Groundwater Depletion, Adaptation and Migration: Evidence from Gujarat, India

PRELIMINARY DRAFT *

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Abstract

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Increasing water scarcity is expected to impact food production and the livelihoods of millions of farmers in semi arid developing countries over the next decades. Multiple studies project that this and other environmental changes will displace tens of millions of 'environmental migrants'. However, such claims are hard to assess because of the lack of rigorous empirical evidence on farmers' adaptive responses. In this paper, we exploit plausibly exogenous variation in localized hydro-geological conditions in northern Gujarat, one of the most groundwater-scarce regions of India, to study the impacts of the gradual depletion of this vital resource. We find that more severe scarcity results in the shrinking of agriculture and increased migration rates by young males, but only those from the dominant land-owning caste (we find weaker evidence for labor shifts away from agriculture within villages). We do not find any evidence that scarcity leads to higher investments in human capital, however, or in improved water use efficiency, despite the large technical potential for doing so. Given the widespread and ongoing depletion of groundwater across India and other parts of the world, the results are a cause of concern for the sustainability of irrigated agriculture and food security in these countries.

1 Introduction

Environmental migration is an old phenomenon: for millennia, human populations were driven to migrate away from areas affected by different forms of environmental and climatic stress (McLeman and Smit 2006). It is also widely projected that future environmental stress including growing water scarcity and climate change will result in mass migration due both to push factors, like agricultural income shocks caused by increasing climate variability, and pull factors, including higher and more stable salaries from urban professions (IPCC Report 2007, World Development Report 2009, Warner 2010). But while environmental migration is much discussed in the academic and policy literature, there is little quantitative evidence by which to assess these claims.

In this study we examine spatial correlations between rural-to-urban migration rates, rural employment shifts out of agriculture, and exogenous variation in environmental stress associated with groundwater depletion in the Indian state of Gujarat. We find evidence that increasing water scarcity is associated with higher rates of migration, and use geological data to establish the relationship causally. We find only weak evidence for labor shifts away from agriculture within villages, and no evidence for adaptation within agriculture, but rather that land cultivation shrinks in response to water scarcity, despite the substantial potential for improving water use efficiency.

Increasing water scarcity is expected to threaten the livelihoods of hundreds of millions of farmers in semi-arid, developing countries (Vrsmarty et al 2000). The depletion of groundwater resources is a major driver of increased scarcity (Konikow and Kendy 2005, Wada et al 2010) and India, the world‘s largest consumer of groundwater, is the country probably most vulnerable to this threat (World Bank, 1998; World Bank, 2010; Shah, 2010; Fishman et al, 2011; Fishman, 2011). Despite widespread concerns in Indian policy circles about the consequences of groundwater depletion, there is little evidence by which to assess the eventual impacts of aquifers “drying up” (Fishman et al 2011). These impacts critically depend on how farmers will respond. Our results shed light on this question by studying these responses in the northern districts of the state of Gujarat - an area where agriculture is critically reliant on groundwater irrigation but where depletion has reached extreme levels (UNDP, 1976; Postel, 1999; Moench, 1992), making it a useful study area as a potential pre-cursor of where other groundwater depleting parts of the country may eventually be heading (Shah 2007).

Water tables in our study area have been rapidly falling over the last 3-4 decades (figure 1), but the rates of decline have been spatially uneven. Our estimates indicate that an additional 100 feet of water table decline is associated with a decrease of $0.15 - 0.25$ in the cropping intensity in the non-rainy season [1] (from an average of about 1.3), and an increase of $7\% - 10\%$ in the incidence of households that have a migrant son (compared to an average rate of 20%). We also find that migration is much more prevalent among the dominant socio-economic groups (land-owning castes), and less common amongst the landless and marginal land owning castes. The correlations we find hold when other candidate drivers of migration are controlled for, including land scarcity and access to social networks in cities. As expected, households with less available land per son, larger overall land holding (a proxy for wealth), relatives in cities and migrant brothers (brothers of the male head of household) are more likely to have sons migrating. Moreover, we do not find similar correlations between water scarcity and the migration of the older generation, which occurred before water depletion may have become a real constraint on agricultural livelihoods. This provides further support for our inference.

