UNIVERSITY OF SAO PAULO
INSTITUTE OF GEOSCIENCES

Temporal Conceptual Models for contaminated Complex Site management, based on a remediation case of chlorinated solvent Commingled Plumes in weathered and fractured bedrock

SASHA TOM HART

Summary of the Thesis presented in the
Mineral Resources and Hydrogeology Program
to obtain the Doctoral of Science title

Supervisor: Dr. Reginaldo Antonio Bertolo

SAO PAULO
2023

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Hart, Sasha Tom
Temporal Conceptual Models for contaminated Complex Site management, based on a remediation case of chlorinated solvent Commingled Plumes in weathered and fractured bedrock / Sasha Tom Hart; orientador Reginaldo Antonio Bertolo. -- São Paulo, 2023.
158 p.

Tese (Doutorado - Programa de Pós-Graduação em Recursos Minerais e Hidrogeologia) -- Instituto de Geociências, Universidade de São Paulo, 2023.

1. Áreas Contaminadas. 2. Modelo Conceitual. 3. Aquífero Fraturado. 4. Remediação. 5. Isótopos. I. Bertolo, Reginaldo Antonio , orient. II. Título.

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Prof. Dr. Reginaldo Antonio Bertolo

Tese de Doutorado

Nº 663

COMISSÃO JULGADORA

Dr. Reginaldo Antonio Bertolo

Dr.Sander Eskes

Dra. Juliana Gardenalli de Freitas

Dra. .Veridiana Martins

Dr. Márcio Costa Alberto

SÃO PAULO
2023

Dedicated to

my mother (in memoriam),

my father

and all the people

that taught me about

love & science.

ACKNOWLEDGMENTS

The journey of this doctoral thesis has been a challenging, intensive and rewarding experience. Crucial support was provided by the people and institutions listed below, amid others, including the many people who helped all us during the terrible pandemic that started while this research was on course.

First, an enormous thanks to my supervisor Reginaldo Bertolo for all the inspiring contributions. He has helped me learn so about science, research and life.

A special thanks to Maria Stella Agostini and Roland Feig for the many productive and enjoyable conversations and also for supporting the development of applied sciences.

I gratefully acknowledge Ramon Aravena for his isotopic orientations and taking me to the laboratories of the University of Waterloo and the incredible Consortium event on solutions for Fractured Bedrock at the University of Guelph.

My sincere thanks to those who also directly contributed to the development of parts of this research, including: Paulo Lima-Lojkasek, Fernanda Barreto, Joyce C. Di Giovanni, Marcos Barbosa and Dr. José Carlos Gouvêa Júnior.

Breakthroughs were inspired by conversations with Rodrigo Cunha, Juliana Freitas, Veridiana Martins, Sander Eskes, Ricardo Kern, Berguedoff Sciulli, Mateus Simonato, Alexandra Suhogusoff, Ricardo Hirata, André Oliveira, Olivier Maurer, Jordi Palau, James Baldock, Allan Thomas, and David Alden.

The research grew with great studies, support, coffee and popcorn from colleagues of CEPAS/IGc/USP: Rafael Terada, Daphne Pino, Lucas Ribeiro, Paulo Galvão, Daniela Osório, Fabio Sartorio, Ana Rios, Carlos Marques, Carlos Oliveira, Amélia Fernandes, Fernando Saraiva, Ingo Wahnfried, Paulo Lima, amid others.

This research counted with thankful funding from BASF (in the name of Bert Neumeier) and key input from people of the University of Oklahoma (in the name of Thomas Kuder), Seequent (in the name of Tim Schurr), Arcadis (in the name of Raoni Azevedo), Mérieux NutriSciences (in the name of Andre Rebouças) and FUSP (in the name of Sheyla Lino).

The development of this doctoral thesis was stimulated and made enjoyable by people I met at RENIF, NICOLE (Latin America and Europe), FAO/UN, USP, Imperial College, SVMA, CETESB, CSD-Geoklock (EBP), ERM (Latin America, North America and Europe), Sanifox, amid others.

