MONSOON ASSEMBLAGES FORUM

The Relational Materiality of Groundwater

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This paper is part of a larger research project which draws out ways of knowing and thinking with groundwater from Chennai, south India. The (under)ground or (sub)terranean environment is a thick and complex, three-dimensional space of "nothing but change," but whose utility is essential to sustaining urban life above it. This paper looks at multiple, specific, and contradictory ways in which the materiality of groundwater is understood and intervened in. Using the case of the ongoing Chennai Metro Rail construction project, and its disciplinary cultures of representation, I bring attention to the ground and its waters as a composite system in both balance and unrest, and an active, vital component of the city. Through unpacking established concepts of strata, porosity, and pressure, I will cast groundwater not as an objective fact, always pictured by, and relative to, a human subject, but as an actual being which humans (and others beyond) perceive, relate to, and come into contact with. I close by drawing from this account a possible further set of concepts which groundwater generates—dynamic states which are common to human and material life—suggesting that a relational theory of groundwater materiality, based on leaking as opposed to bordering, might better respond to the ways in which groundwater troubles knowledge. **Key Words: Chennai, groundwater, hydrogeology, materiality, relationality.**

"A FLUID INTERIOR"[1]

On April 20 2017, multiple news outlets reported that "huge amounts of sludge" had flooded into a Muthiah Street in the North-Chennai residential neighborhood of Washermanpet (Mathew and Chatterjee 2017). The sludge had not been carried in like floodwaters, however, but had rather erupted, or "bubbled forth," from the apparently stable ground. There seemed to be no clear way to describe the substance, which was not obviously industrial effluent, nor sewerage. An even, gray, cement-like, and smooth material had occupied the ground floor of several houses early in the morning before spreading into the street (Figure 1).

Since 2015, tunnel boring machines had been worming through the strata directly beneath Chennai's streets as part of the construction of the first phase of the Chennai Metro Rail

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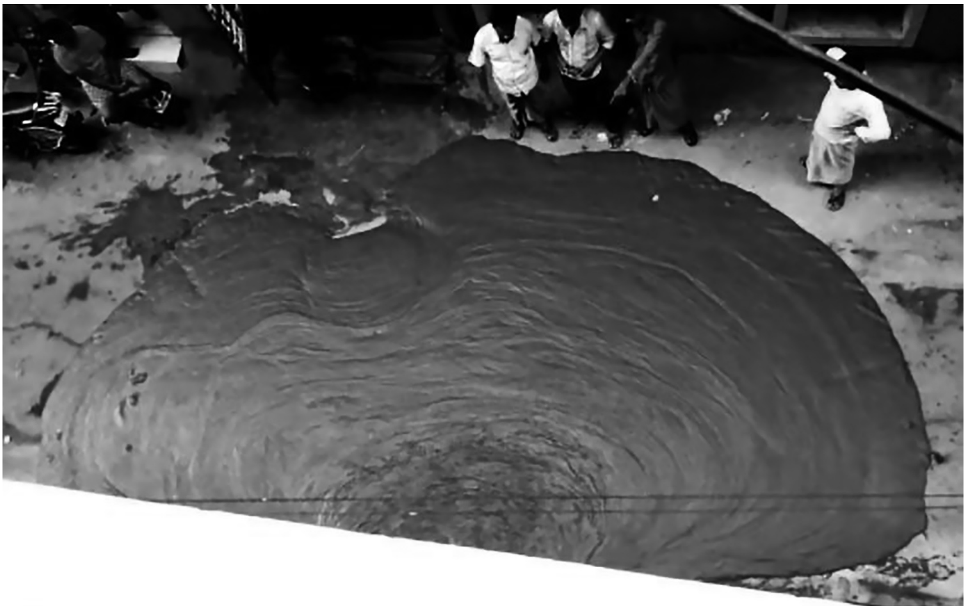

FIGURE 1 Sludge in Washermanpet, North Chennai, April 2017 (Mathew and Chatterjee 2017).

network. The final section of tunnel, from Saidapet to Washermanpet, included a 3.4 km rocky stretch from Chennai Central to Washermanpet at a depth of 28 m (Sekar 2016). This rocky stretch presented particular problems for the engineers and geologists directing the project, of navigating through a variegated and poorly-mapped geological structure. Speculation suggested that additives injected onto the tunnel face to modify the plasticity, texture, and permeability of the soft ground, and mixed with disturbed soils at high pressures, had been forced into a crack in the geological strata, and erupted into a nearby borewell—which had earlier been ordered closed (CMRL 2011)—eventually bubbling and spreading through the street and into houses. Advertising around this time for the metro network, which opened in 2018, promised "fluidity, part of every passenger's daily experience."[2]

A week earlier, following the opening of a massive sinkhole on Anna Salai, which had pulled a public bus deep into the formerly even pavement, further cracks were appearing in the road (Figure 2). A certain entropy was apparent: the fragile and capricious nature of the ground was becoming inescapable. In total, nearly a dozen collapses and eruptions were connected to the construction of near-surface tunnels and stations by Chennai Metro Rail Limited (CMRL) between 2015 and the opening of the first underground sections in 2018. At the same time, anxious residents blamed the tunneling for reduction in groundwater levels (Stalin 2019), at a time of severe drought and lack of water supply.

The attribution of blame (was this the fault of the engineers, the residents, the boring machine, the geological strata?) is not the direct purpose of this paper. Instead, by concentrating on the materiality of groundwater and how it is known, I hope to offer provisional glimpses into

FIGURE 2 Cracks in Anna Salai, April 2017 (The News Minute 2017).

urban processes that are highly charged and highly political: fleeting assemblages around the materiality of groundwater, which have potent political consequences. How can we use these moments as ways into knowing better how human and nonhuman forces collaborate in the making of urban space, and in its deterritorialization? Such moments of shock destabilize the material and conceptual categories that otherwise condition stable urban life, but they are only reminders of an ongoing and unseen dynamic reality that is the rule, not the exception. It is this realization that I wish to explore in this paper: that the ground on which we stand, and in which we build our cities, is capable of much more than static, passive, support; that it has the capacity to surprise and disrupt, as well as to make life possible in multiple ways. There is not one single thing called ground, but multiple grounds, variously saturated, seeping, sinking, and subtended by others. Living with these grounds is living in conditions of unstable hydrogeological emergence.

What follows is divided into three sections. In the first, I raise some methodological questions about studying groundwater through the interplay of materiality and representation, in the context of existing literatures of the underground and other dynamic materialities. Second, I contextualize the paper within an overview of Chennai's groundwater context, and the recent metro construction project. Third, I unpack three concepts—ways in which the metro construction project renders groundwater—that bring into view the materiality of groundwater and help us think with it, both because they are ideas that groundwater helps to generate, but also that groundwater continually exceeds. These are deep as opposed to surface concepts, a set of relational modes from groundwater which are also methodologies. Writing about the tunneling in this way, rather than through the economics, machinery, and other processes, is "letting surprising themes narrate the argument" (Parikka 2016). I close by drawing from this discussion a possible further set of concepts which groundwater generates—dynamic states which are common to human and material life—suggesting that a relational theory of groundwater materiality, based on leaking as opposed to bordering, might better respond to the ways in which groundwater troubles knowledge.