Without exogenous variation in scarcity, the correlations we document be-

[1] defined as the number of crops cultivated in a year

tween migration and the degree of scarcity can be hard to disentangle causally. On the one hand, Respondents in some of the most water-scarce villages in the area claimed the high rates of migration from these villages were the result of water stress. According to this interpretation, environmental stress is acting as a "push factor", driving those who can (especially those who have social networks in cities) to migrate to cities in search of better employment. Migration here is therefore an adaptive response to the growing problem of water scarcity by relatively well-off and proactive households. The poor remain in the village and continue to rely on agriculture as their main source of income (Burke and Moench, 2000), and our survey shows that they often lease or sharecrop land "left behind", but not sold, by migrant landowners. However, an alternative possible explanation of the correlations we observe is that those farmers, or communities, who have extracted their groundwater resources more effectively and rapidly, had invested the associated rents in ways (e.g. higher education) that facilitated the observed employment shifts and migration. These rents may have been almost entirely captured by the land and bore-well owning dominant caste, which explains why landless castes are unable to migrate. To dis-entangle the causal channels, we exploit local variation in geological conditions that can affect the rate of water table declines. Specifically, we find that the presence of a layer of clay in the highly heterogenous geological strata, at depths of $500 - 1000$ feet is associated with deeper water tables and higher migration rates. Since the presence of the clay layer is plausibly exogenous, and would have had no other impact on agriculture other than through its impact on water tables (before the rapid advent of groundwater irrigation in the 1970s, these geological features would have been unknown to farmers), the evidence supports the former interpretation.

We do not suggest that water stress and groundwater depletion are the principal drivers of migration in our study area. Groundwater depletion and the associated migration is taking place against a background of equally rapid economic and social changes in this economically fast growing state that are also likely to be stimulating migration. A rough estimate from our data is that some 20% of migration may be attributed to the decline in water availability for irrigation. In contrast, respondents attributed about 10% of their sons migration to water scarcity. Looking beyond north Gujarat, however, this finding suggests migration may be an important mode of response to depletion in the many other parts of India where water tables are falling, but are still trailing behind north Gujarat in depth.

This paper contributes to the emerging empirical literature on environmental migration. [2] Much of the discussion on environmental migration is based on qualitative investigations and case studies (Warner et al 2009, Feng, Krueger and Oppenheimer, 2010), but several recent studies have attempted to provide systematic, causal quantitative evidence relating environmental stress to migra-

[2]The literature on migration distinguishes between voluntary migration to urban areas based on pull factors, like better income opportunity and quality of life in cities, from involuntary migration based on push factors like drought and other short-term income shocks.. Work on rural-urban migration which is focused on pull factors often builds upon the Harris-Todaro model (1970) which, explains migration as a function of expected rural-urban wage difference adjusted by the probability of finding a job in the urban area. Rhoda (1983) explored push factors of rural-urban migration and found that rural interventions that increase cultivable land, and redistribute land and income tend to reduce migration while interventions that increase inequality, improve access to cities, commercialize agriculture, and raise education and skills lead to increases in migration. Banerjee (1981) found that caste networks play an important role in facilitating migration to Delhi from other parts of India. Munshi and Rosenzweig (2008) propose that rural caste networks, which provided insurance against shocks for centuries in an economy where markets did not function well, restrict geographical mobility in India. Bird and Deshingkar (2009) explore circular migration and find that rates of migration are higher among the poor and more socially marginalized (the scheduled castes, scheduled tribes, and Muslims), especially in drought prone regions. In a survey of seasonal migrants in 70 villages in Gujarat, Rajasthan, and Madhya Pradesh, Coffey, Papp and Spears (2012) find that less educated people are more likely to migrate than more educated people and people from poorer households are more likely to migrate than people from richer households. A study of immigrants in Bangalore by Sridhar, Reddy and Srinath (2010) finds that the lower the level of education of the migrant, the greater the importance of the push factors whereas with increasing level of education of the migrant, pull factors become more important in migration. Our results also confirm the important role played by social networks in India in enabling migration to cities, but also show that push (water and land scarcity) and pull factors (contacts in cities) can operate in parallel.