It was also very important to balance this research with community projects, contact with nature and many sorts of cycles. Many thanks to the incredible people from: CADES, BZO, CTB, SMT, CET, Equipe, Rios & Ruas, Hortas das Corujas, CCC, Fernande, Lentos y Aferrados, neighbours, meditation groups and others.

Finally, I am immensely thankful to all my family and friends for their kind and joyful company throughout the complexities, paths and celebrations of life. By last, many thanks, *muito obrigado* and *muchas gracias* to Juliana, Lucas and Martin.

“The optimist is a fool.

The pessimist is a bore.

What is really good is to be a hopeful realist.”

Ariano Suassuna

ABSTRACT

Contaminated properties and regions, mainly abroad, have been named as Complex Areas due to the existence of technical or non-technical challenges that require atypical longer timelines and management for their restoration. In the United States of America 9.5% of all their identified contaminated sites (126 thousand) have been considered as complex from a hydrogeologic and contaminant perspective. In Europe, continental initiatives were developed to recognize and learn from the complex, large and prominent brownfields. In Brazil, the State of Sao Paulo has classified 18 sites as Critical Areas, a type of Complex Area, representing 0.27% of the total amount (6.6 thousand) of currently know contaminated areas. This research main objective is to evaluate Complex Area management and contribute with its enhancement, based on the development of a more clear and holistic conceptual site model for a remediated site in São Paulo, Brazil, that presented commingled plumes including within former abstraction wells in fractured bedrock. Its complex challenges were evaluated and detailed spatially and temporally with the development of a Temporal Conceptual Model, defined in this study. Several tools were applied, including Compound Specific Isotopic Analysis (for carbon and chlorine) with geoforensic approach, bedrock logging and implicit modelling. Prior to full scale remediation of the study area, an off-site source area with unknown history and limited access presented lower δ13C values (-6.5‰ to -1.8‰ for 1,2-Dichloroethane) and distinct signature than that determined for the downgradient on-site source area (+8.6‰ to +20.0‰). Intermediate δ13C values for 1,2-Dichloroethane were identified further downgradient, within a commingled plume configuration. After bioremediation and thermal treatment, isotopic fractionations were identified. In the former main abstraction well concentrations have continuously dropped over the last 9 years, to below potability limits. Multiple lines of evidence and the site rehabilitation (formally agreed after 22 years management) confirmed the interventions in the area benefited from the using the Temporal Conceptual Model and aspects of Adaptive Management for Complex Areas, such as the definition of intermediate objectives, continuous refinement of the conceptual model and remediation adjustments. In Brazil and other countries there are possibly many other sites similar to this area, with technical and non-technical challenges that prevent meeting objectives in typical timeframes. It is recommended that Complex Areas shall be further identified and managed following international recommendations, while also contemplating local considerations and adaptations, such as: 1) include in the definition of Complex Areas that the challenges should demonstrably present high complexity and require atypical times for rehabilitation (data indicates it typically takes 15 years in São Paulo); 2) consider as a technical challenge the extensive heterogeneous weathering profile, typical of humid tropical regions; 3) consider as a technical and non-technical challenge the high number of unregistered abstraction wells; 4) consider as a non-technical challenge the existence of social-economic conflicts; 5) evaluate in detail, including with isotopic studies, the possible presence of commingled plumes; 6) progressively develop Temporal Conceptual Models (clear and holistic).

Keywords: contaminated land; Complex Sites; Adaptive Management; conceptual model; fractured rock; commingled plumes; remediation; isotopes; geoforensics.

