is central to the medium to long-term strategy within Ireland for the reduction and management of flood risk. The programme is undertaken as part of the EU floods directive and the same initiatives are being undertaken in various countries throughout the European Union.[9] The primary purpose of the CFRAM directive is to reduce risk to human life and assets. Given the examples above it is noted that flood risk analysis within a European

[7] M. Mokrech, *An Integrated Approach For Assessing Flood Impacts Due To Future Climate And Socio-Economic Conditions And The Scope Of Adaptation In Europe* (Amsterdam: Springer, 2015). p245.
[8] Rohit Jigyasu, *ICOMOS Netherlands: Capacity Building: Knowledge Gaps And Research Agenda On Water And Heritage*, video, 2013, https://www.youtube.com/watch?v=sB9IR_KIHr0. [accessed: 09 May 2015]
[9] Office of Public Works, 'Catchment Flood Risk Assessment And Management', *EU Floods Directive*, 2012, http://www.cfram.ie.

context is nothing new, although determining the risk to both moveable and immovable heritage through flooding, and the generation of emergency frameworks in this regard, is still largely in its infancy.[10] ICOMOS Ireland raises the question in this regard, and has asked how flood risk relates to the moveable heritage found within Irelands museums and archives. Although the Museums Standards Programme of Ireland (MSPI) addresses this to a degree through the incorporation of an emergency flood plan within their accreditation system, it is noted that this plan need not take context-specific challenges, or emerging flood data, into consideration. An example of how this might be a concern to movable heritage could be the placement of a secondary storage area, as part of an evacuation plan, within a 1000-year flood-risk area. The idea here being that fluvial flooding is mapped in 10-year, 100-year and 1000-year flooding areas, which is not indicative of the time-period between flood incidents, but rather the statistical risk of that type of flooding happening in parts per thousand. As an example, a 1000-year flood could happen twice within one year, or several times within a 10-year period, although the statistical chance is 1:1000 in relation to the 1:10 chance of a 10-year flood occurrence. It is important to note this because 1000-year flood patterns should not be ignored as a far-off and intangible risk to heritage. To the contrary, should a 1000-year flood occur in any given year, that flood would encompass both 10-year, 100-year and 1000-year flood areas, meaning that any under-developed evacuation-plan based on outdated flood data, or by recent historical flood data, could put moveable heritage at a very specific risk.

[10] Deirdre McDermott, Risk Analysis of Heritage-Based Flood Data, interview by: John du Preez, in person (Dublin, Ireland, 2014).

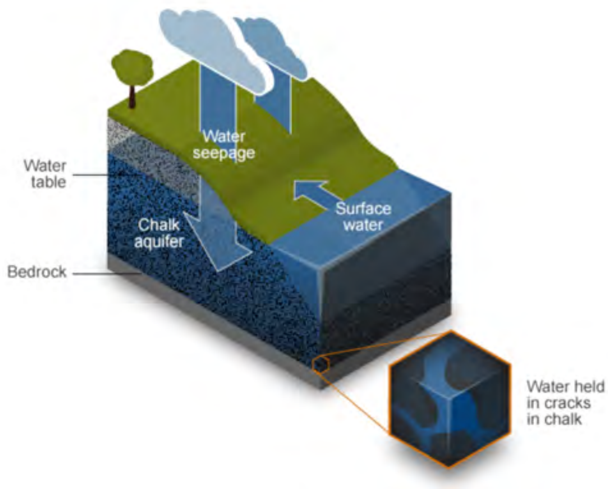


Figure 1 - How groundwater flooding occurs (online: http://www.bbc.com/news/science-environment-26136975)

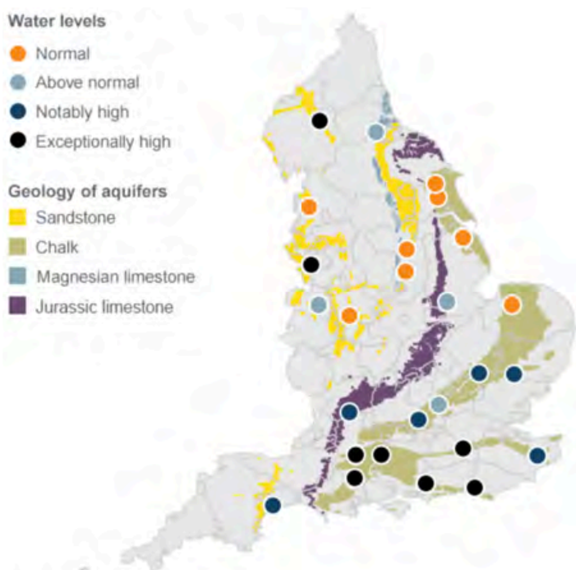


Figure 2 – Groundwater Levels in England, Jan 2014 (http://www.bgs.ac.uk/products/hydrogeology/wellmaster.html)

As can be seen diagrammatically groundwater poses a real and persistent flood risk to areas of high rainfall. As an example, given the geology of south and south-east England, which is more perceptible to groundwater flooding through its primarily chalk geological structure we note a particularly high risk from groundwater flooding.

It is interesting to take a heritage value-mapping and overlay this, within this context, in order to see the relationship between rich heritage areas and groundwater flood risk areas. Although the comparison in this case does not particularly support the risk to ceramics within English heritage, but rather acts as an indicative indicator of heritage saturation within areas of high risk through groundwater flooding. Through such examples it becomes evident that the relationship between groundwater flooding and heritage areas is a tangible area of concern within the heritage sector.

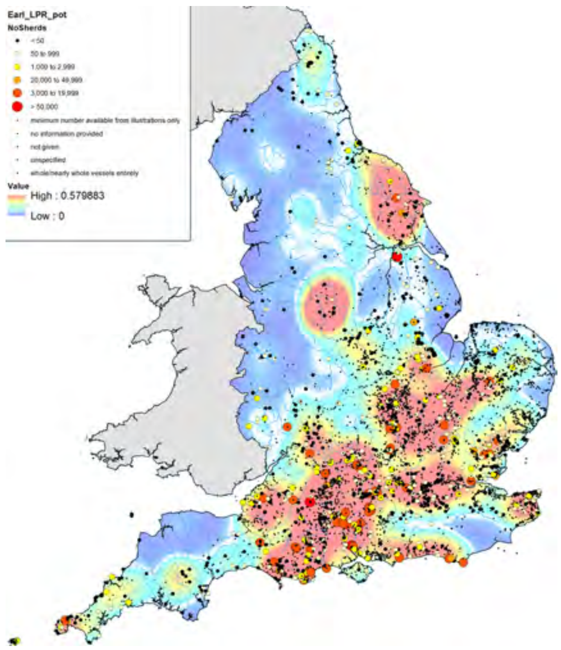


Figure 3 - Ceramic Heritage Density (online: http://englaid.com/category/gis/)

Groundwater relates to this risk management challenge with regards to heritage in several ways:

- **Moveable Heritage** – The relationship of groundwater flooding to heritage lies primarily in the risk management strategies applied by museums and archives in terms of their collections. Many museums use basements for either research purposes or for storage of collection pieces within their portfolio. As such it is imperative to understand the localised groundwater situation as it relates to museum and its surrounding areas. Furthermore, it is important to relate this groundwater information to the management plan, and to implement changes according to specific situations in order to reduce risk to heritage objects. [11]
- **Immoveable Heritage** – The relationship between groundwater and architectural heritage is even more specific than that of moveable heritage. Architectural elements are not specifically at risk through their positioning within flood areas, and considerations such as topology, elevation and drainage mechanisms need to be taken into consideration when determining the risk of flooding to architectural heritage. However, the relationship between groundwater and architectural heritage remains important in the ongoing measurement of changes between the structure and the surrounding environment from a preventative conservation perspective. An example of this would be castles in Ireland that were built with water-drainage systems in place. These systems have effectively drained excess water, maintaining a static relationship between the structure and the environment. Over time these drainage mechanisms may become blocked or fall into disrepair, changing the

[11] *The Heritage Council Museums Standards Programme For Ireland*, ebook, 1st ed. (Dublin: The Heritage Council, 2004). p23.

dynamic between structure and environment, resulting in an increase to structural risk for the architectural element. Such deviations over time also change the geotechnical dynamic between the structure and its surrounding environment, which may negatively affect structural stability over time.[12]

2.1.2. Pollution-Related Studies and the Buffer-Zoning Hypothesis

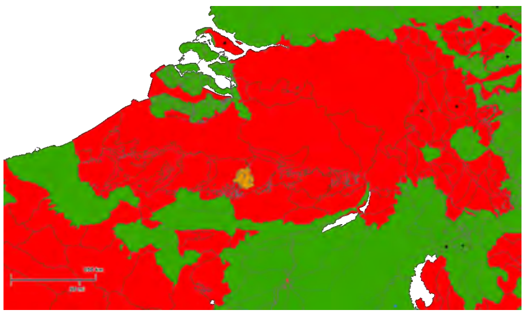


Figure 4 - Sustained upward trend of groundwater pollutants (EEA, http://www.eea.europa.eu/themes/water/interactive/soe-wfd/wfd-ground-water-viewer)

Groundwater pollution indicators, specifically within a European context, are extensively monitored and managed by the European Environmental Agency.[13] These indicators, however, as they relate to heritage structures are underdeveloped and in need of further investigation. The Water Framework Directive (WFD) of the European Environmental Agency (EEA) shows a significant and sustained upward trend of pollutants within groundwater in areas such as Belgium, as indicated.[14] The effects of this change in dynamics are not understood as it relates to heritage assets. Heritage might be affected by groundwater pollutants in the following ways:

- Physical Interaction – The relationship between heritage structures and physical interaction with waterborne contaminates through the medium of groundwater has not been investigated. Given the particular nature of allowable tolerances within heritage conservation the need for investigation into this approach might be necessitated. Given the passive and ongoing nature of the conservation of heritage architecture, the criteria for evaluation and the resulting risks should be considered when measuring groundwater pollutants as they relate to historical structures. An

[12] Grellan Rourke, Flood risk to architectural heritage, Interview by John du Preez, in person (Office of Public Works, Dublin, 9 October 2014).
[13] European Environmental Agency, *Groundwater Monitoring In Europe* (Denmark: European Environmental Agency, 1997).
[14] European Commission, *Common Implementation Strategy For The Water Framework Directive (2000/60/EC)* (Luxembourg: Office for Official Publications of the European Communities, 2007). p45.

example of this is the possible silting of the Rani ki Vav through ongoing interaction with groundwater over an extended period of time.

- Direct Access to Water (well structures) – In the case of direct relationships between groundwater and heritage the importance of groundwater pollutants becomes more evident. In the case of well structures, such as the Stepwells found throughout India, the social aspect of using the wells for their intended purpose, specifically sources of potable water, makes the ongoing measurement and management of groundwater pollutants a necessity for the wellbeing of those that use the structure. What makes this aspect even more interesting is the relationship that the well-structure develops with surrounding urbanisation and industrialisation. Industries encroaching on the aquifer systems of water-based heritage structures directly influence the quality and safety of the water sourced by these structures.[15] The same applies to landscape heritage and the relationship these areas have to the human settlements that reside within their boundaries. Given that aquifer systems range in size and complexity it is important to understand the role that a much larger system can have on a select point within that system, the heritage structure. A possible approach to this would be the development of a framework to map and manage aquifer systems that relate to heritage sites through the concept of groundwater buffer zoning. Such a framework would integrate the aquifer system, where necessitated, as part of the heritage structure and as integral for its continued preservation, culminating in a management and protection plan for groundwater concerns within the developed conservation plan. Buffer zoning, much like it is approached as a visual element in current conservation plans, would seek to protect fragile areas from encroaching industrial pollution and plays a role in the scenario development of the Rani ki Vav case-study.

[15] B.V. Lenntech, 'Sources Of Groundwater Pollution', *Lenntech Water Treatment Solutions*, 1998, http://www.lenntech.com/groundwater/pollution-sources.htm. [Accessed: 13 March 2015].

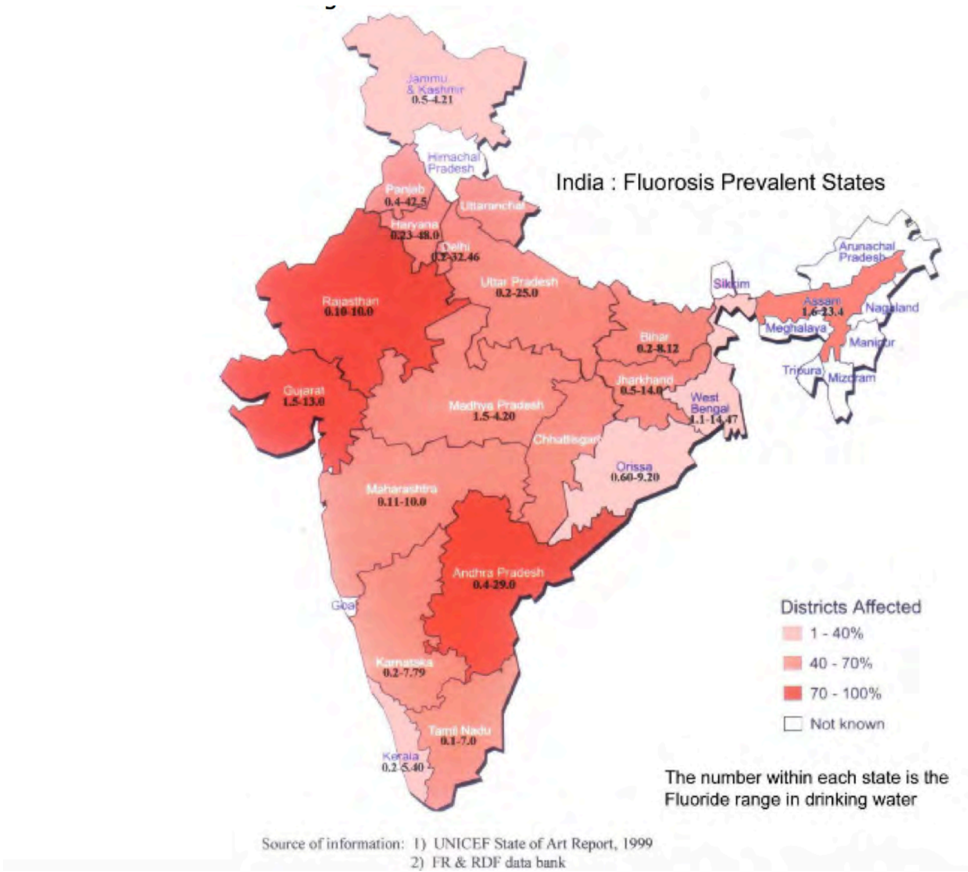


Figure 5 - Fluoride contamination of groundwater (1999, UNICEF State of Art Report, online: http://www.schools.indiawaterportal.org/wq-test/fluoride-factsheet)

2.1.3. Slope Stability

Soddu concludes that groundwater plays a role in failing slope stability.[16] Although the application of slope stability analysis is unique and very specific within the scope of heritage, it does exist in some particular cases. An example would be the Cultural Landscape of Bali Province: the Subak System as a Manifestation of the Tri Hita Karana Philosophy, a UNESCO World Heritage site (inscribed 2012, (ii)(iii)(v)(vi)).[17] The heritage site is essentially a water management system implemented through the use of terraced rice fields as well as through the use of canals and weirs. Given the water-based nature of the site function, in addition to its sloped typology, preventative conservation in terms of slope stability through

[16] S. Soddu, 'Modelling Groundwater Effects On Slope Stability', *RMZ - Materials And Geoenvironment* 50, no. 1 (2003). p349.
[17] UNESCO Centre, 'Cultural Landscape Of Bali Province: The Subak System As A Manifestation Of The Tri Hita Karana Philosophy - UNESCO World Heritage Centre', *UNESCO World Heritage Centre*, 2012, http://whc.unesco.org/en/list/1194. [Accessed: 13 March 2015].

groundwater mapping and management would be appropriate. The same could be argued for the Rice Terraces of the Philippine Cordilleras, another cultural landscape UNESCO World Heritage site (inscribed 1995, (iii)(iv)(v)).[18] These rice terraces, with their steep gradients, form an intricate and fragile system of irrigation. The site was also placed on the List of World Heritage in Danger by UNESCO in 2001 on account of the absence of a monitoring programme or management plan, and was removed from the World Heritage in Danger list in 2012 after efforts were made to improve the conservation and management plan.[19] The Rice Terraces of the Philippine Cordilleras are a prime example of the useful application of slope stability analysis within the scope of a heritage scenario. Electroseismic technology, as the primary chosen method of groundwater mapping within this research, is both equipped to analyse slope stability and also has several precedent studies in this regard.[20]

Figure 6 - Rice Terraces of the Philippine Cordilleras (2014, online: http://www.randomlynew.com/2021/famous-and-beautiful-heritages-of-the-world.html)

18 UNESCO Centre, 'Rice Terraces Of The Philippine Cordilleras - UNESCO World Heritage Centre', *UNESCO World Heritage Centre*, 1995, http://whc.unesco.org/en/list/722. [Accessed: 13 March 2015].
19 Ibid.
20 Robert J. Sterrett, *Groundwater Flow-Systems And Stability Of A Slope* (San Francisco: Indiana University, 1982).

2.1.4. Sustainability – Heritage Landscapes and the Human Settlement

The modern-day challenges of energy reduction and sustainable resource consumption apply to heritage, and the question arises as to what role heritage plays in these overarching concerns. At its core the question is one of relationship between the natural environment and the heritage structure and/or the people who depend on that resource. Human settlements are often an integral part of natural heritage landscapes, and their relationship to the natural environment further strengthens the heritage value connected to the site. An example of this would, again, be the Rice Terraces of the Philippine Cordilleras, a UNESCO World Heritage site. The core heritage value is found in the relationship that the site has with those that inhabit the landscape, and the symbiotic relationship that the human settlements have in reaction to this natural resource. As such the Rice Terraces of the Philippine Cordilleras act as an ideal example of heritage-based precedent of sustainable interaction between human settlements and the natural environment, generating a natural landscape that is valued for both its cultural and natural criteria.[21] Careful monitoring and management of the natural cycles that sustain the preservation of the site need to be in place, and effective groundwater mapping techniques form part of this critical monitoring process.

Figure 7 - Cultural/Natural UNESCO World Heritage, Drakensburg Mountains (Geoff Mason, S.A.)

[21] UNESCO Centre, 'Rice Terraces Of The Philippine Cordilleras - UNESCO World Heritage Centre', *UNESCO World Heritage Centre*, 1995, http://whc.unesco.org/en/list/722. [Accessed: 13 March 2015].

Another example is the Maloti-Drankensburg mountain range in South Africa. As part of the UNESCO heritage value criteria the site is recognised for its cultural aspects as much as for its natural beauty (listed under UNESCO criteria (i)(iii)(vii)(x)).[22] The 'mixed'-category site therefore has, at its core, a heritage value that lies in the relationship between these aspects. The Basotho people, indigenous to these mountain ranges, have roamed the natural landscape throughout their history, depending on the natural resources for survival. It can be deduced, then, that the current indigenous settlements of the Basotho as they occupy the Maloti mountains remain a function of the overall dynamic which adds heritage value to the landscape and as such, their continued preservation remains a heritage concern as much as a social or urban challenge. An understanding of the groundwater resources available within the heritage landscape and the way that these relate to the human settlements thereon in a sustainable and efficient manner, ensuring further ecological coexistence should be seen as a monitoring and management concern within the conservation management plan. In this manner groundwater mapping, analysis and management serves heritage concerns at a sustainability-related level.

When the delivery of sustainable resources is directly related to the ongoing preservation and functional usability of a heritage structure or landscape the priority towards conservation is evident. Cases such as these can be evaluated as follows:

- Preventative conservation approach – Conservation of existing and functioning heritage systems involves the preventative measurements taken through monitoring and management.[23] These could be within the scope of contemporary urban dynamics and how they relate to heritage function, such as the case precedents of ICOMOS Netherlands[24], or the continued functioning of localised human-nature relationship through defined heritage landscapes or monuments, such as the Rice Terraces of the Philippine Cordilleras, or the functioning Stepwells found within

[22] UNESCO Centre, 'Maloti-Drakensberg Park - UNESCO World Heritage Centre', *UNESCO World Heritage Centre*, 2014, http://whc.unesco.org/en/list/985. [Accessed 13 March 2015].
[23] Britta Schaffelke, *Water Quality In The Inshore Great Barrier Reef Lagoon: Implications For Long-Term Monitoring And Management* (Townsville, Australia: Australian Institute of Marine Science, 2011). p1-2.
[24] Tjeerd Blauw, 'Policy Specialist Water Safety And Rural Areas Province Of Zeeland', in *ICOMOS Netherlands: Protecting Deltas - Heritage Helps!* (Amsterdam: ICOMOS Netherlands, 2013), p12.

India (such as Baoliwali Masjid near Delhi, used to source surrounding areas).[25] These cases are particularly relevant in that they actively secure the resources to one or a few human settlements in a sustainable way. Where relevant, the monitoring of water-based criteria in respect of the ongoing functioning of the landscape or structure is an important criteria of a conservation management plan.

- Rehabilitation for future resource management – Although this could be applied to any heritage landscape of resource structure, the case of the stepwells in India are particularly unique and relevant. The ASI (Archeological Survey of India) has already rehabilitated selected stepwells within India as sources of water for surrounding areas, with plans for future rehabilitations underway.[26] What makes these cases specifically interesting is the fact that rehabilitation is largely limited to structural criteria or desilting of stepwells in order to restore a sustainable water flow. As of yet groundwater relationship to stepwells with focus on rehabilitation scenarios as they relate to aquifer dynamics is underdeveloped. Scenarios allowing for more efficient interaction between the groundwater system and the heritage structure would allow for a more effective resource solution, and the gained information would allow for a more sustainable management framework for the ongoing functionality of the structure. Variables such as the local draw from the aquifer system, such as from surrounding agricultural activities, play an important role in case studies such as the Indian stepwells, and the holistic management approach of these systems would ensure the preservation not only of the structure, but also of its functionality and social dynamic.
- Planned resource management and delivery – This relates to the determination of available resources within a defined natural landscape in order to develop a managed approach to growth within the areas in order to maintain cultural links to natural environments in a sustainable way. An example of this would be the Maloti-Drankensburg mountain, a UNESCO World Heritage site. The Basotho people have thrived within this area since the 5th century A.D.[27] The uncontrolled expansion

[25] Desolenator, 'Indian Stepwells - How Stepwells May Be A Solution To India'S Water Crisis', *Desolenator*, 2014, http://blog.desolenator.com/tag/india-step-wells/. [Accessed: 13 March 2015].
[26] Ibid.
[27] UNESCO Centre, 'Maloti-Drakensberg Park - UNESCO World Heritage Centre', *UNESCO World Heritage Centre*, 2014, http://whc.unesco.org/en/list/985. [Accessed: 13 March 2015].

of human-settlements within areas of fragile natural resources puts pressure on both the environment as well as the cultural links that are to be preserved on the heritage landscape, such as the Basotho people and their communities. However, increase in human population in the area is evident[28], and the planned management of heritage landscapes as they relate to human settlement development is necessary to ensure cultural cohesion within a human-population that is largely defined by its interaction with the natural environment. In order to do this effectively, various natural resources, including groundwater delivery, need to be measured and understood to define and meet future human growth.

In conclusion, the role that water plays as a function and catalyst of heritage integration within a sustainable-resource perspective is one that suggests itself as critical, and further investigation is necessary. This research paper addresses the development of possible rehabilitation for future resource management through a case study investigation of a heritage well-structure.

2.1.5. Conservation – Rehabilitation Scenarios for specific projects

When focusing on specific sites and monuments related to water-architecture the option for specific rehabilitation scenarios become a possibility with incorporated groundwater mapping. As a specific case study, the Rani ki Vav stepwell plays an important role in an ongoing trend and interest in the restoration of stepwells within India.[29] Funding has been given for the structural restoration of five stepwells within India in order to provide a source of water for surrounding communities, and to bring these communities closer to their own heritage. Adapting and rehabilitating these wells, however, is restricted because of the following reasons:

- Modern groundwater mapping processes can be expensive and non-feasible for smaller projects.

[28] South African Yearbook, 'Kwazulu-Natal Province, South Africa', *Southafrica.Info*, 2012, http://www.southafrica.info/about/geography/kwazulu-natal.htm#.VQMRYUIk-ng. [Accessed: 13 March 2015].
[29] Prince Claus Fund, *Rehabilitation Of The Hindu Stepwells In India: A Source Of Water And Social Interaction*, ebook, 1st ed. (Amsterdam: Prince Claus Fund), online: http://www.gbsjaipur.org/activities.php?activity=45. [accessed: 09 May 2015]

- Drilling, although expensive, also becomes a high-risk process without adequate groundwater information. This is of particular importance for projects of limited budget.
- Lack of groundwater information may prevent the generation of alternate rehabilitation scenarios, such as the shifting of water-source drilling locations, or the maintenance of sustainable water through the management of aquifer systems within the area.

The interest in these projects have a resonance that goes beyond the localised water they provide. In 2013 the stepwells structures were discussed at the ICOMOS Netherlands conference dealing specifically with the topic of water in heritage and the role of heritage within the scope of sustainability challenges. They were addressed as examples of a heritage approach to sustainability challenges, and their benefits as sources within the context of ever-increasing pressure to existing water supplies.[30] Emphasis needs to be placed on the notion that rehabilitation within this context relies not only on the physical restoration of the monument, but also in the understanding and reconciliation of monument/environment interaction. Sustainable restoration in this regard lies in as much in the understanding of cause as it does in the reaction to that cause. In order to prevent future failure of the site the reasons for the initial change in relationship dynamic need to be understood, addressed, and effectively managed. Furthermore, contemporary technology needs to increase efficiency of the monument function as far as might be done without interfering with the monument or its value. An example might be the deepening of the well-structure to a determined depth, the shift of the source for optimal groundwater delivery, or even the dismissal of future planning for the structure due to irregular or non-sustainable supply. The mapping and analysis of the groundwater model as it relates to the structure is important within the scope of these objectives, and to undertake the groundwater mapping of stepwells planned for rehabilitation would aid in both minimizing risk through unnecessary spending, as well as aid in the delivery of the most efficient rehabilitation solution for the intended project. Post-rehabilitation management is also a critical aspect of the conservation process as groundwater is an ever changing and fragile resource. Abuse of an aquifer system at any point within its area of influence could lead to the permanent collapse of the system as a

[30] Rohit Jigyasu, *ICOMOS Netherlands: Capacity Building: Knowledge Gaps And Research Agenda On Water And Heritage*, video, 2013, https://www.youtube.com/watch?v=sB9IR_KIHr0. [accessed: 19 April 2015]

source for the stepwell itself. Furthermore, lack of management and monitoring could lead to contamination risk of the well supply, resulting in an unusable and unsafe well structure.

In conclusion, well-structures act as ideal case-studies for the relationship between groundwater and heritage structures, and also illustrate the value of heritage structures both within the contemporary challenges of sustainability towards the future, as well as in their capacity to integrate cultural and landscape values through their functional resource delivery. Their role as a catalyst towards heritage awareness and their examples as traditional-method solutions for small local-based resource should also be considered.

2.1.7. ICOMOS Netherlands and the Declaration of Amsterdam

The ICOMOS Netherlands conference of September 2013, "Water and Heritage: Protecting Deltas", is worth particular mention due to its importance in the relation between water and heritage topics. Although the focus was around the protection of delta cities under threat of natural disasters brought about by climate change, the thematic addressed water-related concerns to heritage at various levels. During the same conference Rohit Jigyasu, President of the ICOMOS International Committee on Risk Preparedness (ICORP) discussed the role of the interconnectedness of water and heritage from a sustainability perspective, using well structures as an example of this.[31] Jigyasu argued that civilisations primarily developed according to their critical relationship to water, which is often overlooked when associating heritage with historical buildings and monuments. The development of water-based architecture, in their various typologies, is thus paramount to cultural development and water is an inseparable part of heritage. Jigyasu then furthered his argument of traditional water systems as historic tools of resource supply, disaster management and sustainable delivery mechanisms:

> *"Traditional water systems not only demonstrate wisdom of the past that has evolved through series of trials and errors, these also have great potential for emergency response following disaster. For example traditional system of Hitis (water tanks) located in the dense historic urban fabric of*

[31] Rohit Jigyasu, *ICOMOS Netherlands: Capacity Building: Knowledge Gaps And Research Agenda On Water And Heritage*, video, 2013, https://www.youtube.com/watch?v=sB9IR_KIHr0. [accessed: 19 April 2015]

Kathmandu valley in Nepal or Wells and Tankas in the historic Walled City of Ahmedabad in India have great potential to serve as important sources of water supply during emergency situations. One can also find examples of indigenous warning systems among communities for predicting hydro meteorological hazard events. Their usefulness should also be explored in the light of varying rainfall pattern due to various factors including climate change.

Unfortunately rapid urbanization and development have taken their toll on 'heritage of water' especially in the light of their limited protection and conservation. This has not only resulted in the loss of these irreplaceable cultural resources but also damaged local ecological systems and in the process increased vulnerability of communities to natural disasters.

It is time for us to realise the enormous potential of the heritage of water and utilise it efficiently and creatively for making disaster resilient societies." [32]

The discussions undertaken during the ICOMOS Netherlands conference further support the objectives of this paper, particularly the comments of László Hayde (Lecturer at UNESCO-IHE) as well as Henk van Schaik (former Director of the CPWC). Hayde argued that within the coming future heritage sites will face increasing risk from water from various natural phenomena, and that to address this risk to heritage structures will be a challenge.[33] As a positive, these same historical objects may serve a benefit, not only from an economic or touristic perspective, but also as historical precedents for urban planners in defining future protective stratagies. Hayde furthers this by noting that heritage experts are not trained in water-related topics, and water experts are not trained in heritage-related aspects, but that many "many more skilled experts are needed in both fields to be able to address the water challenges and their contribution of heritage in this context".[34] This can certainly be considered a call to the development of relationships between the heritage and water-related sectors. Van Schaik emphasizes the creation of public awareness of the role of water in world history and the promotion of public participation in the resolving of water-resource

[32] Rohit Jigyasu, 'Reinforcing the Link Between Water and Heritage to build Disaster Resilient Societies', in *ICOMOS Netherlands: Protecting Deltas - Heritage Helps!* (Amsterdam: ICOMOS Netherlands, 2013), p21.
[33] László Hayde and Henk van Schaik, 'Bridging Knowledge Gaps in Water and Heritage', in *ICOMOS Netherlands: Protecting Deltas - Heritage Helps!* (Amsterdam: ICOMOS Netherlands, 2013), p31
[34] Ibid.

issues. Van Schaik noted that the relationship between water and heritage, and the capacity development priorities in this regard, are to be key messages in the 7th World Water Forum in Korea in 2015.

The event culminated in the development of the Statement of Amsterdam (2013), an initial statement on the best practices and approach to the relationship between water and heritage and the way forward in this regard. The statement promotes linkages for mutual benefits between international and national NGO's, national and local governments, civil society and relevant international and national organisations and networks engaged with heritage and water management, urban development, climate change adaptation, sustainability and disaster response, including UNESO, ICOMOS, UNFCCC and UNISDR[35]. The Statement of Amsterdam also promotes fostering of research in this regard through the same and relevant stakeholders. The statement also prioritises the development of national and international strategies for heritage protection from water-related disasters, which include risk-mapping, early warning systems and adaptation measures.

2.2. Groundwater Tools and Technology

2.2.1. Technology – Theory and Description

This chapter introduces the electroseismic technology to be used and adapted within this study as it relates to electroseismic surveys. The basic principles of operation are first discussed in broader terms, giving description of the underlying theory and fundamental function. In the next sub-section core geohydrology terms are provided, after which discussion focuses on the application of electroseismic surveying as it relates to the heritage sector.

[35] ICOMOS Netherlands, *The Statement Of Amsterdam*, ebook. (Amsterdam: ICOMOS Netherlands, 2013), http://www.icomos.nl/media/Water_and_Heritage/Final_Statement_Protecting_Deltas_Heritage_Helps.pdf. [Accessed: 13 March 2015].

2.2.1.1. Background

In his initial paper on the research topic, '*On the theory of seismic and seismoelectrical phenomena in a moist soil*', Frenkel introduces the first developments of electroseismic technology within a groundwater perspective.[36] Within the paper the Helmholtz-Smoluchowski equations are used to measure streaming potential, which originates when an electrolyte is driven by a pressure gradient through a channel with charged walls, as is later proven to be the case within a groundwater measurement context.[37]

Haartsen and Pride further explained this phenomena in 1995 when describing the current imbalances generated through the electromagnetic field by fluid motion relative to a porous matrix. These measurements are indicated at the interface between rock formations of different electroseismic properties. The formed electromagnetic fields at these interfaces can be read at ground-level as measurable interface response data.[38]

The challenge with this approach is that should the seismic waves pass through a homogenous material with no shift in electroseismic property then no readable data will be referred back to the surface for measurement. To solve this, further research was done and Chandler (1980) worked on laboratory experimentation to relate electroseismic response to permeability. In 1998 Haartsen developed a relationship between electroseismic response as a function of salinity, porosity and permeability of a porous medium.[39]

Due to unsatisfied chemical bonding net electric charge can be measured on grains of rock formations. In an aquifer system, such as in a groundwater system, water makes contact with these rock surfaces which are charged and an electrical potential is produced as water is also

[36] J Frenkel, 1944, On the theory of seismic and seismoelectric phenomena in a moist soil, J. *Physics (Soviet),* 8, 230-24l.

[37] Dongqing Li, *Electrokinetics In Microfluidics* (Oxford: Academic, 2004).p618.

[38] M. Haartsen and S. Pride, Modeling of coupled electroseismic waves from point sources in layered media , J. *Geophys. Res., 1995.*

[39] M. Hartsen, 1998. Dynamic Streaming Currents from seismic point sources in homogenous poroelastic media. Geophysical Journal International.

electrolytic in nature. Free ions in the water are then drawn towards the surface of the rock when an *electrical double layer* is formed as a result.[40]

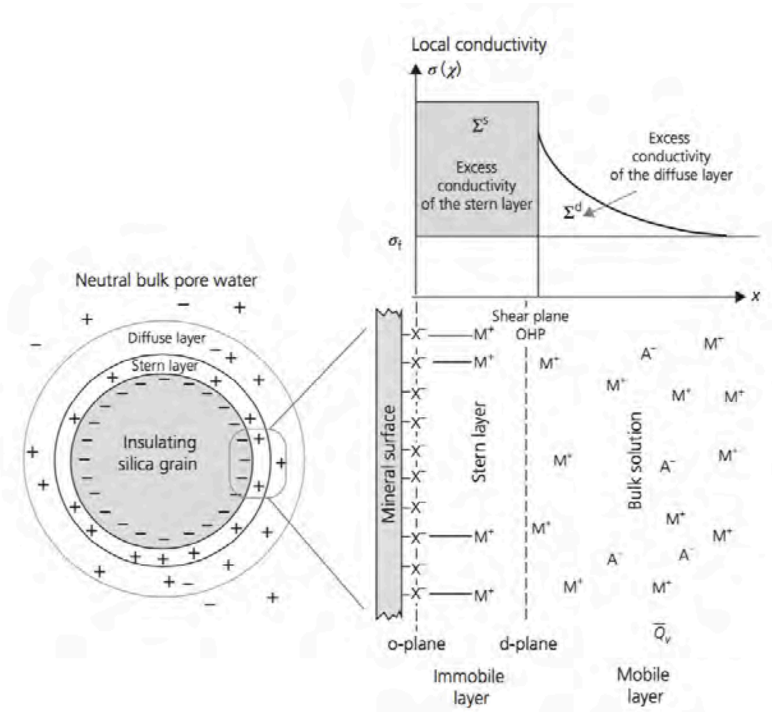


Figure 8 - Electrical Double Layer (Revil et al, 2015. p.2.)

An electric double layer consists of a layer of ions drawn into the solid surface by electrostatic *Van der Waal*[41] forces. The inner layer is called the *Stern layer,* while the outer layer consists of free ions in the water drawn in from the potential difference across the rock grain surface.[42] This outer layer is called the *Gouy* layer. The concentration of ions in the Gouy layer is expressed by the following equation:[43]

$$\varphi(x) = \varphi_0 e^{-kx}$$

[40] V.S. Bogotsky, 2006. Fundamentals of Electrochemistry, Wiley-Interscience, London. p22.
[41] "The attractive or repulsive forces between molecular entities (or between groups within the same molecular entity) other than those due to bond formation or to the electrostatic interaction of ions or of ionic groups with one another or with neutral molecules." – Derived from: IUPAC. Compendium of Chemical Terminology, 2nd ed. (the "Gold Book"). Compiled by A. D. McNaught and A. Wilkinson. Blackwell Scientific Publications, Oxford (1997).
[42] André Revil et al., 2015. *The Seismoelectric Method*. Wiley Blackwell. West Sussex. p. 2.
[43] Bogotsky, 2006. p246.

Where:

k = inverse Debye radius

x = distance from the charged surface

What is important to note at this juncture is the *slipping plane*, which is defined as the area where relative movement between solid and water allow for motion between the outer diffused layer of ions and the inner strongly bough ions. This electric potential is produced by the shearing between the inner and outer ions of the Stern and Gouy Layers. The potential difference (ζ potential) in this phenomenon plays an important role in the electrokinetic effect and is part of the equation used to determine the magnitude of the resulting electromagnetic field as is functionally applied within the technology.[44]

The electro seismic effect can be observed when a fast traveling p wave intersects a water saturated interface of differing anelastic or electrical properties. The electro seismic effect is in effect a form of converted energy, which is released as dissipated energy. This conversion of energy takes place when a fast moving p waves produce slower p waves as it passes through the interface. These slow p waves produce more movement between the rock and water, which in turn leads to a high loss of energy in the form of heat due to friction and electroseismic effects, such as electromagnetic radiation due to ionic movement. Electro seismic signals are produced by the out of phase motion between all the ions in the water and those attached to the rock. The relationship between applied pressure P and electric potential response ϕ for a porous rock is generally given by the following equation as derived from Millar and Clarke:[45]

$$\phi = -CP = -\left(\frac{\varepsilon\varepsilon_0\zeta}{\eta\sigma}\right)P$$

[44] Bogotsky, 2006. p325.

[45] J.W.A. Millar and R.H. Clarke, 1995. *The application of electrokinetic surveying to mining*. Report to MIRO members (Ref. IC 110).

Where,

ϕ = electrical potential response or streaming potential

C = electro kinetic coefficient

P = applied pressure

$\varepsilon\varepsilon_0$ = permittivity of the pore space

ζ = zeta potential

η = fluid viscosity

σ = electrical conductivity

This equation relates the electrical potential response ϕ developed in a porous rock to the stimulus of an incident pressure change P, allowing the rock to be characterised by C on a macroscopic scale when modelling such electro kinetic responses.

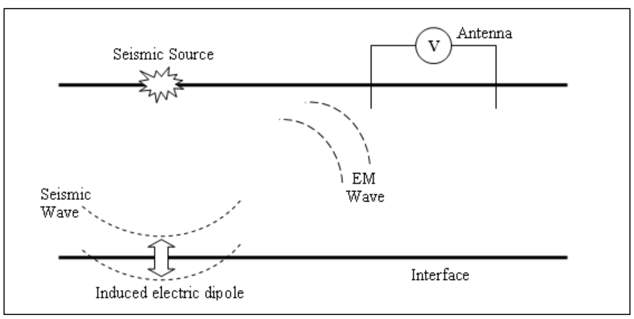


Figure 9 - Seismic wave crossing an interface generating an electromagnetic wave

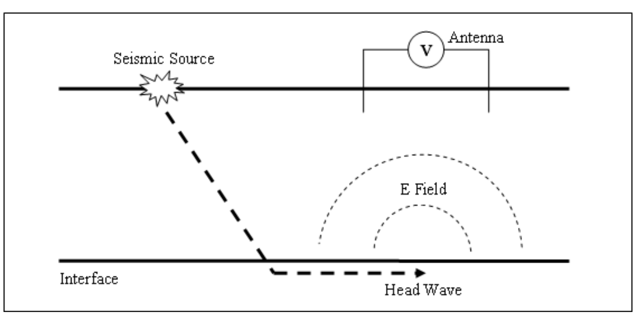


Figure 10 - Head wave travelling along an interface generating an electric field

A seismic wave propagating in a medium can induce an electrical field or cause radiation of an electromagnetic wave. There are two measurable electroseismic effects. The first effect is caused when a seismic wave crosses an interface between two media. When the spherical p wave crosses the interface, it creates a dipole charge separation. The second effect is caused when a seismic head wave travels along an interface between two media. It creates a charge separation across the interface, which induces an electrical field. This electric field moves along the interface with the head wave and can be detected by antennas when the head-wave passes underneath. The electrical dipole radiates an electromagnetic wave, which can be detected by remote antennas and recorded as such.[46]

[46] D. Beamish and R.J. Peart, *Electrokinetic Sounding Applied To Well And Borehole Siting*, Overseas Geology Series (Nottingham: British Geological Survey, 1997).

2.2.1. Geohydrological Terms[47]

Following in this chapter is a list of commonly used hydrology terms and definitions within the possible scope of discourse of a heritage context. A full and detailed list of terms and definitions can be found in the glossary of hydrogeological terms at the United States Geological Survey website.[48]

Aquifer

An aquifer is defined as an underground layer of water-bearing permeable rock or unconsolidated materials. The defining characteristic of an aquifer is its ability to allow for groundwater movement under gravitational or induced pressure. There are three major classifications of aquifers, namely:

a.) Unconfined aquifers

Unconfined aquifers are not confined by any low permeability formations, or cap formations such as clays or shales which prevent water from leaving or entering the aquifer. They are generally classified as aquifers which have an upper boundary, namely the water table. Unconfined aquifers release water through pore drainage mechanisms and generally have high storage capacity and produce high groundwater yields.

b.) Confined aquifers

A confined aquifer is one which is confined both above and below by an impermeable formation. This means that the aquifer is not recharged through direct water seepage from the ground but rather from a recharge point which may be some distance away. Confined aquifers generally have very low storage capacity and water is extracted from them by applying a pressure differential. Generally, confined aquifers are low groundwater yielding aquifers.

[47] All listed definitions available at: Office of Water Data Coordination, 'Glossary Of Hydrologic Terms', *US Geological Survey*, 2013, http://or.water.usgs.gov/projs_dir/willgw/glossary.html. [Accessed: 16 March 2015]
[48] Ibid.

c.) Semi-confined aquifers

Semi confined aquifers are classified as leaky confined aquifer systems. They are usually intersected by fracture systems which connect them to other hydrological systems.

Aquiclude

An Aquiclude is an impermeable formation that prevents the movement of groundwater through it.