tion. Hornbeck (2012) shows that the dust bowl of the 1930s in the American west resulted in large population declines in affected areas. Feng, Krueger and Oppenheimer (2010) find that rainfall induced production shocks result in increased immigration from Mexico to the U.S. Our results differ from these two studies in an important way, since they describe a response to a gradual, well anticipated process of environmental change ("slow onset"), rather to a temporary shock (as in Feng, Krueger and Oppenhimer, 2010) or a permanent but sudden and un-anticipated change (as in Hornbeck, 2012). Migration related to groundwater depletion is a comparatively recent development (Brown, 2004) and while there is some anecdotal or ethnographic evidence indicating out-migration from areas where water and other natural resources are becoming degraded (Chopra and Gulati, 2001; Vighneswaran and Ranjini 2006; Nair and Chattopadhyay 2005, Moench, 2002; Prakash, 2005), as far as we are aware, however, our paper is the first to document a systematic correlation between groundwater depletion and migration over substantial spatial scales.

Section 2 describes the data and the study area. Section 3 presents summary statistics and stylized facts about correlations between the depth of water tables and agricultural adaptations, labor shifts and migrations. Section 4 describes the hydro-geology of the region and uses localized variation in geological conditions to provide causal evidence for these correlations.

2 Data

Our surveys were carried out in a region of Northern Gujarat known for its groundwater depletion (Jain et al., in prep.; Columbia Water Center 2010). Local observation wells records suggest an average decline of about 3m per year over the last three decades (figure 1) and a concurrent deepening of wells to "chase the water table" (figure 2). Interviews with local well drillers identified a group of 10 villages that were especially water scarce due to unique geological conditions. In addition, we randomly selected 50 additional villages in the surrounding areas, that included seven talukas (sub-district administrative units) in three districts (figure 3). In each village, about 5% of household were then randomly selected for the survey.

The surveys included questions on agricultural practices, assets and household demographics, and heads of households were asked about the primary activities and places of residence of each of their sons and brothers. We focused on migration of male family members because female family members mostly migrated out of villages generally due to marriage and not because of the drivers, including groundwater depletion, that are of interest in our study.

3 Stylized Facts

3.1 Access to Irrigation and Agricultural Practices

3.1.1 Summary Statistics and Changes over Time

About 88% of the household surveyed reported that the male head of the household was engaged in agriculture. Agriculture in this semi-arid area is highly dependent on irrigation, and groundwater provides the principal source of irrigation water. Table 1 displays some of the characteristics of irrigation and agriculture in the sample region as reported by respondents and recalled a decade ago. Because of the deep water tables prevailing in the region, bore-wells tend to be extremely deep (typically 300-1000 feet, with an average depth of 580 feet) and use powerful pumps (53 HP on average).

Access to water in this area is determined by a rather complex matrix of cooperative well ownership and water markets. As shown in table B1, a typical farmer obtains water from 1.7 borewells, either as a share-holder in the well or as a water buyer. Shareholders are members of a bore-well cooperative, where anywhere from two to one hundred farmers share the initial cost of constructing a well, and then receive a percentage of the irrigation provided by the well equal to the percent paid for the initial investment. Water buyers, on the other hand, are farmers who are not a part of this cooperative and instead pay for irrigation depending on usage (effectively, per hour) when shareholders are willing to sell surplus water from their borewells.