INTRA-ACTIVE MATERIALITY

By studying ways in which groundwater is known, and how it troubles them, it is my aim—in the words of Karen Barad—to "seek some way of trying to understand the nature of the interplay of the material and the cultural in the crafting of an ontology" (1996, 164). That is, to use the materiality of groundwater as a medium which explicitly evades binary categorizations (social/natural or material/representational), and rather asks: how do they trouble or leak into one another? Groundwater is physically remade through ways of thinking it, just as Barad writes that "*our knowledge-making practices are social-material enactments* that contribute to, and are part of, the phenomena we describe" (2007, 26, emphasis added). The one must be read through the other: neither the object of investigation nor the "agencies of observation" can be subtracted out, or absolutely determined independent of provisional assemblage through which they both come to *be* in a way that is both contingent and emergent, and through which both are remade (Barad 2007, 31). Barad calls this "intra-action," indicating the co-production of knowledge and object. The science I discuss here (hydrogeology) and the material (groundwater) are co-constituent parts of the same story: "the very nature of matter and the very matter of nature [are] (iteratively re-)constituted through a(n iteratively reconfigured) multiplicity of force relations" (Barad 2017, 110).

So, whilst this paper is about the instability of the material itself, it is also about the ways in which we attempt to render chaotic agents as stable environments. I say "render" because this process is something that occurs through the generation of representations. Groundwater both produces and is reproduced in representational and visual cultures. Groundwater research, and its dissemination, is often framed as "making the invisible visible" (Nilekani 2018), and this "invisible and capricious nature of groundwater" (Lapworth et al. 2018) presents immediate challenges for any form of research which tries to approach groundwater. Groundwater is rarely measured directly: hydrologists rely on signs, tracers, responses, and patterns (including tidal fluctuations, and surface temperatures) that can be used to infer a behavior or parameter. As H. B.N. Hynes observed that rivers are manifestations of the landscapes they drain (Hynes 1975), urban groundwater is a kind of archive of urban development, but one that is reciprocal with(in) it. Because groundwater is defined by continuity and contamination, and the impossibility of isolating any particular element, it is less an archive and more like a "ruin" (Bryant 2018): a congregation of matter, very clear in some places, and entirely distorted in others, which presents a "quasi-phenomenological way of thinking past correlationism," forcing us to think past human representations of non-human things, by constantly exceeding and confounding them. The ways in which elements actively change within groundwater in unexpected and unpredictable modes open up the way we must think about the material to worlds beyond the human: groundwater does not present as something to be read, in the way that we think of records or archives. The histories are there, but turbulent and troubled.

Groundwater is not the only material to have these qualities, nor the only area of scientific research that is confronted with problems of measurement. But the "technical difficulties associated with sampling the underground aquatic environment" (Gibert, Danielopol, and Stanford 1994) combined with "the methodological challenge that some of the most interesting anthropocene science poses to geology" (Ahuja 2016) makes groundwater a useful case study.

Vibrant Groundwater

We need to think through groundwater as an active element of cities. In this, I follow others in arguing for the "epistemic, physical, technical, and conceptual" importance of subterranean spaces as a site of multidisciplinary enquiry in the Anthropocene (Melo Zurita, Munro, and Houston 2018), and of the particular importance, and challenges, of "voluminous" thinking (Bridge 2009; Steinberg and Peters 2015). Much of the existing work in these sub-fields of environmental humanities, science and technology studies, and political ecology, focusses on extractive industries (fuels, minerals, and water) and contestations around sites of extraction (Bebbington 2012; Kinchy, Phadke, and Smith 2018), or otherwise the imaginative, literary, and cultural representations of ground which are generated by new technologies of extraction and investigation (Williams 1990). For Rosalind Williams, subterranean spaces, "whether real or imaginary," are the ur-examples of predominantly human-built environments, which "furnish a model of an artificial environment from which nature has been effectively banished" (1990, 2). On the contrary, I prefer to make an argument for the (under)ground in-itself as a site of enquiry, which is to say that the ground doesn't only become relevant when we humans poke, drill, or step down into it.

I use "groundwater" not to describe water in the ground, but rather a hybrid materiality of grounds and waters. Andrea Ballestero (2019) writes that aquifers, "while partially sharing some elements with the cave and the mine also exceeds them." Ballestero describes groundwater as a "dynamic architecture sucking and seeping, swelling and shrinking, absorbing and oozing." Groundwater is not a simple substance but a thick and complex three-dimensional environment, an intra-active relationality between water and ground: one upon which we rely for many aspects of our own lives, but which is not there purely for our ends. I won't talk about groundwater as a series of bounded aquifers, since the definition of an aquifer is subjective, and temporary: being simply the point at which the accessibility and availability of groundwater becomes useful for a specific purpose, in a specific location (Waltz 1969). To name and draw aquifer is to suggest a static body of water, whereas we need to think with groundwater through its inseparably relational materiality.

To think with groundwater, we need to open to the multispecies and more-than-human, to think about "geological conviviality" (Reinert 2016): the specific and complex ways in which geologic existences intersect with humans. Feminist studies has destabilized the neat, distant, and binary relation between bodies and the environment, such as how Elizabeth Grosz described the human body as being "incomplete," "a series of uncoordinated potentialities," which is (re)produced, ordered, and codified—organized—in and through relations with others in the urban environment (Grosz 1992). This position also reminds us not to think of materials a given formations (or objects) with which we interact but, instead, of the "processual, material and perceptual engagement between body and world" (Miles-Watson, Reinert, and Sooväli-Sepping 2015, 3). This doesn't mean avoiding our positionality, erasing the "significant otherness" (Haraway 2003) between ourselves and other forms of life. Indeed, "our humanness is also a starting point, an opening for getting involved in multispecies worlds. [. . .] Our doings are a way to trace the doings of others" (Tsing 2013, 34). I want to think about humans and groundwater as co-existence, not to understand nature "only in relation to human goals and needs" (Tsing 2013, 33), nor in terms of conservation or concern, but in order to establish "some form of empathy" between these worlds (Reinert 2016, 106).

These assertions are driven by my reading of a growing field of enquiry loosely-termed *vital materialism*[3] which has—in the past few decades—sought to give materials a voice in the way we understand the material world in which we live. "Our concepts have been formed on the model of solids," wrote Henri Bergson in the introduction to *Creative Evolution* (1911, xix): our ontology is predicated on the inanimate nature of objects, and the primacy of human subjects, who bring those objects into being. Jane Bennett's *Vibrant Matter* (2010) contests the schema by which the world is divided into living things (like us), on the one hand, and inert "mere matter" (like groundwater), on the other. Bennett instead proposes a broad continuum, in which such matter—including things not directly observable—can be made not only visible, but "thinkable" within "cultural ensembles" sensitive to their effects (2010, xii). The aim is to bring material actors into an understanding of morality, ethics, and politics, in order to "cultivate a broader definition of self-interest" (2010, 13), to open up to "a fuller range of the non-human powers circulating around and within nonhuman bodies." This is marvelous, but by allowing other actors into the worlds of knowledge we have already built, are we really open to what they have to say? Isn't this a materialism assembled onto the ready-made foundation of anthropocentric knowledge systems? Criticism of such approaches includes Tim Ingold's (2007) response to "the ever-growing literature in anthropology and archaeology that deals explicitly with the subjects of materiality and material culture [but which] seems to have hardly anything to say about materials." Ingold's suggestion is that, despite the salutations given to the importance of "materialism" (loosely termed), existing work in this field very rarely mentions actual "materials or their properties," but instead extrapolates wildly after, as Bergson wrote, "only the lightest possible contact with experience" (1911, xx).