Karst

A karst is a void in the ground caused by the dissolution of soluble rock through groundwater movement.

Catchment

A catchment is defined as an area that is drained by a single water course, such as a river or underground preferential flow zone.

Hydraulic Conductivity

Hydraulic Conductivity (K) defines the ease at which groundwater will flow through the pore spaces in a porous rock material. It can be calculated by measuring the time (t) required for a given quantity of water (Q) to move through a specimen of porous rock with a given length (L) and cross sectional area (a) under a static pressure head (h). It is described by the following equation:

$$K = \frac{QL}{Aht}$$

It depends on the intrinsic permeability of the matrix, the level of saturation of the connected pore spaces in the matrix and the density and the viscosity of the fluid within the pore spaces.

Transmissivity

Transmissivity (T) is defined as the amount of water which can be transported through a given length of rock (d) with a given hydraulic conductivity (K). It is defined by the equation:

$$T = Kd$$

Permeability

Permeability is defined as the measure of a porous materials' ability to allow a fluid to pass through it. The SI unit for permeability is m^2. A practical unit for permeability is the *Darcy* (d), or more commonly the *milliDarcy* (md). It is defined by the equation:

$$k = v\frac{u\Delta x}{\Delta P}$$

Where:

- v : is the superficial fluid flow velocity through the medium (i.e., the average velocity calculated as if the fluid were the only phase present in the porous medium) (m/s)
- k : is the permeability of a medium (m^2)
- u : is the dynamic viscosity of the fluid (Pa/s)
- ΔP : is the applied pressure difference (Pa)
- Δx : is the thickness of the bed of the porous medium (m)

Permeability is directly related to Hydraulic Conductivity by the following equation:

$$k = K\frac{u}{pg}$$

Where:

- k : is the permeability, m^2
- K : is the hydraulic conductivity, m/s
- u : is the dynamic viscosity of the fluid, kg/(ms)
- p : is the density of the fluid, kg/m^3
- g: is the acceleration due to gravity, m/s^2.

Primary Permeability

If a porous rock matrix consists of grains of minerals with interlinking pore spaces then the method of fluid conduction will be primary permeability. As such, primary permeability is defined as the transport of fluid through a porous medium through pore space flow.

Secondary Permeability

If a rock is non-porous, such as granite, it can still transport fluid through micro fissures and fractures that reside within the matrix through secondary permeability means. As such, secondary permeability is defined as the transport of fluid through a porous or non-porous medium through micro-fissure or fracture flow.

Porosity

The porosity of a porous medium is calculated by the ratio of the total volume of the voids in a porous medium to the total volume of the medium. This is defined by the following equation:

$$\emptyset = \frac{Vv}{Vt}$$

Where:

- $\emptyset$: Is the porosity
- Vv : Is the pore space volume
- Vt : Is the total volume

Specific Storage

Specific storage is defined as the amount of water release from a confined aquifer per volume of aquifer material while remaining fully saturated.

Specific Yield

Specific yield is defined as the amount of water that a portion of unconfined aquifer will release through pore space drainage under the force of gravity.

Fracture

A fracture is defined as a crack that forms in a rock matrix under geological stress.

Saturation

Saturation is defined as the proportional volume of porous rock pore space that is filled with fluid to the total pore space volume.

Viscosity

The viscosity of a fluid is defined as its resistance to deformation through shear or tensile stress.

Darcy's law

Darcy's law describes the flow of fluid through a porous medium. It is defined by the equation:

$$Q = \frac{-kA(Pb - Pa)}{ul}$$

Where:

- Q : is the total fluid discharge (m^3/s)
- k : is the permeability
- A : is the cross sectional area
- u : is the viscosity of the fluid
- Pb : is the pressure gradient
- L : is the sample length

Flow path

A groundwater flow path is defined as the path of least resistance through which groundwater will flow through a rock matrix.

Groundwater Recharge

Groundwater recharge is defined as the process in which water filtrates into the ground from the surface and becomes groundwater.

Hydraulic head

Hydraulic head is described as the unit elevation of groundwater in a well which is caused by fluid pressure.

Static Water Level

The static water level is defined as the depth to a fully saturated aquifer system. Also known as the water table.

2.2.2. Technology – Development within a Heritage Environment

2.2.2.1. Overview

Electroseismic technology as a technique of groundwater data collection forms part of the development of an overall system for environmental measurement, analysis and management within a heritage context. This system further includes the development of foundational software as well as recommendations towards policy and management development within the scope of the interaction and effective mutual collaboration between these two disciplines.

Electroseismic surveys act in support of all data available for a given site, and all relevant and practical surveying methods, in order to give the most accurate and reliable delivery of recommendations for that site. That said, within this study electroseismic technology is used as the basis for the determination and evaluation of site recommendations. The initial criteria for the selection of this technology is as follows:

- **Background** – Personal background experience of the researcher in the development and use of electroseismic technology, including previous development of hardware as applicable to heritage application.
- **Adaptability** – The potential for adaption to niche applications through the alteration and development of software analysis tools.
- **Applicability** – Relevant technology for shallow heritage-based applications and relating risk analysis, such as slope stability analysis.
- **Versatility** – Minimisation of hardware and development of software allows for a more versatile and portable technology with lower cost restrictions.

The indicators above make electroseismic surveys an evident choice in the potential development of a heritage-based groundwater survey platform. The adaptability of the system in niche applications, such as the heritage sector, allows for alterations that accommodate heritage-specific criteria such as the relationship to heritage risk analysis platforms, or the inclusion of monument risk variables within defined models. The applicability of the technology as it relates to heritage is also a benefit to the use of the electroseismic technology on heritage sites. Firstly, the system allows for shallow application as is applicable to heritage concerns. Secondly, the use of the system allows for development along a broader scope of application within the heritage sector such as previously described. The same system, with the same planned software development, can accommodate a myriad of heritage-based applications within one heritage-centered package. This allows for greater ease of use and cohesion of data delivery. Whether the system be used to determine the risk of slope failure to heritage sites, or be it used for the mapping of large-area groundwater modeling of natural heritage landscapes, the well-planned software package accommodates the technology within the scope of heritage concerns and allows heritage and water experts to make informed decisions regarding the preservation of historical monuments and sites. The versatility of the system as is adapted for heritage-based application allows for greater integration into the heritage sector. The cost reduction through hardware minimisation allows heritage experts, from all over the world, to gain access to the technology that was once limited to very niche specialists within groundwater analysis. That is not to say that the system makes groundwater experts redundant, but rather that the system allows for the quick and effective gathering of information from less accessible sites around the world in a cheap and straightforward manner, and that this information is easily transferable and interpretable in order to make best-practice decisions for a range of sites and applications regardless of geographical location. Developing a system that is cost-effective and portable allows that system to reach relevant heritage areas that otherwise would not have access to specialised equipment. Further intent for the system is in the training of local heritage groups for system operation as to cheaply and regularly receive monitored feedback for sensitive heritage sites.

2.2.2.2. Challenges in the development of existing technology

One of the challenges of bringing two fields together, especially two fields which are so substantially different in nature, towards one unified goal of heritage preservation, is the development of a system which allows this integration at a very pragmatic and realistic level. Concerns regarding the integration of this system within a heritage framework need to be effectively addressed in a way that causes no friction at a system level in order to increase the integration of water-related measurement, monitoring and management within the scope of a heritage professionals repertoire. In light of this objective the primary challenges faced with the integration of the technology within the heritage sector, as speculated by the research, are as follows:

- **Noise** – The most technical-related aspect of heritage integration within the system limitations lies in addressing data noise concerns. Given that the application of the system within a heritage perspective would often be found in populated urban areas, the challenge of noise reduction on the recorded data was a challenge seen from the initial development stage. Noise from electrical systems, such as the noise from overhead or underground power cables, is captured as data within the recording process of the groundwater survey. Should the survey be undertaken within a remote area, such as a rural landscape, the problem substantially subsides, however the urban applications that are evident within the heritage context necessitates addressing the data quality as it relates to noise phenomena in order to produce consistent and accurate information.[49]
- **Cost** – The electroseismic equipment used in a modern mapping process is specialised and expensive. Given that many heritage site evaluations and conservation projects are done on a tight budget these cost limitations might otherwise restrict the usage of groundwater mapping technology within the conservation process. Furthermore, the ongoing monitoring of sites, as is necessary to any given project, is limited by cost concerns. The reason for this high cost is primarily attributed to the specialised nature of the required hardware. Envisioned integration within a heritage context involves a simplification of measurement processes as well as incorporation in various contexts through a wide variety of applications and geographical locations. Further vision for the incorporation of water-related measurement in heritage involves the training and use of local human resources in order to effectively and quickly monitor water-related heritage concerns. Integration of mapping and monitoring within a heritage framework does not work at a project-per-project level, but rather needs to integrate at a local and monument and site level through policy development. This can only be achieved through making the required equipment affordable and easily accessible.

[49] Sen M Kuo and Dennis R Morgan, *Active Noise Control Systems* (New York: Wiley, 1996).

- **Portability** – Given the varied applications of the equipment within the foreseen heritage context the portability of modern equipment needs to be addressed. The very specific nature of existing technical equipment requirements needs to be addressed in a way that makes the equipment approachable by locally trained users. Additionally, the use of equipment within larger areas of influence, such as the previously discussed Maloti-Drankensburg mountain range, or the Angkor Wat temple complex, requires a high level of portability in order to increase mapping efficiency and a reduction of required mapping specialists. The portability of the system also relates directly to the cost. The shift of recording and analysis process to the realm of software development allows for a minimisation of equipment requirements and a reduction of hardware-related costs, benefiting the heritage sector integration concerns through both cost and implementation scenarios. As a development and adaptation process, then, the portability of the electroseismic equipment plays an important role towards successful heritage sector incorporation.
- **Readability / Analysis** – Even within the field of natural sciences the specialisation of hydrogeology remains a niche area of expertise. As such the resulting information remains highly specialised and restrictive towards those outside the scope of required training for data interpretation. In no way does this paper suggest that the aim of heritage incorporation is to eliminate hyrdogeologists from the process, to the contrary the hydrogeologist remains a critical part of the process of making complex heritage recommendations within the scope of its interaction with natural systems. That being said, another aspect of heritage integration does include the aspect of data readability and interpretation by the heritage expert. Given that heritage experts range in expertise, from art historians to architects to engineers and lawmakers, the resulting information from any successful system should be able to communicate that information in a way that's easily interpretable by an educated person in general. Information should be layered in such a way that hydrogeologists seeking more specific information might easily do so, while at the same time heritage experts seeking general overviews of current situations might do so at an overview level, indicating further analysis by related experts. In order to do so the information within the system needs to be represented graphically where possible, and relate to the structure in question when involving specific heritage monuments, in such a way

as to indicate an overview of the relationship between the heritage concern and the natural environment in an easily interpretable and visual way. As such the integration of heritage visualisations as they relate to groundwater models for a part of the system development.

The aspects of system development through hardware minimisation and software optimisation within this research topic relate to the above-mentioned challenges.

2.2.2.3. Software Development

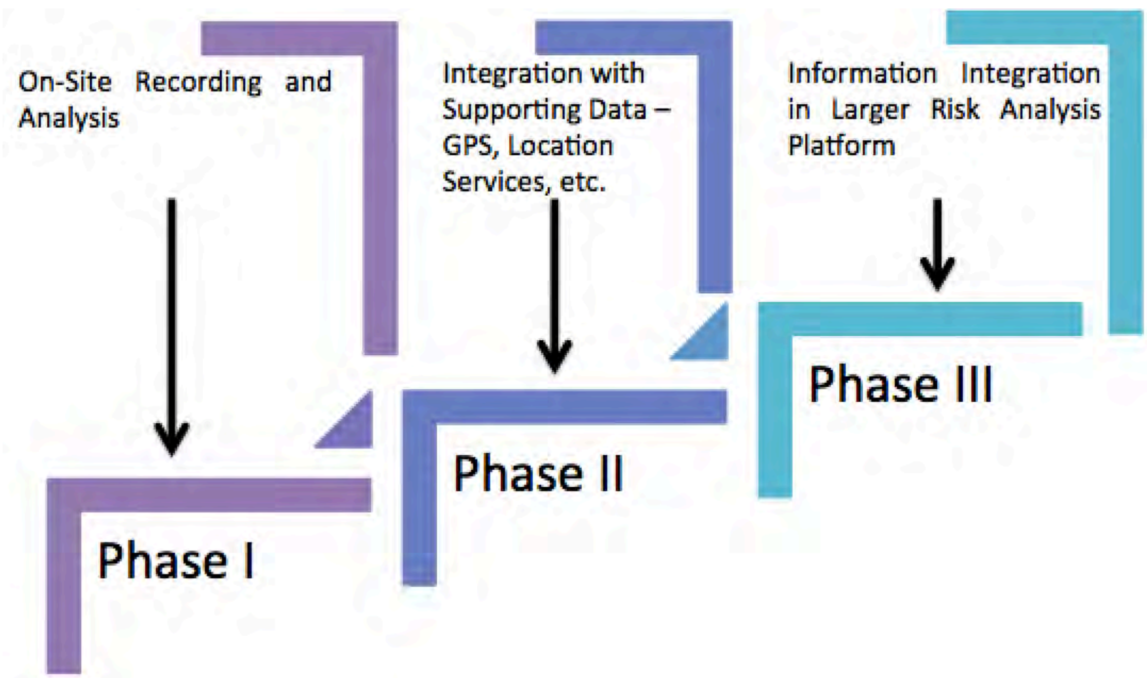


Figure 11 - Proposed software development framework (Author)

The software development is structured within a three-layered development framework with version releases at each layered interval. As an initial basis the software is developed in support of on-site recording, analysis and data deployment. Given that the hardware components of a modern smartphone are more than able to handle the required signal-quality conditions of the recorded data, a mobile-development platform was chosen as the software delivery method of choice, with initial development taking place on the iPhone platform, and successive releases accommodating Android platforms as well, with the intent on delivering the software to the largest range of heritage professionals possible.[50] The framework for software development acts as a phased-development plan for software within a heritage environment. Phase I aims to address the software requirements of the on-site recording and analysis of data. This includes a project management database structure be in place in order to maintain data consistency within the field. New projects can be started quickly and easily within the software, allowing for rapid data collection while on site. The software manages the point-data collected in the field along with the required metadata such as GIS positioning and notes relevant to the project. At this phase the data collected is in its raw form and may be sent as a collected whole for further analysis, all within the functionality of the software application. Basic analysis features will also be available on the mobile platform, largely to give overview of the collected data at an holistic level. Further graphical representation however does find limitations within the hardware of modern smartphones and an accompanying desktop software package allows the import of this collected data in order to analyse collected data and generate full reports on the heritage site, including groundwater-modeling features.

The objective of **Phase I** development is to record and manage collected data from field-work in such a way as to allow for effective and timely analysis of the raw data, and to assist the field technician in the process of collecting data. Furthermore, future releases of Phase I functionality will include cloud-storage management of data, where available, in order to increase the safety of collected data and also to release the data for analysis to third-party experts through an existing cloud-based platform. Noise reduction and signal processing algorithms found within the software approach reduce the need for much of the required hardware and as such reduce cost while increasing portability of the system, addressing heritage integration as discussed earlier in this paper.

Phase II development seeks to integrate the collected data with supporting information in a packaged approach to project delivery. Geo-aware location services such as Global Positioning System (GPS) and Location Services allow for the integration of geographical referencing within the software system. The benefits of this are evident before, during and

[50] Teragonaudio.com, (2015). *How to do realtime recording with effect processing on iOS*. [online] Available at: http://teragonaudio.com/article/How-to-do-realtime-recording-with-effect-processing-on-iOS.html [Accessed 28 Feb. 2015].

after the fieldwork takes place. During initial planning an area to be surveyed may be mapped out and uploaded to the software prior to the work taking place. This geographical information is then used to locate the field technician to the specific locations of the planned mapping points. This allows for more efficient fieldwork that is consistent with expected deliverables. The software in this regard will direct the user to the next waypoint before continuing with the data recording process. During fieldwork the system also serves to benefit the field technician. Locations of actual recording points is logged within the recorded data and can be related to planned locations. This is useful as a means of measuring deviations in this regard due to unforeseen circumstances (e.g. that the planned point was not accessible). Ultimately, the location-aware aspect of the software in phase II allows for the further analysis and visualization options with regards to delivered data. Furthermore, the GPS metadata allows for integration of resulting information within a larger heritage-based (or otherwise) Geographical Information System (GIS) platform, to be used in larger scope analysis and decision making processes. Phase II also seeks to integrate magnetic-field information as normally recorded through magnetometer hardware in support of the information generated through the electroseismic survey. The magnetometer measures the magnetic character of bedrock and overlying sediments, hence locating fault boundaries related to groundwater availability.[51] The accelerometer available on many modern phones allows for measurement of these magnetic fields within 3 axis[52], and the availability of this information at a software level allows for the integration of magnometer readings within the software. Although this information does not replace a thorough investigation using magnetometer technology, it does act as a lower-resolution indicator for data support and to indicate necessity for further investigation. This appended data further supports the delivery of consistent and accurate information. Phase II seeks to incorporate this added functionality in a way that brings the resulting data within the scope of applicability of other resources, such as larger GIS systems, and to make the data more comparable within the multi-faceted nature of heritage management concerns.

Phase III aims to encompass the data acquisition and analysis functionality within a heritage risk analysis platform. The final phase incorporates the management and policy aspects of a

[51] Bisson, R. and Lehr, J. (2004). *Modern groundwater exploration*. Hoboken, N.J.: Wiley-Interscience. p. 49.
[52] Apple, (2015). *Apple - iPhone 6 - Technical Specifications*. [online] Available at: https://www.apple.com/iphone-6/specs/ [Accessed 28 Feb. 2015].

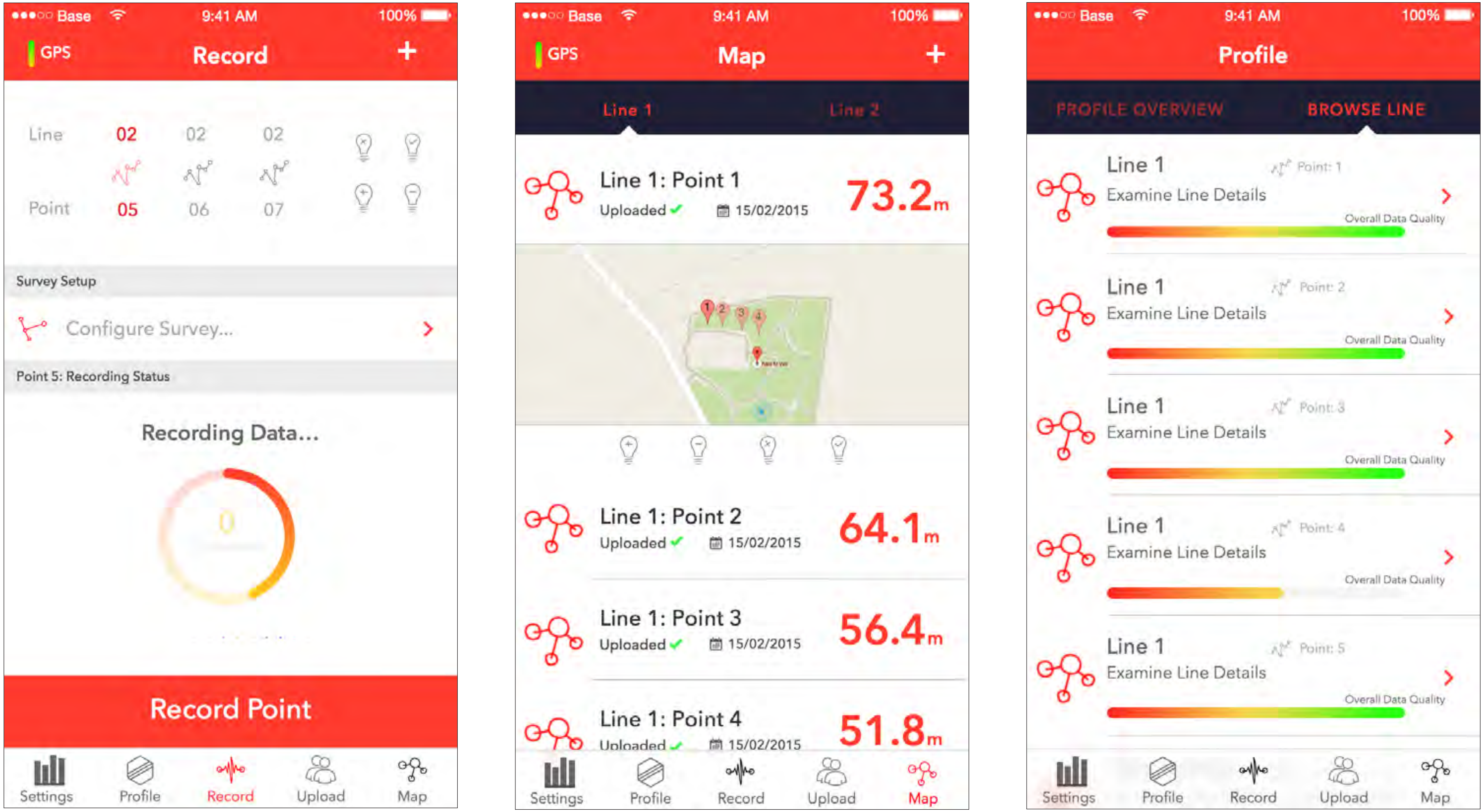
heritage process within the system in order to bring together all relevant information for the heritage decision-making process. Challenges at this level include access management to personal information and the role of different stakeholders within the heritage management process. As an example, the incorporation of financial data for the site might lead to a better decision-making tool, however, that information should remain private at all but approved levels of access, although groundwater information might be accessible at different levels of permission. In order to achieve this the Phase III release is integrated within a 3-tier information access framework. As a base-level the database contains the public and core information for that monument or site, including its basic information, category, location, unique identifier, and similar. Above this the second layer includes additional information that is related to the site including non-critical data such as groundwater reporting and analysis, specific heritage-group identifiers and similar. The third and final layer includes stakeholder-specific information of a more private nature, such as financial and tourism reporting, site risk reporting, and site-related communications. The system manages data from a bottom-up approach and changes at the core layer reflect through to the upper stakeholder related information.

For the research paper the software development focuses on Phase I and the effective collection of data at a survey level.

2.2.2.4. Hardware[53]

As per the heritage integration challenges indicated previously, an important aspect of hardware development lies in the minimisation of field equipment in order to reduce cost and increase portability, while at the same time maintaining a high quality of data. Initial efforts towards this end saw the reduction of equipment to a one-node measurement tool that needs to be set up at every point within a profile line. Although this is time consuming in itself, the reduction of required equipment in the field, and the portability thereof, greatly increases the efficiency of the field survey process. Further development saw the shedding of noise reduction hardware from the measurement technology by processing data more

[53] Technical support for hardware development aspects within this paper were done under the guidance and encouragement of Aquatronic Solutions, who further assisted with the interpretation and validation of collected site-data.



View 1,2,3 - Software Development Visualisation (Author, 2015) effectively within the software environment. This allowed for further reduction of technology cost and represented a first revision of the emerging heritage-related product. The first revision of the hardware development aimed to record data of each point within the profile by triggering the recording of that data through the hammer striking the shotpoint. This was done by connecting a switch to the hammer which, when used to strike the source plate, triggered the start of the recording of the resulting data. In testing this worked well in the sense that it allowed for the easy separation of resulting datasets and simplified the management of culminated data. There were problems however, which related to further development and improvement of the system. The first issue was the fragile switch on the hammer, and the connecting cable, which often broke in the field and was fairly unreliable. As a result spare parts including additional switches and connecting cables for the hammer assembly had to be brought to the field in case of on-site remedy requirements. This was obviously not ideal, and further development took place to address these issues. The solution came in the form of further software-based signal processing. A noise reduction approach that takes place is the 'stacking' of collected data to eliminate noise phenomena and harmonic noise elements such as power-cable interference. This is done by repeatedly striking the source plate at the same position and collecting data which is stacked on itself to generate an average result from the stacked range. Ten-point stacking was found to be optimal with negligible benefit beyond this point. Given that the successive shots of the stack were undertaken immediately after each other and without delay it was noted that the separation of the resulting recorded data was redundant and placed extra stress on the hammer-switch approach. This was addressed by rethinking the process altogether, and rather than triggering the recording of the data through the strike of the hammer, recording the data arbitrarily and processing it through software methods proved to be a much more efficient notion. Given that the hammer needs to be lifted and re-swung between seismic shots, a continuous recording of data was made possible by signal processing techniques within the software which analyses the resulting single-file in order to pick up separate shots with intermittent spans of relatively low signal information. This approach meant that recording of the data could be done without the need of the hammer switch, and it was removed altogether. This allowed for a much more robust and simplified field kit and greatly increased the reliability of the hardware. The next process of minimisation took place in the reduction of recording equipment requirements, again through the signal processing capacity improvements built into the software. Tests were undertaken to determine the minimum requirements for signal bitrate and frequency, which was determined to be 128kbps at 44.1KHz given the relationship between signal and noise-related phenomena.[54] Further noise-isolation at a hardware level was incorporated through the use of non-stock connecting cables. Over-the-shelf clips do not have a soldered connection to the cables they connect to, creating unnecessary level of noise. It was determined that the creation of soldered clips to low-noise cabling adds a lot of benefit towards the reduction of noise within the resulting data signal. The simplistic construction of these cables can be done easily with the use of minimal equipment, and instructions for assembly have been developed for field-technician purposes.[55]

This reduction in minimum-specification is important in that it opens up recording options within stock consumer technology such as stand-alone audio recorders or modern mobile smartphones and tablets, allowing for mobile-platform software development in support of hardware recording technology. Another benefit of this is the resulting redundancy of laptop requirements for field surveys. This is particularly important as it further reduces the field equipment requirements, not only in terms of the laptop itself, but also the additional battery packs that make up the previous requirement for a full days field operation. This substantially reduces weight of field equipment, further increasing portability and survey efficiency. As an added benefit, the fragility of field equipment is reduced, allowing for a more robust survey experience, which is of particular importance within rugged terrains or on longer profiles which take the field surveys some distance from support.

The latest revision of the hardware is developed with strategic direction towards the heritage-based requirements for effective technology integration. The hardware consists of the following elements:

- Recording Nodes – These stainless-steel pins form the physical connection with the soil and record the resulting data formed by the seismic source. The pins are

[54] Sen M Kuo and Dennis R Morgan, *Active Noise Control Systems* (New York: Wiley, 1996).
[55] Cables require low-noise cabling soldered directly to clamps in order to minimise noise in the resulting data. Cables prove fragile in field operation and should be handled delicately. RCA plug should be clean and free of dust between during survey recordings.

recommended to be 20 mm in diameter and 500 mm in length with a tapered point. With positive results in testing the use of regular 200 mm nails proved efficient with negligible noise gains and were implemented in the research surveys.

- Connecting Cables – The connecting cables that join the recording nodes to the recording device are made according to specification with soldered clips and low-noise cabling in order to ensure consistent and high-quality data. These cables are easily made, and instruction on their assembly is readily available. Cables are recommended to be tested between survey points to ensure consistent results, and a spare set is to be available on-site in order to easily continue with surveys in the case of faulty cables through damage or wear.
- Recording device – The mobile application installed within a compatible platform, such as an iOS or Android device with sufficient specification acts as the field recording technology. Recommendation is made to ensure the device is fully charged before fieldwork commences, and depending on the length of the planned survey, an extra mobile battery pack might be required.
- Hammer – A 14-pound over-the-shelf hammer is sufficient as a seismic source for shallow groundwater application. The hammer is to be durable and of good quality to ensure the safety of the field operators.
- Source Plate – The source plate, or 'shotpoint', is used in order to have a flat and heavy surface on which the seismic wave can be generated through the strike of a swing with the hammer and to ensure consistent seismic waves are generated in an optimal and repeatable manner. The source plate is recommended to be a flat plate of steel around 200x200mm, however, any heavy steel profile with a flat base and upper surface will suffice.
- Additional Equipment – Any additional equipment as recommended for the specific site requirements and for health and safety reasons, including visibility-vests, hardhats, gloves, medical packs and safety cones. Additionally, an extra pair of connection cables and a mobile battery-source are recommended. A common-sense approach to health and safety is required, and aspects such as bottled water for hydration and applying suntan-lotion before long durations in sunlight are at the field operator's discretion.

2.2.3. Field-Survey Process

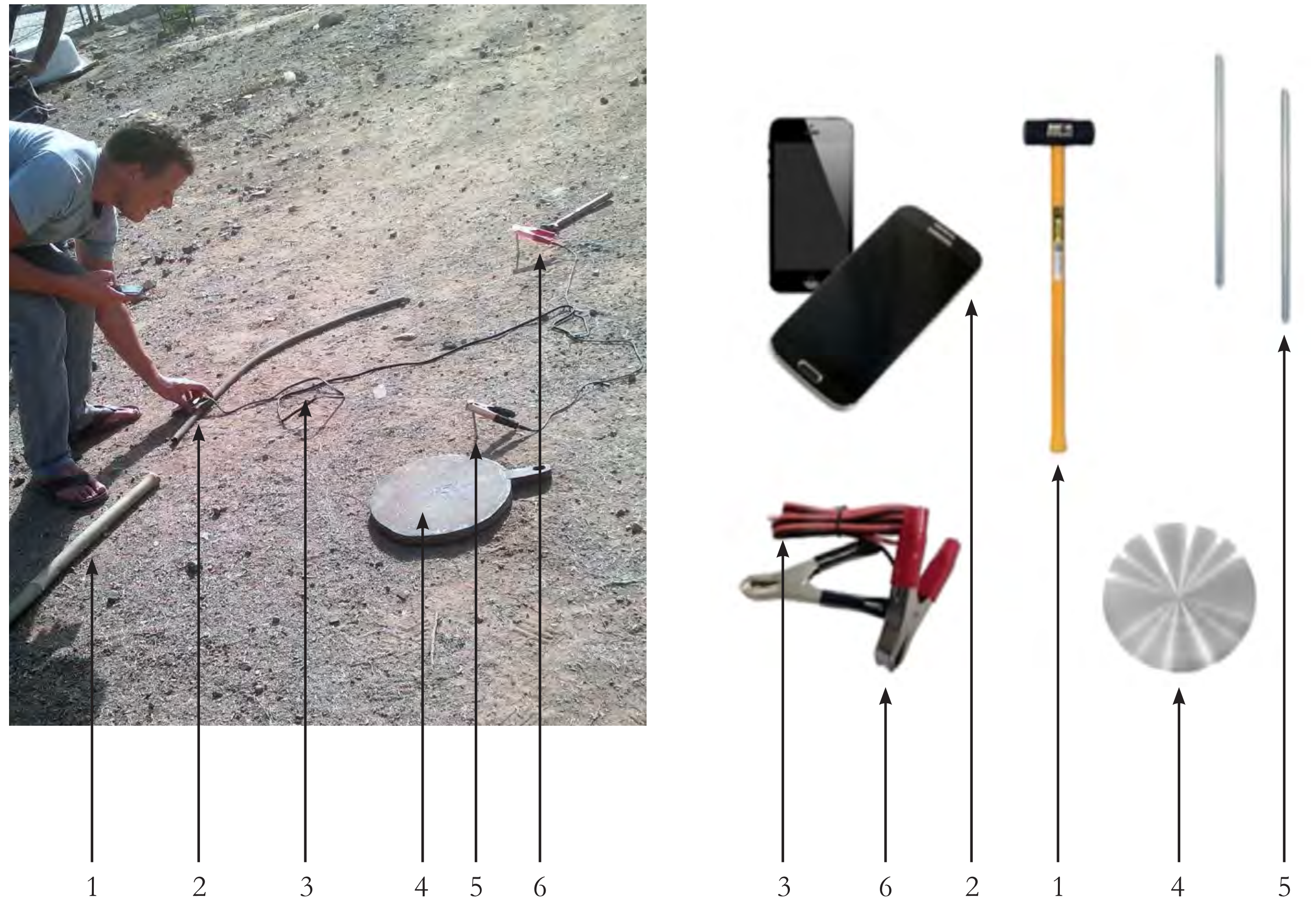
The field survey process involves the collection of the raw data from the site, which is later processed and analysed to generate the resulting report information. Field surveys are generally done in grids, allowing for effective generation of three-dimensional information through line interpolation. Lines, or profiles, are straight, single arrays of points set out within a site survey plan. Each profile allows for 'section' through that particular cut of the site. The combination of these profiles allows for an mapping of the site as a whole. Site surveys are planned prior to commencement of work on-site through the use of Google Earth or similar geospatial technology in order to determine the best overall profile layout for the given area, and to determine the required point density within those profiles. These points are then GPS-flagged and imported into a mobile GPS system to specifically locate each point on site easily and accurately. Once the first point of the first profile is located, the following processes beings:

Figure 12 – Field equipment and sounding (Author)

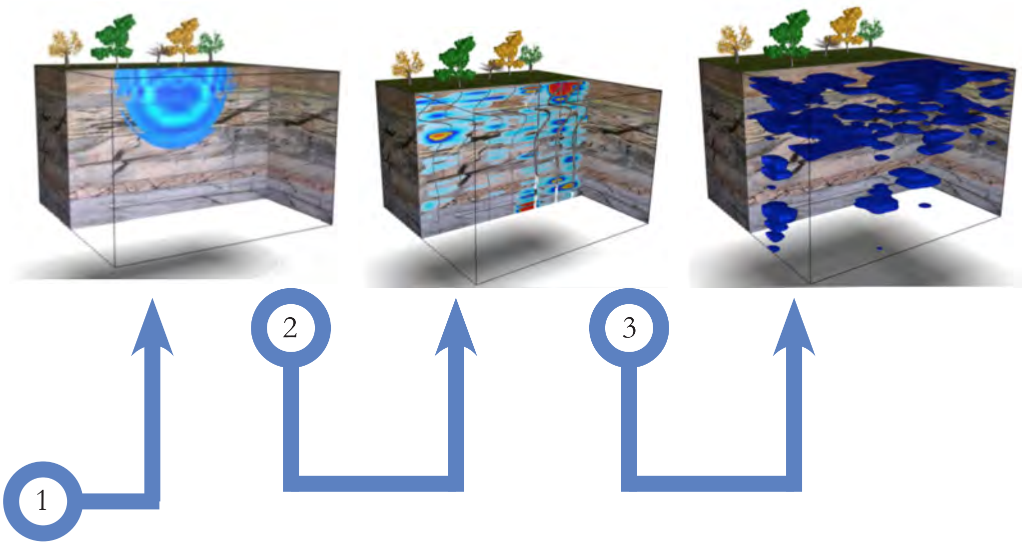
1. Safety always comes first, and all precautionary measures should be put into place first. Protective gear, cordoned off areas, and equipment checks as required. Safety requirements as defined for any specific site should be adhered to. Team-members to be briefed regarding safety procedures and survey processes.

2. The actual point is GPS-located and the position stored. Often, some planned point locations are inaccessible (fenced in, very steep hill, dangerous location, etc). The actual-location data is uploaded and used during data analysis.
3. The shotpoint is placed on a prepared, flat surface area, and the two nodes are positioned adjacent to the shotpoint and 2m from one another. The nodes are hammered into the ground and a secure and steady node connection is ensured as this is critical to the quality of the resulting data.
4. The cables are connected to the pins and connected to the recording device. The device is set to record for the given sounding, and profile number/sounding number is noted for data quality purposes.
5. The sounding takes place with a predetermined amount of strikes with a 16lb hammer onto the shotpoint. The hammer should be used by the same person, ideally throughout the survey, but at least throughout the individual profile as to ensure consistent data across the range of collected datasets.
6. Once the sounding is complete the data is checked for validation, after which the point of the shotpoint is physically marked on site for future reference. Photographic logging as per project requirement.
7. The equipment is removed and the process begins again at the next point in the profile. Once a profile is complete the data is saved and a new data-set is created in order to keep the information in a chronological order.
8. Notes, sketches and photographs are taken in order to log the survey process. Anomalies and specific challenges on site are noted in order to determine their possible influence on the resulting report.

The subsequent chapter deals with the implementation of the process discussed above in the collection, analysis and reporting of a relevant heritage-based case-study.



Required Equipment for Field Survey (author)



The plate, or shot-point, is struck as one sounding in a stack that makes up a point in a line profile

The seismic wave permeates through the sub-surface strata, generating an electro-seismic response as it travels (see chapter 2)

The data is recorded for each point. A series of points creates a line profile which allows for the analysis of a cut, or section, as a visual representation of the 2-dimensional array.

A series of 2-dimensional profiles forms the basis of 3-dimensional visualistion of sub-surface conditions. The incorperation of a heritage structure model allows for a visual representation of spatial relationship.

Process of Mapping Field Data (author)

3. Case Study: The Rani Ki Vav, Patan, India

3.1. Overview

This chapter introduces the Rani ki Vav case study in approach to heritage-based application for the system as discussed in the preceding chapter. The chapter introduces stepwells, first in general, before focusing on the Rani ki Vav itself. Finally, the application of case-study data collection and analysis is documented and conclusions thereon are reported.

3.1.1. Stepwell Overview

The term stepwell, with its 'steps' and 'well' combination, is representative of the two basic criteria of the well structures that it represents within India. The well, as that which defines it as distinctive, has a series of steps, usually around five to six stories, that leads towards the water source. Other well-monuments exist within India, such as traditional 'kupa' which is a simple vertical shaft with a parapet wall being the only visible built element above ground-level, usually with a bucket mechanism for collecting water, reminiscent of its European counterpart. Although various well-structures exist, none have the architectural complexity or functional dynamic as that of the stepwell structure. Stepwells, especially within their elaborate height of complexity as is the case with the Rani ki Vav, are located primarily within the Gujarat province.[56]

3.1.1.1. General Function

At its core, the primary function of a stepwell is to provide water, either to travellers along a route or to the local communities that rely on it. It was mentioned previously that stepwell structures are primarily focused in the Gujarat area, and this phenomena further indicates the functional development of the stepwell structure. Gujarat is an area of rainfall extremes, with low amounts of available water in the dry months, and high amounts of rain in the rainy season. It is within this context that the well structure of the stepwell as it relates to its functional cycle, is invaluable as a civic construction. Rivers and small lakes in the area dry

[56] Kirit Mankodi, *The Queen's Stepwell At Patan* (Bombay: Frano-Indian Research Pvt. Ltd., 1991). p29-31.

up fairly quickly within the dry season, and efforts for water preservation through dams do not retain their supplies for very long due to sun exposure. Furthermore, the water supplies stagnate and go stale over a certain time. The stepwells address many of these challenges through their typology. Being a subterranean structure, the first beneficial aspect is the large amount of protection from the sun, resulting in a water supply that remains available for a longer period of time. This is further emphasised as being of importance by the construction orientation that the stepwells have in common, reducing the waters exposure to sunlight.[57] Secondly, the water that is in the well is supplied by access to groundwater systems, recirculating water supplies and maintaining a fresh and clean supply of water for the community. Given that the water is otherwise only revitalised through a few short rainy months, this is critical to the health of those that the well supplies, and the continual supply of water to nearby villages. Lastly, the form of the stepwell, a depression in the ground, acts as a catchment, or cistern, for water collection during the rainy months. In this way the stepwell functions both as a rainwater catchment cistern as well as an access point to groundwater such as a typical well, but the relationship between these two aspects is brought into play through the recycling of catchment water, allowing for a supply of fresh water that otherwise would go through a process of stagnation.[58]

[57] Kirit Mankodi, *The Queen's Stepwell At Patan* (Bombay: Frano-Indian Research Pvt. Ltd., 1991). p30.
[58] Tim Davie, *Fundamentals Of Hydrology* (London: Routledge, 2008).p166.

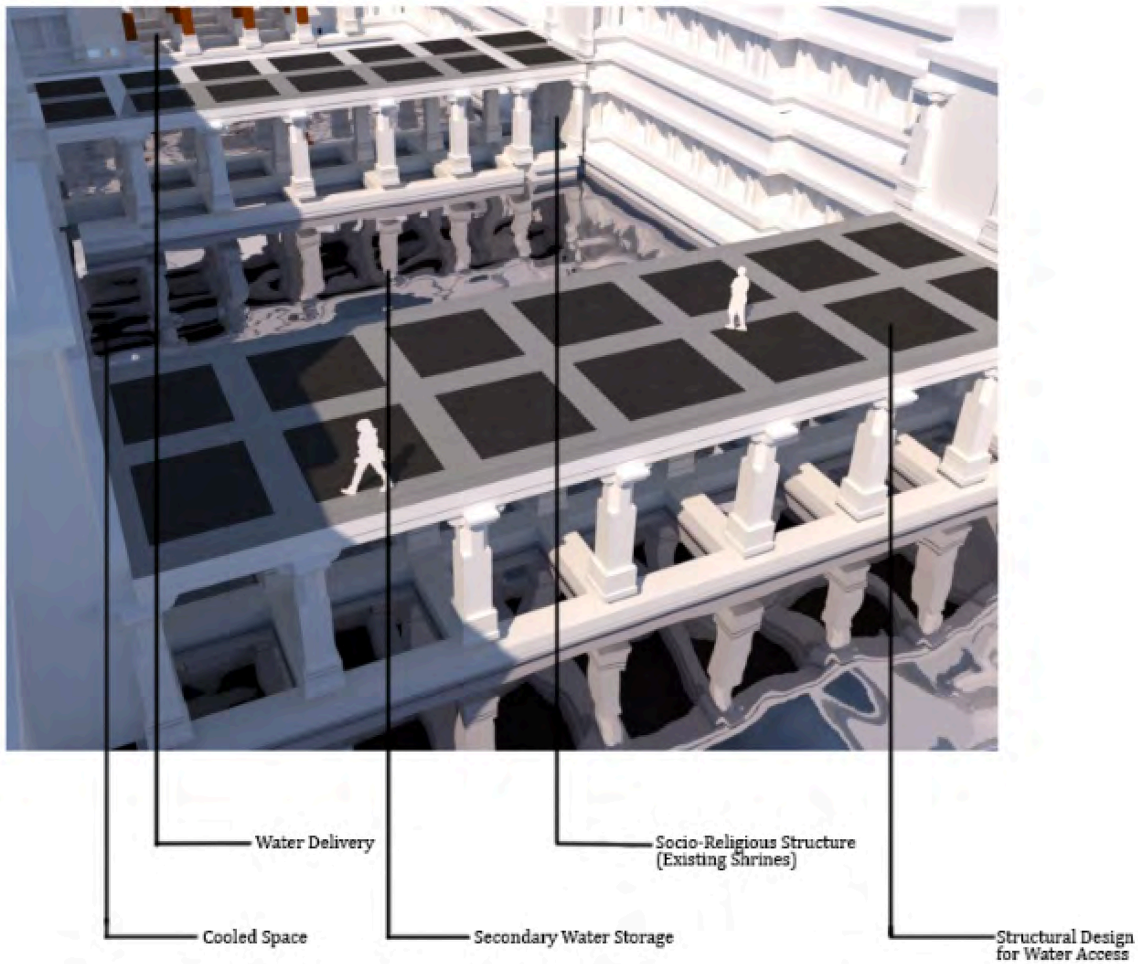


Figure 13 - Conceptual render of functional stepwell structure (Author)

In contradiction to this ideal functional system however, it was often found that the spread of diseases occurred through the well as a medium. In many cases well closures were ordered by British authorities as these wells were seen as the cause for the spreading of disease[59]. Although this is documented as correct, the nature of the stepwell itself can not be seen as inherently at fault for water-borne diseases, nor for the fact that many were using these wells from various locations, in as much as it would apply to any other water-sourcing typology of the time. Water from stepwells, through the use of troughs and drainage systems, were also used to provide water for livestock and surrounding fields.