The confined aquifers on which the regions agriculture is crucially dependent have a low rate of natural recharge and have been mined by local farmers for several decades. To cope with falling water tables, farmers have mostly resorted to deepening wells and the use of more powerful pumps. Table 1 shows that farmers recall current wells to be 220 feet deeper than they were a decade ago, and pumps to be more powerful by 20 HP. Increased energy use can, in theory, partially compensate for the deepening water table, but eventually, hydrological constraints will set in, such as lower porosity at deeper strata. Survey results for several irrigation indicators suggest this process is already underway in this region. For example, the time required to irrigate a parcel of a given size (during the wheat crop) was reported by farmers to have increased from 3.5 to 5.8 hours over the last decade [3] and the time they have to wait between their turn to use the well has increased from 12 to 16 days over the decade. The decreased availability of water seems to have forced farmers to reduce the area under cultivation in the rainless winter and summer seasons, when irrigation is critical for cultivation, by about 7% and 17% respectively. There are also indications of reductions in the number of irrigations applied to crops, but in smaller relative amounts (3%-4%), suggesting most of the response occurs on the extensive, rather than the intensive margin.

[3]The time required to irrigate a parcel provides a good proxy of the rate of flow from a well since farmers commonly flood irrigate the plot until water reaches its farthest corner

3.1.2 Correlations with Water Tables

To examine whether the decline in irrigation water availability is correlated with drops in water tables, we regressed several irrigation indicators on the depth of wells (a proxy for the actual depth of the water tables, which is farmers cannot observe with precision). Results are reported in Table 2. The first column reports OLS regressions. Other columns report results from parallel regressions that include sub-district (Taluka) fixed effects (column 2), quadratic spatial trends (column 3) and soil types (column 4). The results suggest that the power of pumps, length of the wait between irrigations the cropping intensity and the incidence of bore failures (drying up) are quite robustly correlated with the water depth. The reduction in the cropping intensity suggests farmers are no longer able to compensate for deepening water tables. However, these regressions do not establish a causal connection - we will return to that in a later section.

3.2 Labor Shifts and Migration

3.2.1 Comparing Two Generations: Sons vs. Brothers

to study patterns of labor shifts and migration, the surveys requested heads of households to report the primary activity and place of residence of each of their sons. This approach misses households all of whose family members have migrated, so our results only apply to the migration of the younger generation of households that still reside in the village. However, to compare these patterns across generations, we also requested each head of household to report the primary activity and place of residence of each of their brothers. Table 3 reports some differences between these two groups. About 16% of households reported having at least one migrant son as well as at least one migrant brother (uncle), suggesting the rate of migration has not changed substantially across the generations (in both generations, almost all migrants were reported to have migrated to a big city rather than to another villages or a small town). Interestingly, however, the stated reason for migration did differ substantially across the generations. While the primary stated reason for both generations of migrants was a more attractive employment opportunity in the city, the rate was higher for the older generations, and water scarcity was significantly more frequently stated as the main reason for migration for the younger generation (by 7%). This is consistent with the gradual worsening of the water situation: the older generation of migrants tended to migrate some 10 years earlier than the current generation. Off course, self reported reasons for migrations may fail to distinguish between the push and pull factors and our empirical investigation will address the question below. The other main difference between the two generations is the more frequent shift in employment, away from farming, amongst the younger generation (by 10%).

3.2.2 Employment Shifts and Water Scarcity

Table 4 reports regression results for the probability of a household having at least one son (columns 1-4) or brother (columns 5-8), among those who reside in the village, whose primary occupation is not in agriculture (linear probability model. Results from Logistic regressions are similar and are not reported). For each group, the first column reports the OLS regression. The second column includes additional household level controls that may affect employment shifts. The third column includes sub-district fixed effects, and the fourth column includes village fixed effects. In all regressions, errors are allowed to be correlated within villages.

In addition to water scarcity, proxies by the depth of bore wells, we consider additional variables that represent commonly considered drivers of migration or employment shifts. These include the household's total land holding, as a measure of wealth; The presence of (non-immediate) relatives in cities, as well as, for sons, weather an uncle has shifted employment, as a measure of social networks in cities or connections in non-farming enterprises; An indicator of whether the household belongs to the regionally dominant land holding caste, the Patels; For sons, the amount of land available per son, as a measure of land pressure.