RESUMO

Propriedades e regiões contaminadas, principalmente no exterior, têm sido nomeadas como Áreas Complexas devido à existência de desafios técnicos ou não técnicos que exigem prazos e gerenciamentos mais longos atípicos para sua restauração. Nos Estados Unidos da América 9,5% de todas as áreas contaminadas identificadas (126 mil) foram consideradas como complexas da perspectiva hidrogeológica e da contaminação. Na Europa, foram desenvolvidas iniciativas continentais para reconhecer e aprender sobre áreas que fossem complexas, grandes e proeminentes. No Brasil, o Estado de São Paulo classificou 18 áreas como Áreas Críticas, um tipo de Área Complexa, representando 0,27% do número total (6,6 mil) de áreas contaminadas atualmente conhecidas. O principal objetivo desta pesquisa é avaliar o gerenciamento de Áreas Complexas e contribuir com o seu aprimoramento, tendo como base o desenvolvimento de um modelo conceitual mais claro e holístico para uma área remediada em São Paulo, Brasil, que apresentou Plumas Combinadas inclusive em antigos poços de captação em rocha fraturada. Os seus desafios complexos foram avaliados e detalhados espacial e temporalmente com o desenvolvimento de um Modelo Conceitual Temporal, definido neste estudo. Várias ferramentas foram aplicadas, incluindo Análise Isotópica de Compostos Específicos (para carbono e cloro) com abordagem geoforense, perfilagem do meio fraturado e modelagem implícita. Antes da remediação final da área de estudo, uma área fonte externa com histórico desconhecido e acesso limitado apresentava valores de δ13C mais baixos (-6,5‰ a -1,8‰ para 1,2-Dicloroetano) e assinatura distinta daquela determinada na área fonte interna localizada à jusante (+ 8,6‰ a +20,0‰). Valores intermediários de δ13C para 1,2-Dicloroetano foram identificados em região mais à jusante, em uma configuração de Pluma Combinada. Após a bioremediação e tratamento termal, fracionamento isotópico foi identificado. No principal antigo poço de captação as concentrações tem continuamente caído há 9 anos, para abaixo de limites de potabilidade. As múltiplas linhas de evidência e a reabilitação do local (formalmente acordada após 22 anos de gerenciamento) confirmaram que as intervenções na área se beneficiaram do uso do Modelo Conceitual Temporal e de aspectos da Gestão Adaptativa para Áreas Complexas, como a definição de objetivos intermediários, contínuo refinamento do modelo conceitual e ajustes na remediação. No Brasil e em outros países, possivelmente existem muitos outros locais semelhantes a esta área, com desafios técnicos e não técnicos que impedem o cumprimento dos objetivos em prazos típicos. Recomenda-se que mais Áreas Complexas sejam identificadas e gerenciadas seguindo recomendações internacionais, contemplando também considerações e adaptações locais, tais como: 1) incluir na definição de Áreas Complexas que os desafios devem comprovadamente apresentarem alta complexidade e exigir tempos atípicos para reabilitação (dados indicam que tipicamente leva 15 anos em São Paulo); 2) considerar como desafio técnico o heterogêneo extenso manto de intemperismo, típico de regiões tropicais úmidas; 3) considerar como desafio técnico e não técnico o alto número de poços de captação não outorgados; 4) considerar como um desafio não técnico a existência de conflitos socioeconômicos; 5) avaliar detalhadamente, inclusive com estudos isotópicos, a possível presença de Plumas Combinadas; 6) progressivamente desenvolver Modelos Conceituais Temporais (claros e holísticos).

Palavras-chave: área contaminada; Área Complexa; Gerenciamento Adaptativo; modelo conceitual; aquífero fraturado; Plumas Combinadas; remediação; isótopos; geoforense.

TEXT INDEX

1. INTRODUCTION

The Metropolitan Region of Sao Paulo (MRSP) has a population of approximately 21 million people that is served by a public water supply system from surface water reservoirs (located up to 82 km away) at an average rate of 62 m^3/s (SABESP, 2021). This region is geographically located in the Alto Tiete Basin, which presents a water availability index of 131 m^3/year/habitant (FABHAT, 2016). This is more than 10 times lower than the limit considered critical by the public water supplier and international standards. This public water system is supplemented by private wells that abstract groundwater. FUSP (2009) estimated there was a total of 12000 wells (only 3460 registered) that added approximately 11 m^3/s of groundwater to the water system, with possibly 100 to 200 new wells being installed every year. When possible, wells are typically a favoured water source due to lower overall costs and less inconveniences related to periodic surface water shortages.