[59] Victoria Lautman, *India's Forgotten Stepwells*. 28 Jun 2013. ArchDaily. http://www.archdaily.com/?p=395363 [Accessed 14 Mar 2015].

The stepwell's functional core as a source of water supply was not its only purpose however. Within the area the utilitarian nature of the well was considered so important to sustainable communities that this value was expressed through the well structure as it developed into a monument structure. Ever more elaborate ornamentation, especially through carving of a religious nature, were used to adorn the walls and columns of these stepwells, and these carvings themselves are of critical value within the UNESCO World Heritage value criteria used for the Rani ki Vav stepwell.[60] In addition to its use as a monument, the orientation of the stepwells and their inherent structure supported their role in a leisure capacity for the local communities. The stepwells, given their location just outside of the city radius, as is the case today with the Rani ki Vav, were also important refreshment stops for travelling caravans and military marches, even to the point that these stepwells were often seen as the objective destinations for a days worth of traveling. In this way the stepwell forms another function of economic and militaristic support for the area as a whole, giving further value, not only at a utilitarian but also at a propagandistic level.

The stepwells also acted as a shrine of worship, in large part due to their inherent relationship to water. Not surprisingly, especially within the arid Gujarat area, water was seen as an important aspect of human life. Furthermore, the provision of water was seen in a divine context, and hence related to deity worship.[61] Within the Rani ki Vav this is still further evident through the sculpture and frieze depictions.[62] In many cases the well forms part of a larger religious complex, and is often built adjacent to a temple structure. When this is not the case it is common to see a shrine integrated into the well structure itself, and even contemporary worship takes place within these shrines, giving the well a specific religious capacity. The construction of wells did not specifically mean that water was a result, nor did the provision of water mean that water was a sustainable product of the structure, and often, through silting or hypothesised aquifer-related failure, these wells ceased their water provision. This resulted in a religious practice of devotion, worship and sacrifice in order to maintain water supply through a religious approach. This is of particular interest in its relationship to measured scientific approach and its full-circle dynamic with contemporary

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[60] Archeological Survey of India, *Rani Ki Vav (The Queen's Stepwell) At Patan, Gujarat – Nomination Dossier* (New Delhi: State Party of India, 2013). p221.
[61] Ibid. p236.
[62] Jutta Jain-Neubauer, *The Stepwells Of Gujarat* (New Delhi: Abhinav, 1981).p69.

worship and social practices. As a further complexity of the stepwells capacity as a shrine of worship it should be noted that several ceremonies and traditional worship activities take place at stepwells to this day.[63] Stepwells are considered to have a residing deity inherent within their utilitarian function as a provider of water, and the feminine Mother-Goddess (Vãrudi) aspect of this worship relates to many specific phenomena of water-related worship, such as notions of fertility. This is seen in contemporary ritual as well, such as through the worship of a recently married couple seeking blessing of fertility. Previously the same notions resulted in the wells forming a complex relationship with the social aspects of the surrounding communities who relied on the provision of the well, through the gracious actions of the related divinity, resulting in self-sacrifice in some instances (though mostly a dedication of a small amount of blood, from a finger for instance, was seen as sufficient) and also resulting in other feminine-related connection through religion, such as the purification of a new mother after the birth of her child.[64]

Stepwell location is often attributed to its specific sub-function as discussed above, and one of three situations exist in this regard:

1. The stepwell is located adjacent to a temple, or within a temple complex.
2. The stepwell is located on the outskirt of a town or village.
3. The stepwell is located at a critical point alongside a major transportation route.

The stepwell's category within one of the above criteria does not eliminate its function in other regards. As an example, a stepwell within a religious complex or with an adjacent temple might very well have been a stop for passing caravans, or a stepwell on the edge of a village most likely also acted in a religious capacity. The category definition does however give clues as to the context in which they were built, and to the priority of the rulers of the time, which is often an interesting dynamic in a time with shifting ruling authorities and religions.

[63] Karan Mahajan, 'Stepwells And Civilization', *The Utopian*, 2008, http://www.the-utopian.org/post/2340612672/stepwells-and-civilization. [accessed: 19 April 2015]
[64] Jain-Neubauer, p6.

3.1.1.2. Stepwell Typologies and Categorisation

At its broadest scope the typology of a stepwell needs to be defined in terms of water-based structures within India in general.

Water-Collection System	Vernacular term	Articulation	Salient Features	Purpose	Example
Terraced Rainwater Harvesting	'Tanka' (Underground water tank)	None	Arched support peirs, water collection through narrow opening, No human access to water surface	Human Consumption	Residential Buildings, temples, Mosques
Subsoil Aquifer	'Kua' (Well)	Horizontal band at ground level.	Cylindrical shaft, No human access to water surface	Human Consumtion, Livestock, Irrigation	Numerous, used since pre-historic civilisation.
Subsoil Aquifer	'Vav' (Stepwell)	From simple to complex articulation. Religious and secular iconography.	Stepped corridor to water-level. Structural cross-bracing which acts as internal architectural elements. Circular well-shafts.	Human Consumtion, Livestock, Irrigation. Social and religious use.	Rani ki Vav
Subsoil Aquifer	'Kund' (Tank)	From simple to complex articulation. Religious iconography.	Square or rectangular. Receptacle to contain water. Steps on multiple sides for water access. Can have shallow recharge wells.	Primarily for religious purposes. Secondary human and livestock consumption and for irrigation.	Panna Meena Kund
Surface Runoff	'Talao' (Tank/Pond)	Negligible	Utilises natural depressions fed by large catchment areas.	Human Consumtion, Livestock, Irrigation. Household chores.	Sahastralinga talao

From the table above we see that stepwells and stepped ponds form the most elaborate forms of water-related architecture in India, although their functions and typologies are distinctive from each other. The narrowing of the stepwell typology is in contrast to that of the stepped pond, which is fully open to the sky and as such well lit all the way down to the its lower levels. The stepwell however has an orientation away from the sun and a narrow form restricting access to direct light. This is to limit water evaporation within the structure and to allow for a cool and comfortable space, giving emphasis to the pragmatic nature of the stepwell structure. The stepped pond, largely used for religious purposes, had a different function which is made clear through its architectural typology.

The ‘Aparajitprichchha’ is the earliest text to devote a full chapter on discussion of stepwells, wells, ponds, etc. (Chapter 74). The information given in Chapter 74 is classification of stepwells into following four types[65]:

	Type	Characteristic	Example
1	Nanda	One entrance, three pavilion towers	Rani ki Vav
2	Bhadra	Two entrance, six pavilion towers	The stepwell at Adalaj
3	Jaya	Three entrance, nine pavilion towers	The stepwell near Dhank
4	Vijaya	Four entrance, twelve pavilion towers	Stepwell in the village of Chaubari

The historical catagorisation into four types is further extended within a contemporary definition (refer to Annex 1)[66]. The Rani ki Vav is catagorised as a *Nanda* variation of stepwell style, and falls within ‘category A’ within the variants of this style as defined by the ASI. The Rani ki Vav has lateral stairs within the straight stepped singular corridor, making it a transition-type style, using elements from ‘Kund’ (tank) typologies. To emphasise this fact, compare the image of the stair typology below to that of the Chand Baori, illustrated in figure 18.

Figure 14 - Rani ki Vav stair typology (Author)

Later stepwell monuments such as the Dada Harir ni Vav stepwell (late 15th century) in Ahmedabad omits this feature as stepwell architecture moves entirely into its own

[65] R.J. Vasavada, 'Rani Ki Vav (The Queen's Stepwell) At Patan, Gujarat, India', (Presentation, Mumbai, 2012). p16.
[66] Ibid. p20.

architectural style of construction. The Rani ki Vav, as per the 'nanda' definition is an 11^{th} century construction, and one particular aspect of this style is the presence of a pond, or 'kunda', adjoining the structure. The Rani ki Vav finds correlation to similar structures such as the Mata Bhawani stepwell (11^{th} Century), also in Ahmedabad. The interesting comparison between these two structures shows that from a construction perspective their architectural approach is almost identical, even though the Mata Bhawani stepwell is of a considerably smaller scale. The Mata Bhawani stepwell uses a very plain, non-ornate ordering for its pillars and pilasters, suggesting that although constructed at a similar period to the Rani ki Vav, it was built within a different, more pragmatic, context. This suggests that although stepwell typologies may be categorised within an architectural definition, each stepwell remains different in terms of size, iconography, primary function and site-specific nuance. Another approach to categorisation is by historical period, as follows:

- The Indus Civilization period (circa 3rd millennium B.C.)
- The Early Historical period (opening centuries of the Christian era till 6th century A.D.)
- The Pre-Solanki period (6th -11th cent. A.D.)
- **The Solanki period (11th to mid 13thCent.A.D.)**
- The Vaghela period (mid 13th to 14thCent.A.D.),
- The Rajput/Sultanate period (13/14th 16th century), and
- The Rajput/Mughal Period (16th to 18th century)
- Post Mughal/Modern Period (19th century onwards.

Indian Journey's article on the variation of stepwells, in addition to the ambiguity that exists in terms of the definitions used for variations of water-based architecture in India, suggests that a simplification of typology definition should be used in terms of the general stepwell structure.[67] This is particularly the case when typology relates to the surrounding natural context since variation within one category often relates to aesthetic alteration, which is

[67] Indian Journeys, (2009). *Stepwells of Gujarat*. [online] Available at: https://indianjourneys.wordpress.com/2009/12/31/stepwells-of-gujarat/ [Accessed 5 Mar. 2015].

more of an art-historical categorisation and less relevant within both a structural and geological perspective.

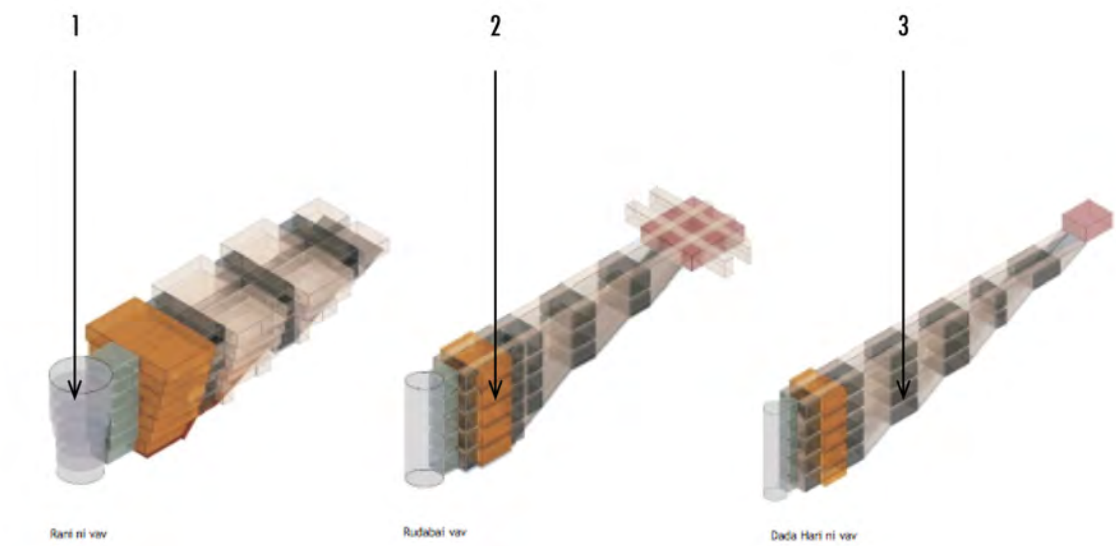

Figure 15 - Stepwell typologies and concurrent features

Categorisation of base typology within the scope of this research therefore revolves around the inherent stepwell characteristics as follows:

1. The circular, vertical well shaft that terminates the narrow path towards the water source is inherent within general stepwell construction. Through its circular form and vertical nature the well acts as a hierarchy within the architectural composition of the stepwell structure. Within a geological context the circular well also acts as a hierarchical apex in that it is the functional point of groundwater access, and relates the structure to the surrounding natural context at a very specific point. Groundwater analysis therefore focuses on this particular point within the stepwell structure, regardless of structural deviations.
2. The pond area adjacent to the well is not a necessity within the stepwell composition but does appear regularly within stepwells of sufficient size. The ponded area acts within the functional scope of the structure and as such forms part of the system cycle of the functional stepwell.
3. The use of pavilions is inherent in all stepwell typologies and is emphasised in stepwells of larger size. These pavilions are structurally necessitated as lateral

supports for the narrow shaft that makes up the volume of the stepwell, and prevents the structure collapsing inwards due to exerted forces pressing onto the sidewalls. These lateral braces are used as social and functional pavilions for water access within the architectural solution. These unifying typologies are relevant within the scope of the research in that they are fundamental in the structural stability of any stepwell structure. As such, any rehabilitation scenario for stepwell structures needs to take the structural integrity of these supports into consideration.

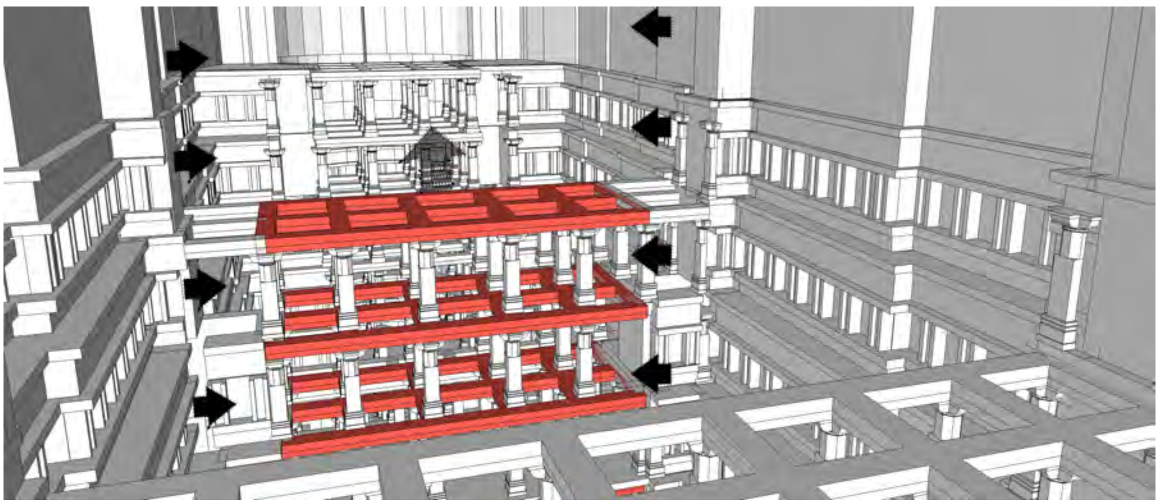

Figure 16 - Force diagram of transverse bracing (Author)

The narrow nature of the stepwell form is also consistent and alters slightly within the variations of structure scale. The narrow corridor relates directly to the function of the structure in that it minimises light and heat in efforts to preserve the water contained therein. Architecturally this form is used to the structures benefit and relates to the richly adored walls and columns. Structurally this form relates to the effective access to subsoil aquifer systems and allows for a lateral bracing system to be used in order to reach the required depths.

3.1.1.3. Examples of water-based architecture in the vicinity of Rani ki Vav

Figure 17 - Stepwell locations, Gujarat (Vasavada, 2012)

As indicated, the Rani ki Vav is located within a area of numerous stepwell structures. Although many stepwells exist within the arid Gujarat area these vary greatly in style, size, function, condition and complexity. The Rani ki Vav, the only stepwell that has UNESCO World Heritage status, represents the height of stepwell design in many aspects, particularly with regards to its artistic merit. That said, in many ways the Rani ki Vav is not representative of the range of stepwell constructions in and around Gujarat, nor could it be given the drastically different specimens to be found in the area. When we consider the term 'stepwell' more loosely, as is often done in informal literature, this becomes even more evident as different subterranean water-based structures are seen within the same category of function. This is not altogether a negative trend as it allows for an appreciation of the general scope and variation of water-based heritage within Gujarat and India in general.

Figure 18 - Chand Baori (online: http://www.bringchange.in/2015/04/the-incredible-architecture-of-chand-baori/)

One example of exemplary water-based architecture in neighboring Rajasthan is the Chand Baori stepwell. Although significantly different from the form of the Rani ki Vav, this structure is highlighted as a pinnacle of geometrical sophistication within the water-based heritage of India. Through its lateral stairways giving access to subsequent platforms of the tapering retaining wall the structure is vastly different to that of the Rani ki Vav. It is well lit and its intricacy and complexity comes through the architectural design more so than through artistic embellishment. It is also a precursor to the Rani ki Vav as can be seen by the use of similar stair typologies within the design of the Rani ki Vav, with the Chand Baori being constructed in the 8th century A.D.[68]

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[68] Morna Livingston, *Steps To Water: The Ancient Stepwells of India* (New York: Princeton Architectural Press, 2002). p41.

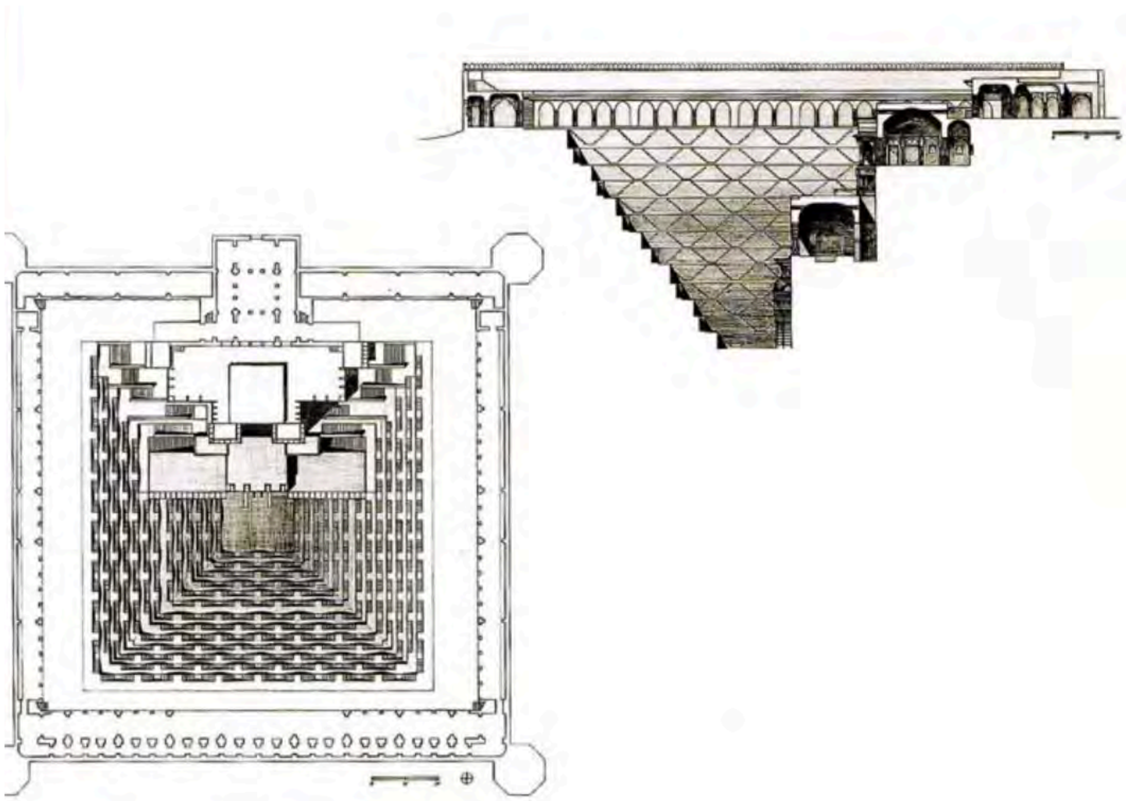

Figure 19 - Chand Baori sketch-plans (online: http://www.bringchange.in/2015/04/the-incredible-architecture-of-chand-baori/)

An ideal example of stepwell architecture in Gujarat is the Dada Harir ni Vav which in itself is likely worth the recognition of World Heritage status. This structure does not compare with that of the Rani ki Vav in terms of artistic expression, nor does any other, but its value lies in the exemplary engineering and functional fluency that is evident within the universal composition. The structure is inconspicuous and minimal at ground-level, and the haptic shock expressed from the visual vertical access once one has arrived under the entrance gazebo is memorable to say the least. The transition into the stepwell void is immediately accompanied by a reduction in air temperature and an eerie and magical diffused light in approach of the lower levels. The structure stands solid and timeless against the pressing natural forces, and the exquisite engineering feat envelops the user from all sides with a myriad of pavilion access levels, hidden spiral staircases, the catchment pool and finally the shaft of the well itself, which, as a somewhat anti-climatic feature, currently shines down on a dry bed of sand.

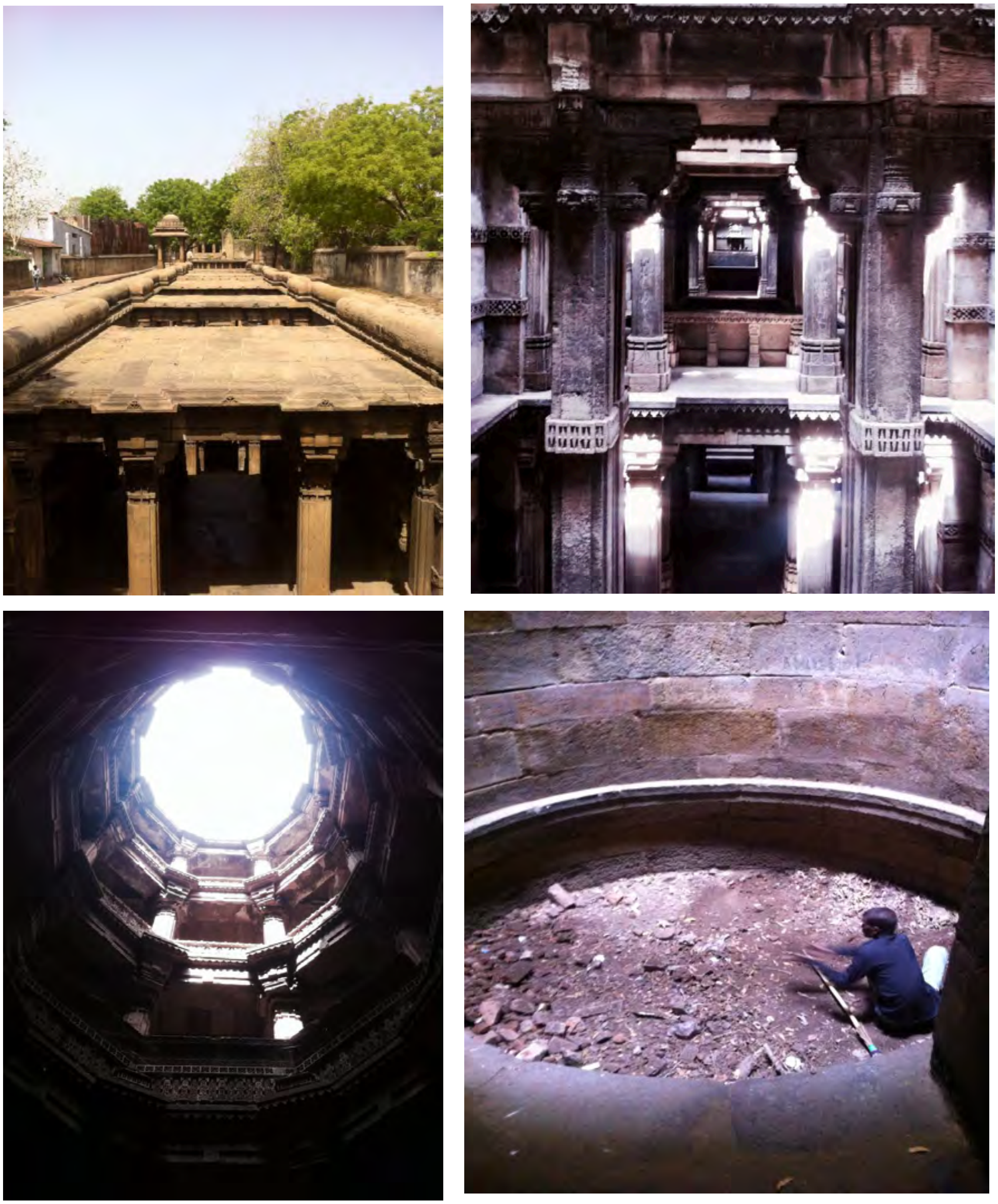

Figure 20 - Dada Harir ni Vav (2015, Author)

Another neighboring example closer to the typology of the Rani ki Vav is the Adalaj Stepwell. This structure, dating to the very end of the 15th century A.D. is a clear architectural development on stepwell architecture. We see that the structure has its own intricate and complicated carving patters, although the style has dramatically changed from that of the Rani ki Vav. This is because of the influence of Muslim Architecture on the structure and given that the Adalaj Stepwell has both Muslim-inspired floral and Islamic iconography in combination with Hindu and Jain gods and depictions it can be seen as a 'hybrid' solution intently expressing the context in which it was built. As can be seen on plan the structure layout also deviates from that of the Rani ki Vav, particularly with regards to the entrance design, although the defining characteristics as indicated for this research paper remain consistent within the plan and section of this structure. Its beauty in its own right is undeniable and its separation from the Rani ki Vav takes place largely within the scope of artistic development.

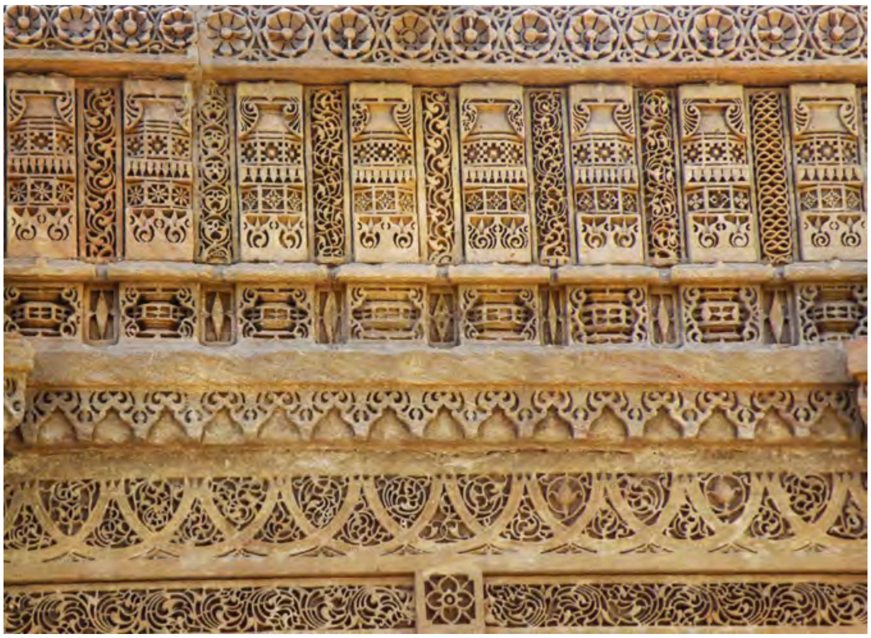

Figure 21 - Adelaj Stepwell (Creative Commons, online: http://en.wikipedia.org/wiki/Adalaj_Stepwell)

Vasavada discusses several stepwells within the Gujarat area that are of particular significance due to their unique characteristics. Yang mentions these as part of a previous serial-nomination for UNESCO World Heritage status for the stepwells of India[69], and as such several are noted and listed as follows[70] (Rani ki Vav excluded):

[69] Prof. Minja Yang to John Du Preez, 'Query Regarding RLICC Thesis Topic Proposal', email corrospondance, 30 March 2014.
[70] Vasavada. p69-81.

Figure 22 - Navghan Kuo (2012, Vasavada)

Name of the Vav and Location: Navghan Kuo, Uparkot, Junagadh, Gujarat :

Period of construction: 3rd century to 5th century A.D.

Description:

- Rock-cut stepwell.
- Characterized by
  - Open stepped corridor leading to the water in the well.
  - Comparatively shallow, requiring short flight of steps.
  - Stable constructions which do not require internal support.
  - Side walls are horizontally stepped and widen slightly towards the top.
  - The Corridor is separated from the well by a screening wall or archway.

Figure 23 - Mata Bhavani (Vasavada, 2012)

Name of the Vav and Location: Mata Bhavani, Asarva, Ahmedabad, Gujarat

(Note: This is a currently active temple)

Period of construction: 11th Century A.D.

Description:

- Structural stepwell.
- Characterized by
  - Three storied.
  - Addition of a small kund.
  - The pillars and pilasters are throughout this structure of the very plain Ruchika order, which is rarely found in Maru-Gurjara style traditions.
  - Architecturally, close to Rani ki Vav but it is more plain and small in structure.

Name of the Vav and Location: Ankol Mata Vav (Davad, Modasa, Idar), Gujarat

Period of construction: End of the 11th Century A.D.

Description:

- Structural stepwell.
- Characterized by
  - Shows primary stage of Pure Maru-Gurjara style at primary base in the Stepwell architecture.
  - The first experimental stage of temple architecture in stepwell architecture.

- Three stories pavilions with decreasing dimensions in decreasing order, towards reaching last pavilion/well.
- Rucaka type of pillars and rich ornamentation on the wall of the Stepwells.

Name of the Vav and Location: Batris Kotha Vav, Kapadvanj, Kheda District, Gujarat
Period of construction: 11th century A.D.
Description:

- Structural stepwell
- Characterized by
    - Pyramidical steps are present at the upper part of the Vav.
    - Lower levels are silted up, stepwell is in a dilapidated state.
    - Earliest evidence of
        - Introducing pillars with brackets in the stepwell for support of the structure,
        - Expansion of Stepwell in Horizontal base e.g. Broad entrance and pavilion, and
        - Small heightened triangular shaped stairs.

Name of the Vav and Location: Nadir ki Vav in NagakaGau near Ghumli, Gujarat
Period of construction: Late 12th century A.D.
Description:

- Structural stepwell.
- Characterized by
    - More elaborate example of L-shaped stepwell design.
    - The corridor is surrounded by terrace 1.5m high.
    - The entrance to the well is flanked by two lateral gate towers
    - At the end of the 'Nala' where the corridor turns to the north, two shrines flank the corridor at ground level, giving further religious emphasis.

3.1.1.4. General Condition of Existing Stepwells

The state of conservation of stepwells throughout India has, in general, been one of decline in recent years.[71] Mankodi subtly suggests that part of this may be attributed to the lack of prioratisation of stepwells by scholars, who were "*preoccupied as they are with temples, which are both more ornate architecturally, and have greater variety in terms of sculpture*".[72] Many of the historical accounts of these stepwells come from European travellers to India who noticed the structures as wholly different from any European counterpart. Examples of these authors are Arthur Malet (early 19th century), and Col. James Tod, through his book 'Travels in Western India'. The contemporary situation, however, sees a greater interest in the comparative relationship of monuments and temples. This has resulted in a quasi-abandonment of the stepwell in Indian heritage sectors, although the enlisting of the Rani ki Vav is an important shift away from this trend.[73] Lautman (2013) further suggests that the prioritisation of water-management both within India and globally are giving a reemphasis to the rehabilitation of these structures in the hope that they might once again serve to source and collect water. Currently there are a few that are in a decent state, in particular those that have a value to the tourism market. That said, the majority of the stepwells in India are in a state of disrepair, for several reasons. Firstly, under British rule the stepwells, seen as areas of stagnating water, were considered unhygienic and sources of disease. As such many were covered or filled in. Secondly, the advent of more advanced water-supplies negated the functional need for stepwells, making them a redundant part of the evolving city. Many of these sites have sadly found new uses as dump sites, latrines or storage areas, and others have simply been left in a state of decay. Education into the importance of these historical monuments, and a possibility of rehabilitation are possible activators to the continued revitalisation of these valuable historical monuments.

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[71] Victoria Lautman, *India's Forgotten Stepwells*. 28 Jun 2013. ArchDaily. http://www.archdaily.com/?p=395363 [Accessed 14 Mar 2015.]
[72] Kirit Mankodi, *The Queen's Stepwell At Patan* (Bombay: Frano-Indian Research Pvt. Ltd., 1991).p29.
[73] Victoria Lautman, *India's Forgotten Stepwells*. 28 Jun 2013. ArchDaily. http://www.archdaily.com/?p=395363 [Accessed 14 Mar 2015.]

Figure 24 - State of stepwell conservation (2011, Lautman)

3.1.2. Current Water-Situation in India

India has the second largest population on earth and as such has tremendous demands for fresh, potable water. Research by the World Bank has indicated that although steps have been taken to remedy the situation, poverty is still rampant in India, and the low-income bracket makes up 52% of the current population.[74] Although improvements have been made for the delivery of fresh water within India, the large water demand in combination with the large area to accommodate, has left rural areas in need of fresh water.[75] Although a combination of efforts, as reported by UNICEF, shows an optimistic and staggeringly successful rate of water delivery to rural areas, vast amounts of surface area are still to be addressed, and even if this is accomplished water delivery mechanisms within India face small amounts of redundancy for further human-growth tolerance. As such, a concern within India is the availability of sustainable water resources within a long-term delivery plan. As quoted by Snyder, "*Many rural communities in India who are situated on the outskirts of urban sprawl also have little choice but to drill wells to access groundwater sources. However, any water system adds to the overall depletion of water. There is no easy answer for India which must tap into water sources for food*

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[74] Worldbank.org, (2014). *World Bank - India*. [online] Available at: http://www.worldbank.org/en/country/india [Accessed 5 Mar. 2015].
[75] Kulkarni, V. (2014). *Overcoming Water Scarcity | UNICEF*. [online] Unicef.in. Available at: http://unicef.in/Story/516/Overcoming-Water-Scarcity [Accessed 5 Mar. 2015].

and human sustenance, but India's overall water availability is running dry. India's water crisis is often attributed to lack of government planning, increased corporate privatization, industrial and human waste and government corruption. In addition, water scarcity in India is expected to worsen as the overall population is expected to increase to 1.6 billion by year 2050. To that end, global water scarcity is expected to become a leading cause of national political conflict in the future, and the prognosis for India is no different.".[76] Snyder further suggests that a positive aspect of the water-delivery challenges within India is that the country is one with high rainfall, even in the arid areas, such as Gujarat, although there are no water-catchment programmes in place.[77] It is within this light that the relationship of water-delivery challenges for rural India to historical precedents becomes evident. Not only is the restoration scenario of existing water sources an important aspect to sustainable water delivery within rural India, it is also an example to contemporary solutions for the challenges ahead. Even in cases where restoration scenarios are either not possible or not feasible, the education in light of these structures, and the exposure thereof, are an important way that heritage sectors can play a role within the development of a sustainable future, both within India and in other countries around the world as well.

[76] Snyder, S. (2015). *Water In Crisis - Spotlight India.* [online] The Water Project. Available at: http://thewaterproject.org/water-in-crisis-india [Accessed 5 Mar. 2015].
[77] Ibid.

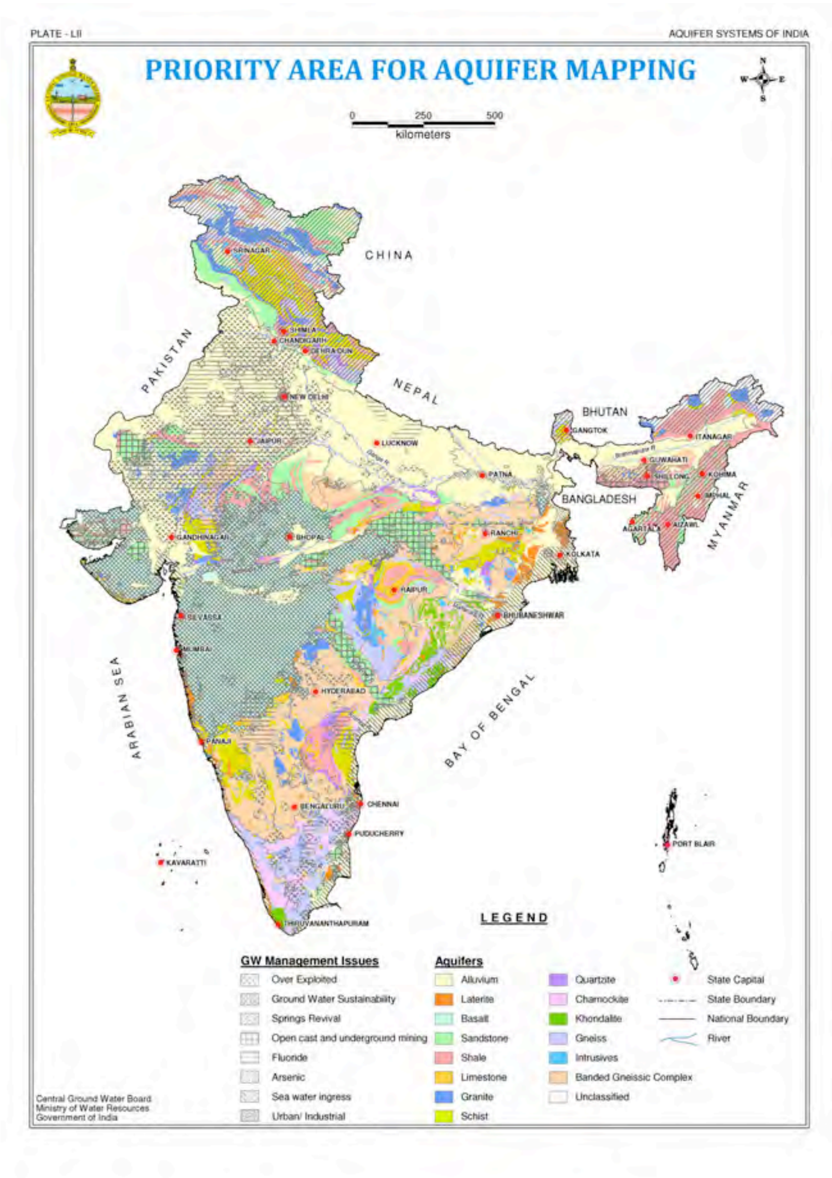

Figure 25 - Priority area for aquifer mapping (Groundwater Board, India, 2001)

3.1.3. Current Water-Situation in Gujarat

Reports on the current water situation in Gujarat suggest that urgent emphasis must be placed on the mapping and management of groundwater resources for the area. Much of the groundwater resources are used as both sources for potable human consumption as well as for agriculture and livestock supply. Overuse of groundwater supply within the area is a subject of serious concern. Although groundwater, when managed, can be a sustainable source of water supply, local farmers in the area, through political and financial complexities, often misuse this supply for farming purposes. The lowering groundwater supply, which has dropped 80m in the last 30 years, is indicative of this overuse and lack of management. Farmers are forced to dig deeper wells and over-extract on supply. The continuation of this might lead to the collapse of major aquifer systems in the area, which is not reversible, and would lead to the collapse of water supply in the area, both for farming and for human consumption. Salanisation of groundwater aquifer systems is also of major concern and it is not a reversible process and eliminates potable water supply for human consumption within the area. It is relevant to note that electroseismic surveys allows for the mapping of salanisation within groundwater aquifer systems, and as such groundwater mapping within the Gujarat area serves a dual purpose in this regard. Regardless of process, the groundwater resources in Gujarat should be seen as a fragile and critical component to human activity within the area.[78] Although accessing groundwater through heritage structures is not a solution in itself to the challenges of groundwater management within Gujarat, it is certainly an approach to responsible and sustainable social relationship to groundwater resources. As a first step within the understanding of the relationship between human consumption and groundwater availability Quevauviller has addressed initial steps, albeit within a European context, although these apply to the situation within Gujarat, and surmise to the monitoring the resource use and potential sources of pollution. Basic information on how groundwater resources are being used and who is using them is as essential for management as scientific data on the aquifer system itself. Without understanding how groundwater resources are being used, particularly for irrigated agriculture, it is impossible to identify points of management focus.[79] Quevauviller continues by arguing that devising management systems requires detailed knowledge of such factors as the actual locations where groundwater extraction is occurring, the efficiency with which it is used and its role in agriculture and other water-use systems. Programmes for registering wells and estimating, either directly or indirectly, the amount of groundwater extracted are essential steps, and one that has precedent in similar environmental conditions in South Africa, where a groundwater management database for critical areas has been established. Similarly, it is important to

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[78] J. Hitz (2011). *The Worsening Water Crisis in Gujarat, India – State of the Planet*. [online] Blogs.ei.columbia.edu. Available at: http://blogs.ei.columbia.edu/2011/01/18/the-worsening-water-crisis-in-gujarat-india/ [Accessed 5 Mar. 2015].