We do not find significant correlations between any of the above factors and the employment shift decisions of the older generation (uncles). However, there seem to be a relatively robust correlation between well depth and the land-owning caste to employment shifts by the younger generation (sons): households with wells that are a hundred feet deeper seem to be 19%-25% more likely to have a migrant son. In a later section we will attempt to examine whether there is a causal basis for this correlation.

3.2.3 Migration and Water Scarcity

Table 5 reports similar regressions for the probability of a household having at least one migrant son (columns 1-4) or brother (columns 5-8). Starting with the older generation (brothers of the household head), we find, this time, a robust and strong association between the presence of relatives in the city and the probability of migration - an increase of 32%. We find no evidence of a correlation between migration rates of the older generation and the depth of wells. This is consistent with the near lack of mention of water scarcity as the reason for migration of these individuals.

The results are different for the sons of the household. We find that an increase of 100 feet in the depth of wells is associated with about 2.5% increase in the probability of a household having at least one migrant son. This correlation is robust to the inclusion of the other controls, except for village fixed effects: however, there is little variation in water depth within villages: most of it occurs on larger spatial scales across villages. The signs of the other controls are also significant with signs as expected. Greater total household land holding increases the probability of migration, but the amount of land per son (a measure of land pressure within the household) is negatively associated with migration. Having relatives in the city or having an uncle who has migrated to the city are both positively and strongly associated with greater probability of migration. Households belonging to the dominant Patel caste are more likely to migrate.

3.2.4 Educational Investments and Water Scarcity

Labor shifts away from agriculture, especially if they also involve migration to cities, may well require investments in education. Since the decline in water tables is a gradual process of which farmers are well aware, and which has been going on for decades, farming household may have invested in the education of their sons in anticipation of water depletion and the higher rates of migration, or alternatively, the response may be adaptive, but not long in planning for. As a partial check, we ran similar regressions for the share of sons in a household that have received different levels of education appropriate to their ages: secondary, higher secondary (ages 16-18) and higher. Table 6 reports the results. We find no association between well depths and educational attainment at any of these levels. About 87% of sons of sufficient age receive secondary education, 53% receive higher secondary education, and 43% receive higher education. The land owning caste (the Patels) are about 30% more likely to receive higher secondary or higher education.

4 Disentangling The Causal Links with Geological Data

The correlations observed in previous sections need to be interpreted with caution. Associations between well depths and migration and labor shifts can be interpreted as adaptive responses, but they can also be driven by unobserved correlates, and interpreted in other ways. For example, it is possible that deeper wells and water tables are a mark of more intensive extraction taking place over past years which has provided local farmers with greater rents that are then used to enable labor shifts or migration of younger generations. In this section we exploit the plausibly exogenous high local variability in hydro-geological conditions to better identity the impact of water scarcity on agricultural outcomes, labor shifts and migration.

4.1 Some Basic Facts About the Regional Hydro-Geology

We present here a few basic simplified facts about the regional hydro-geology that are important for the purposes of our empirical strategy. We refer the reader to the hydrological literature for more details.

The flow of water from a given well (the well yield) is determined by a complex combination of factors, which include the power of the pump, the depth of the water tables, and the properties of the rock strata. Over time, changes in the water table are determined by a balance between extraction and natural recharge. However, depending on the rock strata, changes in the water table for a given balance of extraction and recharge can vary a great deal. In particular, the presence of impermeable layers (such as clays) in the strata can impede the rate of natural recharge greatly, leading to accelerated drops in water tables.

Geo-hydrological research in the North Gujarat has documented the complex alluvial aquifer system in the area as a mixture of permeable and impermeable layers of non-uniform spatial arrangements. Permeable layers, such as sands, hold greater amount of water and allow a relatively free flow of water, whereas non-permeable layers, such as clays, do not allow water to flow through (or more precisely, allow it to flow in extremely slow rates). For example, Kavalenkar and Sharma (1992), state that (see figure 4):

> for certain zones the aquifer has a high proportion of the more permeable sandy horizons; at other locations the horizons contain more clay; there is no distinct continuous layering in the aquifer.