Groundwater exists in MRSP mainly within the crystalline fractured bedrock and represents an important strategic supply resource for the present and future generations (Rebouças, 1992; Bertolo et al., 2015). Its vast abundance is threatened by increasing demand, management difficulties, climate change and contamination. It typically presents very good natural quality and a certain degree of protection from anthropogenic contaminants provided by shallower units (soils enriched with organic matter, sediments and weathered rock) that retards flow and enhances degradation processes (Bertolo 2017). Comprehensive analytical monitoring data of these supply wells is limited, however contaminants, such as dense chlorinated solvents compounds, have been identified in several crystalline fractured bedrock wells of MRSP (Hart et al. 2007; L´Apiccirela 2009; Fiume, 2014; Bertolo 2017; Lima 2018; Barbosa 2019; Pino 2019; Pino et al., 2022). Many impacted supply wells potentially exist in MRSP, such as in the several former industrial areas, and pose a large challenge from a scientific and management perspective. These potential impacts shall be further evaluated and, in order to be managed, have its origins identified. Regions with multiple sources may also present commingled plumes, with complex overlapping responsibilities and challenging technical requirements (NJ DEP, 2017; Bertolo 2017; ITRC, 2017). Unaddressed uncertainties can postpone the required solutions and feed geoforensic disputes (Teixeira & Abreu, 2018, Barbieri et al., 2023).

Since the 1980´s, it was recognized that at any type of contaminated site data should be collected to develop a local conceptual model indicating “hypotheses regarding the contaminants present, their route of migration, and their potential impact on sensitive receptors” (US EPA, 1987). According to Sale & Newell (2011), the first step to manage a contaminated area is to develop a clear and holistic view of the sites and their challenges. This shall be expressed in a conceptual model, including characterization of the different contamination compartments (phases and locations). Kresic & Mikszewski (2013) recognizes that conceptual model development is typically refined over cycles that include steps of data collection, analysis, presentation and visualization. The visualization of the data and the conceptual model are considered crucial steps in order to allow stakeholders evaluate if the study has reached its objectives and can be finalized (Figure 1).

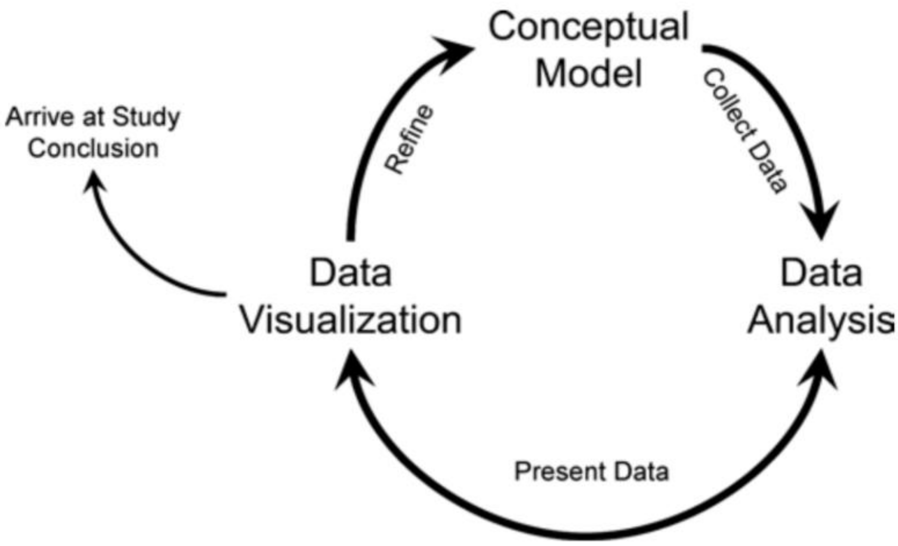

Figure 1 - Conceptual Model general workflow (Kresic & Mikszewski, 2013)