[79] P. Quevauviller (2008). *Groundwater science and policy*. Cambridge: RSC Publishing. p 21.

identify, as far as possible, other activities that could have substantial impacts on groundwater conditions. This includes the basic information on potential point and non-point sources of pollutants arising from industry, domestic sewage and agricultural chemical use.[80]

3.1.4. Groundwater Analysis of the Rani ki Vav – Purpose and Benefits

The purpose of groundwater analysis within the context of the heritage sector has been discussed previously within this paper. Additionally, the purpose of groundwater mapping and management has also been discussed within the context of the Gujarat area. These purposes for groundwater analysis of the Rani ki Vav can be summarised as follows:

- Site specific purpose and benefit
    - Possible rehabilitation scenarios for the Rani ki Vav
    - Should rehabilitation be possible, and feasible, the most effective approach can be determined, maximising performance and reducing cost
    - Further understanding of the relationship between the natural environment and a water-based World Heritage site in order to understand this relationship in other related situations
    - Noting of management concerns for groundwater related aspects as they relate to the Rani ki Vav
- Community based purpose and benefit
    - Possible contribution to water-related challenges for the Gujarat area
    - Social implications of a functional water source
    - Detection of groundwater salanisation risk, and the role it plays within community consumption
    - Further exposure of the newly listed Rani ki Vav and its heritage significance
- Province based purpose and benefit
    - Further investigation into the groundwater related challenges faced by Gujarat and nearby provinces within India

80 Philippe Quevauviller, *Groundwater Monitoring* (Chichester: Wiley, 2008).*p28*.

- Contribution to groundwater management framework data for sustainable water-source solutions within the area
- Technological purpose and benefit
  - First case study directly relating heritage to groundwater through direct measurement for active rehabilitation scenario development
  - Hardware and software testing for heritage-based groundwater related application, and the development of this knowledge for future heritage sector applications

3.1.5. Location of the Rani ki Vav

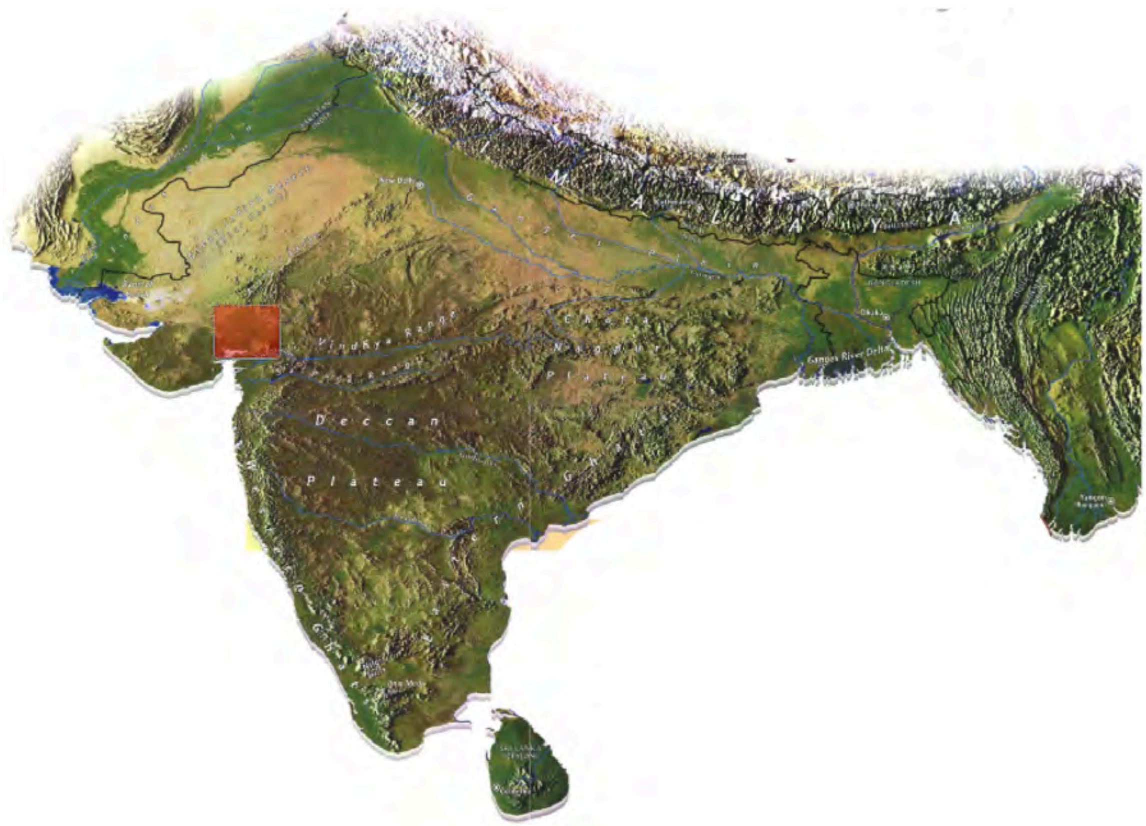


Figure 26 - Location of the Rani ki Vav, India (Adapted by Author)

The unique form and functional approach to subterranean water as defined by the stepwells is an important and interesting element of built heritage within the Indian context. Rajasthan and Gujarat hold many existing examples of these structures that date as early as the 7th century, but the high-period of monumentality and elaborate sculptural forms found within these structures is unique to Gujarat.[81] Gujarat, a state of India, is located on the western side of India and is about 196,204 km^2 in area. The area has historical significance to India, particularly as an area of economic influence. Gujarat also plays an important part in world history, having within its borders major sites of the Indus Valley Civilisation such as Lothal and Dholavira. Furthermore, the site was well known to both the ancient Greeks as well as the Roman Republic as well as the Persian Empire, and its maritime culture and trading function was noted and described by the Greeks within a book entitled *The Periplus of the Erythraean Sea: Travel and Trade in the Indian Ocean.*[82]

Patan, located within the state of Gujarat, was built in 745 A.D. as a fortified capital city for the area. The town has a population of 133,737 (2011 census). Significantly, the town was estimated to have a population of 100,000 during the 11th century, being within the top-ten largest cities in the world by 1000 A.D. The correlation of this date to the 11th century construction of the Rani ki Vav gives further understand to the structure's historical context.[83] From a water-based architectural element perspective the large size of Patan at the time gives emphasis to both the demand for water by the surrounding community and also emphasizes the symbolic role of water to a large population within an area of harsh climactic shifts.

3.1.3. Case Study – Selection Criteria

The Rani ki Vav was selected as an ideal case study for the application of the developed technology within the heritage sector for several reasons, these are listed below:

1. World Heritage Site – The Rani ki Vav, inscribed on the UNESCO World Heritage list in 2014[84], represents a case study with unique attributes related to World Heritage status. Access to the site, as an example, has proven to be a particular challenge given

[81] Jain-Neubauer (1981), p9.
[82] William Schoff, *The Periplus Of The Erythraean Sea: Travel And Trade In The Indian Ocean By A Merchant Of The First Century* (Montana: Kessinger Publishing, LLC, 2010).
[83] Tertius Chandler, *Four Thousand Years Of Urban Growth* (Lewiston, N.Y., U.S.A.: St. David's University Press, 1987).
[84] The Biharprabha News, 'Gujarat's Rani Ki Vav Added To UNESCO World Heritage Site List', 2015, http://news.biharprabha.com/2014/06/gujarats-rani-ki-vav-added-to-unesco-world-heritage-site-list/. [Accessed: 6-March-2015].

this status and the added protection it affords. Furthermore, aspects such as buffer-zoning areas around the site add a further dimension to the analysis. The dossier for the site gives further information on the monument, including existing monitoring criteria and special structural concerns. Adopting a World Heritage site as a case study gives further emphasis to the social aspects relating to the site and allows for debate within this regard, as well as from a touristic perspective. Lastly, the study might relate to site management derived through policy, bringing to light the relationship between structure and environment prioritised at a policy-framework level.

2. Nature of the Structure – The Rani ki Vav serves, primarily, as an access point to groundwater resources. It is a water-based subterranean monument that closely integrates the heritage structure with the surrounding natural environment through its core function, and as such it makes an ideal first-case scenario for the investigation relating groundwater resources to heritage structures as it does so in a very direct way.
3. Relationship to Human Settlements / Sustainability Aspects – The Rani ki Vav has played an important role in the establishment of the surrounding human settlements through history and its role in contemporary society is limited to its role as a static monument. An interesting investigation lies in the link between the monument and the surrounding human settlements in a more dynamic and relevant way. In relation to this are the correlating sustainability aspects that play a role in the connection between the human settlement and the monument. These aspects relate, also, to the current groundwater management approach adopted by the surrounding farmers and other consumers. As such a complicated web of social interaction exists within any developed scenario.
4. Restoration Scenarios – The current condition of the Rani ki Vav is ideal for possible development of restoration scenarios. The monument has lost connection with the groundwater source it originally accessed and has since dried up. As an initial investigation it was envisioned that the prospect of active and positive rehabilitation scenarios serves to better explore the role between the surrounding natural environment and the monument structure. Although the exploration would be valid in a functioning water-based monument, this would be more of a management study

than one of active reconnection, making the status of the Rani ki Vav ideal for the purpose of the study.

5. Pollution and Waste-Management Studies – Although beyond direct scope of the research paper, the role of pollution and waste-management on the resulting rehabilitation scenario plays an important role in the cycle of human consumption. Pollution as it relates to the aquifer system also relates to this selection criteria, including salination of potable water sources, which might be of concern for over-utalised aquifer systems through lack of a groundwater management framework within the area.

3.2. Historical Development

3.2.1. Historical Context

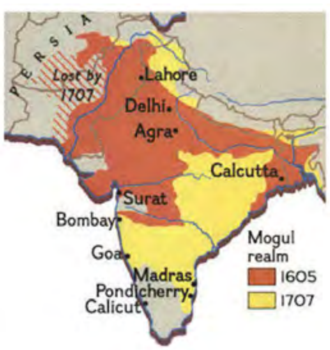
A brief historical outline frames the Rani ki Vav within the social, political and religious developments within Indian. Indian history is of particular complexity, where rulers of large kingdoms rule in overlapping time-period and dynamics shift not only within the scope of these kingdoms, but also through interaction with exterior influences. As a thoroughly simplified outline the history of India can be divided into six broad periods as defined by the National Geographic Society[85]:

Early and Ancient India – The Indus Valley civilisation with its sophistic urban dynamic and systems of writing and measurement, emerged around 2500 B.C.E. About a thousand years after this the Aryans brought from the north a culture and rituals that developed into the roots of modern Hinduism. The Mauryan's took power in 320 B.C.E., through political developments that evolved through the conquests of Alexander the Great, and their empire peaked through most of the 3rd century B.C.E.

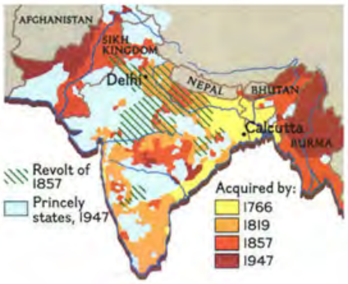
[85] National Geographic Society, *'India Turning 50'*, *National Geographic Magazine*, May, 1997. *Map insert.*

Gupta Empire – This period encapsulates the classical period of Hindu art, literature and science, peaking during the reign of Chandragupta II (375 – 415 A.D.). The series of rulers within the Gupta Empire promoted Brahmanism, which was a precursor to modern Hinduism. The empire later collapsed during expansion efforts of the Huns in the 5th century.

Sultanate of Delhi – The 5th to 13th centuries were riddled with external invasions and are defined as a period of complex political turmoil and boundary shifts. It is during this period that the Rani ki Vav is built. The push of Muslim rule into India resulted in the establishment of a Muslim sultanate in Delhi in 1206 A.D. In 1526 A.D. the Mogul Empire was formed and brought a relative stability to the developments of the preceding centuries, an empire that would last for the next 200 years.



Mogul Empire – During the period of the Mogal Empire India found the attention of European markets, and Europe started vying for sea-routes with Arab merchants to Indian supplies. As such, European ports were established in India during this time and trade agreements were made with the emperors of the time. The Mogul period is described as one of religious tolerance, and a period which produced exquisite art and architecture. The period ended at the death of Aurangzeb in 1707 A.D.

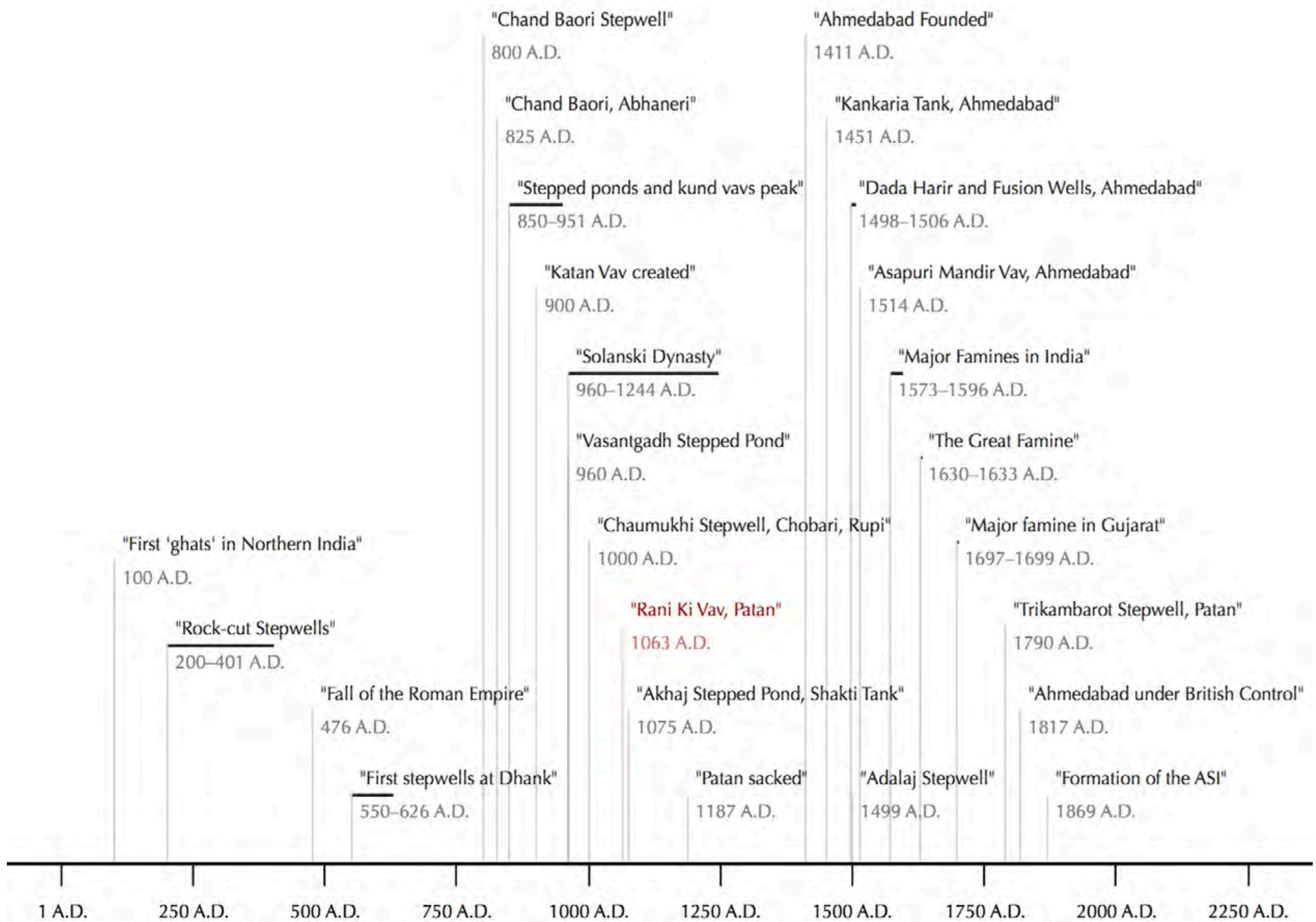


British Expansion – Taking advantage of the power-void experienced in India during the early 18th century, the British East India Company started gaining control of parts of India and, through careful manipulation and political maneuvering, established a total control within the century, with the addition of controlled 'princely states'. The Indian British Colony was established in 1858 as Britain seized control of the East India Company's holdings at that time. Unrest was rife, and resulted in the 1857 Indian Revolt, which was suppressed by British forces in 1859.

Independent India – From 1858 there was a discontent for British rule and inequality. After World War I there were increasing calls for independence, largely catalyzed by Mohandas Gandhi. In 1940 conflicts between the Muslims and Hindu-run government of India called for action, and in 1947 an independent India and Pakistan were declared.

It is safe to surmise that the construction of the Rani ki Vav (1022 – 1063 A.D.) finds itself in a transition period within Indian history. The influences of Muslim culture do not project on the structure of the Rani ki Vav itself, but do however on many stepwell constructions within Gujarat. The switch towards a more secular function for stepwells and the resulting shifts in architecture express this transition period and its influence on the area. The Rani ki Vav was commissioned during the early reign of the Solanki Dynasty (960 – 1243 A.D.).

3.2.2. Timeline of Stepwell Development in India


"First 'ghats' in Northern India"
100 A.D.
"Rock-cut Stepwells"
200–401 A.D.
"Fall of the Roman Empire"
476 A.D.
"First stepwells at Dhank"
550–626 A.D.
"Chand Baori Stepwell"
800 A.D.
"Chand Baori, Abhaneri"
825 A.D.
"Stepped ponds and kund vavs peak"
850–951 A.D.
"Katan Vav created"
900 A.D.
"Solanski Dynasty"
960–1244 A.D.
"Vasantgadh Stepped Pond"
960 A.D.
"Chaumukhi Stepwell, Chobari, Rupi"
1000 A.D.
"Rani Ki Vav, Patan"
1063 A.D.
"Akhaj Stepped Pond, Shakti Tank"
1075 A.D.
"Patan sacked"
1187 A.D.
"Ahmedabad Founded"
1411 A.D.
"Kankaria Tank, Ahmedabad"
1451 A.D.
"Dada Harir and Fusion Wells, Ahmedabad"
1498–1506 A.D.
"Adalaj Stepwell"
1499 A.D.
"Asapuri Mandir Vav, Ahmedabad"
1514 A.D.
"Major Famines in India"
1573–1596 A.D.
"The Great Famine"
1630–1633 A.D.
"Major famine in Gujarat"
1697–1699 A.D.
"Trikambarot Stepwell, Patan"
1790 A.D.
"Ahmedabad under British Control"
1817 A.D.
"Formation of the ASI"
1869 A.D.
1 A.D.
250 A.D.
500 A.D.
750 A.D.
1000 A.D.
1250 A.D.
1500 A.D.
1750 A.D.
2000 A.D.
2250 A.D.

3.2.3. Chronology of Rani ki Vav Construction

The Rani ki Vav is an 11th century structure built during the Solanki Dynasty which ruled in early Gujrat at the time. Udaymati, the queen to Bhimdev I (1022 A.D. to 1063 A.D.) is assumed to have commissioned the construction of the Rani ki Vav in commemoration of the death of her husband. The construction is believed to have taken five years to complete, from 1063 A.D. to 1068 A.D. The Udayamati Stepwell as it was previously and originally called in English, has since adopted the name of The Queen's Stepwell given its unique commissioning by Udaymati.

The Rani ki Vav was one of three stepwells built during the same period, the other two being the Ankol Mata Stepwell at Davad and the Mata Bhavani Stepwell at Ahmedabad, however, the dating of these additional two stepwells is not as clear as that of the Rani ki Vav, and with contribution from Jain-Neubauer (1981) investigations were made into the chronology of these three structures based on historical, inscriptional and stylistic elements.[86] Mankodi proposes a theorised chronology as follows: King Bhimadeva had first thought of building the Modhera temple for worship. His son, Karnadeva, built the Ankol Mata Stepwell as a recreational structure, giving onus to its orientation, due north-south, which provides maximum shade during the summer period.[87] After Bhimadeva's death, Queen Udayamati built the Rani ki Vav as a reflection of love and devotion to her late husband. Their son, Karnadeva, later constructed the Bhavani Stepwell for utilitarian purposes in the new capital of Karnãvatì. Both collective construction of these three stepwells in the 11th century are important in that they show the multi-functional approach to Stepwell architecture in general. Although initially envisioned as a structure of worship, these structures often acted as areas of recreation as well as utilitarian structures and important sources of water for the surrounding community. The Rani ki Vav is unique in its devotional qualification for a well-structure within India, and investigation into the sculptural style of the structure shows that the reverberation of this quality is echoed in the stylistic approach to the monument as one of devotional dedication.

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86 Jain-Neubauer, Jutta. *The Stepwells Of Gujarat*. New Delhi: Abhinav, 1981.p19.
87 Mankodi, Kirit. *The Queen's Stepwell At Patan*. Bombay: Frano-Indian Research Pvt. Ltd., 1991., p7.

3.2.4. Architectural Description

Jain-Neubauer defines five types of architectural stepwell forms.[88] The Rani ki Vav forms part of Type I of these defined forms and meets definition with all four components listed, namely –

1.) It has a stepped corridor which begins at natural ground level and leads uniformly to the underground water-source area.
2.) It has compartmentalised areas at regular intervals with pillared multi-story pavilions.
3.) It consists of a draw well at its terminus.
4.) It has a large storage tank (kunda) for surplus water storage.

Using the most recent survey data, that of the Archeological Survey of India (ASI) found within the UNESCO World Heritage Nomination Dossier, the monument measures 70 meters in total length, from the base of the torana to the inner edge of the shaft. It has a width of 23 meters and a depth of 28 meters.[89] The orientation is almost due east-west, with a deviation noted by Mankodi of 3 degrees off of this axis.[90]

3.2.5. Current Condition of the Rani ki Vav

The existing condition of the Rani ki Vav coincides closely to the defined pathologies of the ASI report submitted to UNESCO. Emphasis is currently placed on the maintenance and preventative restoration of the sculptural elements within the structure, and the care of these elements is evident on-site. Protective balustrades protect sculptural elements from visitor interaction, and watchful caretakers ensure their upkeep. The more sensitive areas as defined by the ASI are currently off-limits to the general public. A balustrade cuts the structure off from pedestrian movement roughly halfway through its length. Through observation from this point some structural pathologies are noted, such as the slight buckling of transverse elements. These have been addressed by the ASI and are being measured and remedied where possible. To note, these are of particular interest to any rehabilitation scenario that

[88] Jain-Neubauer, Jutta. *The Stepwells Of Gujarat*. New Delhi: Abhinav, 1981.p34.
[89] Archeological Survey of India (2014), p28.
[90] Mankodi (1991), p30.

might exist for the structure as they play a direct role in the structural capacity of the monument. The site is in a good state of conservation and is clean and well maintained.

Figure 27 - Rani ki Vav (Author, 2015)


Rani ki Vav (Author, 2015)


Rani ki Vav (Author, 2015)

3.3. UNESCO World Heritage Site

The Rani ki Vav was inscribed as a UNESCO World Heritage Site on the 22nd of June 2014 after its initial nomination by the Archeological Survey of India (ASI) in February 2013.[91] The Nomination Dossier, which was submitted by the State Party, India, through the Archeological Survey of India (ASI), is a valuable resource for updated information on the structure, especially as most literature in this regard is fairly dated. Information describing the Rani ki Vav as a World Heritage site primarily comes from this source.

3.3.1. Overview of Selection Criteria

UNESCO defines the selection criteria of nominated world heritage within the scope of ten points of eligibility. The protection, management, authenticity and integrity of the heritage site, along with social human interaction, act as important qualifying criteria within the nomination process.[92] For a world heritage nomination the site needs to have an outstanding universal value and also meet at least one selection criteria as listed by UNESCO. Within the nomination dossier for the Rani ki Vav the ASI selected two criteria, namely (i) and (iii):

(i)

to represent a masterpiece of human creative genius;

(iii)

to bear a unique or at least exceptional testimony to a cultural tradition or to a civilization which is living or which has disappeared;

Within the nomination dossier, the ASI justified these criteria through the following statements:

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[91] The Biharprabha News, 'Gujarat's Rani Ki Vav Added To UNESCO World Heritage Site List', 2015, http://news.biharprabha.com/2014/06/gujarats-rani-ki-vav-added-to-unesco-world-heritage-site-list/. [Accessed: 6-March-2015].

[92] UNESCO Centre, 'UNESCO World Heritage Centre - The Criteria For Selection', *Whc.Unesco.Org*, 2014, http://whc.unesco.org/en/criteria/. [Accessed: 6-March-2015].

Criteria (i): "*Rani Ki Vav is a highly celebrated stepwell, a type of subterranean water architecture, unique to the north-western frontiers of the Indian sub-continent. As a highly celebrated stepwell, it immortalises the creative endeavor of art, architecture and engineering skills of incomparable skills and quality. As the most evolved and complete stepwell, its surfaces, pavilions, columns, friezes, niches, brackets and the shaft remains adorned by innovative ornamentation that drew from religious, mythological and secular themes. With its innovative design and ornate form, this property also introduces a new form of subterranean water architecture to the world".*[93]

Criteria (iii): "*Rani Ki Vav is the most evolved and celebrated stepwell that testifies the unique tradition (of constructing a stepwell) of north-western region of the Indian subcontinent. The practice started in the 3^{rd} millennium BCE, evolved in early-medieval times and ceased by the late 19^{th} century CE, where these structures were ascribed with sacred and secular values. As a memorial to the Solanki King Bhimadeva I, it was an act of piety to provide water and a social space for the city of Patan and a larger transient community, by Queen Udyamati. Embodying the values associated with water, Rani Ki Vav, also exhibits a successful technological innovation that stored and protect groundwater against the adversities afforded in its context".*[94]

It is of interest to note that the UNESCO inscription took place under the selection criteria of (i) and (iv) rather than (i) and (iii) as applied through the nomination dossier. Selection criteria (iv) is as follows:

> (iv)
>
> to be an outstanding example of a type of building, architectural or technological ensemble or landscape which illustrates (a) significant stage(s) in human history;

The change of selection criteria within the inscription was revised by UNESCO and accommodates the justification statement as expressed by the ASI within a more appropriate catagorisation.

UNESCO gives the following statements in terms of the integrity and authenticity of the site:

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[93] Archeological Survey of India, *Rani Ki Vav (The Queen's Stepwell) At Patan, Gujarat – Nomination Dossier* (New Delhi: State Party of India, 2013). P12.
[94] Archeological Survey of India, pp 13.

Integrity: *"Rani-ki-Vav is preserved with all its key architectural components and, despite missing pavilion storeys, its original form and design can still be easily recognized. A majority of sculptures and decorative panels remain in-situ and some of these in an exceptional state of conservation. Rani-ki-Vav is a very complete example of the stepwell tradition, even though after geotectonic changes in the 13th century it does no longer function as a water well as a result of the change to the Saraswati River bed. It was however the silting of the flood caused during this historic event, which allowed for the exceptional preservation of Rani-ki-Vav for over seven centuries.*

All components including the immediate surrounding soils which adjoin the vertical architecture of the stepwell are included in the property. In terms of intactness, the property does not seem to have experienced major losses since its flooding and silting in the 13th century. However, Patan like many Indian urban centres is experiencing rapid urban growth and the western expansion of the city towards Rani-ki-Vav has to be carefully controlled to protect the integrity of the property in the future."

Authenticity: "*The property is protected as a national monument by the provisions of the Ancient Monuments and Archaeological Sites Act of 1958 amended by its revision of 2010 and accordingly administrated by the Archaeological Survey of India (ASI). It is formally designated as an ancient monument of national importance and surrounded by a protective non-development zone of 100m to all sides of the architectural structure. The buffer zone has been included in the adopted Second Revised Development Plan, which ensures its protection from any inappropriate development.*

The management of the property is under the sole responsibility of the ASI and steered by a Superintending Archaeologist with an in-house team of ASI archaeologists working and monitoring on site. Any proposed interventions require scientific review by the superintending archaeologist who may be advised by experts in a specific field. A management plan has been prepared by the ASI for the property and its implementation commenced in 2013.

The approaches taken to risk preparedness and disaster management planning should be further developed given that Rani-ki-Vav is situated in an earthquake prone area. Few interpretation facilities exist on site and the only information sources are two stone panels erected by the ASI. The Rani-ki-Vav would benefit from a more holistic concept to visitor management including local community concerns and revenue models. An information centre with food court and office building is planned on site but its location needs to be *selected with care as some directions, in particular the western direction are more vulnerable with regard to developments which may change the view perspectives and settings of the property. For any future intervention in the property or buffer zone, Heritage Impact Assessments in accordance with the ICOMOS guidance for Heritage Impact Assessment on World Cultural Heritage properties should be carried out before any plans are approved and implemented.*"[95]

3.3.2. Pathology

The State of Conservation analysis within the ASI nomination dossier gives an optimistic survey of the condition of the site as of 2013.[96] Although an holistic overview of the state of conservation of the monument is beyond the scope of this research paper, the state of conservation issues as they relate to any possible rehabilitation scenario, or any other form of action restoring water within the well, do play a significant role in the feasibility of the study. As indicated within the UNESCO report, the following pathologies play a potential role in possible scenarios offered within the scope of this paper:

Level 1 – The lowest level of the structure, indicated as Level 1, is the central point of concern within water-related scenario development. This is the, at its core function, centre point of the structure and the point of intersection between the natural environment and the well structure. It is also the well proper, and subject to water-related phenomena and potential structural challenges. The ASI nomination dossier points to minimal pathologies at this level.[97] Of potential concern might be the conservation over the structural iron bracings that are present within the well shaft. Marginal rusting has occurred on these bracings and investigation into the reaction of prolonged exposure to water needs to be analysed and addressed by the relevant engineering professionals.

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[95] UNESCO Centre, 'UNESCO World Heritage Centre – Rani Ki Vav (The Queen's Stepwell) at Patan, Gujarat, *Whc.Unesco.Org*, 2015, http://whc.unesco.org/en/list/922/. [Accessed: 6-March-2015].
[96] Archeological Survey of India (2014), p137-143.
[97] Ibid. p137.

Figure 28 - Rani ki Vav Tank (ASI, p.137)

Further relevant concern lies in the state of conservation of the water tank area (kunda), adjacent to the well to collect and store excess water both from rain overflow as well as well water. Although tanks in stepwell typologies are not unique to the Rani ki Vav, the size of the tank in this case is uniquely large. At a structural level a central bracing mechanism stretching over two accessible levels acts as lateral support for the loads experienced by the retained void of the tank. At an architectural level these bracings provide access to water of varying depth as pavilions within the tank. The ASI notes these braces as structurally stable with minimal movement, however, structural stability modeling is recommended for any remediation actions taken, and a risk analysis based on the load of water on a full tank needs to be considered before changing the load dynamics on the structure.[98]

[98] Archeological Survey of India (2014) p138.

Rani ki Vav Tank (ASI, p.138)

Level 2 – No relevant pathologies

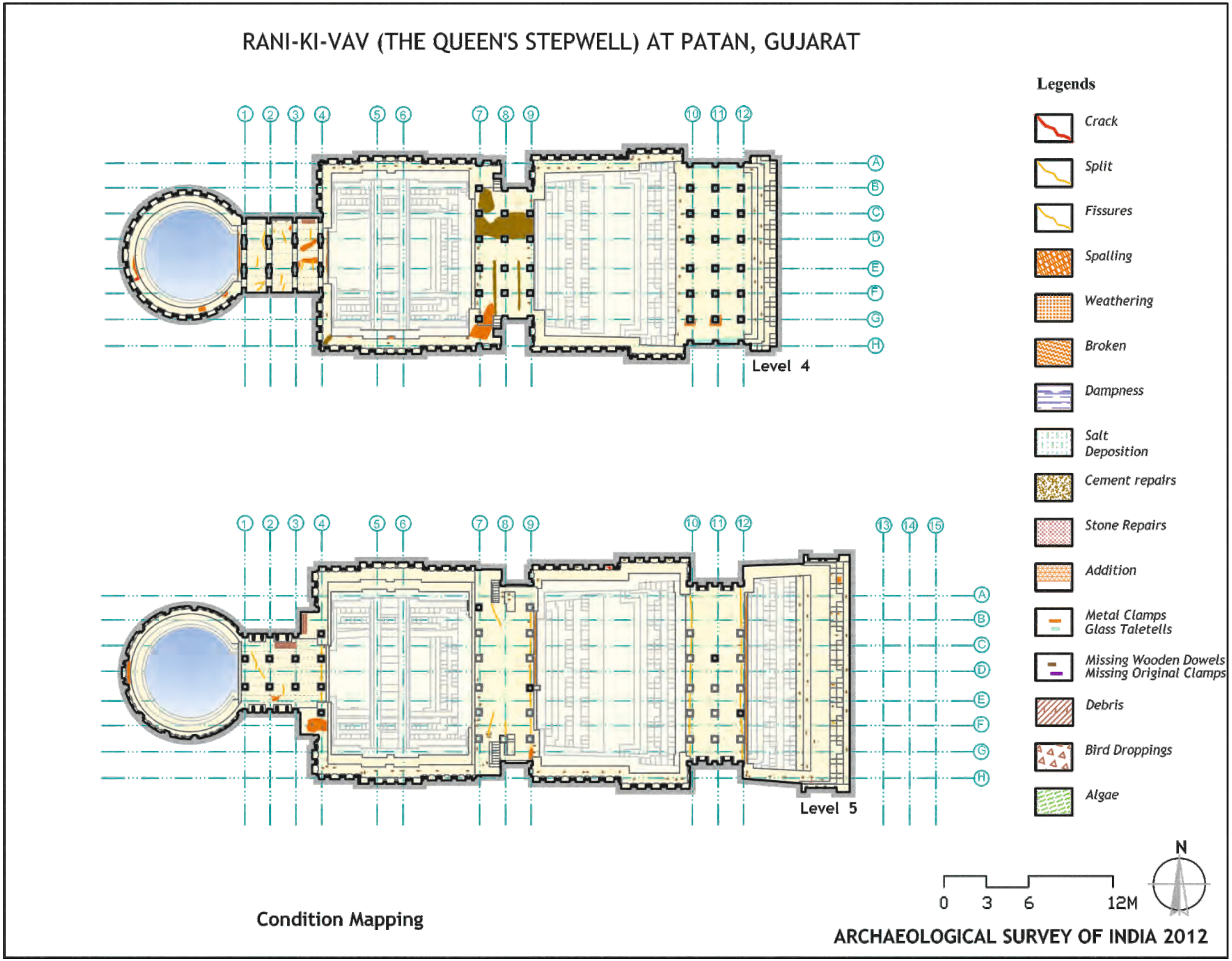
Level 3 – Spalling, micro-flaking and hairline cracks can be identified on several stone members. These relate to the structural stability of the monument and are therefore relevant to rehabilitation scenarios. These pathologies have since been addressed and stabilised by the ASI, though specialist analysis is recommended.[99]

Level 4 – No relevant pathologies

Level 5 – The absence of a roof exposes the floor to the elements, and as such the ASI is exploring conservation options in this regard.

Level 6 – At this uptmost level retaining wall support is in effect to prevent pressure of the surrounding soil from collapsing the structure. A brick wall was also constructed (19th century) on top of this wall in order to hold back soil from falling into the well. The integrity of this wall is paramount for both the structural stability of the monument as well as for prevention of soil collapse into the well.

[99] Archeological Survey of India (2014) p140.


RANI-KI-VAV (THE QUEEN'S STEPWELL) AT PATAN, GUJARAT
Legends
Crack
Split
Fissures
Spalling
Weathering
Broken
Dampness
Salt Deposition
Cement repairs
Stone Repairs
Addition
Metal Clamps
Glass Taletells
Missing Wooden Dowels
Missing Original Clamps
Debris
Bird Droppings
Algae
Level 4
Level 5
0 3 6 12M
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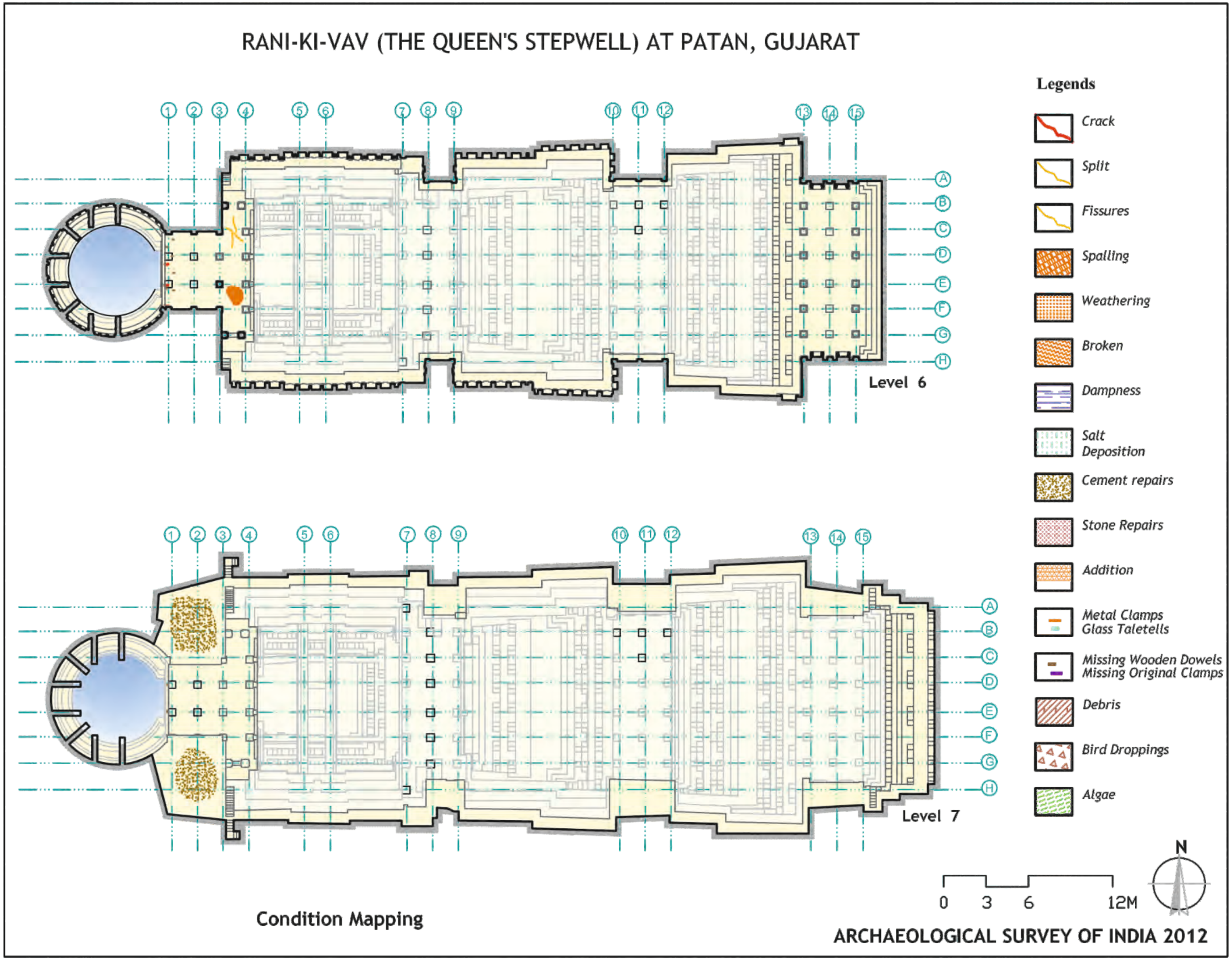
Condition Mapping
ARCHAEOLOGICAL SURVEY OF INDIA 2012

Fig. 4.6


RANI-KI-VAV (THE QUEEN'S STEPWELL) AT PATAN, GUJARAT
Level 6
Level 7
Legends
Crack
Split
Fissures
Spalling
Weathering
Broken
Dampness
Salt Deposition
Cement repairs
Stone Repairs
Addition
Metal Clamps
Glass Taletells
Missing Wooden Dowels
Missing Original Clamps
Debris
Bird Droppings
Algae
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Condition Mapping
ARCHAEOLOGICAL SURVEY OF INDIA 2012

Fig. 4.7

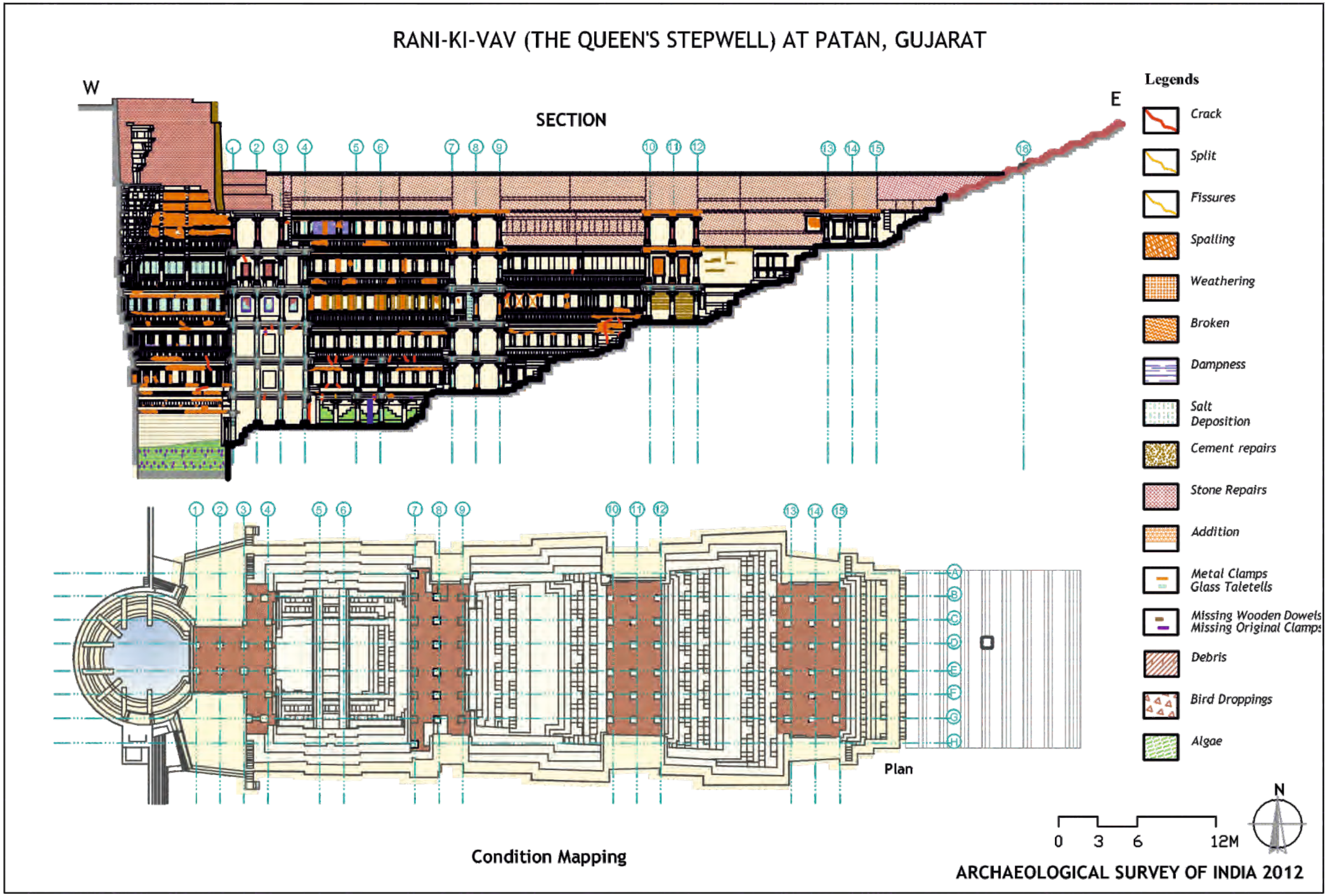
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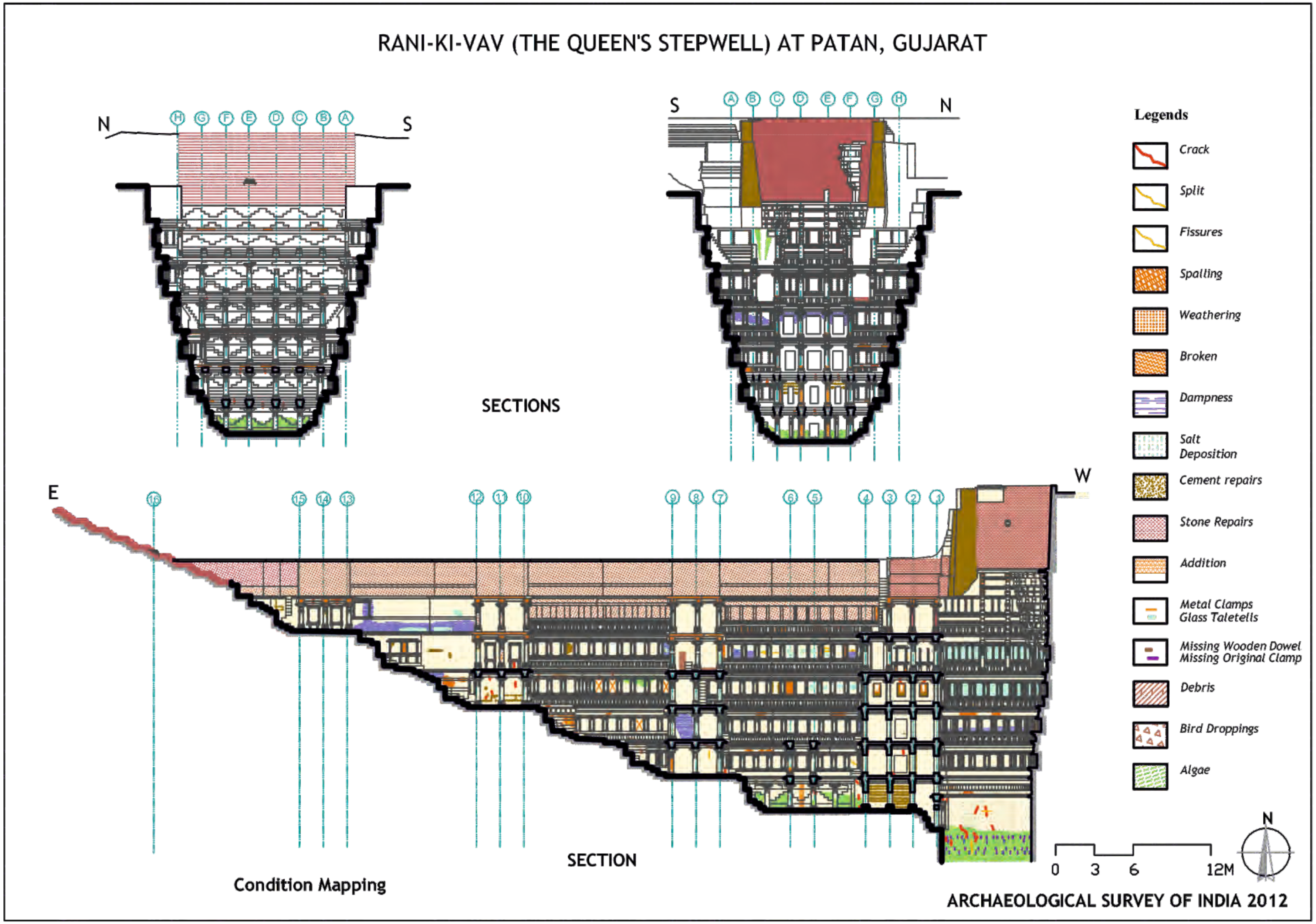
Fig. 4.8



RANI-KI-VAV (THE QUEEN'S STEPWELL) AT PATAN, GUJARAT
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Dampness
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Cement repairs
Stone Repairs
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Metal Clamps
Glass Taletells
Missing Wooden Dowel
Missing Original Clamp
Debris
Bird Droppings
Algae
0
3
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12M
ARCHAEOLOGICAL SURVEY OF INDIA 2012

Fig. 4.9

Figure 29 - Added retaining walls (ASI, p.127)

3.3.3. Conservation Plan

The Archeological Survey of India has included a full annexed conservation plan as part of its dossier submission to UNESCO in fulfillment of UNESCO World Heritage nomination requirements.[100] Conservation efforts have been underway since 1937 and for the first several decades consisted primarily of site excavation and preservation aimed at stabilising the structure and the sculptural elements.[101] It is of particular interest that the water table and groundwater, in general, is noted as an external factor being used as an indicator to monitor the state of conservation of the site, but no further mention is made of groundwater monitoring or management within the conservation plan.[102]

Indicator	Observation	Methods	Monitoring Period
Water-table in the area.	Being a subterranean structure and having a well, it is important to have a knowledge of the water table in the region.	Obtain data produced by the water commission on a regular basis.	Yearly.