In such a vein, Nigel Clark and Katherine Yusoff have laid out an argument for looking at socio-political worlds through their relationship with particular geological forces and formations. Beginning with Clark's description of the earth as a dynamic and volatile force that exists beyond its relationship to human life (2011), Clark and Yusoff (2017) ask us to engage with variability "through the issue of the relationship of social existence to the forces of the earth," and to expose "the inherited concepts and categories of social thought [...] to the forces, magnitudes, and durations with which the earth sciences work." Grounds can't be cut off from their formation (or their futures). This sense of a restless, temporal instability must also be retained. "It makes little sense to agonize over our contributions to earth processes without as full an understanding as we can get of the dynamics and potentialities that are constitutive of material reality in and of itself" (Clark 2011, xiv). Keeping this in mind, I try in what follows to pursue groundwater as a material, albeit though its unstable records and partial traces.

THINKING WITH GROUNDWATER FROM CHENNAI

The purpose of the previous section is to establish that the object of enquiry of this paper is not groundwater-as-such but the always hybrid, multiple, specific, and contradictory ways in which different people get at it: scientific abstractions, research methods, instruments of measure, policy, and legal frameworks. Groundwater is not an archive, but it produces one. My wider project uses a kind of quasi-archival research, which takes as its material the physical holes opened in the ground, but also the ways in which engineers, geologists, and other professionals represent and understand the groundwater environment, and eventually work with(in) this material. The following section situates this research in Chennai's broad geologic context.

Chennai and the Indian Peninsula

Thinking with groundwater in relation to urban development necessitates a broad understanding of the spatially- and temporally-distributed nature of urban settlement. As a way of thinking through groundwater in Chennai, I start with the Eastern Ghats—a discontinuous mountain range spanning India's Coromandel Coast, stalking the Bay of Bengal from Odisha, near the border with Bengal in the North, through Andhra Pradesh, to eventually meet the Nilgiri Hills near Coimbatore in southern Tamil Nadu (Figure 3). From these mountains, comes the material that forms the plains. The main rivers of Tamil Nadu—Pallar, Pennai, and Kaveri—flow from there, carrying matter which by its transmission becomes known to us as alluvium, and eventually draining into the shallow Bay of Bengal. Irrigated, trenched and bunded, bearing the marks of the massive continental engineering project of surface-water management, these vast fields of sand are the temporary rests of this alluvial matter. Rocky outcrops duck and bob, in and out of the plains, separating the low-lying coastal region from the high mass of the Deccan Plateau (Cushing 1913; Wadia 1919) (Figure 4).

Chennai sits upon and within this young, low-lying coastal plain held between the Eastern Ghats, and the Bay of Bengal.[4] The seemingly smooth plains are also fundamentally three-dimensional. By its very nature, a landscape of overlain sediments is thick, deep, and complex: a "geomorphic system" composed "of interacting processes and landforms that function individually and jointly to form a landscape complex" (Chorley, Schumm, and Sugden 1984, 5). A complex which is also not firm in its heterogeneity—certainly not an absence of nature—but dynamic, shifting, and saturated with both vapor and life:

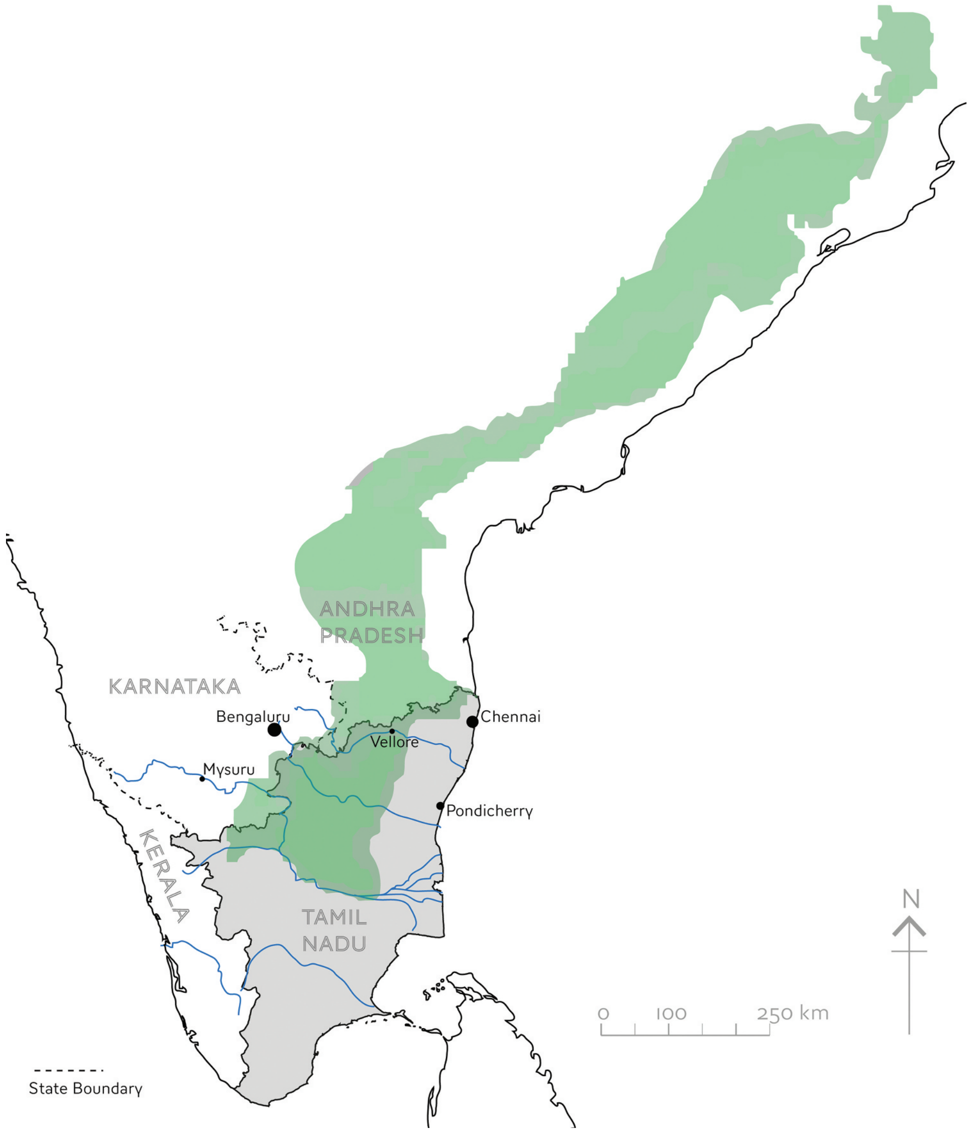

FIGURE 3 Tamil Nadu (gray) as the southern terminus of the Eastern Ghats (green). Drawing by the author.