Advances in the characterization of contamination in porous media environments has steadily advanced since the 1970’s, while in fractured rock media it started mainly in the late 1990’s and at a slower pace (NGWA, 2005; Barbosa 2019). More recently comprehensive investigation methodologies were developed to characterize fractured bedrock aquifers (Cook, 2003; Fiacco et al., 2004; Golder, 2010; Parker et al., 2012). It is typically more difficult to characterize fractured rock contaminated sites due to highly complex challenges, such as: extensive depths; heterogeneous fracture distribution and discontinuity; flow and contaminant behaviour in fracture networks; interactions with rock matrices; high financial demands. Specific contamination challenges were also reported at fractured rock aquifers within tropical humid regions (Hart et al., 2007; Fanti et al., 2017; Bertolo 2017; Lima 2018, Sartorio 2019; Pino, 2019, Pino et al, 2022), such as extensively weathered heterogeneous rock profiles (Figure 2).

Figure 2 – Soft weathered rock collected in MRSP from the saturated zone, 20m above fresh gneissic rock. Weathering processes had increased its matrix porosity and iron content. The fracture with yellow surface was considered natural and indicative of groundwater flow. Dense chlorinated solvent compound impacts were identified at the fracture surface and in the matrix (Hart et al., 2007).

Despite the increasing demand for fractured bedrock groundwater and concerns about contaminated sites under tropical humid conditions, the amount of published studies about such complex scenarios is still relatively scarce. Furthermore, specific publications about recognition and management strategies of complex contaminations are even more scarce and recent. In Brazil, according to IBAMA (2022) three States (Sao Paulo, Rio de Janeiro and Minas Gerais) have listed the classification of their contaminated sites and one specified those classified as Critical Areas (São Paulo). Critical Areas can be considered a type of complex site mainly due to non technical issues such as disputes among stakeholders (CETESB, 2017). In such cases the management decisions shall be based on further involvement of the environmental agency of Sao Paulo and include a communication plan. In October 2022, the environmental agency had classified 18 Critical Areas (0,27%), out of a total of 6588 contaminated sites (CETESB, 2023). In at least two

Critical Areas (“Bairro de Jurubatuba” and “Aterros industriais Mantovani e Cetrin”) abstraction wells were required to be monitored. In Europe, initiatives such as the Welcome Project were developed to recognize and learn from the complex, large and prominent brownfields (typically named as Megasites). In order to manage them several Integrated Management Strategies were proposed and applied (Schadler et al. 2011). In the United States of America since 1988 complex sites with requirements considered technically impracticable from an engineering perspective are eligible to request Technical Impracticability (TI) waivers that can define alternative rehabilitation requirements (USEPA, 2012). Between 1988 and 2011 a total of 91 TI waivers were formalized, citing mainly groundwater impacts (85 cases), volatile organic compounds impcts (60 cases, mostly chlorinated solvents), complex geology setups (54 cases, mostly in fractured bedrock) and presence of Dense Non Aqueous Phase Liquid (DNAPL; 43 cases). Between 2008 and 2011 the total amount of given waivers notable reduced (5 TIs over this 4 year period), possibly as a recognition that “there have been significant scientific advances and technological innovations and improvements that may be relevant in evaluating the appropriateness of new TI waivers” (USEPA, 2012). Several authors (NRC, 2013; Vogel, 2015; Harclerode et al., 2016; Price et al., 2017; ITRC, 2017) revised the knowledge about complex sites and recognized their extensive prevalence and specific requirements.

According to NRC (2013) “there is general agreement among practicing remediation professionals, however, that there is a substantial population of sites, where, due to inherent geologic complexities, restoration within the next 50-100 years is likely not achievable.” In the context of contamination, restoration is typically understood as an act that produces conditions similar to the former or original state with no use restrictions due to the contamination. NRC (2013) identified the existence of at least 126 thousand contaminated sites in the United States of America and estimated that about 12 thousand (9,5%) could be considered as complex from a hydrogeologic and contaminant perspective. ITRC (2017), moved ahead and defined a Complex Site as a “site where remedial approaches are not anticipated to bring the site to closure or facilitate transitioning to sustainable long-term management within a reasonable time frame”. According to ITRC (2017), Complex Sites present “multiple attributes that present remediation challenges and therefore take much longer to reach site objectives compared with typical sites”. ITRC (2017) recognized the importance of continuously updating and addressing the conceptual model of Complex Sites, however did not mention formats or tools for this task different than those previously recommended for all types of sites.