The table above is extracted from the existing information relating to groundwater within the conservation plan (Table 9: External Factors being used as indicators to monitor the

[100] Archeological Survey of India (2014) p253-321.
[101] Ibid. p254.
[102] Ibid. p280.

state of conservation). The information and its methods are not sufficient for the preservation of groundwater related cohesion to the structure in any sustained way, and is in need of further development. Furthermore, it is noted that the water commission has indicated a drop in groundwater levels within the country, including the Gujarat area, and has implemented strategies towards the stabalisation of these at critical areas.[103] That said, no water management plan with relation to the Rani ki Vav is in effect up to this point. Concern as to the relationship between groundwater related monitoring and monument conservation should be addressed at policy level where such management objectives relate directly to the functional capacity of the structure.

Future conservation plans for the Rani ki Vav are planned up until 2018 within the conservation framework of the ASI, these are as follows[104]:

2014-15: Fourth level is to be taken up for removal of surface accretions and consolidation, wherever necessary. Minor structural repairs are to be carried out before chemical treatment and consolidation.
2015-16: Fifth level is to be taken up for removal of surface accretions and consolidation, wherever necessary. Minor structural repairs are to be carried out before chemical treatment and consolidation.
2016-17: Levels 1 and 2 are to be taken up for removal of surface accretions and consolidation. Structural repairs are to be carried out before chemical treatment and consolidation.
2017-18: The whole area of the Vav including sculptures and plain surface will be given a preservative coat of silane siloxane mixture. Before the application of the preservative coat, fungicidal coat will be given to arrest further re-growth of micro-vegetation. The preservative coat will be given only on completely dried-up surface.

The future conservation plans for the site are therefore focused on the final consolidation efforts with maintenance schedules being carried out thereafter. Of note within this plan is

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[103] Business Standard, 'Survey On Ground Water', *Business-Standard.Com*, 2014, online: http://www.business-standard.com/article/government-press-release/survey-on-ground-water-114121800709_1.html. [accessed: 12 March 2015].
[104] Archeological Survey of India (2014), p281.

the structural securing of the first two levels, level 1 and 2, within the 2016-17 period. Once these are in place any theoretical rehabilitation scenario would be supported by the structural stabilisation efforts that have been implemented.

The buffer zoned area around the property border falls within the conservation plan as well. Properties within the buffer zone are listed within the conservation plan, and it is of interest to note that of the 88 listed properties, only 5 are not of agricultural function, giving a 94% agricultural function within the surrounding buffer zone.[105] This is of significant relevance to the relationship between the natural environment, the monument and human consumption of groundwater within the local context of the site and further suggests the postulation of threat to the functional aspect of the heritage structure through over-exploitation of groundwater resources, largely induced through lack of management of groundwater within the buffer zone area.

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[105] Archeological Survey of India (2014), p308.

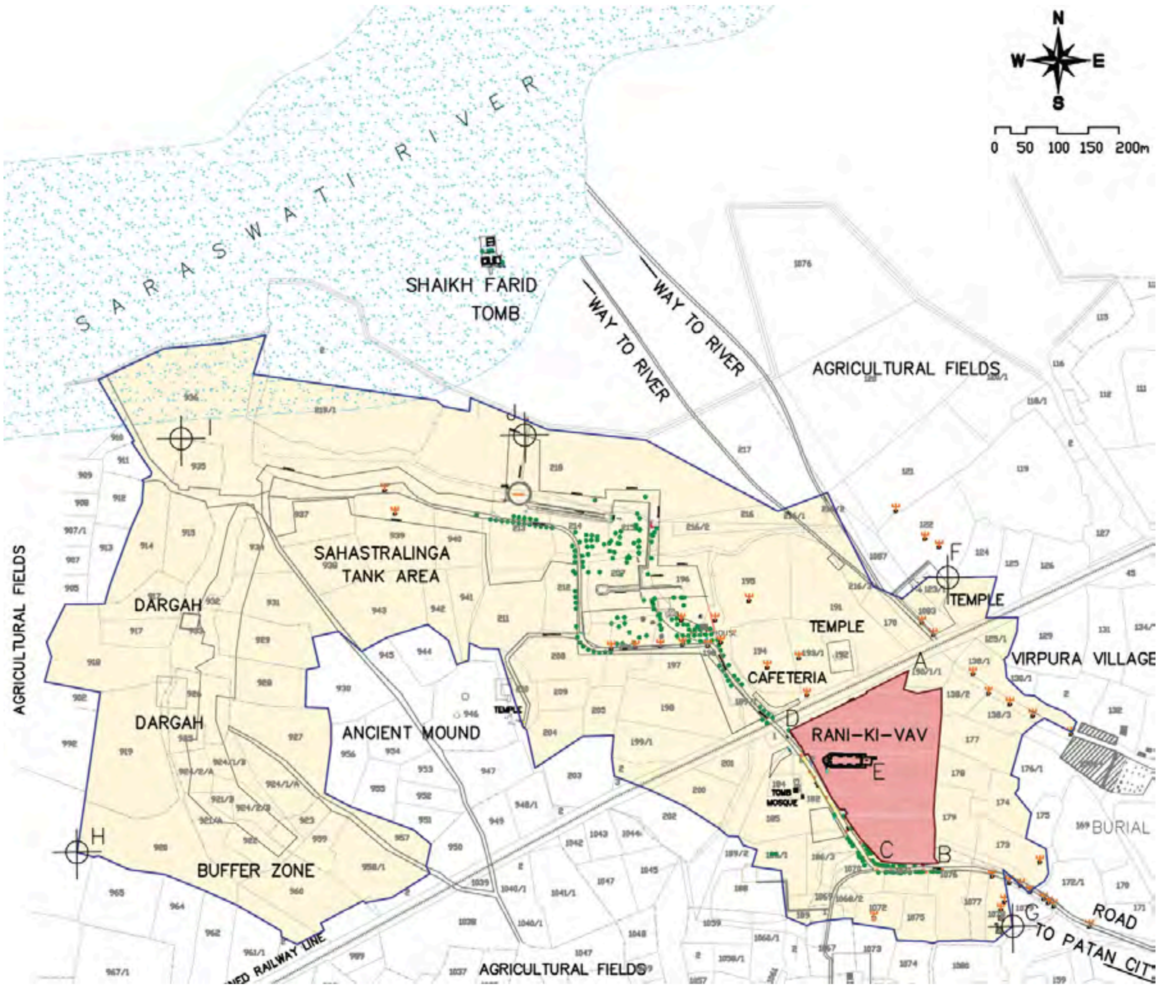


Figure 30 – Site Location and Surrounding Buffer-Zone (ASI, p82)

A summarised list of indicated stakeholders is as follows:

- **Government of India**
  - Archeological Survey of India (ASI)
- **Government of Gujarat**
  - District Administration, Patan
  - Tourism Corporation of Gujarat
  - Police
- **Non-Governmental**
  - Vir Maya Trust (Hindu Temple Management Body)
  - Jain Temple Trust (Jain Temple Management Body)
  - Fakir Sect Trust

- Shop Owners
- Pilgrims to Shaikh Farid Tomb and others
- Tourists (Domestic and International)
- Residents Community
- Academics
- Road and Building Department (State Highway)
- District Panchayat (Approach/Link Roads)
- Gram Panchayat (Village Roads/Pathways)

3.4. Groundwater Context: Rani ki Vav and surrounds

The Archeological Survey of India noted the following in their nomination dossier as submitted to UNESCO for World Heritage inscription, with regards to local groundwater utalisation and agricultural pressures:

"The Rani Ki Vav is surrounded by agricultural land (and) were farmed until recently (by) practicing traditional flood irrigation and non-mechanised farm machineries. The last decade has, however, witnessed groundwater management by the farmers and well-quipped agriculture practices, like drip irrigation and sprinkler irrigation, in addition to raising yield of cash crops, namely castor, cumin, mustard besides vegetables. Despite now 100 per cent utilization of the surrounding agricultural land as against 50 per cent in the last decade, and the resultant agricultural boost, the property has no imminent threat of encroachment"[106]

This statement is in direct contrast to contemporary outlook of the groundwater situation faced by the Gujarat area. Hitz, as mentioned earlier in this paper, discusses the critical condition of groundwater utalisation within the province.[107]

It is indicated that groundwater is currently being used at an unsustainable rate, and further usage in this manner will either result in the collapse of the providing aquifer systems, or in the salinisation of these systems making the provided water unusable for consumption.

[106] Archeological Survey of India (2014), p144.
[107] Hitz, J. (2011). *The Worsening Water Crisis in Gujarat, India – State of the Planet.* [online] Blogs.ei.columbia.edu. Available at: http://blogs.ei.columbia.edu/2011/01/18/the-worsening-water-crisis-in-gujarat-india/ [Accessed 5 Mar. 2015].

Snyder discusses the increased drop of the water-table in the area as indicative of this looming crisis, especially within the arid Gujarat area which is largely supported by groundwater supply.[108] The ASI report, in itself, indicates a drop in the water table to below 200m in 2013[109], which indicates a non-managed approach to groundwater utalisation in the surrounding area. This is of critical importance to the Rani ki Vav as a monument which finds its essential function in the access of groundwater resources. The relationship between the monument and the natural environment, through the access and utalisation of groundwater, forms an essential part of the essence of the monument, and this relationship should be seen as part of the heritage conservation effort. Should the local aquifer system collapse it will remain collapsed open-endedly, and is non-reversable, and forever sever the relationship between the monument and its functional aspect. As such, groundwater utalisation by surrounding farmlands plays an important role in conservation management of the monument.

3.5. Study Report

3.5.1. Overview

The Rani ki Vav is a UNESCO World Heritage site that is located on the outskirts of Patan, India. The closest business hub to this is Ahmedabad, which is roughly 138 km from the site and acted as a base during the research stay. The necessity and relevance of the stepwell typology becomes evident once in the Gujarat region during the summer months, where temperatures during the research stay were as high as 46 °C. It is within this context that the notion of cooler protected spaces becomes apparent and the protective notion of water conservation reveals its priority. That being said, the Rani ki Vav is currently a "dead" or static monument with no connection to its original function. The site serves primarily as an anchor for the surrounding garden spaces in its current context. Local patrons enjoy the well-kept garden spaces on hot summer days, and the stepwell serves as a recreational curiosity to most that visit the site, with focus lying almost squarely on the exquisite carvings to be enjoyed within the structure. The more sensitive conservation areas on the lower

[108] Snyder, S. (2015). *Water In Crisis - Spotlight India*. [online] The Water Project. Available at: http://thewaterproject.org/water-in-crisis-india [Accessed 5 Mar. 2015].
[109] Archeological Survey of India (2014), p137

levels, as one progresses towards the well-point, are restricted to the general public and roughly half of the structure is not accessible to visitors.

The emphasis on sculpture within the monument is clear during a visit to the site, and this is rightfully so as the detailing, conservation and beauty of these elements are nothing short of breathtaking. It is clear that the Rani ki Vav was inscribed as a World Heritage site through its artistic merit and in this regard the stepwell stands out among the many others in the area. With this in mind it should be noted that these stepwells represent not only artistic achievement but also feats of ingenuity and engineering genius. It is also to be noted that the Rani ki Vav, although unique in its delivery of artistic sculpture, does not accurately represent the entire array of stepwells to be found in the area, nor can it, as these alternative examples follow different layouts, sizes, locations and address a range of practical, religious and propagandistic functions throughout a wide timeline in history. The Rani ki Vav, therefore, becomes less of an ideal monument in terms of its representation of stepwells as a whole, but rather should be seen in its own unique and complicated regional and functional context.

The survey period took place during April 2015 and into May 2015. The Rani ki Vav was surveyed as a grid, with two profile lines being mapped on either side of the structure at 40m interval. Additionally, two points on either side of the structure intersecting the axis were taken in order to fully map the groundwater scenario as it relates to the structure itself. A typical equipment configuration was used for the survey, and terrain was primarily the short grass of the surrounding garden areas.

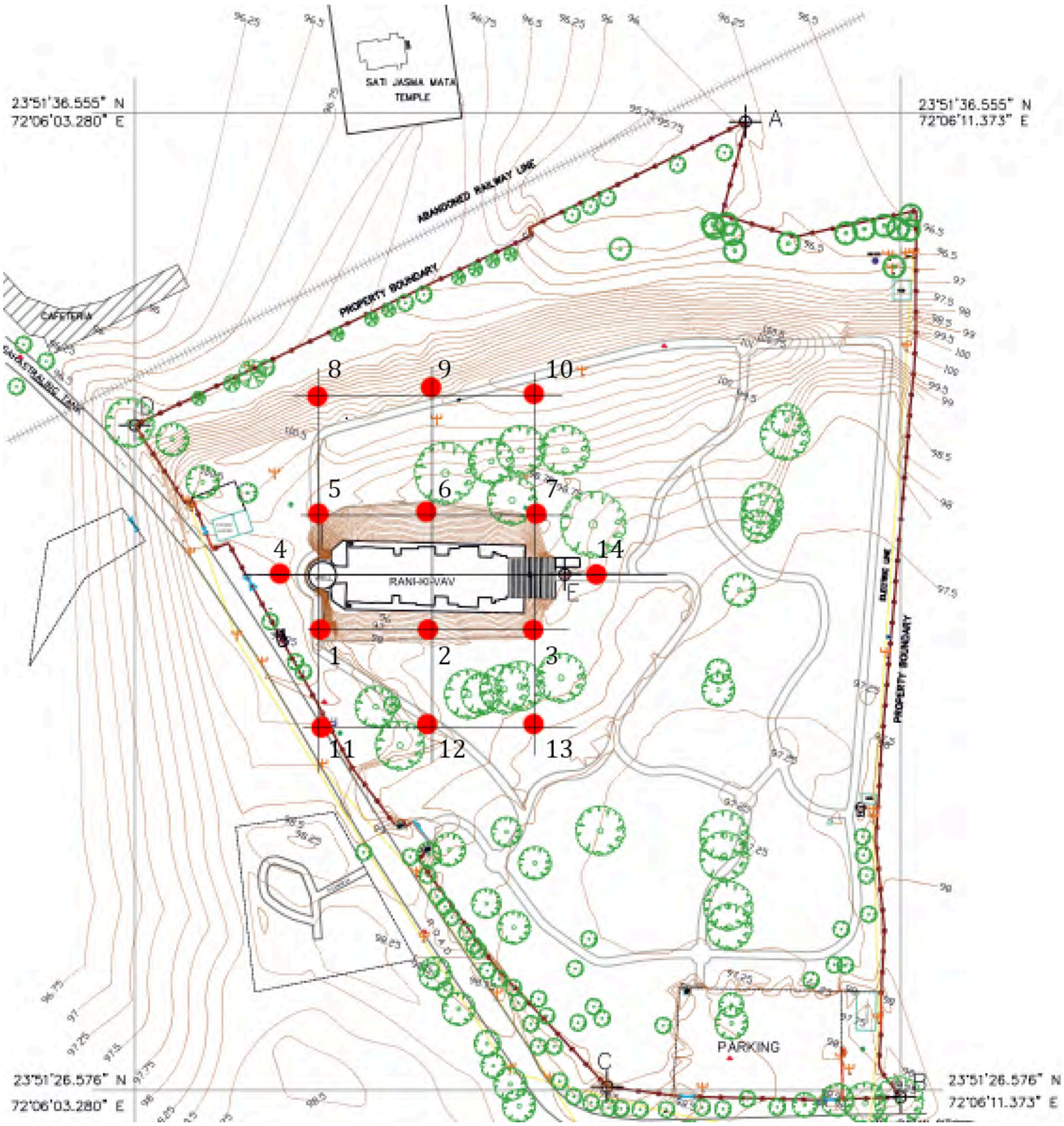


Figure 31 - Survey grid as planned on site (adapted by author)

The grid-mapping above indicates the layout of points completed during the survey and their related numbering. Geographically the points are listed as follows:

Point	Latitude	Longitude	Elevation (m)
1	23.85866882	72.10138605	82
2	23.85862917	72.10176365	82
3	23.85862014	72.10213456	82
4	23.85887402	72.10129234	82
5	23.85913504	72.10140926	82
6	23.85912375	72.10178358	81
7	23.85909967	72.10214225	81
8	23.85945016	72.10143151	82
9	23.85944859	72.10180285	81
10	23.85945099	72.10219441	81
11	23.85829414	72.10154555	82
12	23.85827267	72.10186854	82
13	23.85826932	72.10214735	82
14	23.85880189	72.10227379	82

3.5.2. Research Assumptions

The following assumptions are made when interpreting the acquired electroseismic data sets at the Rani ki Vav:

- The site geology at each survey point is assumed to be of similar seismic velocity parameters. This is not always the case as slight variations in geological formation density, porosity, compressibility and stratification are always present. This results in slight variations in the seismic velocity profiles between each unique sounding location even if the geology is similar. Statistically, these variations can be up to 25%

of the base velocity model for the site.[110] As such, any interpretation of the depth estimates for ES responses must account and compensate for these potential depth estimate variations. In most cases, the unique seismic velocity profile for each survey point generally can not be fully known, a general seismic velocity model is applied to all the survey points in a project. This may produce some variations in the interpreted depth of the resultant responses.

- Even though the vertical resolution of an electroseismic sounding is relatively high, with samples being taken every 8 to 12 cm on the velocity model used, it is important to note that a great deal of raw resolution is lost during the processing of the data. This is due to filtering and smoothing constraints applied to the data sets. As such, it is not practically possible to accurately delineate geological features thinner than 1m in thickness.
- Electroseismic data sets for 2D and 3D interpretations rely heavily on interpolation to describe the correlation between geological and hydrological features. As interpolation parameters are set to default values that assumes that the geological setting of any particular site is mostly stratified in a horizontal or near horizontal plain, these interpolation strategies should always be considered when interpreting complex geologies.
- In the case of un-calibrated hydrological data interpretations, it must be understood that all electroseismic hydrological data is subjective and relative to the maximum recorded electroseismic response values. These data sets must be considered with reference to the geological setup of the site. For example, a low permeability formation such as a granite generally does not host high permeability, or hydraulic conductivity, aquifers. There may be slight variations in the hydraulic conductivity or permeability in the makeup of such geologies. However, a relative electroseismic interpretation of such a geology may be misinterpreted as a high permeability aquifer. The best way to avoid these misinterpretations is to calibrate the model to the hydrological parameters of a known well that resides within the same geology as the survey site.
- Electroseismic methods cannot predict the groundwater yield that an interpreted

[110] André Revil et al., 2015. *The Seismoelectric Method*. Wiley Blackwell. West Sussex.

aquifer will produce. Any estimates of groundwater flow potential, discussed in this study report, is merely an indicator of where the best interpreted location is for groundwater flow. Electroseismic data cannot currently determine the porosity of a formation.

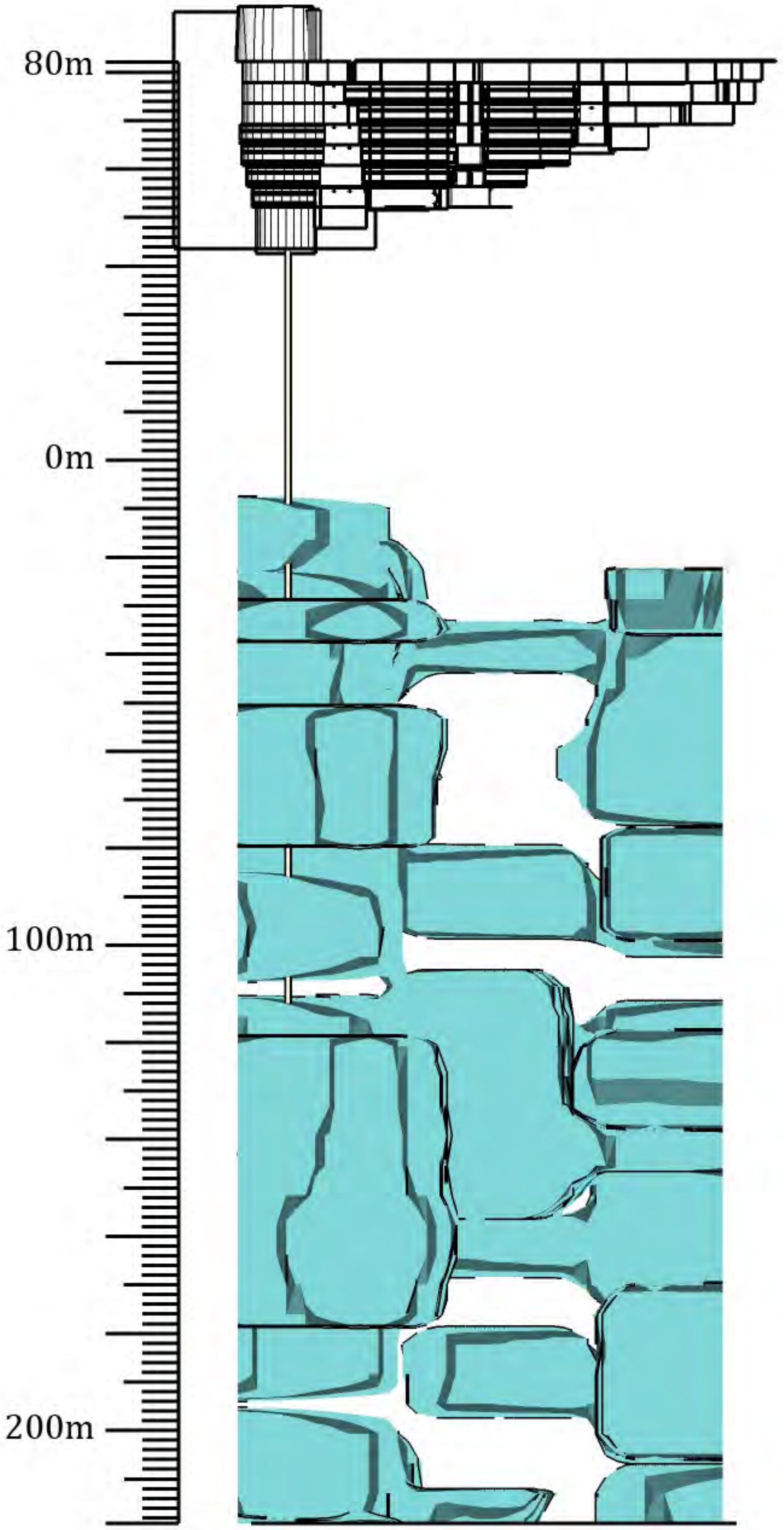
- The electroseismic processing and interpretation workflow assumes that the data collected in the field was done on surface soil and sediment conditions of similar characteristics. It assumes that the site soil conditions are uniform in moisture content, electrical conductivity and soil composition. It is also assumed that the electroseismic electrode placement and recorder settings were conducted in exactly the same manner for each sounding and that noise sources were removed as far as possible. The seismic source energy is also assumed to be consistent in strength, for every seismic event generated to produce a recorded electroseismic conversion.
- Electroseismic methods can not differentiate between fully and partially saturated aquifers. As such, electroseismic methods cannot determine if an aquifer has been partially dewatered or if an aquifer is fully saturated. Even if an aquifer has been depleted, there is still water within the aquifer which allows an Electro-seismic conversion to take place which describes the permeability of the aquifer and the pore space fluid characteristics. However, it will not indicate whether the aquifer is productive or not. With this in mind, all aquifers delineated by electroseismic methods are assumed to be fully saturated and capable of yielding groundwater.

Data is shown in industry standard Universal Transverse Mercator (UTM) conformal projection, which uses a 2-dimensional Cartesian coordinate system to give locations on the surface of the Earth. Elevation data is shown in 'meters above sea-level' (masl) standard format.

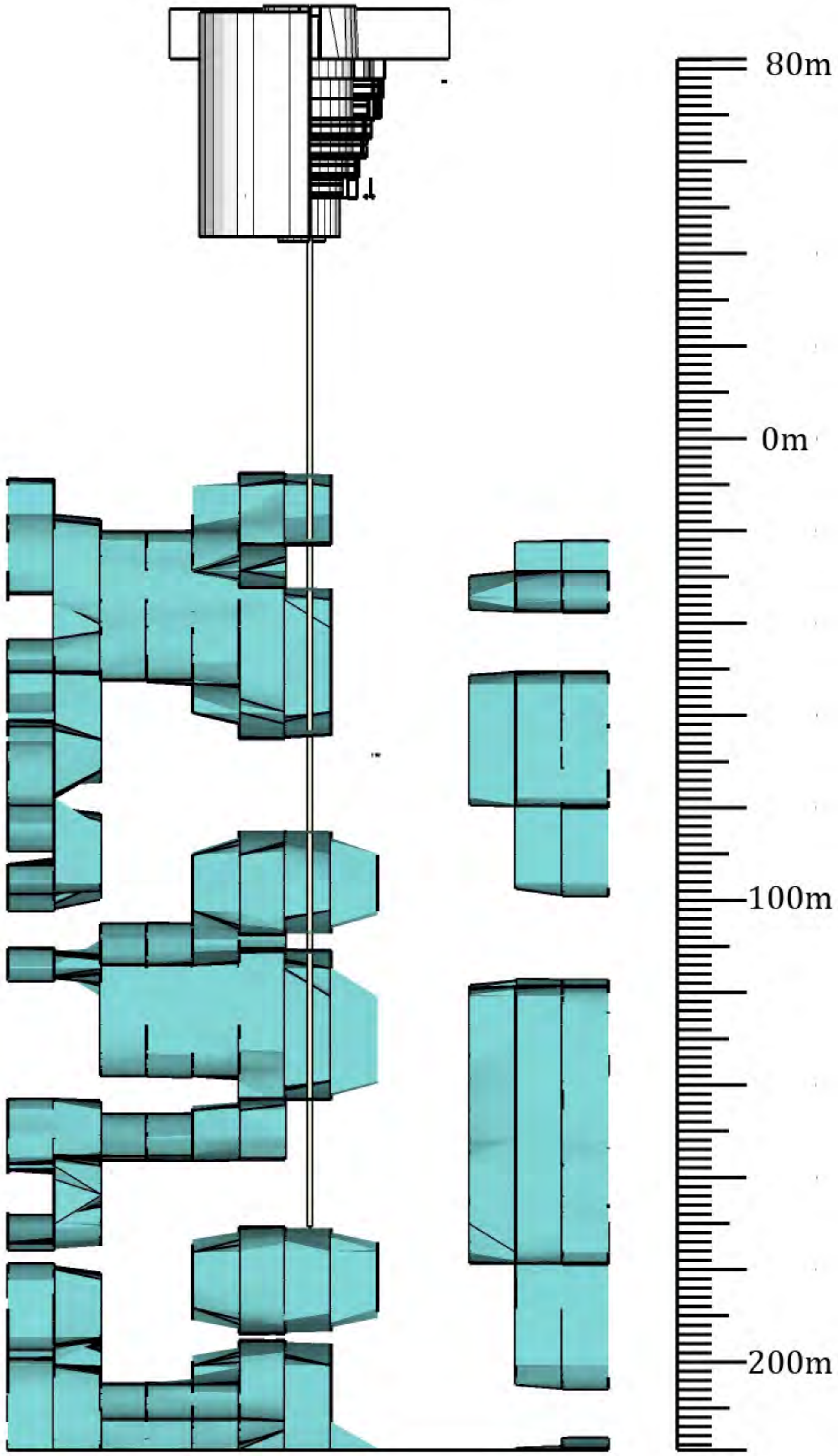
3.5.3. Signal-to-Noise Ratio (SNR)

Signal-to-noise ratio (SNR) is a measure that compares the level of a desired signal to the level of background noise. It is defined as the ratio of signal power to the noise power.

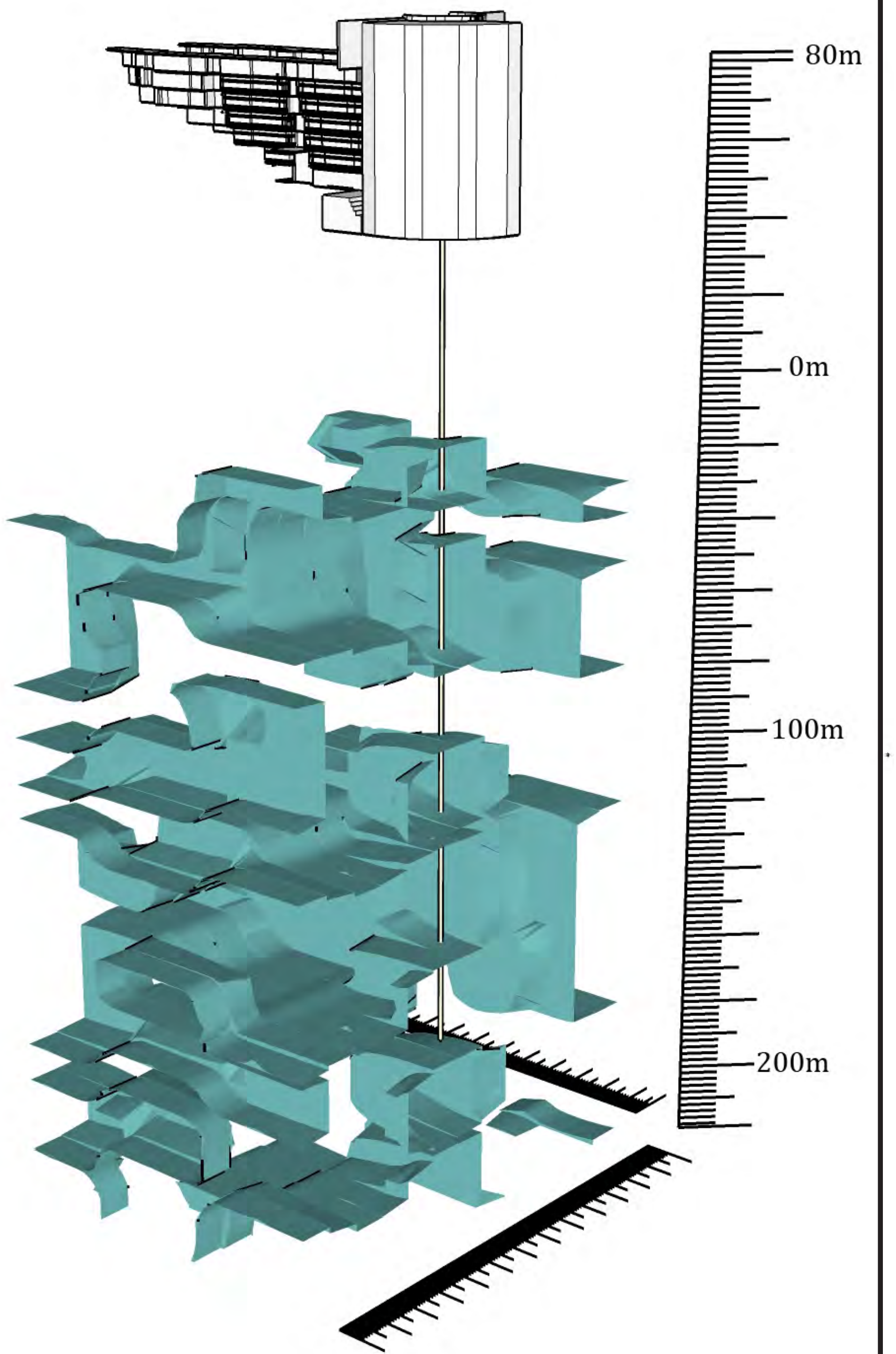
The signal to noise ratio for each sounding data set is calculated by summing the peak power of the individual detected seismic source induced electroseismic responses in volts, which have been selected by the correlation algorithms for use in the stack. This value is then divided by the number of used strikes to determine the average electroseismic response peak value. The noise floor is then determined by the summation of the frequency domain data divided by the number of frequency bins used. The Signal-to-noise ratio is then calculated by dividing the Average peak electroseismic response data by the calculated average noise floor level. SNR equates to a measurement of survey-quality and relating data risk on a given site-survey. For the Rani ki Vav the full-survey average signal to noise ration was calculated at 1431.65812. This indicates a ratio of 1:1431 and shows a minimal noise result for the site survey. The remote nature of the site location plays a large part in the low noise levels enjoyed within this case study.