> the Chennai region is geologically vibrant with active geodynamics viz. tectonics and tectonically induced riverine and coastal geomorphic processes. (Ramasamy, Vijay, and Dhinesh 2018)

Into this context, comes the north-eastern monsoon: a set of interrelated seasonal phenomena, and associated behaviors, rhythms, cycles, and uncertainties. These (re)saturate, cleanse, and

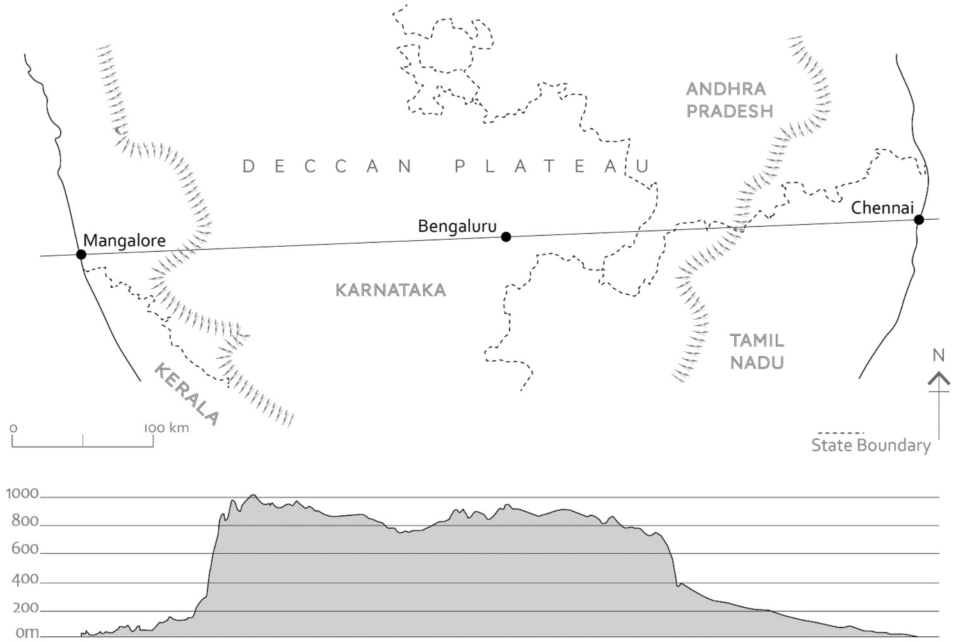

FIGURE 4 Section of the Indian Peninsula from coast to coast (exaggerated y-scale). Drawing by the author.

swell the ground. Everything about the city depends upon this region, and the complex relations in and between land and climate, from the Ghats, to the plains, and to the bay. Chennai, characterized by its wide beaches, is not a fixed point, but the boundary at which alluvial matter stops collecting, can no longer form deltaic solids because of the force of the sea. It is a point of balance, in constant tension to either side. Thinking about Chennai through both the Eastern Ghats, and the Bay of Bengal, is a way of beginning to read the city outside of more bounded narratives of urban form.

The monsoonal delta climate defines a spatially-shifting landscape. That is to say, large amounts of sediment, carried and deposited by seasonal rivers, continually reshape the land, as it sways between states of liquidity and solidity. In the immediate area of the Chennai region, the recent alluvium deposited by the three main rivers—the Kortalaiyar, the Adyar, and the Cooum—is underlain by hard rock in the southern and western zones, and by conglomerate and sandstone in the North and West (Ballukraya and Ravi 1995; Geological Survey of India 1999). The movements of rivers have, over time, added geological complexity to this sequence, alongside gradual erosion and sedimentation, decay and compression, transmission and settlement.

This dynamic geology has long sustained human livelihoods. Tools found at Atirampakkam, 50 km north-west of Chennai, in 1863, have since been dated to up to 1.5 million years ago. That is older than any human settlement found in Europe and predates the alluvial deposits that produced Chennai's landscape. As noted by Robert Bruce Foote, this meant that "great changes in the physical geography of the Indian peninsula have taken place since the time when the implement-makers first inhabited the country" (Foote 1868). The excavations vividly capture the entanglement of human and earth systems over time, as the strata—laminated clay beds—conceal tools and other human-made objects (Pappu 2007). Here, then, a relatively young geological landscape, and an especially deep history of human inhabitation, combine to offer a remarkable parallel between the scales of material histories of the landscape itself, and of its human occupation.

Degrees of Saturation

Chennai has a heterogenous groundwater system, patchy and bounded, where areas of high permeability are separated by material of lower permeability. Chennai's groundwater varies at a fine scale according to the geological strata, recharge potential, and the technologies used to access it. The level of saturated groundwater is typically only a few meters below ground level and oscillates variously by between 0 and 6 m between mean high and low periods (wet and dry season), and flooding is as common a problem as drought. Relatively modest extraction of groundwater, both deep and shallow, by means of "ring wells, dug wells, filter point wells, bore wells and tube wells" (Balakrishnan 2008), has a significant effect on the water levels both locally and in surrounding areas, which also vary according to proximity with old tanks and surface reservoirs (Ballukraya and Ravi 1995, 95–96). Overexploitation accelerated with the introduction of new technologies of sinking wells deeper and pumping water faster (Acciavatti 2017), allowing farmers and households to withdraw from the regulated sphere of surface water distribution into the uncharted space of groundwater.

The typical groundwater movement is seawards, with a gentle slope approximately correlating to that of the terrain above. The groundwater strata have continuity with the sea, meaning seawater intrusion is possible, and this regularly occurs when groundwater levels inland are low, leading to brackish water being drawn from domestic wells. At other times, the seaward flow maintains the freshwater-sea interface, and prevents sea water from intruding inland, meaning that the near-surface strata, when tapped by shallow wells along the coast, can often been found to yield relatively fresh or "sweet" water despite the proximity to salt water, and despite groundwater levels being below sea levels (Ballukraya and Ravi 1998, 279). This is typically after the monsoon increases groundwater levels (Vutla and Ravichandran 2011), both recharging, and "flushing" through the aquifer, diluting contaminants and moving them via increased flow rates, improving water quality.

It can be seen from this brief account that both the landforms, and groundwater environment of the Chennai region are the result of fluvial processes. But noting that many of these processes played out in such recent history that they have been contemporaneous with histories of human inhabitation helps to remind us, as Philip Steinberg and Peters (2015) stress, that we must resist the tendency to view (sub)terranean matter as "fixed and grounded," finished, complete. Though techniques of geological investigation "abstract and dematerialise [...] the vertical element of volume" (Ibid.), in the rest of this paper, I go on to utilize records connected with the Chennai Metro Rail construction project—geological surveys, borehole logs, the daily accounts of tunneling, press coverage, and conversations—as a way to start to think with groundwater as a vital component of urban infrastructure.