Several authors (NRC, 2013; Vogel, 2015; Harclerode et al., 2016; Price et al., 2017; ITRC, 2017) recommended that Complex Areas remediation shall be managed with the application of Adaptive Management (NRC, 2003). This type of approach was developed over the last few decades initially focused on other natural systems, such as ecosystems, fauna, flora, water resources and climate change. Adaptive Management proved to be particularly useful when there is a high degree of uncertainty. It promotes that planning shall predict that results will be used in the assessment, development and application of solutions. Tests, assessments and dissemination of learning must be part of these programs so that the necessary knowledge is obtained to improve decision-making processes (NRC, 2003). Adaptive Management strategies should "incorporate sustainable risk management approaches early in the project lifecycle to confidently assess performance and overcome barriers associated with risk perception, uncertainty, and lack of transparency" (Harclerode et al., 2016). This suggests the need for developing strategies that produce a comprehensive understanding of the risks and an efficient communication with the wide range of stakeholders. Adaptive Management aspects were incorporated into Integrated Management Strategies developed and applied for remediation of Megasites (Schadler et al., 2011).

According to David F. Alden, one of the co-authors of ITRC (2017), these several efforts related to Complex Areas should help "invite the wider research community to continue to pursue underpinning science that helps address complexities encountered at field scale" (personal communication, 2023).

To further research these topics and contribute to the development of Complex Area solutions within the Brazilian context, a study area in MRSP was selected for its conceptual model to be revised and further developed. Its management and complex challenges were evaluated, including remediation of commingled plumes in fractured rock former abstraction wells. The conceptual model was updated with new formats and based on new data provided by several tools, including pioneering applications of isotopic analyses.

In general terms, the study area corresponds to a former industrial property in a mixed-use area (without subsurface constructions, apart from supply wells), within the MRSP, State of São Paulo, Brazil. It is located in the alluvial plain of a nearby river which is the natural regional groundwater discharge area. Since the 1990´s flooding events have become rarer in this region and industrial activity has diminished (Figure 3). Since 2000, following identification of contaminants in former abstraction wells, the area has been subject to investigation and remediation works. Based on the results of these works and also contributions produced by this research, this Complex Site was considered rehabilitated by the environmental agency in 2021.

Figure 3 - Site after flooding event (March 2019) with water marks above 1m high on one of the former industry walls. In the uphill background are recent commercial and residential buildings.

Discussions, conclusions and recommendations developed within this research effort were also incorporated into: two papers published in international journals (Hart et al. 2021 and Hart et al. 2022); one paper published in a national journal (Gouvêa Júnior, 2018); one paper submitted to a national journal (in 2023); a book chapter (Barbieri et al. 2022); presentations delivered at scientific events organized by Brazilian institutions (IGc/University of Sao Paulo, AESAS, SENAC, RENIF and Instituto Ekos) and international entities (Nicole Latin America, ReLASC, Battelle and University of Guelph).

2. OBJECTIVES AND STRUCTURE OF THE THESIS

This main objective of this research is to evaluate Complex Area management and contribute with its enhancement, based on the development of a more clear and holistic (i.e. integrated) conceptual site model for a remediated site in São Paulo, Brazil, that presented commingled plumes including within former abstraction wells in fractured bedrock.

The specific objectives of this research are:

- Define a format to present clear and holistic conceptual site models for Complex Sites, considering spatial and temporal aspects.
- Evaluate and apply compound specific isotopic analysis and fractured bedrock characterization tools to enhance the site's conceptual model, including recognition of contamination sources, commingled plumes and remedial processes.
- Evaluate and apply implicit modelling to increase the level of detail and provide tridimensional visualization of the site's conceptual model evolution over time (therefore establishing a quadrimensional model).
- Identify site's technical and non technical challenges that were considered important for its remediation and management, including those characteristic of sites located in tropical humid regions.