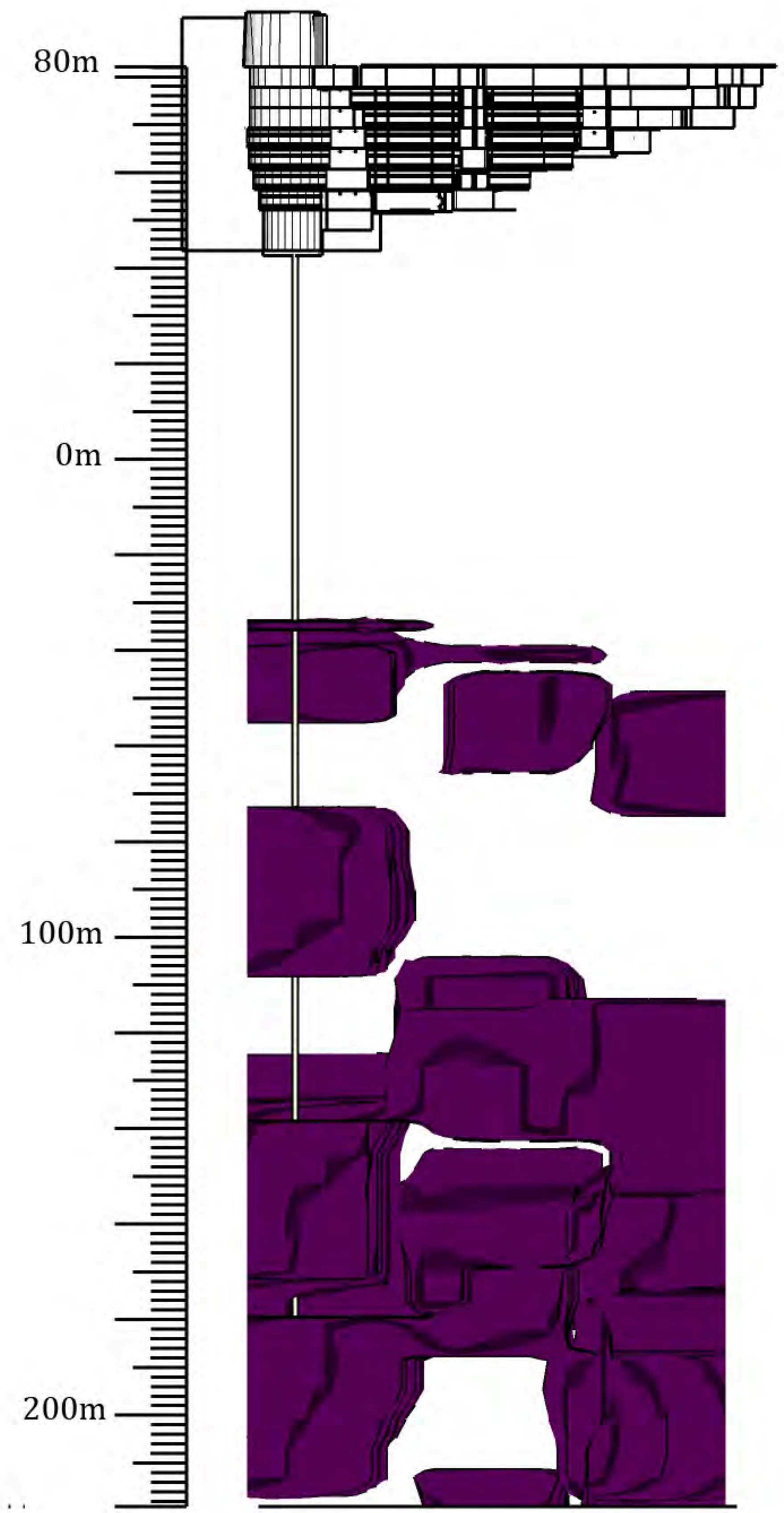
View 1 - Northern Elevation



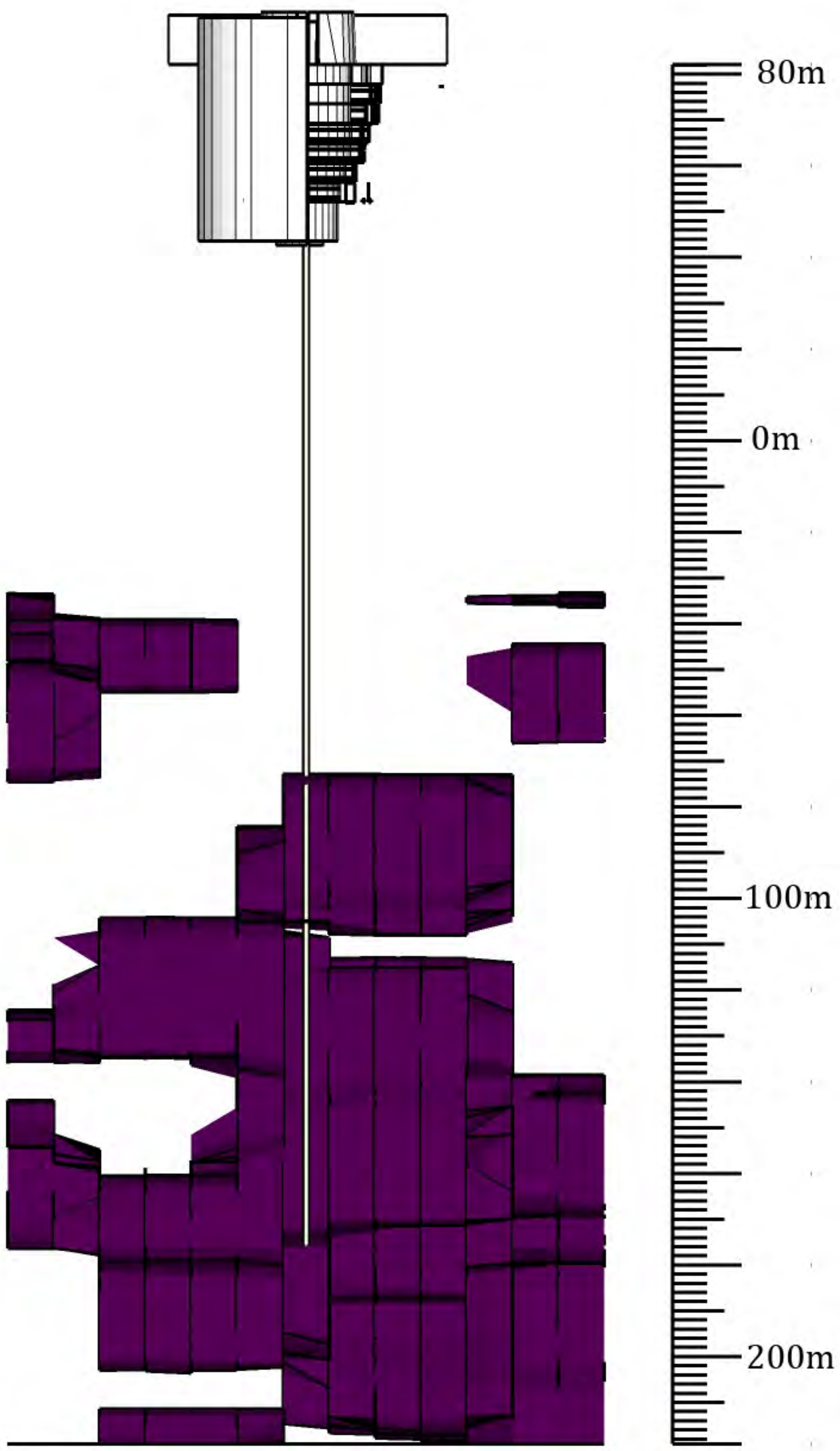
View 1 - Eastern Elevation



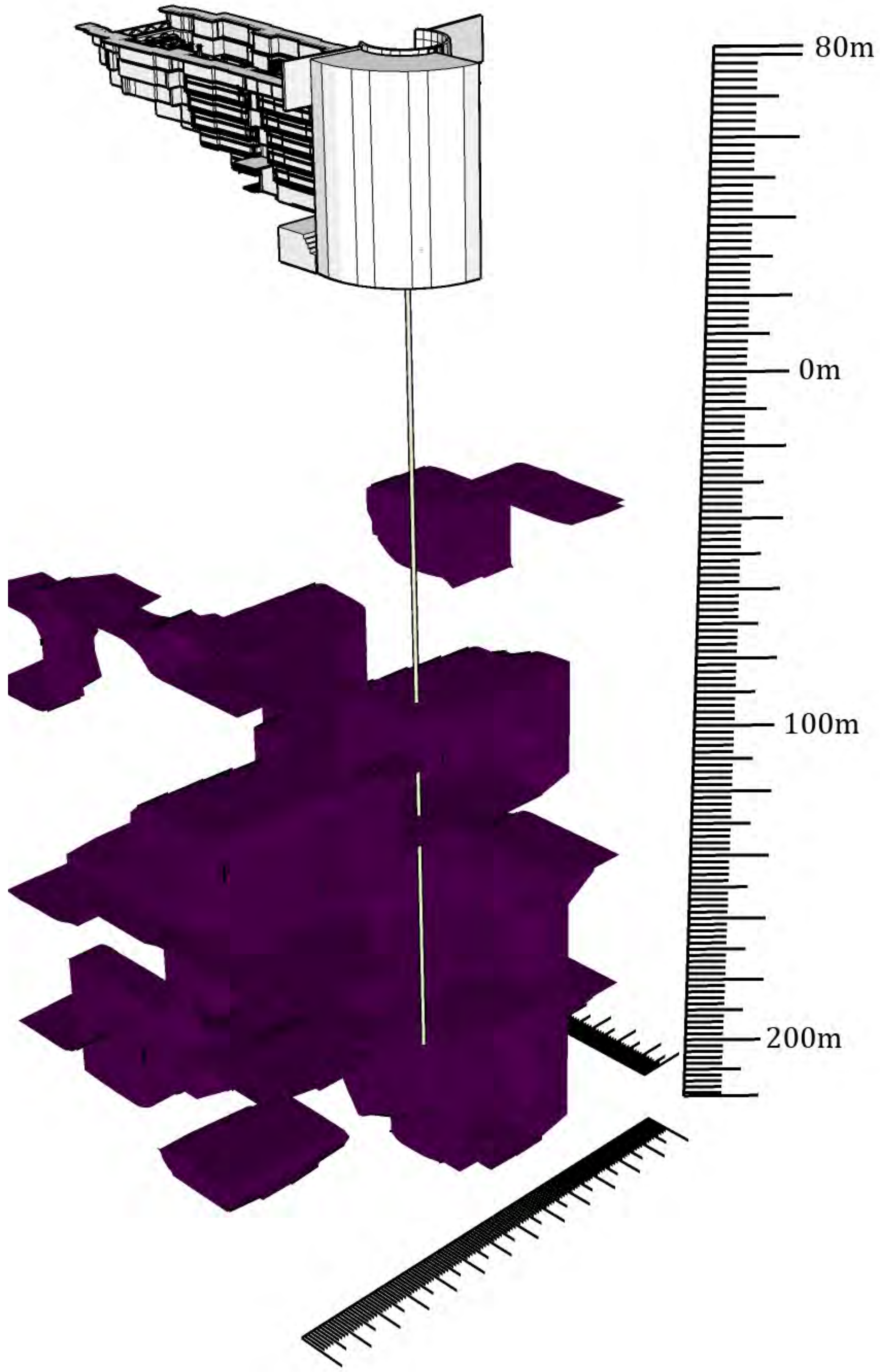
View 1 - Spatial Relationship



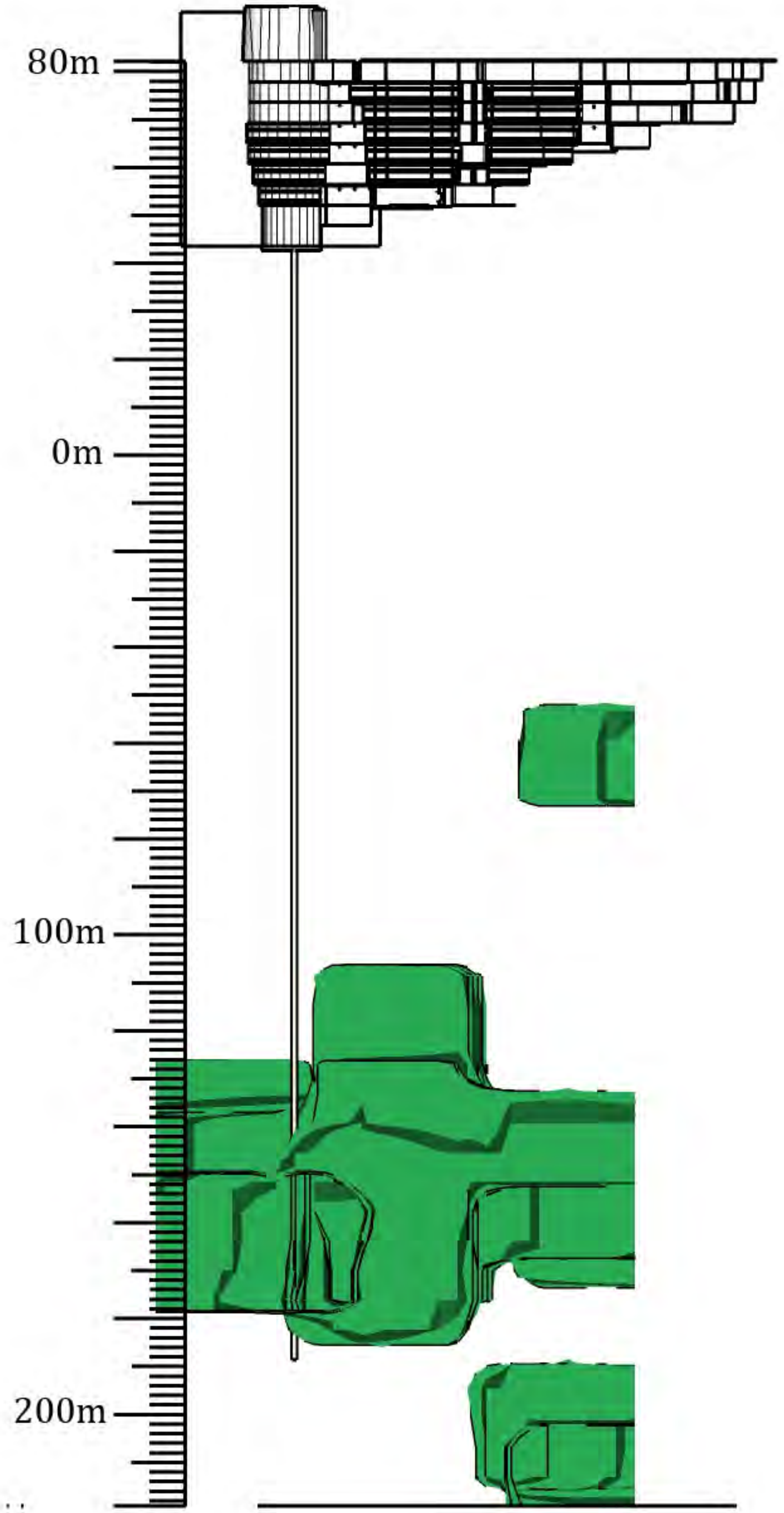
View 2 - Northern Elevation



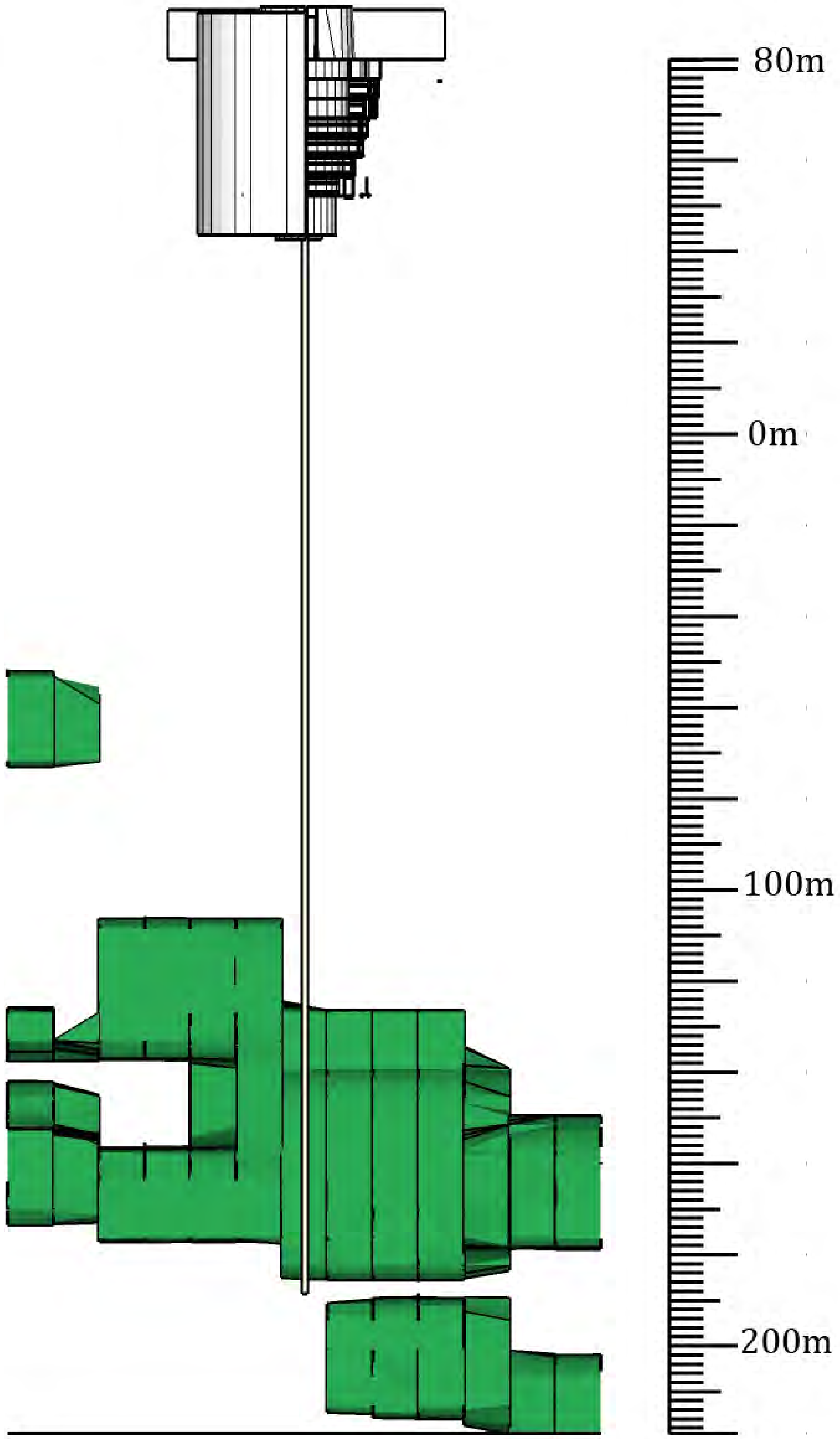
View 2 - Eastern Elevation



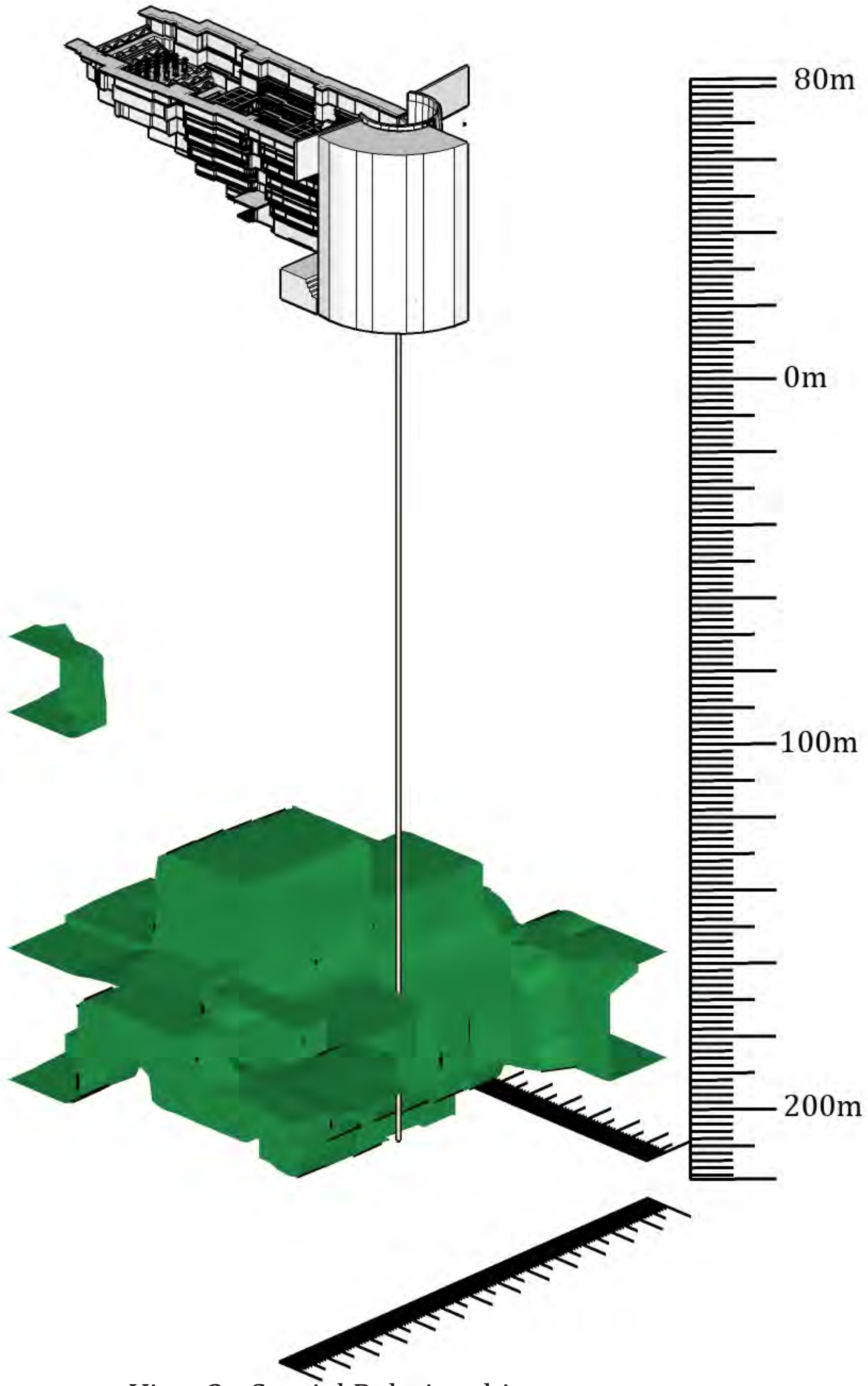
View 2 - Spatial Relationship



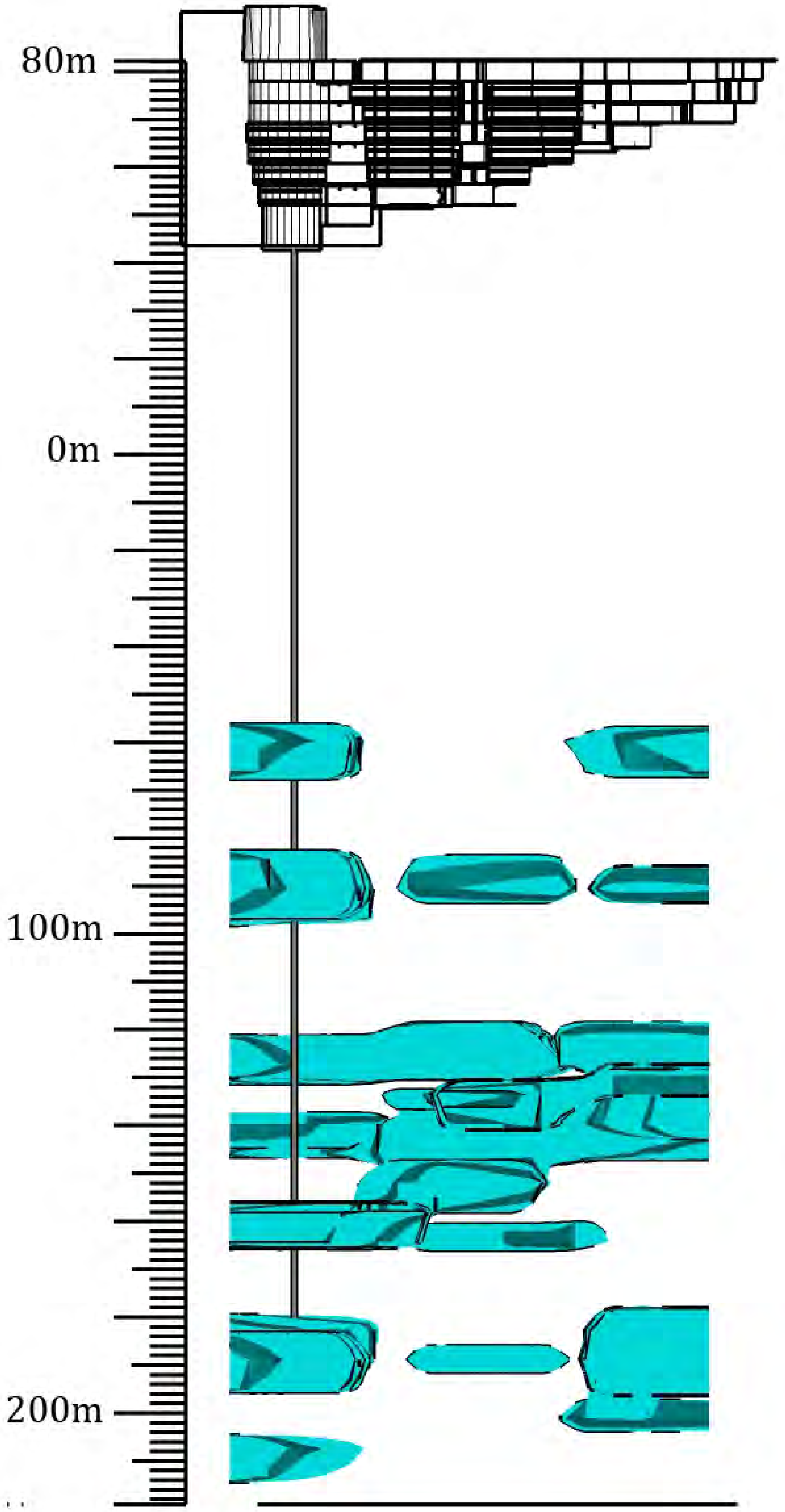
View 3 - Northern Elevation



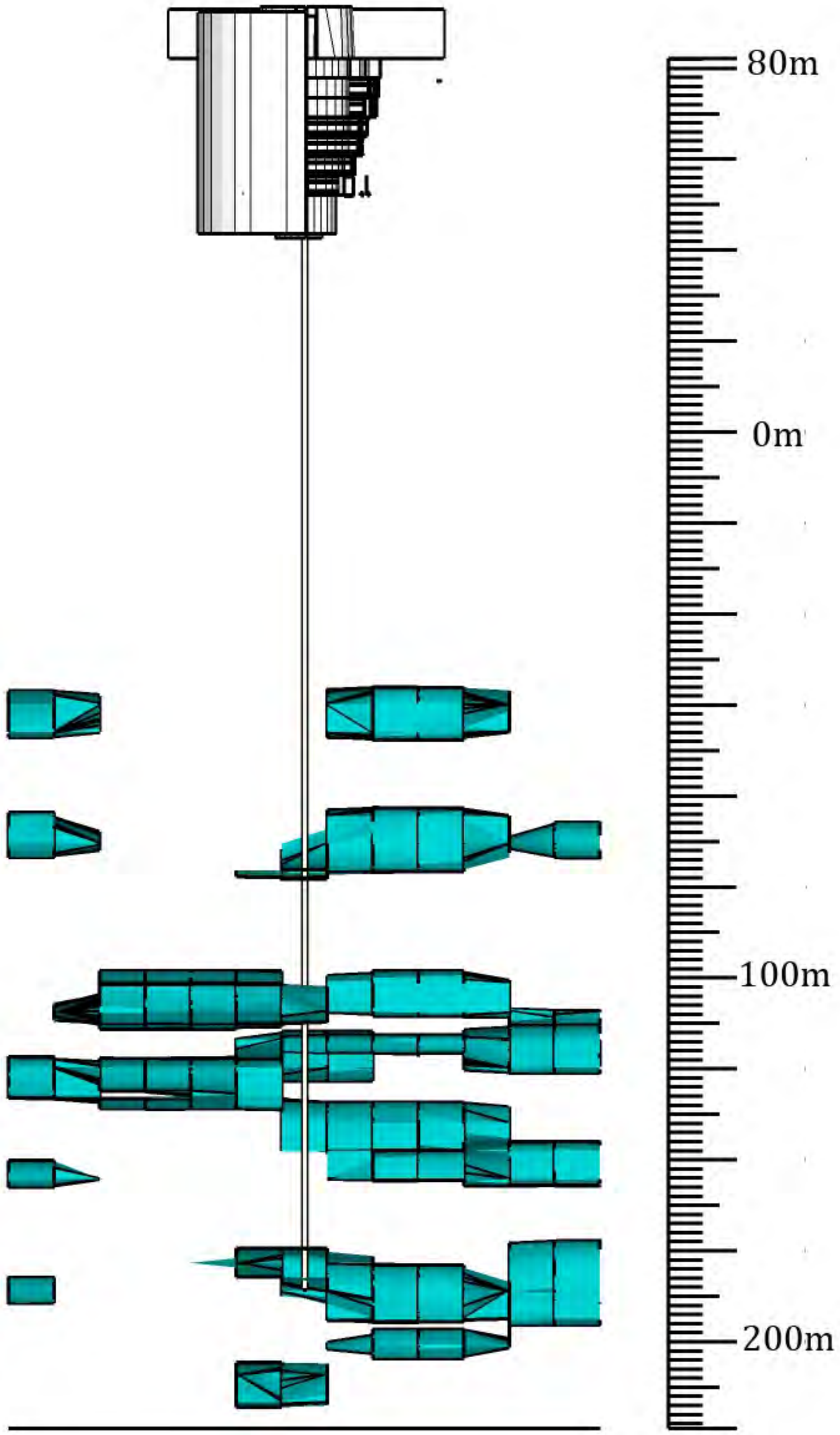
View 3 - Eastern Elevation



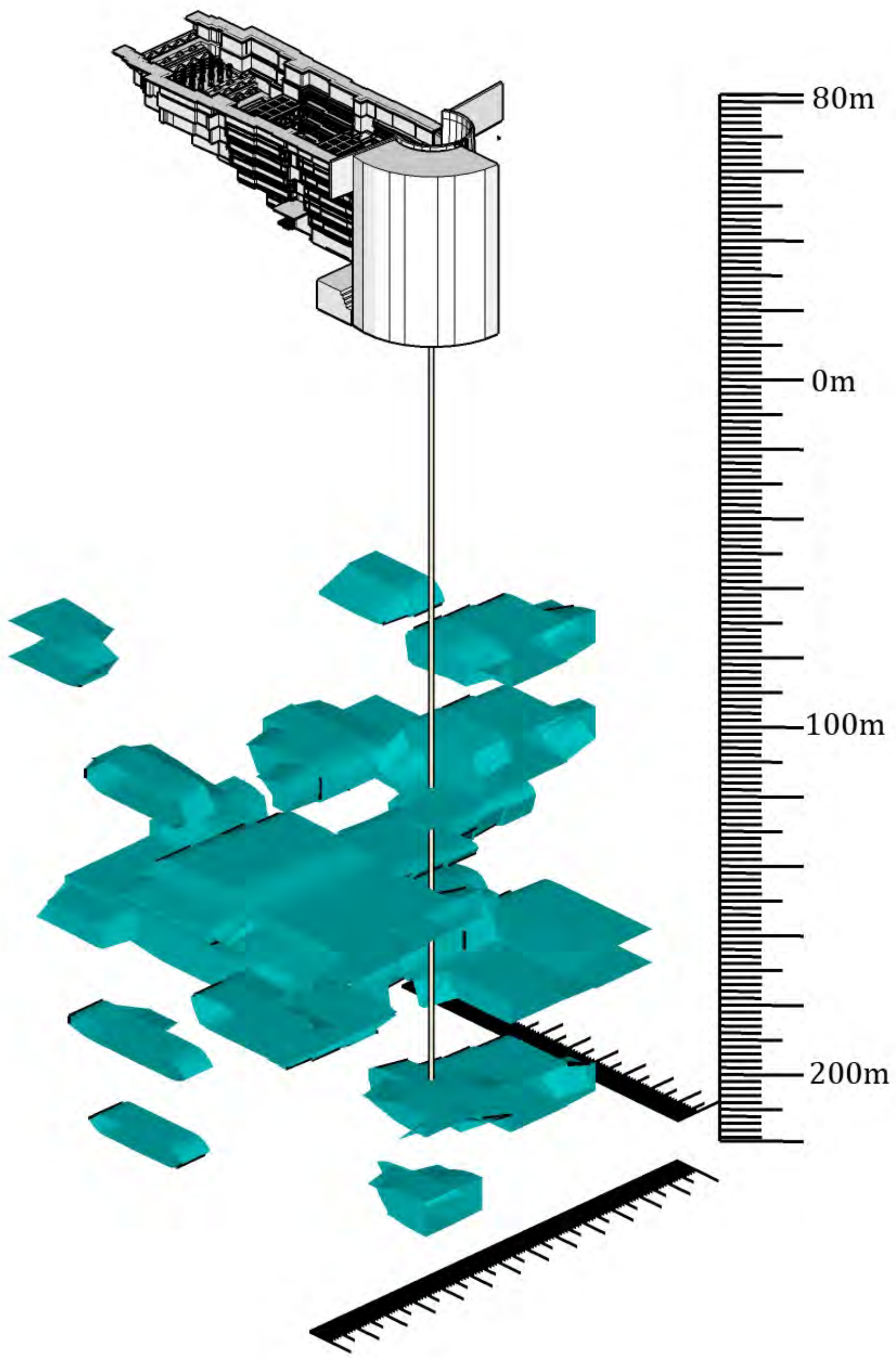
View 3 - Spatial Relationship



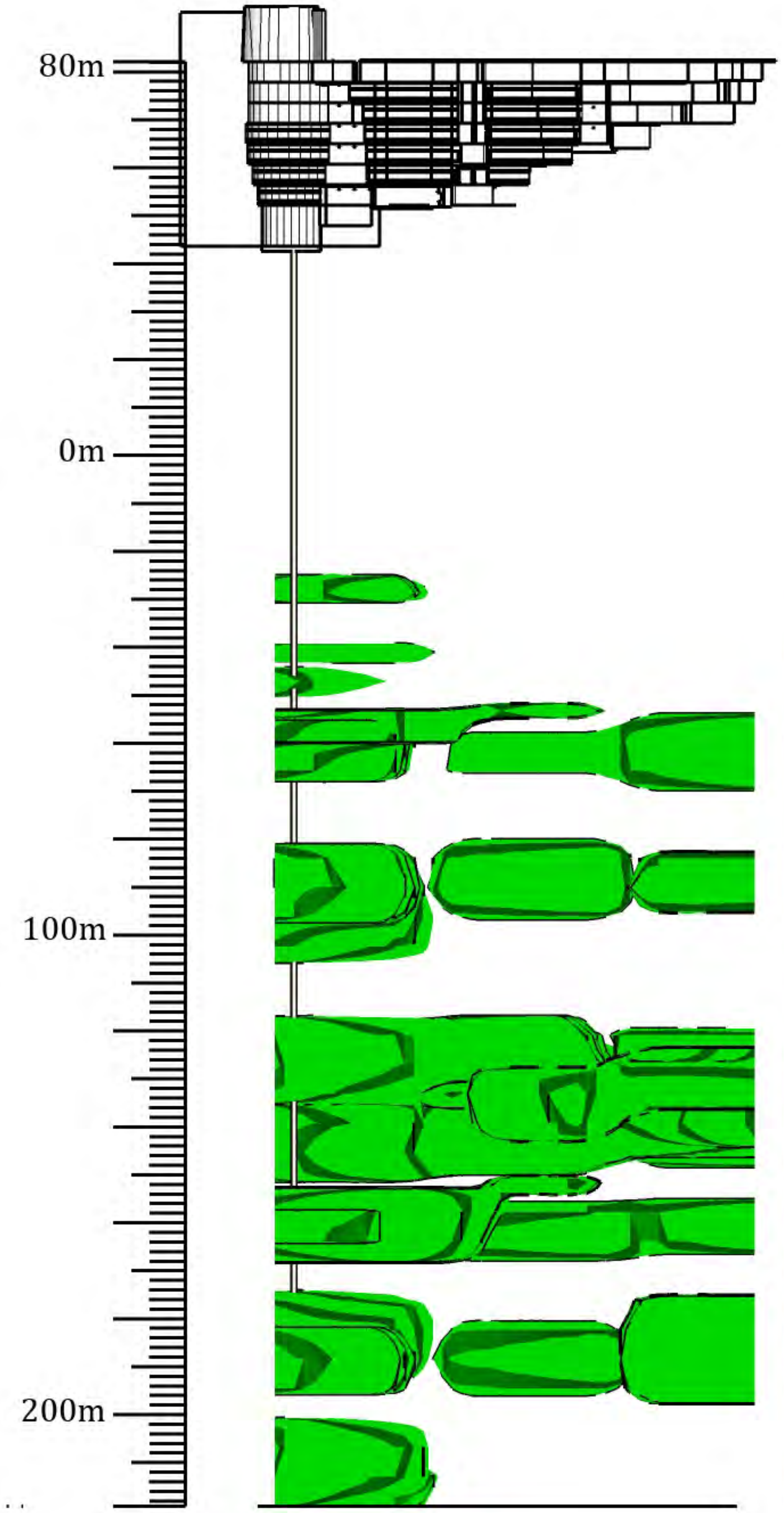
View 4 - Northern Elevation



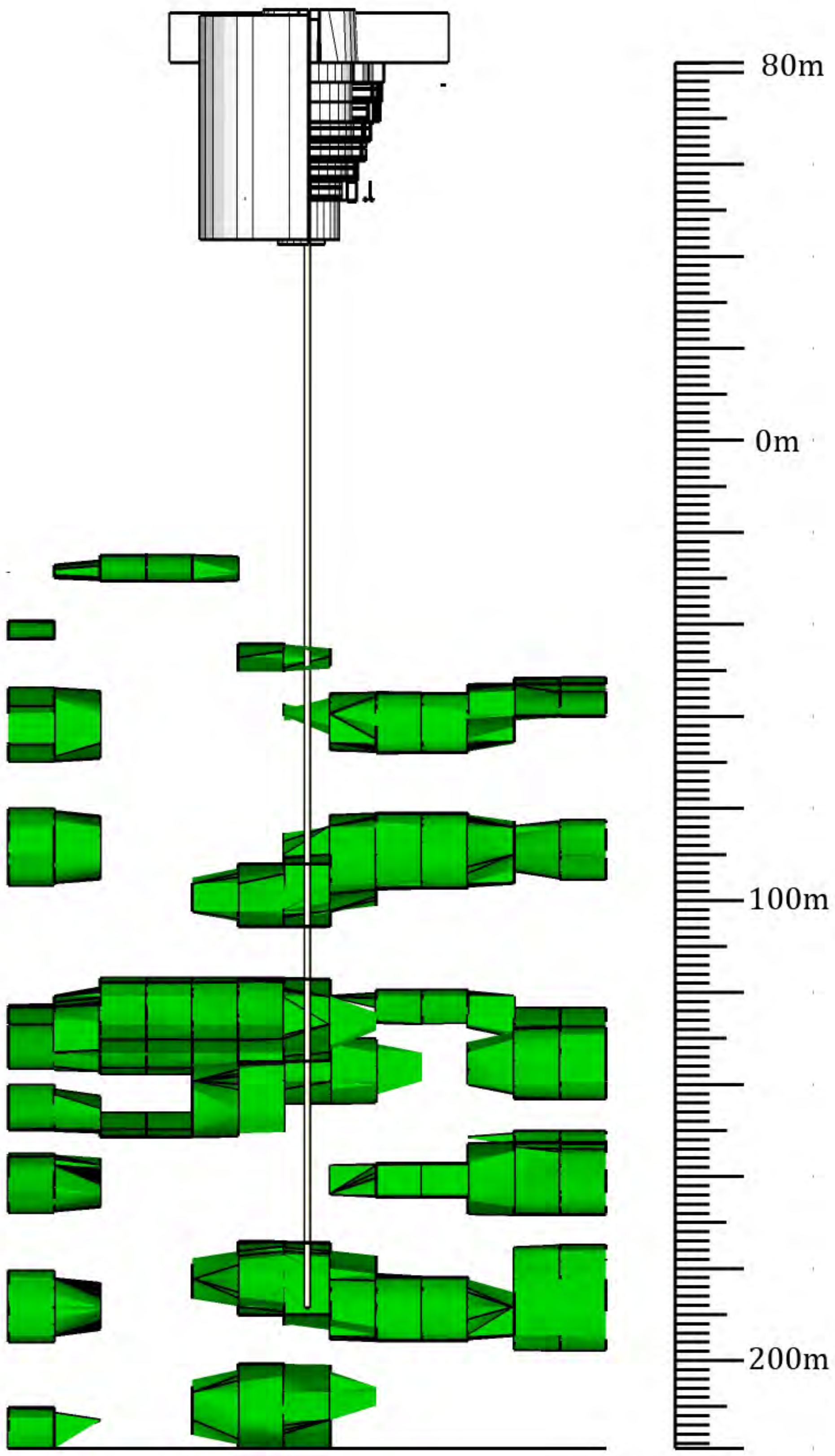
View 4 - Eastern Elevation



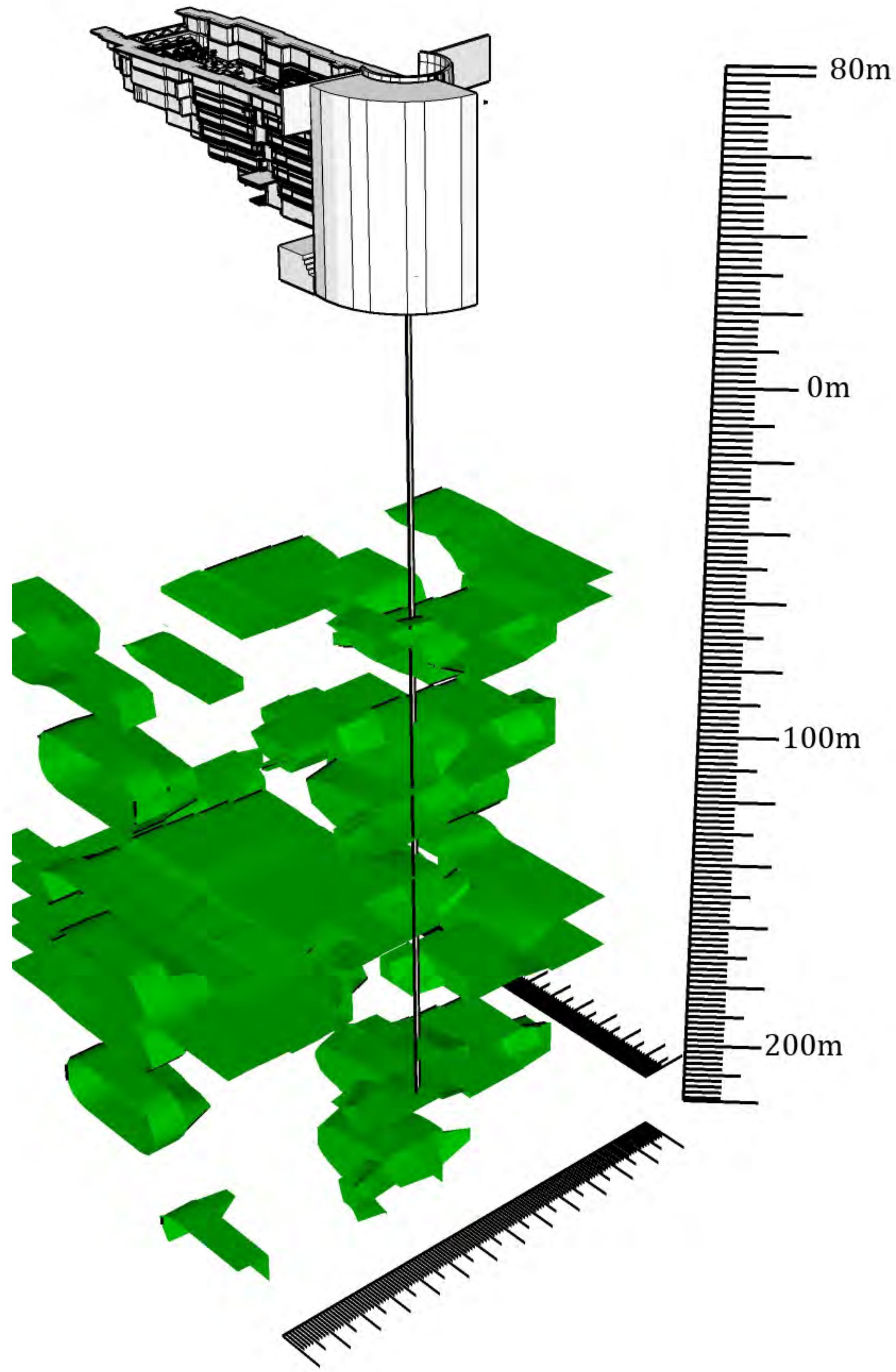
View 4 - Spatial Relationship



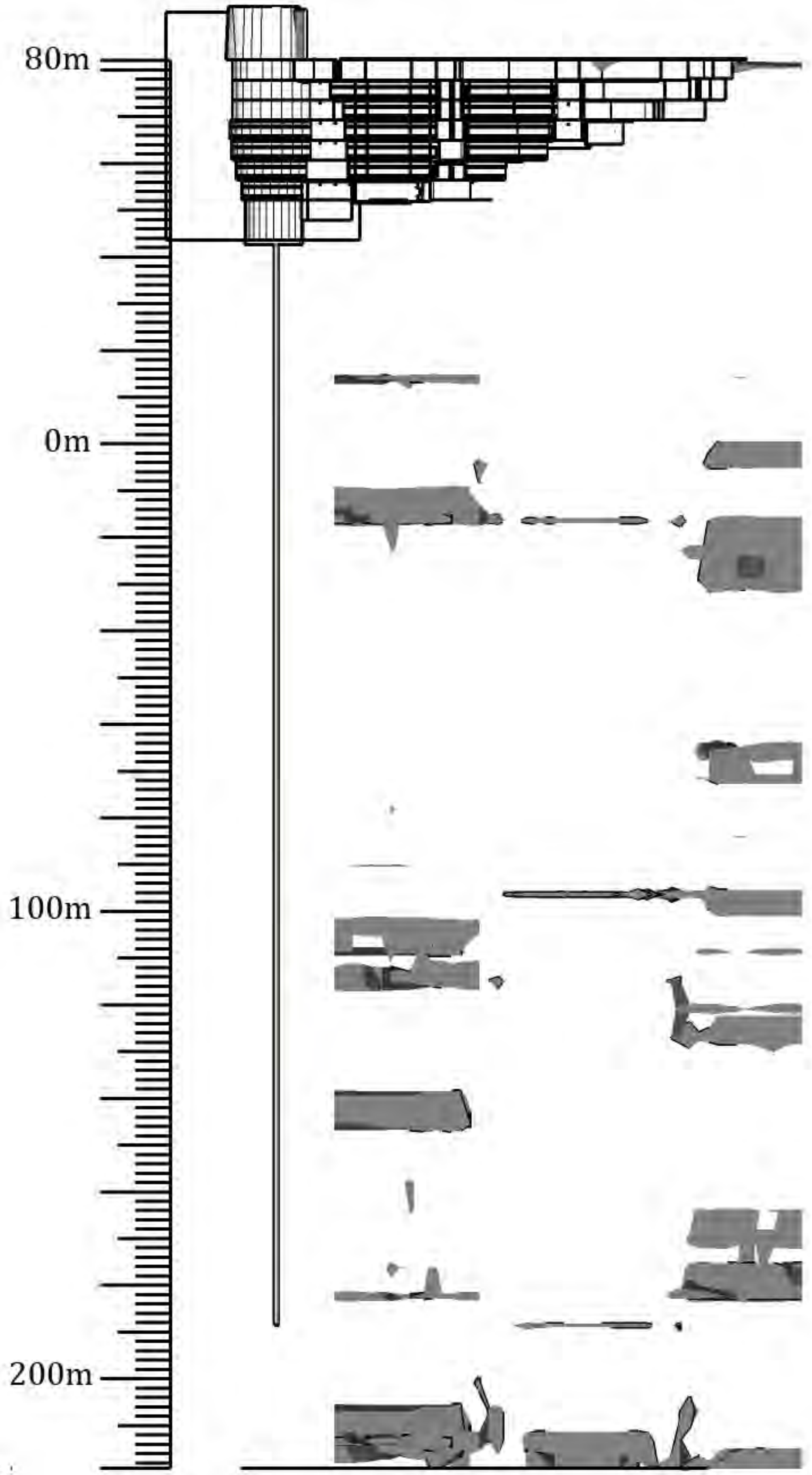
View 5 - Northern Elevation



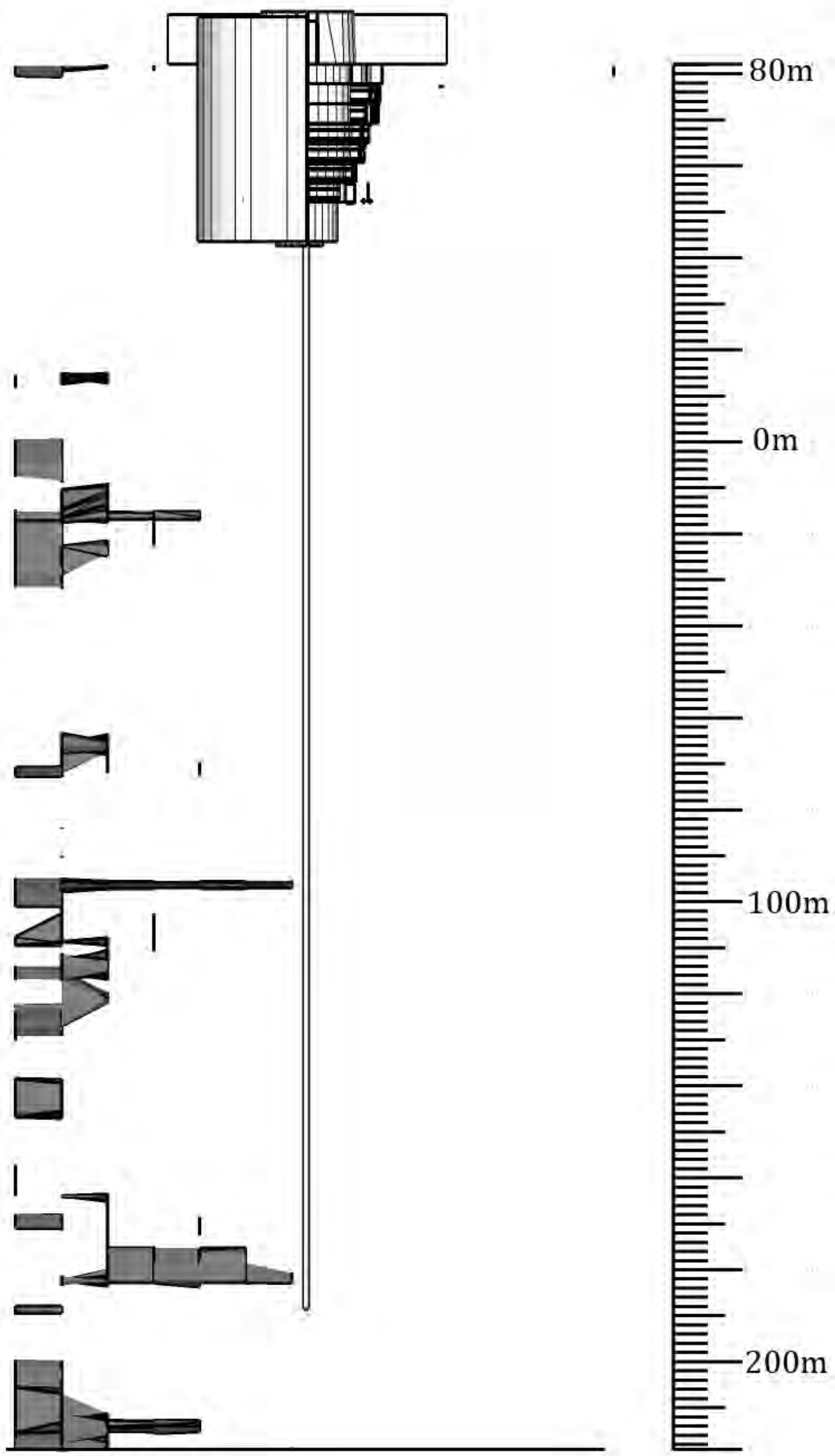
View 5 - Eastern Elevation



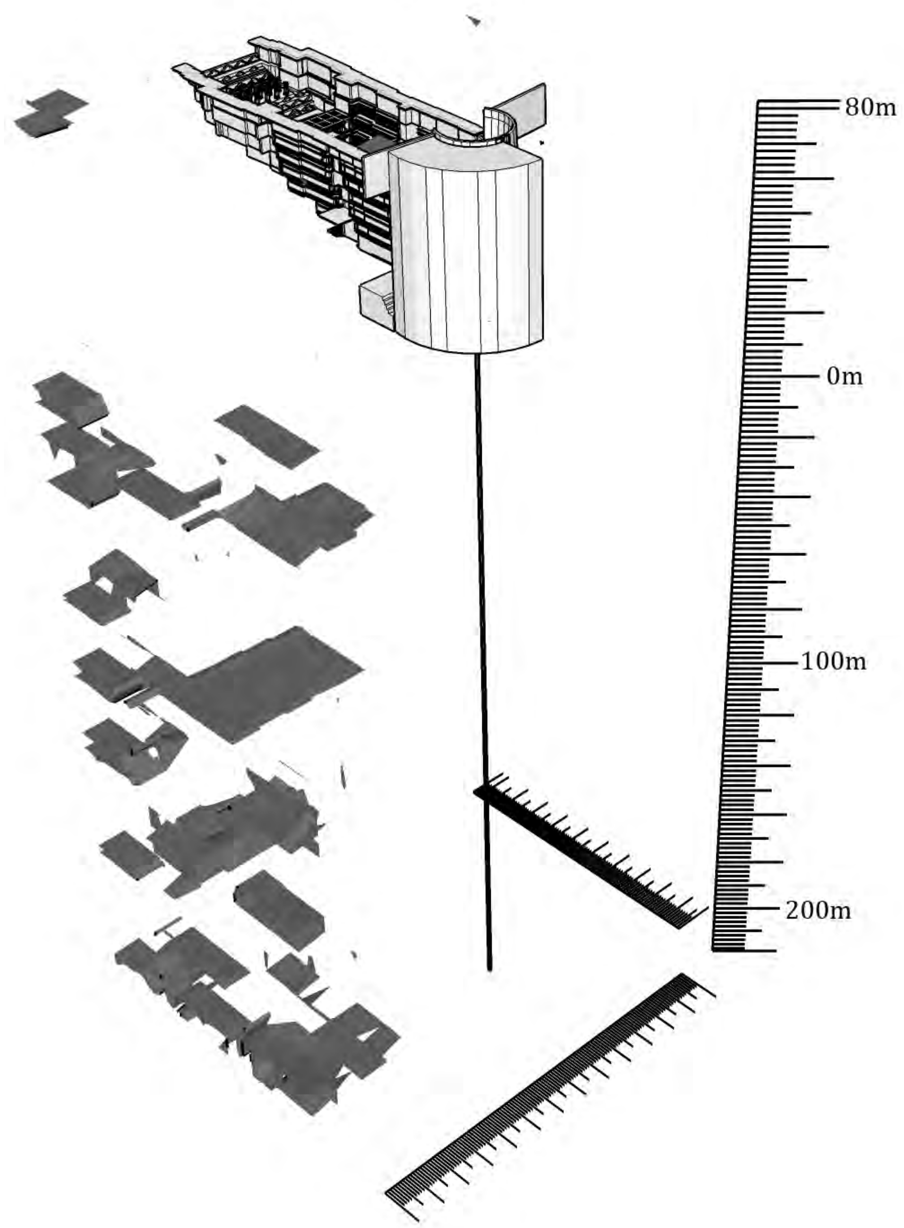