THREE RELATIONAL CONCEPTS

Begun in 2007 as a joint venture between the Government of India and the Government of Tamil Nadu, the Chennai Metro Rail project uses a mix of underground tunnels and elevated sections. Construction began in 2009, with tunneling work commencing in 2012. In this section, I will unpack ways in which the project utilizes certain disciplinary concepts and methodologies in order to remake the groundwater environment as something which can be intervened in: the tension between stability of representations and instability of material forces, as well as how disciplines have tried to account—both implicitly and explicitly—for this tension. Documents issued by CMRL, for instance, are full of representations that mix technical information with visually-derived imagery. Photographs and technical drawings are mixed in curious ways such as the overlaying of a perspectival projection of the tunnel path onto a photograph from the surface above (Figure 5). This produces a speculative assembly of different kinds of information, some experimentally derived, others projecting, and also leaves much out. The point of the following critique is not to slur technological and scientific imaginations, or to dismiss the utility of specialized representations, but to recognize their limits and understand where they come from.

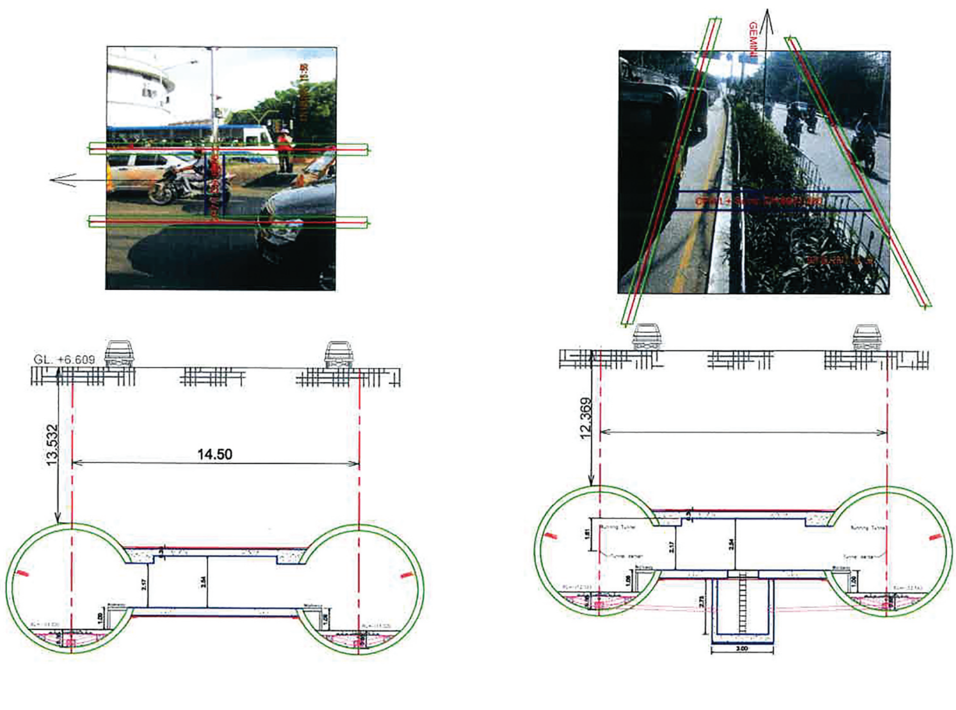

FIGURE 5 Tunnel alignment description. From CMRL tender documents.

Strata

Each phase of the metro construction has been preceded by detailed geotechnical survey work, which provides the bulk of the material for this section. Survey work for the section of corridor 1 beneath Anna Salai was done twice, in 2005 and 2009.[5]

Stratigraphy is the science of describing and classifying rocks for the purpose of "arranging them in the chronological order in which they were lain down on the surface of the earth" (Krishnan 1956, 89). Stratification, the process, the way these materials are laid down, has always been reflected in modes of understanding broader societal/political dynamics. Certain laws of geology—subtension, superposition, continuity—become fundamental to thinking with strata. The physical process, the way these materials are laid down, though, has always been

FIGURE 6 Sampling rig in Chennai, 2018. Photograph by the author.

secondary to the system of classification. Stratification is fundamentally a way of conceptualizing the composition of the ground.

Strata are less often directly viewable (as in an excavation, or a cliff) but rather inferred from the boreholes collected as part of geotechnical survey work: cores of earth which provide the raw material for the stratigraphic section. The methodology of the survey work privileges, above all else, the borehole, and the core sample—a process and a physical archive, which together are used to produce a drawn record of sub-surface lithography. With this method, a boring rig (Figure 6) sits upon made ground of recycled and compacted rubble, and drives a 150 mm-diameter hollow casing attached to an auger, to a depth of 30 m into the ground. The drilling rig, and type of casing used, are selected according to the presumed ground conditions. Disturbed samples, direct from the drill head, are taken for use in physical tests, and "undisturbed samples," of 450 mm length and sealed with wax in 100 mm-diamater tubes, are taken every 3 m (Systra, and Indian Geotechnical Services 2015) (Figure 7).

The material core is instrumentalized, in order to undertake physical tests: visual lithography, and grading of samples according to weathering (in the case of rock), or grain size analysis (clay—silt—fine/medium/coarse sand—fine/coarse gravel), in the case of unconsolidated material. Lab testing included standard penetration test (SPT), shear tests (stress/strain), consolidation testing, and compressive strength testing (for rock). The hole is also utilized, for measuring permeability, and depth of water table. In more detailed surveys, chemical analyses of water extracted from the holes is also used.

From these cores and holes, a picture of the subsurface is developed through the description and classification of strata: a way of setting boundaries by classifying matter vertically. The borehole locations are drawn, and subdivided according to the agreed set of strata, then connected to form horizontal bands of material (though which often subtend and consume one another). Whilst the boundary between hard rock, and silty sand, is easier to define (though the sand may penetrate fractures in the rock), the classification of independent alluvial strata

FIGURE 7 Box of core samples from Washermanpet survey. From CMRL tender documents.

requires a judgment from the surveyor to mark where a named stratum ends, and another begins. Strata must be defined. Guesswork adds to the partiality of the knowledge produced.

The translation from individual holes, to flowing horizontal strata in two-dimensions, occurs (explicitly) within the section drawing as means of communication. This is a process of inference, whereby a box of core samples (vertical, linear) becomes a flowing, two-dimensional section, which may eventually be turned into part of a quasi-three-dimensional diagram, or by further inference become part of a three-dimensional model: estimating (guessing) what goes on in the regions between where the samples have been taken.

Geological sections like this are speculative, they draw something unseen, and un-viewable. Both in the hidden-ness of underground structures, and in the evasive and anti-pictorial movements of the material itself. As a compromise, they draw only the solid strata, as if its saturatedness were irrelevant. Or perhaps just too awkward to draw? Philip Scarpino (2018, 105) recalls the inscription of extinction events in sedimentary rock, as a fossil record "in effect serves as the 'database' or the 'archive' that documents the evolution of life on earth." Groundwater is not like a geological record. As Shannon Mattern (2017) observes: "the climate archive (like most archives) gets wilder and dirtier the deeper you go." In the case of groundwater, the archive is sufficiently churned and bowed just below the surface, such that it is almost impossible to understand as neatly-delineated strata.

Unlike the "biorecords," the "big and slow" data sets of sediment collections (Mattern 2017), which act as proxies for processes we cannot or do not see, groundwater does not become physical documents. Some dirt, such as the disturbed and undisturbed core samples, becomes data in (an) archive, but it hasn't taken with it the conditions from whence it came. In any case, material data is irreducible to digital data: it doesn't translate.