The structure of this doctorial thesis document was defined in a logical and articulate format in order to facilitate the comprehension of the research, including the resulting papers and minimizing repetition of their content.

Chapter 1 presents an introduction to the research, followed by Chapter 2 with the general and specific objectives, as well as this discussion about the thesis structure.

Chapter 3 presents the main materials and methods that were used during the research. They are complemented and further discussed in the following papers, which also include specific literatures reviews and descriptions of the study area.

Chapter 4 presents the published paper "Temporal conceptual model of contaminated complex sites applied for the management of a former supply well area in tropically weathered bedrock" (2021). It proposes the Temporal Conceptual

Models format and presents the initial one that was developed for the study area, including comprehensions and uncertainties about the site evolution. This is a paper that was published in English in the international journal Sustainable Water Resources Management in February, 2021 following its format requirements (therefore this and the following papers may present format differences, including for chapters and figures numbering).

Chapter 5 presents the published paper "Hydrogeochemical and isotopic evaluation of VOC commingled plumes in a weathered fractured bedrock aquifer treated with thermal and bioremediation" (2022). This paper includes the results of the Compound Specific Isotopic Analysis (CSIA) study that was used to tackle uncertainties and further develop the Temporal Conceptual Model. It was published in English in the international Journal of Contaminant Hydrology in January, 2022.

Chapter 6 presents the submitted paper "Implicit modelling to detail the Temporal Conceptual Model of a Complex Area with remediation of commingled plumes, in the Metropolitan Region of São Paulo". It further discusses the definitions and proposes translations into Portuguese (within the original version) for Complex Areas and Commingled Plumes, in addition to further developing the study area Temporal Conceptual Model with the application of Implicit Modelling. This is a paper that was submitted in Portuguese (and translated here) to the Brazilian journal Geologia USP Série Científica in January, 2023. To present, no decision has been provided about its publication.

Chapter 7 discusses the main results of the long term monitoring campaign, in addition to presenting an evolution graph for concentrations of the main former abstraction well.

Chapter 8 presents the overall conclusions acquired during this research, in addition to general recommendations for future works.

The bibliographical reference descriptions are provided at the end of this thesis, except to those that are part of the papers.

3. CONCLUSIONS

This doctoral thesis evaluated Complex Area management aspects based on the development of a more clear and holistic conceptual site model for a remediated site in the MRSP, Brazil. This site presented several challenges characteristic of Complex Sites, such as commingled plumes within former abstraction wells in fractured bedrock. The conceptual model was developed following a Temporal Conceptual Model strategy, defined in this study, considering the site evolution and management actions. Several tools were applied, such as compound specific isotopic analysis and implicit modelling. The results allowed further detailing (spatially and temporally) of the conceptual model, including identification of contamination sources, commingled plumes and rehabilitation processes.

Chlorinated ethanes and ethenes geoforensic isotopic analyses and hydrogeochemical results allowed characterization of source areas and their commingled plumes, before and after thermal and bioremediation treatments. Prior to full scale remediation, a recently identified off-site source area with unknown history and limited access presented lower δ13C values in groundwater (-6.5‰ to -1.8‰ for 1,2-DCA) than the downgradient on-site source area (+8.6‰ to +20.0‰). Intermediate δ13C values for 1,2-DCA were identified further downgradient from the sources, within commingled plumes patterns. The isotope and concentration results presented typical degradation patterns associated with biotic reductive dechlorination for chlorinated ethenes and dihaloelimination for 1,2-DCA. Results following remediation treatments show further levels of isotopic enrichment, for chlorinated ethenes and chlorinated ethanes in the tropically weathered and deeper fractured bedrock groundwater. Hydrogeochemical results, isotopic mass balance and Carbon-Chlorine isotope slopes were coherent with remediation treatment and a commingled plume setting. After bioremediation and thermal treatment, isotopic fractionations were identified. The results of this study confirmed the proposed Temporal Conceptual Model and identified the need for further studies to evaluate isotopic dynamics under thermal remediation, including thermal-induced hydrolysis processes.