View 5 - Spatial Relationship



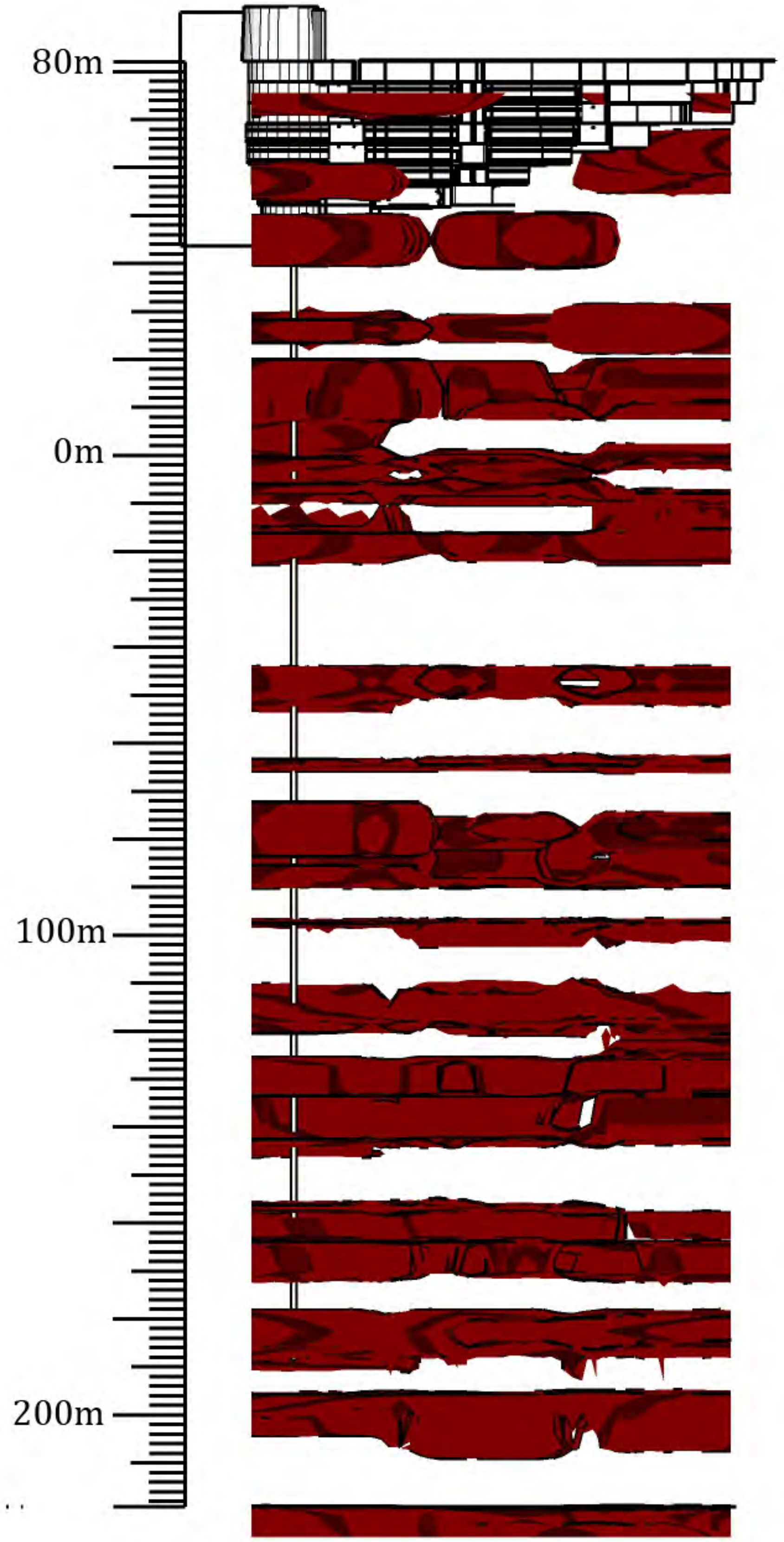
View 6 - Northern Elevation



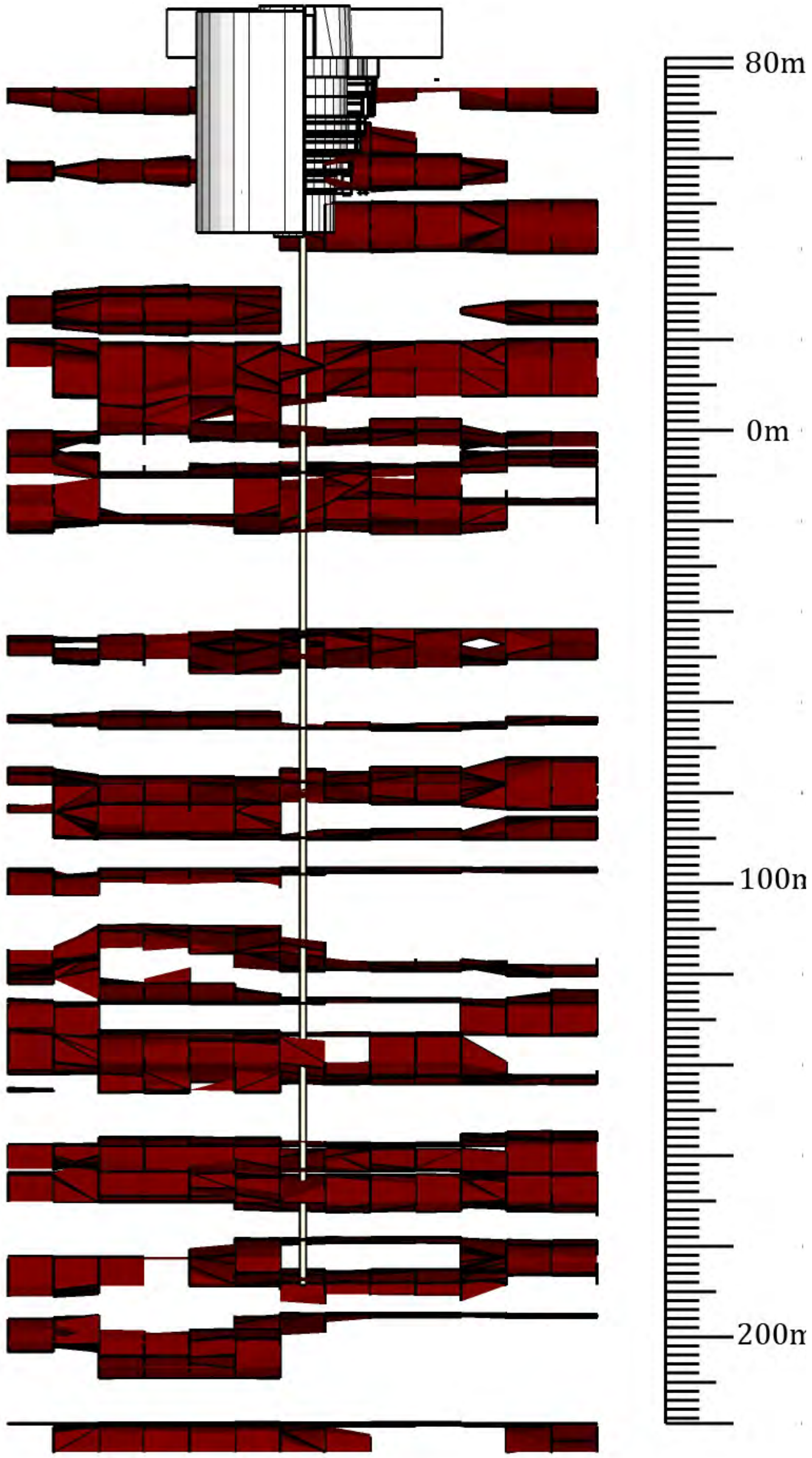
View 6 - Eastern Elevation



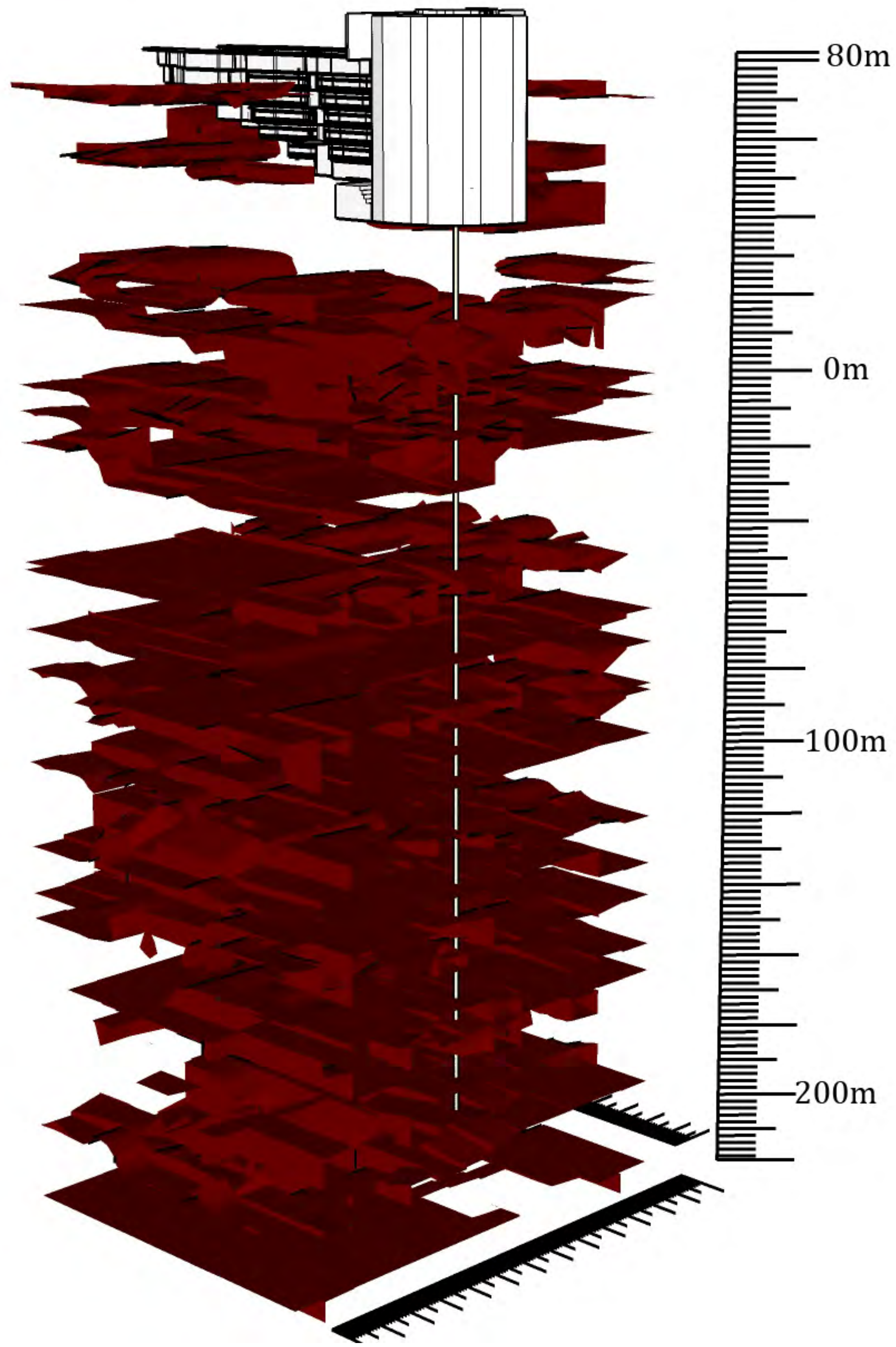
View 6 - Spatial Relationship



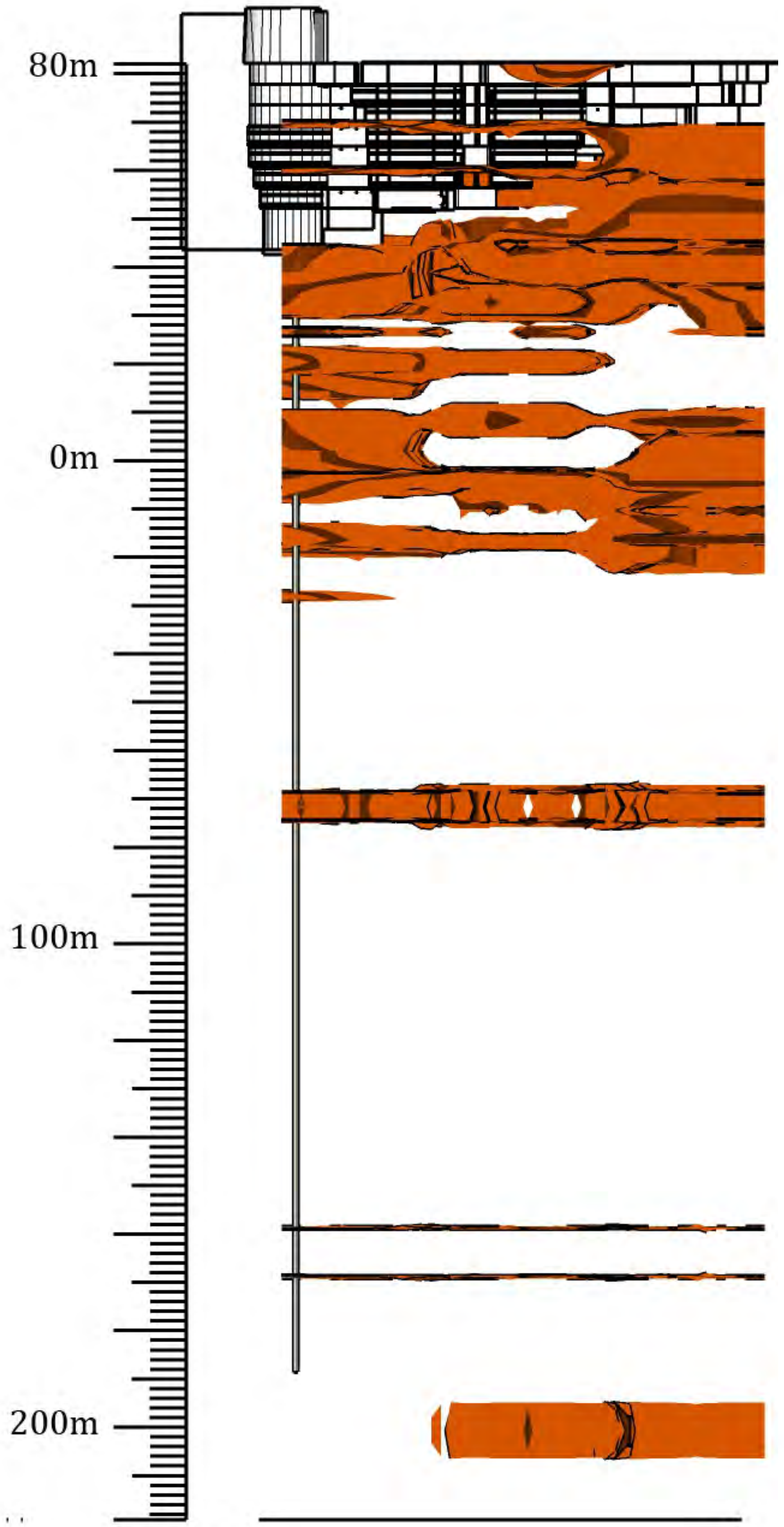
View 7 - Northern Elevation



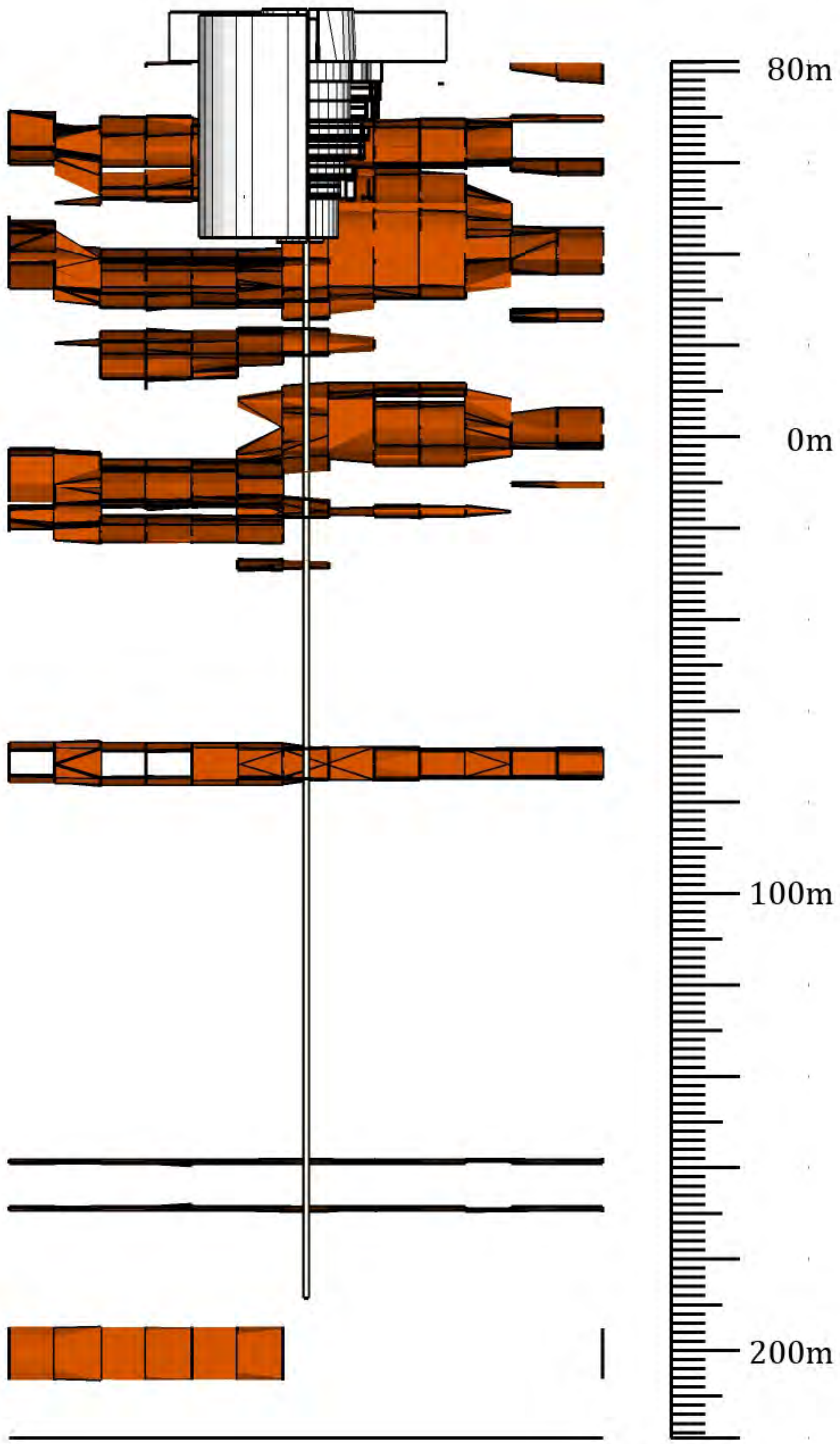
View 7 - Eastern Elevation



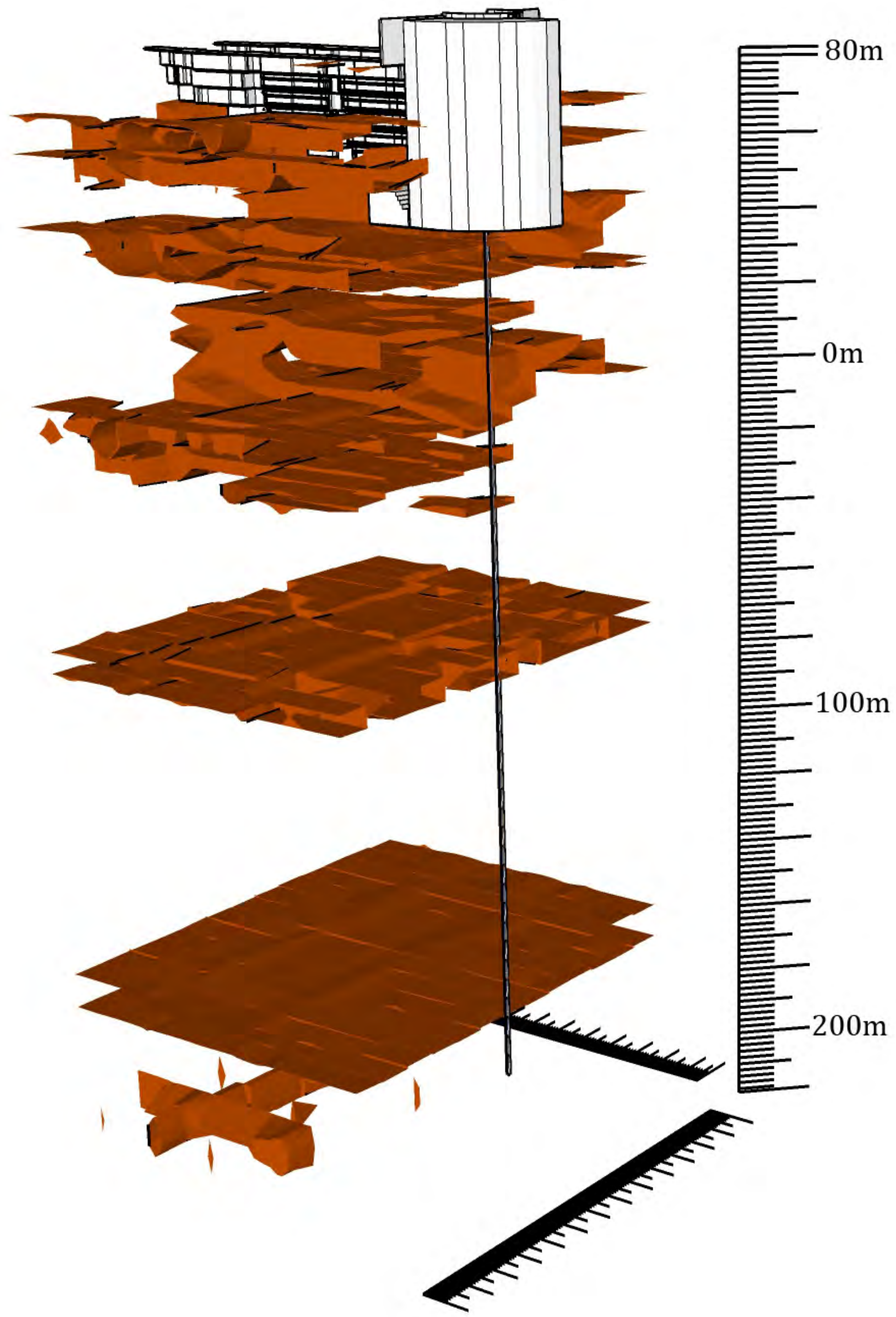
View 7 - Spatial Relationship



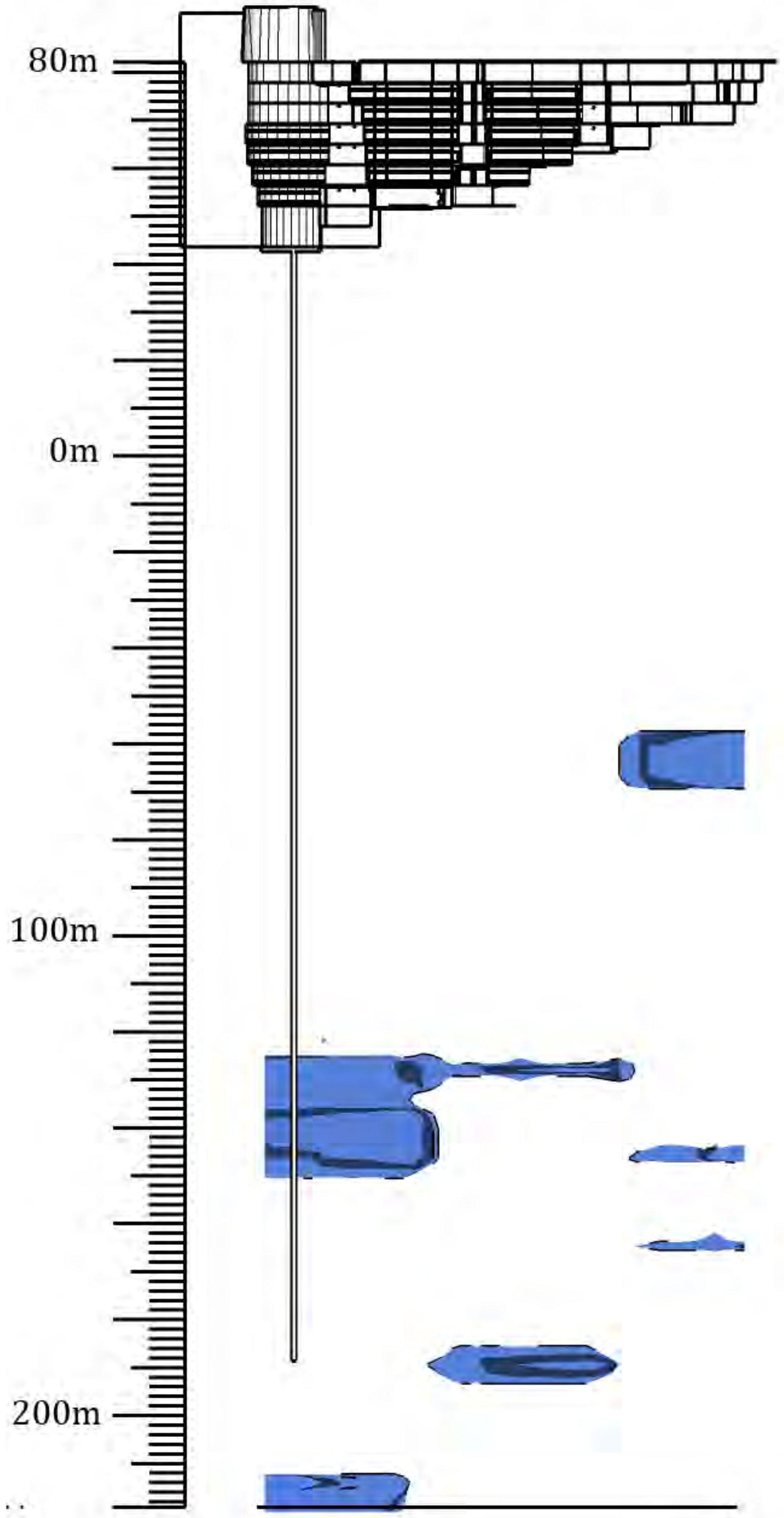
View 8 - Northern Elevation



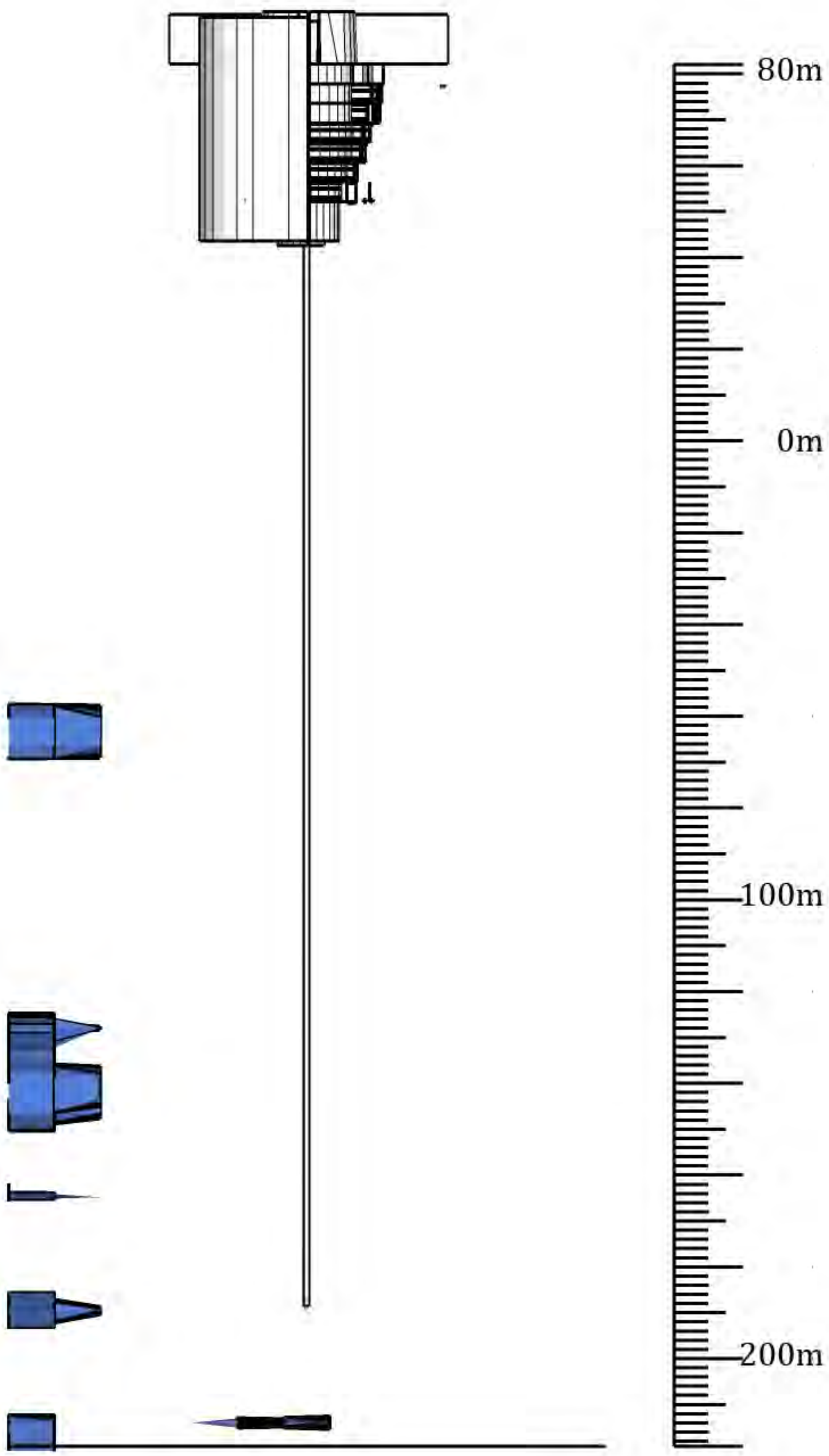
View 8 - Eastern Elevation



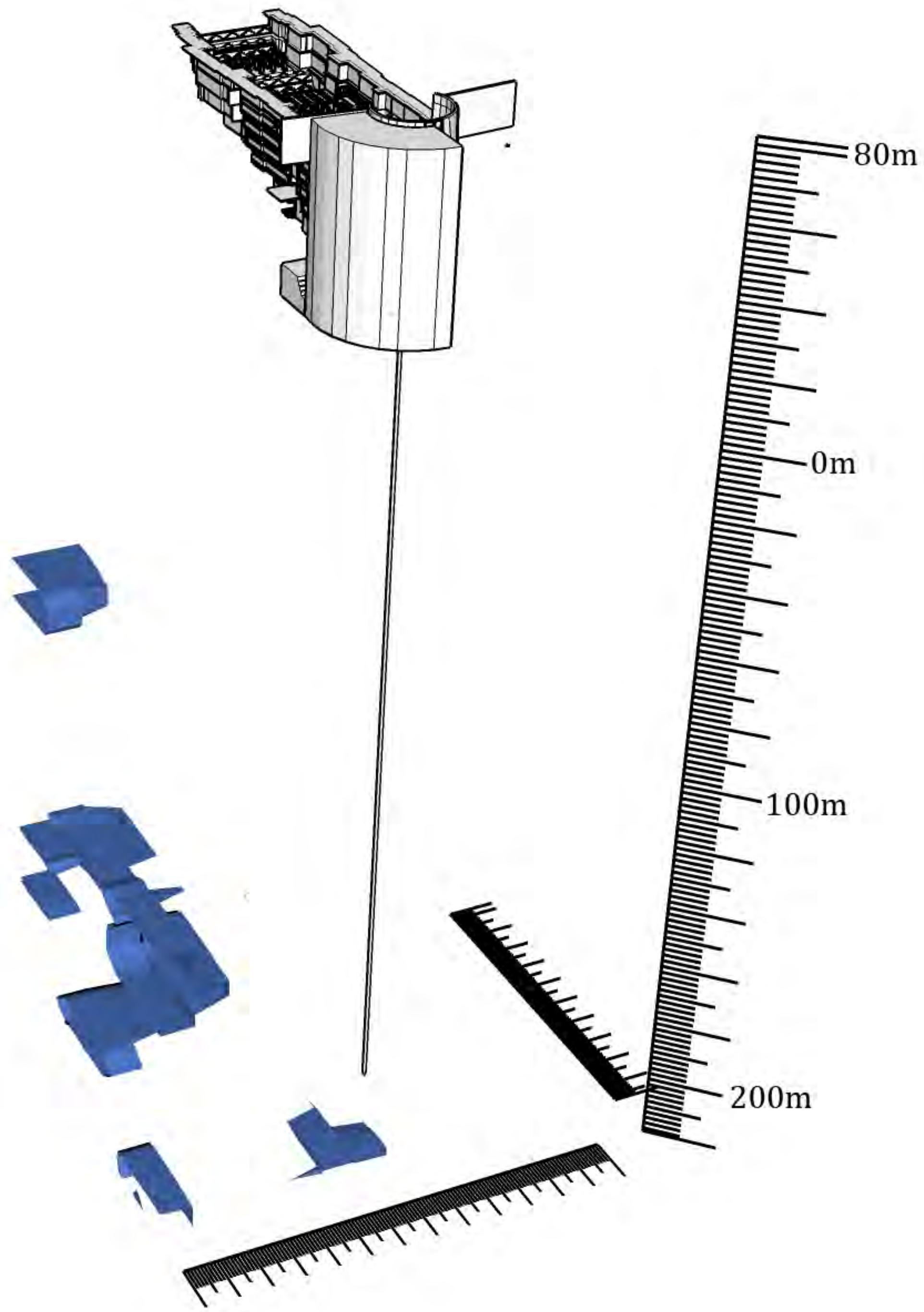
View 8 - Spatial Relationship



View 9 - Northern Elevation



View 9 - Eastern Elevation



View 9 - Spatial Relationship

3.5.4. Analysis Report

View 1 –

Description: Shows the electro-telluric resistivity data associated with possible permeable formations.

Observation: Although not indicative of yield-bearing structures, the diagram indicates a range of permeable formations from sea-level and below.