The particular section reproduced above (Figure 8), which includes the area where the eruption that began this paper occurred, renders strata as neatly distinct from one another, distinguished by hatches relating to material classifications based on particle size (clay, silt, sand, gravel). But at the same time, they seem to flow into one another. The authority of the borehole logs as source material when superimposed onto the section is undermined by the abstract, speculative geometries the supposed strata are forced into. You could be forgiven for forgetting that such an environment has dynamic capacities because of the ways in which it is stabilized in the representation.

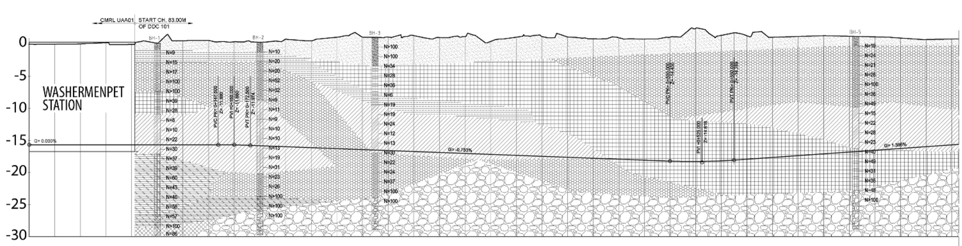

FIGURE 8 Section of Washermanpet tunnel from geotechnical surveys prior to construction. From CMRL tender documents.

Strata and assemblages

Just as strata here is a method of composition derived from physical science, Deleuze and Guattari's concept of "strata" is way to think both of "assemblages," and how such formations might "impl[y] a before, a beneath, a beyond to the human presence that draws our attention to other modes of relating" (Povinelli 2016, 137). For Deleuze and Guattari, strata are on a continuum with assemblages, assemblages being looser or less tightly held formations. Deleuze and Guattari remind us that the geologic is not some static or absolute base, but as an always shifting platform, an 'inheritance,' which the earth constantly flees and destratifies. But strata as rather passive, fixed entities persist in both Deleuze and Guattari's concept and the representations above: the Chennai Metro Rail project utilizes scientific knowledges and technologies in 'a new organising of the general flows of the earth' (Yusoff 2017). These methods are, in themselves, moments of destratification and recomposition. But groundwater escapes its geological holding structure: the drawings show only the ground, not the water, the solid (or very slowly moving), but not the more dynamic (Ballestero 2018). Manuel Delanda suggests doing away with the term altogether, since strata are simply more stable forms of assemblage (DeLanda 2017; Deleuze and Guattari 1987). Yusoff (2017) suggests that we recognize strata "as planes of social production that both constrain and are expressive of relations," and which organize modes of expression: "the relations between the material and expressive elements of strata offer a methodology for political geologic analysis that excavates the constitutive power relations that derive from geologic forces that exceed but continue to animate the social field." Clark (2011) argues for an understanding of conditions as a layering of actions (assemblages) upon one another, each action or assemblage bequeathing 'worlds left for others to inherit,' the former organizing and enabling the latter as the 'condition of later existence' (Clark 2011, 50).

What this account of groundwater problematizes, though, is the rather passive and inert nature of these immaterial strata. In this account, groundwater is constantly destratifiying—not being destratified, but doing the work itself of reorganizing social-subterranean relations. What is crucial, if destratification is to be a useful concept, are the gaps (or intrastratum) between these unstable and destabilizing environments, and their static representations in law and politics. Accounting for this means to describe the intra-strata assemblages: how operations traverse different strata and bring their productions into novel arrangements.

Porosity

The identification of ground as distinct strata, both physically and conceptually, attempts to render it knowable, and workable: quantifying its particle, strength, and consolidation attributes produces an image of a material which is consistent and comprehensible, but also static and lifeless. The concept of porosity challenges this view, by demanding an engagement with changeability, movement, and uncertainty.

As a geologist in Chennai told me, "water is there everywhere."[6] Water can occur within the ground because of voids, or pore spaces within materials. And "flow occurs through the small passages of porous rocks" (Hubbert 1940, 796–797). "Storage" is the ratio of free space (pores/voids) to the total volume, and "permeability" the facility by which fluids travel through the material.

Hydrology in the 19th century developed around quantifying these properties of porosity, conductivity, flow, and developing written equations to account for them. Groundwater hydrology as a science, and understanding of the surface-ground interrelation, developed out of necessity, initially during the late industrial revolution, as utilization of groundwater increased along with industrialization, population rise, and urbanization (Bowen 1986, 12–13). It became necessary to develop groundwater resources, by developing ways of knowing them.

The need to develop filtration methods directly led to the production of Darcy's Law governing flow through porous media, the foundation for quantitative analysis in groundwater hydrology (McDonnell and Anderson 2008, 1). So, at the inception of the discipline, it is founded as a quantitative one, and one which is concerned with mapping groundwater *as a resource* (see also Freeze and Cherry 1979). As Mary P. Anderson notes, most foundational concepts and major developments in hydrology were established during municipal surveying operation motivated by the quantification of water resources for the purpose of extraction. Henry Darcy's work was empirical, and experimentally derived.[7] As part of a report to the city of Dijon on the efficacy of various methods of filtration, along with the engineer Charles Ritter, Darcy constructed an apparatus within a local hospital to hold a measurable column of sand, within a 350 mm-diameter pipe (Darcy 1856), through which a flow of water could be passed. Using graded sands from the Saone river, varying the pressure at the top of the column, and noting the rate of water discharge at the base of the column, Darcy and Ritter showed that "for an identical sand, it can be assumed that the volume discharged is [directly] proportional to the head and inversely proportional to the thickness of the sand layer that the water passes through" (Darcy 1856, 456). That is, that there is a linear relationship between hydraulic head (or pressure gradient) and the rate of flow through a porous medium. The factor that relates the two is the hydraulic conductivity (porosity) of the material.

What was really important here, as later shown by Hubbert, was that the coefficient of permeability in Darcy's equation is "a specific conductivity parameter depending on both the properties of the fluid and the medium" (Hubbert 1940, 785). This means that groundwater is a relational material, indivisible into "ground" and "water": its properties are the result of the interactions in and between multiple parts.

Impermeable models

Despite this, the quantification of such processes remained based upon the division of ground and water: flows, which are multi-directional and unequal, were reconceptualized as two-dimensional, with secondary flows relegated as downward and upward leakage, and defined by a parameter. Hubbert, broadly considering energy transfer, defined flow as based on "fluid potential"—a value which developed beyond simplistic understandings of flow being based on pressure, but still reductively stated that "The flow of a fluid is a mechanical process" (Hubbert 1940, 796–797). In Chennai, layers of water-holding materials such as sands, are confined below and between beds of clayey, less-porous materials (aquitards). In such situations, the vertical transmission of water is crucial. "In ground-water motion in general, the direction of flow may have any inclination from vertical to horizontal" (Hubbert 1940, 794).