It was concluded that investigation and remediation strategies in the area benefited from concepts advocated in Adaptive Management, such as successive refinement of the conceptual model, overall evaluation of results, definition of intermediate objectives, and optimization of remediation strategies. In this context, were also recognized uncertainties related to the delineation of external sources as well as the complexity of flow in the fractured rock. Nevertheless, the main impacted former abstraction well (PP-05), after influence of reconfiguration, commingled plumes and remediation actions presented continuous decreasing contaminant concentrations (between 2013 and 2022), towards bellow VOCs drinking standards. Throughout the long-term monitoring campaign the highest concentrations was identified in a localized well of the hard weathered rock unit, possibly due to potential limited residual mass of the commingled plume within a double porosity media of difficult access. Based on the available results, including multiple lines of evidence and the Temporal Conceptual Model, this Complex Site was considered rehabilitated by the environmental agency in 2021 (after 22 years of specific management) with no complete risk pathway identified under the current and foreseen scenario.

This study confirmed that the Temporal Conceptual Model strategy allowed a more clear and holistic understanding of the challenges of this Complex Area, that potentially can be used at other sites. In MRSP, throughout Brazil and other countries there are possibly many other sites similar to this study area, with technical and non-technical challenges that prevent meeting objectives in typical timeframes. For example, former industrial regions that exist in MRSP are known to present multiple sources and high potential for commingled plumes. Management challenges, such as mega scales and complex geochemistry, are also common in mining and agriculture areas throughout Brazil. Some activities even in forestry regions, such as the mining in the Amazon forest that has caused extensive mercury contamination, also present major challenges and uncertainties that clearly require long term unusual management strategies. In the United States of America, studies indicated that 9.5% of all their identified contaminated sites (126 thousand) could be considered as complex from a hydrogeologic and contaminant perspective. In Europe, initiatives have been developed to recognize and learn from the complex, large and prominent brownfields (typically named as Megasites). In Brazil, the State of Sao Paulo has classified 18 Critical Areas, a type of Complex Area, currently representing only 0.27% of the current total amount (6.6 thousand) of identified contaminated areas.

It is recommended that Complex Areas shall be further identified and managed following international recommendations, while also contemplating local considerations and adaptations, such as: 1) encompass in the definition of Complex Areas those contaminated areas that have been proven to present several challenges of high complexity and require more time of continuous management actions than typically needed for an area to be rehabilitated (estimate it typically takes 15 years in São Paulo and 20 years in the USA); 2) consider among the technical challenges (of Geological Conditions, Figure 4) the existence of extensive weathered profiles in humid tropical regions (due to its high heterogeneity and control of contaminant distribution); 3) encompass among the technical challenges (Hydrogeological Conditions, Figure 4) and among the non-technical challenges (Institutional Measures, Figure 5) the pumping from unregistered abstraction wells (because they generate uncertainties about flow and contamination, as well as difficulty in management) 4) consider among the non-technical challenges (Figure 5) the existence of social-economic conflicts such as those related to insecurity, exposure, irregular occupations (due to their instability, associated risks and difficulty of dialogue); 5) evaluate in detail, including with isotopic studies, the possible presence of commingled plumes (due to the limited knowledge of this situation in several areas of Brazil and its recognition being essential for proper management); 6) progressively develop clear and holistic Temporal Conceptual Models.

The adequate identification and management of Complex Areas, as well as a clear and holistic understanding of their challenges (such as commingled plumes) expressed in Temporal Conceptual Models, have great potential to assist in the understanding and rehabilitation of other contaminated lands throughout Brazil and possibly in other countries. The development of new studies and applications of Adaptive Management, Compound Specific Isotopic Analyses and Implicit Modelling can also be of great value, including to increase confidence of current and future stakeholders. Contaminated Complex Areas have major challenges that shall be adequately understood and managed so the next generations can thrive in an ecological balanced environment with access to essential resources, such as healthy earth and groundwater.

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