View 2 –

Description: Indicates the interpreted electro-seismic coupling efficiency of the site.

Observation: The data indicates that there are at least partially saturated groundwater-bearing geological systems from depths of sea-level and below.

View 3 –

Description: Shows the interpreted fracture data associated with higher probability of groundwater flow.

Observation: This indicates that there is a probable fractured groundwater flow formation at a depth of 140m below sea-level.

View 4 –

Description: Indicates the normalised un-calibrated hydraulic conductivity for the formations under the site.

Observation: The data indicates that there is what is interpreted to be a continuous aquifer system at a depth of 140m below sea-level.

View 5 –

Description: Indicates the software interpreted groundwater flow potential for the site.

Observation: The data indicates potential groundwater flow zones at a depth of 140m below sea-level. There are also indications of a number of other smaller flow zones from 20m below sea level.

View 6 –

Description: Indicates the interpreted indications of bedding plane fracturing under the site.

Observation: The data indicates the site is more fractured to the north of the structure. This is relevant to any possible rehabilitation scenario.

View 7 –

Description: Indicates the probable geological interfaces under the site.

Observation: The data indicates that site is geologically stratified with a great deal of geological variation.

View 8 -

Description: Show the interpreted geological interfaces calculated from the electro-telluric data.

Observation: The data indicates major geological resistive interfaces at depths of 40m, 0m, -60m and -160m.

View 9 –

Description: Indicates the interpreted fractures associated with higher permeability formations.

Observation: The data indicates that there may be some fracturing associated with primary permeability formations to the north of the site. This relates to effective positioning of rehabilitation drilling scenarios.

3.5.5. Observations and Recommendations

The following observations regarding the Rani ki Vav site are noted:

1. The first feasible water-bearing aquifer system is located around 140m below sea-level, or around 200m from surface level.
2. The site is geologically stratified which suggests a complex relationship between geology and water-transport networks. However, resistive layering as indicated suggests a degree of upper and lower system isolation.
3. Increased fracturing slightly north of the well-point of the Rani ki Vav suggests a location offset for any future drilling solution should be considered.

There has been a dramatic drop in the natural groundwater level on site over the last decades, resulting in the disconnection of the Rani ki Vav to its natural environment and practical functionality. This is primarily the result of excessive agricultural demands on the groundwater systems in the area. The overuse of groundwater in the area is clearly indicated as unsustainable through the study, and the Rani ki Vav acts as a testament in this regard. It is important to stress the severity of this problem, not only from a heritage perspective but also as a concern for future human development in the area, and further research in this regard is urged. Furthermore, the development of a groundwater management plan is recommended for the area.

3.5.6. Rehabilitation Scenarios

Scenario 1 – Albeit an unrealistic approach, for the sake of thoroughness the natural rehabilitation approach is discussed. Given enough time, the underground water systems that feed the Rani ki Vav would eventually regenerate themselves through natural process. Given that the existing condition is the unsustainable overuse of groundwater from the area, the scenario would require the halting of groundwater use both at the site location and in the surrounding agricultural lands for a period long enough to allow natural regeneration to occur. This process, which can be estimated more reliably through further investigation, could take anywhere from 50 to 100 years.[111] The benefit of this approach is the completely natural and passive process that would occur in order to rehabilitate the heritage site. The primary drawback is the holistic nature of the remedial actions required, which are particularly unrealistic given the dependency on groundwater within the area.

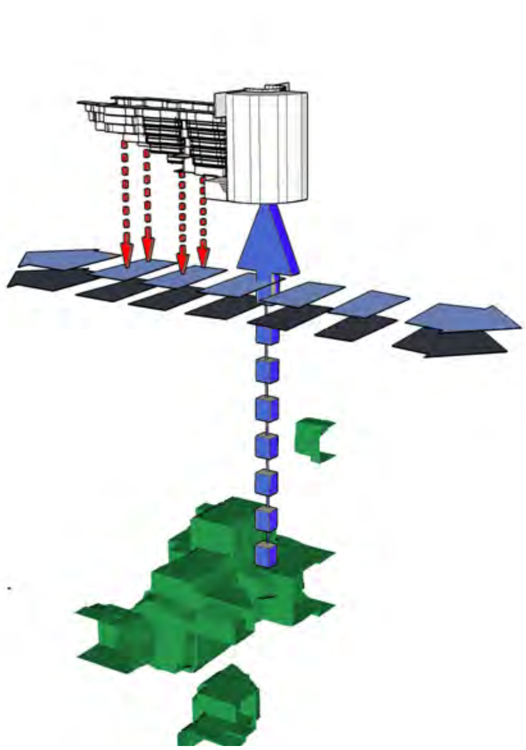


Figure 32 - Upper aquifer recharge approach (Author)

Scenario 2 – Scenario 2 looks at the rehabilitation of localised shallow-level groundwater systems that feed the Rani ki Vav. This scenario recommends the drilling of a borehole to the depth of 140m below sea-level in order to reach the saturated and flowing aquifer system indicated at that depth (view 3, 4 and 5). The resulting water-yield is to be pumped into the Rani ki Vav which, in turn, provides a recharge source for the shallow-level systems that source the monument. The nature of the Rani ki Vav as a source of groundwater recharge has previously been discussed within this paper, and this scenario acts as a 'kickstart' to the same process. The monument is an ideal structure in this regard as minimal evaporation will take place on the pumped water, and given that it would not be used for agricultural purposes, water losses within the system would be negligible. This method essentially recharges shallow-level aquifer systems through the use of deep-level aquifer sources. The assumption, therefore, can be that the net result of this action on groundwater loss is zero. That said, further investigation needs to take place on the larger aquifer system network that sources the Rani ki Vav before remedial action can take place. The localised system can be very large, and the process or rehabilitation, in turn, can take very long to complete. Furthermore, given access to newly-available shallow-level water sources could result in the overuse of groundwater yet again by local farmers and other consumers, leading to the same result as experienced today. Mapping of the aquifer system as it relates to the

111 W Dragoni and B. S Sukhija, *Climate Change And Groundwater*. London: Geological Society, 2008. p118.

Rani ki Vav would need to be completed to understand the area of influence of the groundwater system, and management policy developed and implemented in order to maintain a sustainable rehabilitation scenario. The mapped area of influence would need to be protected and managed as a groundwater buffer-zone in relation to the protected World Heritage site.

This method is inherently passive in nature and requires minimal intrusive intervention on site. The borehole connection to lower-level water sources simply provides a means of reconnection of the well-structure to the underground water it sources. In essence, this method acts as a catalyst for self-regeneration of upper-aquifer systems in an effort to rehabilitate the self-sustaining cycle of a functional stepwell structure. The negative of this approach is the extensive mapping and management that would be required to understand the relationship of the Rani ki Vav within the scope of the larger aquifer system. Given the size of the aquifer, a longer amount of time might be required until a level of self-sufficiency has been achieved, and protection of the designated buffer-zone to undeclared water extraction would need to be in place.

Scenario 3 – Scenario 3 discusses Scenario 2 with the inclusion of aquifer separation through permanent and organic methods. When an aquifer's size and complexity is unknown, or when a specific part of that system needs to be partitioned, an option exists to separate that aquifer through various methods. A benefit of this method is that the larger aquifer system as it relates to the Rani ki Vav can largely be ignored, and outward water-pumping and usage would make no difference to the functional aspects of the Rani ki Vav. This is traditionally done through the addition of various grouting techniques where materials are pumped underground in order to cease the aquifer systems at strategic locations. This separates a section of the aquifer system off from the larger whole to act as an independent system. The benefit of this system is that more careful planning of aquifer buffer-zoning and catchment areas can be achieved, and further control can be maintained within the defined area. There are also positive aspects in light of pollution management should the water in the Rani ki Vav be planned for human consumption. Additionally, through this method groundwater rehabilitation of the localised aquifer would be achieved far quicker than would be possible with scenario 2. The negative of this method is the permanent nature of the technique to be used. Once completed the aquifer would be permanently separated from the larger system. This is also a negative when looking at the prospect of future technologies. As an example, should future water solutions include large desalination plants being used to provide water for all, making groundwater usage redundant in future, that slowly reinvigorated underground water system would not interact with the forever-isolated aquifer system of the Rani ki Vav. Furthermore, given that this is a conservation scenario, the approach does not coincide with ethical frameworks in place for reversible conservation approach to heritage preservation.

It is within this challenge that contemporary studies on organic aquifer isolation techniques should be mentioned, which allow for the same aquifer compartmentalisation, but with the added benefit of full reversibility of the process. This would allow for a fully reversible isolation of the Rani ki Vav catchment area, allowing for compartmentalised rehabilitation of the site with reduced cost, research and management requirements.

3.5.7. Structural Recommendations

The present site pathologies exist largely as isolated occurrences of superficial phenomena, such as mold and pollution areas which have to be addressed due to the artistic value of the site, but which have negligible impact on the structural stability of the structure. The lateral supports of the monument in the form of the series of pavilions show some buckling due to the forces of the earth pressing up against the two longitudinal walls. These walls have been further braced by a supportive retaining wall on the upper level, and the pavilions are under observation and have not worsened since their measurement. Any rehabilitation scenario would require the input of a conservation engineer. That being said, the nature of the forces involved indicate that a water-load within the structural cavity would aid and alleviate some of the earth-baring forces being experience by the otherwise empty volume of the structure. Should water be present in the structure this would help in balancing the opposite forces and allow for a reduction of pressure on the structural pavilions. It is with this in mind that it is recommended that any rehabilitation scenario brings into account the recommendations of a qualified engineer, and also that it is suggested that rehabilitation of the monument might serve it positively from a structural equilibrium perspective.

3.5.8 Case-Study Conclusion

The 'National Conservation Policy for Monuments, Archeological Sites and Remains Protected by the Archeological Survey of India' document of 2013 discusses the relationship between function and conservation of monuments within India. Article 1.04. states that "*All Monuments, once declared so, transcend their original function and should be conserved as exemplars of bye-gone civilizations, eras and epochs, and represent exemplary human creativity, building crafts tradition, patronization, architectural and/or artistic and/or engineering accomplishments, and also serve as tangible manifestation of historical and cultural events and developments of our past that spreads over several millennia.*[112]". Within this statement it might be suggested that the relationship between the Rani ki Vav and its surrounding natural environment, as part of a functional interdependency, is irrelevant within the scope of the protection viewpoint defined by the ASI, which focuses on the transcendent nature of the historical monument and its exemplar nature as testament to historical technology. With that said, it must be noted that the same document states that the aspect related to the 'livingness' of a protected monument has only been attempted for a religious monument in use (as per the notification) under Section 16 of the AMASR Act, 1958.[113] It can therefore be argued that the priorities raised through contemporary sustainability issues and future wellbeing of local inhabitants around the given site, as discussed within this paper, necessitate the reconsideration of conservation approach for heritage structures of this nature.

However, this puts the developed conclusion at somewhat of an impasse. Although the natural groundwater context of the surrounding area suggests that heritage reuse scenarios be implemented as a matter of priority, the dramatically changed context of the structure itself suggests otherwise. The Rani ki Vav, once on the outskirt of an influential city with its related commercial activity, finds itself now in a more ambiguous situation. The site is largely used as a recreational getaway for local inhabitants, and its location and situation suggest a less prioritised nature in terms of water delivery for core human consumption. Its artistic nature, however, which is wholly separate from its functional use, does have a value that is evident in its current situation. It could be suggested that, at this stage in time, the

[112] Archeological Survey of India, *National Conservation Policy for monuments, archaeological sites and remains protected by archaeological survey of India,* 2013. p6.
[113] Ibid. p23.

rehabilitation of the Rani ki Vav to its fully functional state of water delivery would prove somewhat redundant. That does not mean that rehabilitation of related sites share the same outcome, nor does it mean that the rehabilitation of the Rani ki Vav is never to be considered or necessitated, but rather that given the current state of context and value criteria of the historical monument, the best approach would be to 'prepare and wait'. With that mentioned, remedial action as to the preservation of the functional connection to groundwater should be managed and addressed by the conservation plan as to maintain this connection as far as possible. This remedial action should take place as per scenario 2 or 3 as discussed above, albeit in a limited form as recommended by a professional geohydrologist. Furthermore, this action should take place as part of a larger groundwater management plan for the area, in which the Rani ki Vav acts as a landmark and benchmark of progress over time.

4. Secondary Case Study: Vadaj Stepwell, Ahmedabad

4.1. Overview

The Vadaj stepwell (or Stepwell at Wadaj) is located within the city of Ahmedabad, roughly 135km from the Rani ki Vav site. It is selected as a secondary case-study because it differs from the Rani ki Vav in the following aspects:

1. Protection Status – Whereas the Rani ki Vav is a UNESCO World Heritage site and under the full protection of the ASI, the Vadaj Stepwell is the direct contrast of this prioritised protection. It is only protected at a city-level and is not covered or financed through the ASI heritage protection and conservation framework.[114]
2. Size and Location – The Vadaj Stepwell is significantly smaller than the Rani ki Vav. Also, the location of the stepwell in Ahmedabad City makes for a very different context to that of the Rani ki Vav on the outskirts of Patan.
3. Active Conservation – The stepwell is currently undergoing conservation work and rehabilitation of the site is more plausible than it would be with the Rani ki Vav, as well as more practical given the desired conservation outcome and site location.
4. Age – The Vadaj Stepwell is an 18th century structure, making its construction date far later than that of the Rani ki Vav.
5. Ornamentation – The Vadaj Stepwell is largely void of ornamentation past structural detailing, especially when compared to that of the Rani ki Vav, and its nature is far more functional that that of the older Rani ki Vav structure.

The Vadaj Stepwell is located within a populous and bustling area of Ahmedabad in the Gujarat region. The site itself is adjacent to New Wadaj Road which runs into Ashram Road, considered the primary traffic 'artery' of the city. As such it falls in a very busy location, but also next to a large amount of low-cost housing that falls on its eastern and north-western sides. The site is in proximity of several hospitals that accommodate the plots around it.

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[114] Vipul Rajput, 'Vadaj's Forgotten Vav', *Ahmedabad Mirror*, 2010.

Figure 33 - Vadaj Stepwell before restoration (Vipul, R., 2010)

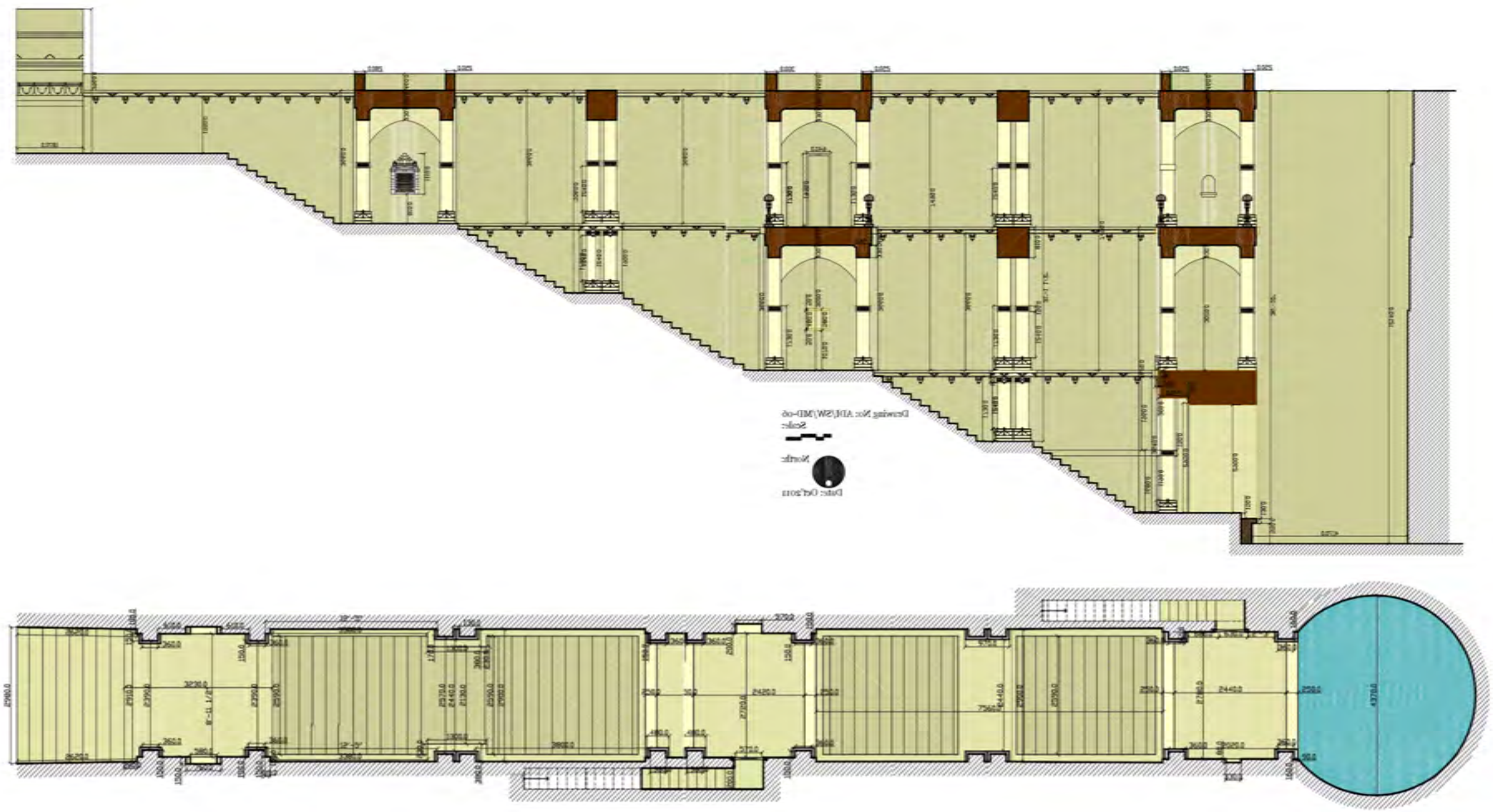
The Vadaj Stepwell is an 18th century structure which has, to this point, suffered at the hands of neglect for many years. Except for those that live nearby, many locals in Ahmedabad do not even know about the structure and it is fairly concealed at the moment, which is of particular pity given its prime location and proximity to a primary road in Ahmedabad. At one point the structure was largely overgrown with vegetation and starting to fall apart. The site was used as a refuse yard for local inhabitants, and the surrounding lands where not maintained. It is with great optimism, therefore, that the newly started conservation works on the site have begun. The structure itself has been cleared of vegetation and cleaned up substantially. Structural pathologies are currently being addressed and the site already looks substantially better than it did just a few years ago. The grounds around the stepwell are to be developed into a local parkland area, which would be a great addition for the surrounding area. As of June 2015 the conservation project was underway and in full progress. Conservation works seek to address previous remedial actions (dating from 1935)[115] that used incorrect conservation methods. Works are currently underway on both structural conservation as well as garden rehabilitation.

[115] Trambadia, Ashish, and Poonam Trambadia. Conservation of Stepwells. Interview by: John du Preez. In person. Ahmedabad, India, 2015.

Figure 34 - Vadaj Stepwell during restoriation (Author, 2015)

It is within this context that the rehabilitation of the Vadaj Stepwell should be considered and placed in comparison to that of the Rani ki Vav. Firstly, in contrast to the Rani ki Vav, the Vadaj Stepwell has minimal issues regarding the conservation of fine elements, which currently makes up much of the conservation challenge of the Rani ki Vav. Secondly, its location and size make it an ideal candidate for well rehabilitation. Should a rehabilitation scenario be possible it would not only support the notion of stepwells in sustainability solutions, but also compliment the current efforts as envisioned for the site presently.

The monument itself is a small, beautiful gem hidden away within a large and vibrant city. Although certainly without the grandeur and intricacy of the Rani ki Vav, the value of the Vadaj Stepwell lies in the fact that it separates itself in this regard. The restoration and reintroduction of this stepwell to the local community is a positive that is allowed by its ambiguity and its pragmatic nature.

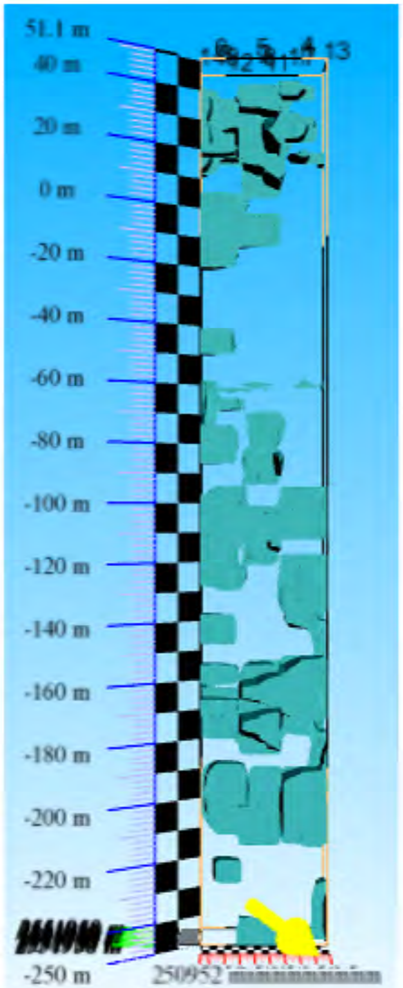


Vadaj Stepwell (New Wadaj Road)
(Trambadia Conservation Architects, 2011)
Section and Upper Level Plan (scale indicated)

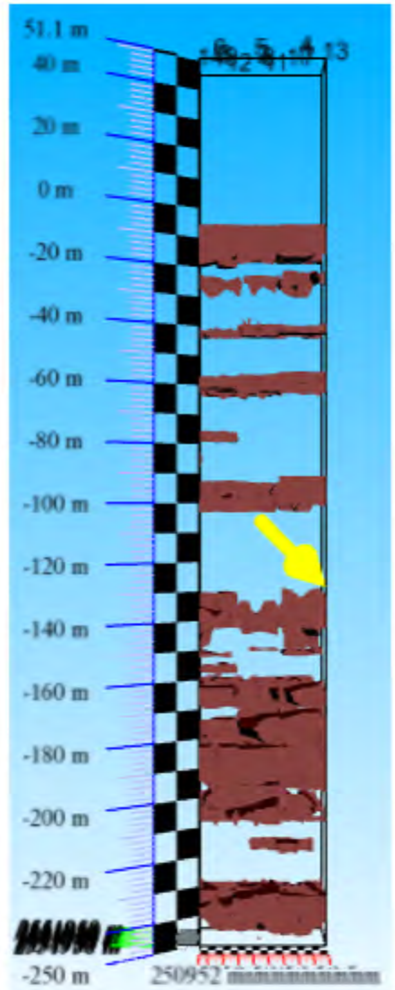
4.2. Report

Figure 35 - Survey-grid layout (Author, 2015)

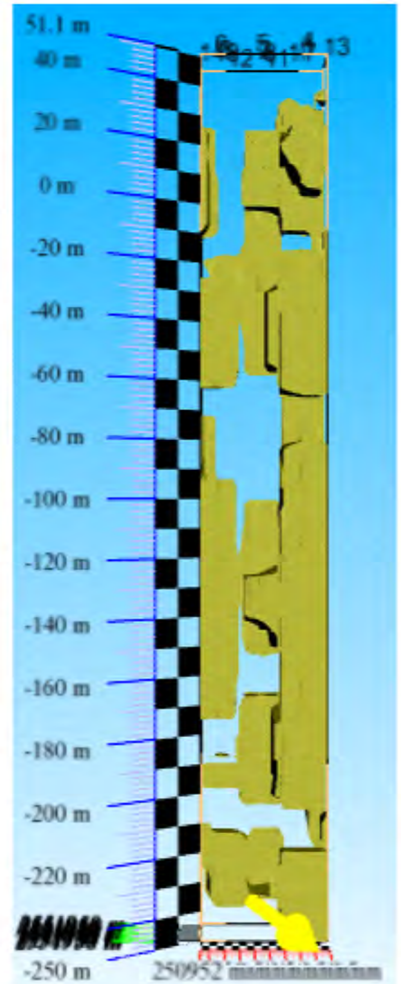
The site survey took place in a grid-structure similar to that of the survey done at the Rani ki Vav site. Two profile lines were mapped on each side of the stepwell, with three points on each. The challenge in this regard was limited space around the structure and as such profile spacing had to be reduced in order to accommodate the profile lines. Furthermore, noise from the surrounding city, powerlines and civil structures in and around the site played a role in the data-collection process. This is in stark contrast to the relatively 'noise-free' data enjoyed at the Rani ki Vav site. The process of data collection remained consistent between sites, however, 10-point stacking was used on the points at the Vadaj Stepwell in an effort to effectively reduce noise levels in the resulting data-sets through further data averaging.



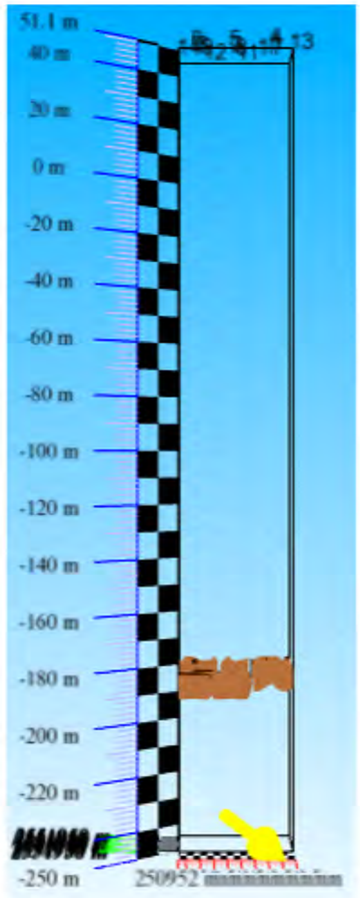
View 1



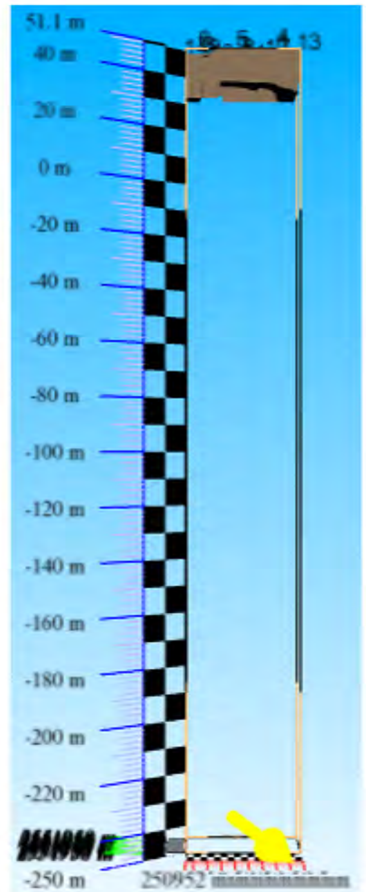
View 2



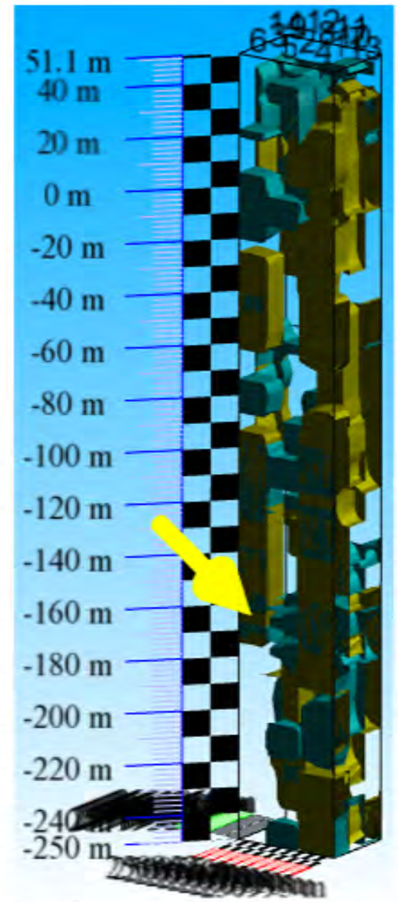
View 3



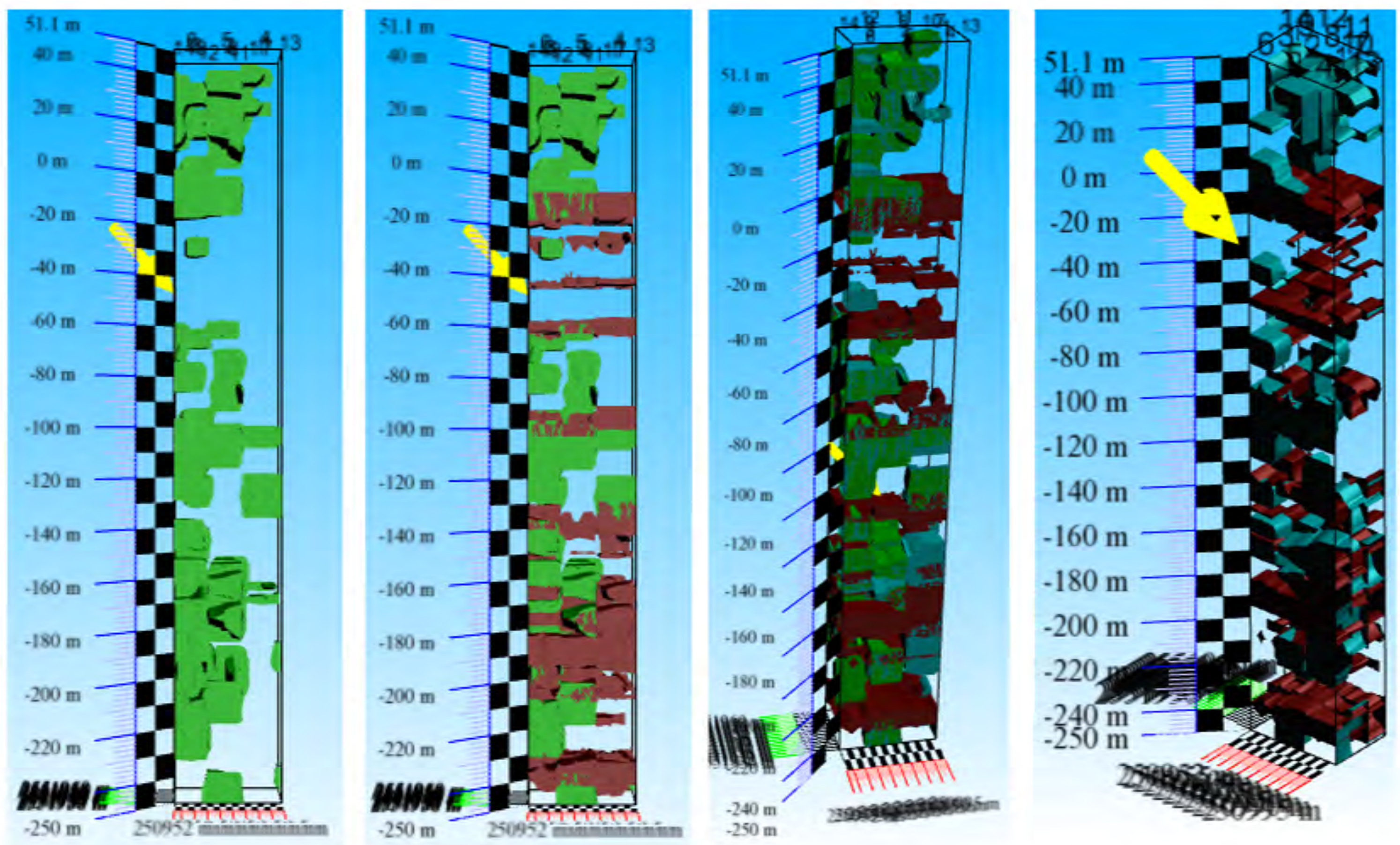
View 4



View 5



View 6



View 7 View 8 View 9 View 10

View 1 -

View 1 shows the Hydraulic Conductivity Tomography (ESKT) results of the Vadaj site survey. With this data primary rechargeable aquifer systems are indicated up to a depth of roughly -200m below sea level. The mapped data indicates these aquifer structures as being present at 100m, 160m and 180m below sea level. Additionally, the data indicates the presence of a shallow surface system up to a depth of 20m above sea level.

View 2 –

View 2 shows the Electroseismic Interface Angular Response Tomography (ESIAT) of the Vadaj site survey. This analysis allows for the correlation of inter-point interfaces to determine the position and depth of major geological changes, and is useful in relating these changes to mapped aquifer systems in order to better understand the groundwater context of the site. The view indicates strong and clearly defined levels of geological change. Of particular note within this view is the distinct horizontal layer that occurs at 0m. This layer likely acts as a confining layer within the groundwater interaction context for the site. Furthermore, the same is to be noted at 60m and 100m below sea level. This view, when layered with additional information, gives a better idea of the relationship between local geology and groundwater systems on site. This comparison is made in a forthcoming view.

View 3 –

The Electro-Seismic Change in Absolute Response Tomography (ESCAGT) relates to the existence of clays within the sub-surface context. The view indicates occurrence right through the measured depth spectrum and is indicative of lower permeability due to the inherent water-retention nature of clay-like materials.

View 4 –

The Electro-telluric Interface Tomography (ETIT) is resistivity data that describes the position and depths of interface indicators that occur at the boundaries between two geological units with differing electrical conductivity. This allows for the interpretation of lithological interfaces within the sub-surface context and is useful as a comparative layer in addition to electroseismic mappings. The clear indication at 180m below sea level is indicative of the biggest change, electrically speaking, which represents a large formation change at this level.

View 5 –

The Electro-Seismic Change in Total Response Tomography (ESCTGT) is indicative of unconsolidated materials that overly saturated consolidated geological formations. As such it maps the overlaying topsoil layer that occupies the site. As illustrated in the view, the topsoil layer is roughly 10m to 15m in depth. This unconsolidated layer is able to accommodate water flow, given that the water-table level is in support of such action. The Vadaj well structure falls within this unconsolidated layer and is indicative of a substantially reduced water-table level, giving indication to the state of the shallow-level aquifers within the site and the local area.

View 6 –

View 6 overlays the ESKT data with the ESCAGT as measured for the site. This relates the general primary rechargeable aquifer systems on site with the clay-composition within the same volume. The data further indicates the depth of interest for optimal aquifer utalisation at 160m to 180m below sea level.

View 7 –

The Electro-Seismic Groundwater Flow Potential Tomography (ESGFPT) indicates the most likely position for groundwater flow. It combines all the relevant electrical and hydrological ES response data of the formations under the site to determine the normalised relative inferred percentage of probability of groundwater flow. It is important to note that the data represented is not an indication of the absolute probability of groundwater flow, but rather the most likely location/s of groundwater flow, when compared to all the other electroseismic locations surveyed. This view is of particular interest in that it clearly shows the upper and lower aquifers as already indicated and relates to the ESIAT data (view 2) allowing for scenario development with regards to sub-surface context of the site.

View 8 –

View 8 compares the ESGFPT data (view 7) to the ESIAT data (view 2) in order to further understand the relationship between groundwater and geological features of the site. As can be seen (indicated with a yellow pointer) the proposed confining layer as indicated on view 2 corresponds to the void of flow potential within the same volume. This suggests that the layer is an aquiclude largely or fully separating the shallow and deep aquifer systems on site. This is important in the process of scenario development for the site and allows for a very similar approach as to that defined for the Rani ki Vav site.

View 9 –

View 9 includes and overlays hydraulic conductivity tomography into the comparative layering of view 8. Although this inclusion does not illustrate any new findings, it does further illustrate both optimal aquifer depth of 180m below sea level and also the aquiclude volume as discussed.

View 10 –

Hydraulic Conductivity Tomography (view 1) is overlaid on Electroseismic Interface Angular Response Tomography (view 2) to further indicate and surmise the proposed context of the sub-surface volume for the Vadaj Stepwell site. The view sufficiently shows the various defined characteristics of the site:

- The upper aquifer system falls above the aquiclude layer at roughly 20m above sea level.
- The distinct aquiclude layer at a depth of 20m to 60m below sea level acts as a confining layer between aquifer systems.
- Deeper level aquifer system is indicated at 160m to 180m below sea level.

4.3. Conclusions and Recommendations

The Vadaj Stepwell site is very similar to that of the Rani ki Vav site and further emphasises the scenario proposed for both. It must be noted that although the similarities between these two sites could be representative of geological characteristics of the area, they are not interdependent or connected systems. It is as such that their likeness is an opportunistic coincidence that allows for a similar approach to be taken in a very different heritage context.

The site includes both upper and deep aquifer systems that likely act independently of each other. This is postulated as a result of the aquiclude formation that forms a distinct layer between them. The Vadaj Stepwell as a structure occupies a volume within the unconsolidated topsoil level that continues to a depth of about 15 meters. As a structure, therefore, it ends within proximity of the consolidated layer below the topsoil layer and functioned through the utalisation of flowing water available to the topsoil layer. This is indicative of a much higher water-table level during construction, and the drop in water-table level is in correlation with both that of the Rani ki Vav as well as the general area as a whole. It is proposed, therefore, that no reliable water source is currently available from the upper aquifers due to over-pumping and lack of recharge within the area as a whole. The recommended course of action for water-access on the site would be to drill to a depth of 180m below sea-level either at the well source location, or slightly deviated, at point 3 on the survey grid.

The scenario recommended for the site would be the same as scenario 2 or scenario 3 as indicated for the Rani ki Vav site, which suggests the pumping of deeper water sources in order to act as a recharge for the upper aquifer system. The scenario is supported from a geological context perspective, given the distinct aquiclude layer present in this site mapping. This confining layer will support the recharge of the upper aquifer system by preventing seepage deeper than that of the upper aquifer itself. Furthermore, this action acts as a catalyst for the regeneration of the upper aquifer in support of a sustained water-source for the Vadaj Stepwell.

The unique characteristics of stepwell typology makes the structure an ideal source of recharge for the upper aquifer systems. The protected and shaded void enjoys minimal exposure to sunlight and evaporation is negligible, meaning that water-loss is minimal and the structure simply acts as a means of recycling water distribution within the groundwater context. This suggests somewhat of a symbiotic relationship between the structure and the surrounding environment, in which the structure can very well support the regeneration of upper-level aquifer systems in order to stabilise future supply to itself.

The Rani ki Vav falls in a very different social context to that of the Vadaj Stepwell. Whereas the Rani ki Vav is a UNESCO World Heritage Site, is on the outskirts of a less populated area, and is valued primarily for its artistic features, the Vadaj Stepwell is located in a highly-populated area with a huge social benefit for rehabilitation. The site has minimal artistic features to be concerned about, especially in comparison to that of the Rani ki Vav, and its nature is far more pragmatic than that of the Rani ki Vav, both today as it was during construction. The scale and level of protection status of the Vadaj Stepwell also promotes the consideration of rehabilitation for social benefit of the local population, and is possibly a unique and valuable case-study in heritage-based response to contemporary sustainability challenges.

5. Conclusion

The research represents, in part, an application of groundwater investigation within the heritage sector. Through the research presented it can be concluded that groundwater mapping, analysis and management play a relevant and important role in the criteria of concern for heritage preservation. This paper does not reflect the entirety of the relationship between the heritage structure and its surrounding environment, but rather focuses on one application of that relationship. As such, further investigation into this relationship in varying contextual situations is urged. Furthermore, the implementation of the management of this relationship should be researched further and occupy an important part of any conservation plan where necessitated. The paper proves through the comparison of two stepwells, which although geographically and typologically similar, have different contextual situations, that the integration of information based on the surrounding environment should be taken on a case-by-case basis, and that the information should be prioritised and implemented as is needed for the site and/or monument concerned.

The Rani ki Vav proved a very interesting case study in that its location and situation suggest a very different approach to that of the holistic sustainability challenges faced within the Gujarat area. That a scenario is possible does not necessarily justify that scenario in terms of the monument preservation, and in the case of the Rani ki Vav the best course of action at the moment would seem to be the continued actions of the existing conservation plan, albeit with integrated efforts for groundwater-monument rehabilitation as indicated through scenario two and three in the research document. In other words, that rehabilitation takes place but on a subtle and non-touristic level. This is deeply possible at the Rani ki Vav site, since the well point and adjacent tank area are off-limits to the general public as part of the conservation solution. This supports water-rehabilitation scenarios within the structure without implementing the idea of a 'living' structure to the general population. That efforts be made to rehabilitate this connection to the natural environment is important not only for the Rani ki Vav itself, but also for the surrounding area in general. Furthermore, the action of controlled rehabilitation supports the monument conservation efforts both structurally and superficially. The Rani ki Vav should be seen in light of its functional achievement in as much as for its intricate artistic elements, given that it was primarily a pragmatic structure in service of its surrounding community, and this research paper recommends that further investigation be made into the restoration of the Rani ki Vav in this regard.

Auxiliary concluding remarks are as follows:

- Management of groundwater in the Gujarat area is important for the continued provision of basic needs for the people and agriculture that rely on it, and the incorporation of a stringent and measured management plan is urged. Furthermore, the investigation in the reuse of stepwells in this regard is strongly recommended as a sustainable method of basic service delivery for local communities.
- The incredible stepwell monuments in the area are wildly under-represented within both the global and Indian tourist markets. Being a typology that really surprises and positively affects visitors, it is urged that further emphasis be placed on the promotion of these structures and the education associated with their function and history in effort to further ensure their continued protection. This does not only relate to the Rani ki Vav, but even more so to the little-know structures scattered throughout the area. Stepwell-centric tours do not currently exist, and it is recommended that these be considered by the relevant tourist authorities. The Rani ki Vav, obviously on top of any stepwell list, should certainly be presented in the context of other nearby stepwells, these being at the very least:
    - The Dada Harir ni Vav – A spectacular 16th century monument in testament to the ingenuity of stepwell design, and what should be considered a World Heritage candidate.
    - The Adalaj Stepwell – A monument giving comparative context to the artistic achievement of the Rani ki Vav while uniquely identifying itself at a typological level.
    - The Vadaj Stepwell – A small and functional 18th century stepwell with enormous potential to integrate into the lives of the local community.

Figure 36 - Community involvement and education (Author, 2015)

Education into the role of groundwater and natural process as it relates to stepwells and heritage structures in general is recommended for both conservation professionals and general interest groups.

Software requires further development in order to integrate successfully into the heritage sector and proved a challenge within real-world survey application in this research paper. Further experimentation and research with regards to heritage-based knowledge in the groundwater and geological sciences is recommended and considered a relevant and useful source of information for continued successful heritage conservation efforts.

The continued conservation of these beautiful and functional structures should be considered a priority, and the hope is that their relevance and role in contemporary sustainability issues might open a discourse for similar structures and scenarios elsewhere in the world. The role of heritage in response to future sustainability has still much to be explored, and it is the role of the conservation expert and researcher to meet these challenges.

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