The theory of "leaky aquifers" (Hantush 1960) is a means of thinking about these heterogenous systems, by accounting for multi-directional and unequal flows. A material is defined as *isotropic* when it is equally permeable in all directions, but this is rarely the case, since groundwater also form strata.[8] In order to deal with this, geologists reconceptualize secondary flows as variables to a primary chosen directionality:

> Strictly speaking, the actual flow in such systems is three-dimensional. However, with certain assumptions [. . .], the flow can be treated as two-dimensional, augmented or diminished in the direction of flow by downward and upward leakage. (Hantush 1960)

The process is this: geologists first attempt to understand the zones through which this fluid is moving. After that, they apply laboratory-derived metrics to determine the expected flow rate in each zone. "The fluid that is moving beneath the surface is controlled by a mathematical equation. After you decipher this, you simply calculate the flux of water using the equation."[9] In order to enable such working, the ground is divided into "cells" at different resolutions, such as 1 km x 1 km, or 500 m x 500 m (the finer resolution producing a more accurate result, but more complex calculations). "For each small cell you need to feed in the required parameters: how much is the storage, how much is the transmission capacity." This is difficult to assign, and requires a lot of guesswork. When this is established, though, the modeler can discern how much water would have come from any point, based on estimated rainfall and pumping data. Flow is controlled by the gradients already established by the parameters assigned to each block. "If water table is inclined, only then it moves. If it is flat, then there is no flow. So, based on that we carry out the computation. It is actually very, very simple."[10]

I raise this, most of all to note that the standard procedure employed in groundwater modeling is two-dimensional, and quantifies vertical flow only as a proportion of the total: "it is an approximation of real-world conditions [. . .] To reduce the complexity."[11] Additionally, data itself is very difficult to get, and the authenticity is always questionable. So modeling is highly contingent on what is available:

> This is the problem you can see in almost every part of India, there is no proper measurement, or proper gauging [. . .] So, when you want to do a model, you have to calibrate, and you have to validate. To validate those models, you have to know the discharge, the previous measurements, and we don't have that measurement [. . .] My accuracy will be based on the data I am using.[12]

Data is cleaned, averaged, manipulated: the porous medium is again separated from the fluid flowing through it, in an attempt to make flows manageable. But as I am arguing, the solid material and the fluid cannot reasonably be divided. It is currently fashionable for urban designers to describe the ground of cities as a "sponge," but this way of thinking denies its relational materiality. Just as Barad's intra-action reminds us that object and observation cannot be subtracted out, these elements are as much of each other as they are independent, and thinking with groundwater should not rely on separation.

Pressure

Key to the development in characterization of groundwater as a combination of both water and ground, was Oscar Edward Meinzer of the United States Geological Survey (USGS), whose work developed the insight that aquifers are "compressible." Meinzer (1928) developed his theory from Karl von Terzaghi's pioneering work on effective stress and consolidation—the way that particles within a material behave in relation to one another under pressure.

Using the example of a train coming into a station, and leaving some time later, Meinzer demonstrated that the load on the ground above was "squeezing water out of storage." Under the increased load of the train, the porous material (ground) is compressed, reducing the available pore space and forcing the groundwater out of storage, resulting in increased water table and greater yield to nearby wells. When the train exits the station, the reduction in potential recharge results in land subsidence. If this water is removed, then the effect of the train leaving the station later on would be for the land to subside as there was no longer the same quantity of water to hold it up. Stress is transferred from pore water to the skeletal structure of the porous material (Poland and Davis 1969)—i.e., the pore pressure, along with the structure of the material (as per Terzaghi), does the holding up of the ground surface. When the pore pressure is decreased, the overall stress on the ground-water complex remains the same, and so the effective stress in the structure of the porous medium—"grain-to-grain load"—must increase. Depending on the consolidation and compressibility of the material, this may lead to subsidence. This was only conclusively documented as recently as 1969.[13] Before, it had been thought that the structure of the material operated independently of the fluid part.

This moment is transformative because it establishes an important principle: that land is not a holding vessel for water (as per the sponge concept) but that land and water are intimately connected—that the storage and flow of groundwater are essential to the land. The combination of pore pressure, along with the structure of the material, does the holding up of the surface:

> The pore space in an artesian aquifer is filled with water that is under hydrostatic pressure. Thus, the artesian water exerts a force that acts against the weight of the overlying rocks. [...] There are several lines of evidence that the artesian water, especially in strata of sand or soft sandstone, supports a part of the load of the overlying rock and that the aquifers are compressed when the artesian pressure is decreased and expanded when it is increased. (Meinzer 1928, 263)

Unlike Darcy, whose controlled experiments pictured sand and water as separate entities, which interacted under his control, Meinzer "had described the physics of hydraulic capacitance in hydraulic materials" (Narasimhan 1998). Hydraulic capacitance is fundamentally relational, produced within the interaction between ground and water.

Groundwater had become a material with capacities and relations. The qualities of groundwater come out through the interaction of ground and water. This is a crucial point: that its relationality is fundamental. Thinking in terms of pressure, not strata, offers an image of the ground as a squashy co-ordination of surfaces, wedges, beds: degrees of saturation, densities, and flows.

Groundwater in this view has become a material whose relationality is fundamental to its capacity as a resource that makes Chennai liveable. It is a constellation of forces in tension and compression. It becomes clear that these "more complex hydrogeologic environments [...] cannot be represented by the idealized configurations" of strata and porosity (Freeze and Cherry 1979), that balance and change are both fundamental to their behavior:

> Groundwater is much more complex, but we are representing a few factors only. We have put some basic parameters—hydraulic conductivity, porosity—we are generalizing things, you know? This is not actual representation. We cannot say what is happening inside, we are just representing, that is what I mean.[14]

Tunneling groundwater

Pressure is a means of thinking about groundwater which is fundamental to tunneling: "There is probably no engineering project that requires a more compatible marriage between geology and engineering than the construction of a tunnel" (Freeze and Cherry 1979, 487). Maintaining soil pressure is increasingly difficult where the strata is inconsistent through the height of the tunnel, and "an alternating sequence of more-permeable and less-permeable formations," as in Chennai, creates a constant inconstancy that is near impossible to predict. Unconsolidated sand and gravel deposits and permeable sedimentary strata such as sandstone and limestone create slippages, cracks between spaces:

> It is very difficult to do watertight excavations, nobody can do 100% watertight construction, there are always leaks and sediments. They have faced a lot of problems with the construction: surprises, things that were different to survey information.[15]

All the conversations I've had with engineers render water as a separate, and problematic substance, to be considered (and dealt with) apart from rather than together with the ground. But we have seen how groundwater as an irreducibly multiple material presence starts to come through in thinking about it as coupling, as stress. But this complexity is negated by the formats in which groundwater is modeled and quantified, formats which then provide the evidence to inform the real material construction activities that take place within it.[16] Thinking through porosity and pressure shows us that the tunnels are not just being dug through ground, but through groundwater—such that statements like "the primary geotechnical problem encountered during tunnel construction [is] the inflow of groundwater" (Freeze and Cherry 1979) no longer make sense.

CONCLUSION: TOWARD LEAKY THEORY

One thing we can take from this account is the idea of leaking as a fundamental and relational aspect of groundwater, and good to think with. Leaking brings out the intra-active relationality not only of groundwater as material but also of its resistance to absolute classification. This definition is in contrast to infrastructural leaking, which is cast as anomaly or failure. The modeling theory of leaking renders the constant vertical movement of groundwater between geological strata as secondary and incidental—a factorable anomaly rather than something central to the behavior of the system. But what if we refocus leaking as primary, not secondary?

> Every thing is constantly leaking . . . the only way to point to something is by bordering it, but the border (embankment) isn't a border, it is a site of exchange, it is constantly being maintained. (Povinelli 2017)

Leaking is not the glitch but the thing which enables the system to exist. Leaking is also a process by which groundwater exceeds categorization, it reminds us that strata, porosity, and pressure are relational concepts that describe dynamic states of being. As Ingold so powerfully evokes, "As the underbelly of things, materials may lie low but are never entirely subdued." It is the emphasis on properties of materials over material objects that I find so important here: to focus on what they do and how they change rather than what they are. To say that matter, specifically groundwater, is always processual and relational, means it is hopeless to try and characterize it based on separation and division. Its resistance to the clarity of classification, to the status of and object, or a number of objects, is its ontological strength by which it makes its own argument for itself as a "be-ing" not a "th-ing":

The project of hydrology throughout the 20th century has been the development of written equations to account for groundwater flow (below the water table, typically toward a pumping well), and unsaturated flow (in the unsaturated layer above the water table)—gaining increasing complexity as they took into account such parameters as earth tides, gravity drainage, compressibility, and delayed response processes (see e.g. Neuman 1972). These techniques, as employed in the Metro Rail surveying and monitoring, were developed for specific, industrial processes: core sampling relating to fossil fuel extraction, soil analysis to agricultural production. They are ways of getting at (and intervening within) specific aspects of a complex materiality, and which are often caught out by those aspects which they neglect.

This discipline is based on developing analytical solutions, estimates, parameters. As T.N. Narasimhan stated: "Estimation [...] is a fundamental task in many branches of Earth sciences and engineering" (Narasimhan 1998). But this is only one system of knowledge and understanding, with a particular history and motivation. Instead, paying attention to the ground as a kind of ludic infrastructure offers a way out of representation as an attempt at control, and demands that we work with not just in or on. My argument here is not about discounting certain concepts in favor of others, but refracting—to use Barad's (2007) term—certain codified and insufficient concepts though and alongside those which are incomplete or emergent, in order to better understand their interplay.

Whilst "knowledge projects entail the drawing of boundaries" (Barad 1996, 183), what groundwater does, because it is so elusive, is to take away authority from all of these perspectives, these processes of pointing to something and bordering it, of performing an act

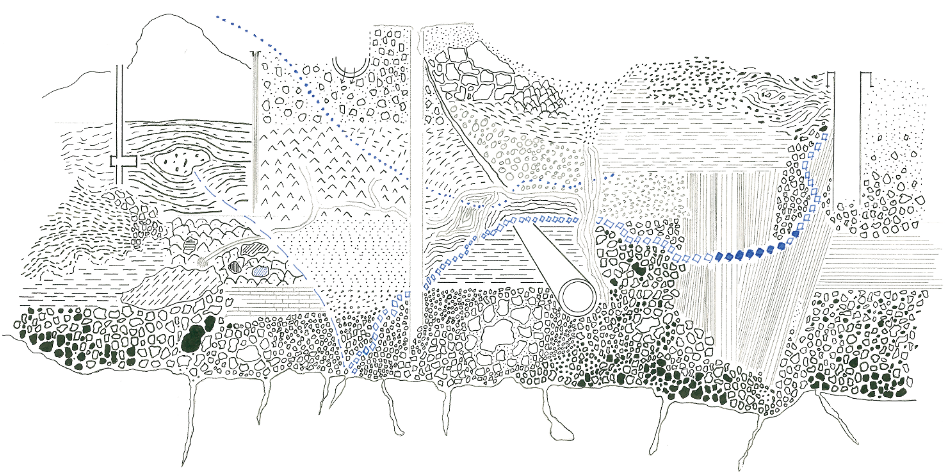

FIGURE 9 Thinking groundwater relationally. Drawing by the author.

of identification. It questions such authoritative framings. It says that no image can be more-than-partial. As Deleuze and Guattari observed: "thought lags behind nature" (1987, 3). In this way, infrastructural questions go (well) beyond human intentionality and return to worlds of materials and flows, again to materials as "nothing but change."

Groundwater is a fundamentally relationality material. The nature of groundwater—its unpredictability, indeterminacy, elusivity—is not a vulnerability, something which we are forced to adjust to, but fundamental to its being and also to what it offers up. What I hope I have started to do here is to articulate an image of the groundwater environment of Chennai as thick, deep, and complex—a site of intra-action and relation—and whose support is not unconditional (Figure 9). The turning of the earth, or the portion of groundwater parceled off as leaking, or the cracking of strata, or the sinking of surface: these things are not the faults but the processes which enables the system to exist. Leaking, sinking, swelling, and cracking are all conditions of relationality, which materials like groundwater help us to know.

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NOTES

1. This phrase is taken from Shubangi Swarup's novel *Latitudes of Longing* (2018).
2. CMRL Promotional Video, May 2013. https://www.youtube.com/watch?v=Tcn05fP5tSg.
3. Along with many other, often overlapping but also divergent namings and groupings.
4. To offer a rough order of magnitude for "young": most of the fluvial deposits are of the recent Quaternary period (less than 2.5 million years ago), including Holocene (since 12,000 years ago) and late-Pleistocene (less than 1 million years ago). Some boulder gravels are of the late Neogene period (up to 5 million years ago). The Charnockite rock, in contrast, is pre-Cambrian, or over 500 million years old.
5. Contract UAA-02 from AG-DMS to May Day Park. Survey work undertaken December 2005-January 2006 by RITES (depth 30 m) and September-October 2009 by Geo Foundations & Structures PVT. LTD (depth 30 m).
6. L. Elango (Geology, Anna University), interview by author, Chennai, January 25, 2018.
7. Although his lab-based experiments are in contrast to almost all future developments in the science, which are derived from field observations.
8. The artist Shezad Dawood—whose recent work negotiates the material geographies, and cartographic histories, of ocean space—would also remind us that "the sea has strata as much as the land does" ("EX-ART: Liquid Imaginary" Symposium, University of Westminster, 20 July 2018).
9. L. Elango (Geology, Anna University) interview by author, Chennai, January 25, 2018.
10. Ibid.

11. Ibid.
12. Anandaruban P. (Geology, Anna University), interview by author, Chennai, July 17, 2018.
13. Recounting the history of groundwater science in the US is relevant, since this professional knowledge was directly exported to India via the USGS International Water Resources Programme in the 1950s (Acciavatti 2017; Taylor 1976).
14. Anandaruban P. (Geology, Anna University), interview by author, Chennai, July 17, 2018.
15. CMRL engineer, telephone conversation with author, June 29, 2018.
16. "Coupling" is also a concept used in groundwater modeling: "tight" coupling denotes a simultaneous process, whilst "loose" coupling refers to interrelated but separated processes, possibly computed by separate models.

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