In the course of extensive discussion we've had with local geologists and well drillers, it was repeatedly and independently stated that the presence of a particularly impermeable layer of dark clay in some locations is the single most important factor determining variation in water conditions across different villages (and in some cases, across wells in the same villages). This dark clay layer occurs at depths ranging from 500-1000 feet, suggesting that the only possible impact on local agricultural conditions is related to water depths and well yields. In particular, it is plausible that prior to the irrigation boom and before wells reached these depths, local farmers were not aware of the presence of the dark clay layer and it had no impact on their agricultural practices.

We have collected data on the occurrence of dark clay layers in the strata at various villages from two sources. First, we interviewed the prominent well driller in the area. The driller identified, for about 100 villages in Mansa and Vijapur Talukas, the depth of the water table and whether there was a dark clay layer in the strata (see figure 5). No mention was made of the reason for requesting the information or of any of the data we collected in these villages. Second, we approached the Gujarat Water Supply And Sewerage Board (GWSSB) for this information. GWSSB drills drinking water wells in all villages in the area and maintains records of *lithologs* obtained in the course of drilling these wells. These lithologs detail the type of strata encountered at each depth in the course of drilling the wells, and hence provide an indication of the presence and depth of dark clay layers. We were able to obtain this data for all villages in Vijpaur Taluka (Mehasana district) but not for Gandhinagar district (Mansa Taluka). However, we used these to verify the information provided by the well driller and in all but one villages found them to be in perfect agreement.

4.2 Impacts of Geo-hydrological Factors

The impacts of the presence of the dark clay layers were investigated through similar regressions to those reported in previous sections. First, we regressed various indicators of water availability and irrigation on the presence of dark clay layers, and then turned to employment shifts and migration.

4.2.1 Agricultural Impacts

In table 7 we report the estimated impact of a dark clay layer on several irrigation related and agricultural indicators. The first column reports OLS estimates. The second column includes taluka (sub-district) fixed effects. The third column includes spatial controls, in order to make sure correlations with clay layers are not driven by other factors that may be spatially correlated with it. These include spatial trends (linear and quadratic), the distance to the nearest irrigation canal and the distance to the nearest market town. The fourth column includes soil fixed effects, in order to check results are not driven by a possible correlation between the presence of deep, dark clay layers, and soil characteristics.

Results indicate that where a dark clay layer is present in the strata, wells tend to be 95-188 feet deeper, depending on the specification; the time required to irrigate a plot of given size cultivated with wheat in the winter season increases by some 0.5-0.8 hours; The time farmers wait between consecutive "turns" to use their well increases by 1-2 days; And pumps tend to be more powerful by some 9-15 HP. Despite these adjustments, agriculture seems to suffer some consequences: The cropping intensity tends to be lower by about 0.3 crops per year. We find no robust impact on the number of irrigations, suggesting farmers adjust mainly on the extensive margin rather than the intensive margin. Finally, well failures are more common in areas where dark clay is present (by about 0.8 failures per decade).

4.2.2 Clay Layers, Migration and Labor Shifts

Having established the impact of the dark clay layer on water availability, we now re-estimate the regressions for migration and labor shifts except that we replace the well depth variable by the plausibly exogenous indicator of the presence of dark clay. Tables 8 and 9 report the results. We find weak evidence for the impact on labor shifts within the villages. As table 8 shows, the presence of a dark clay layer is correlated with a 10% increase in the likelihood a household has a son which resides in the villages but doesn't farm, but the impact is reduced by half and no longer significant when other variables are controlled for.

Table 9 shows, in contrast, a highly robust impact of the clay layer on the likelihood a household will have at least one migrant son, raising it by some 9%-15%, depending on the specification. The impact is robust to the inclusion of other controls, sub-district fixed effects, soil fixed effects, spatial controls (as detailed above) and the spatial clustering of standard error in a radius of 20 Km. Finally, we re-estimate the education regressions in table 10, and as before, find no association with clay layers.

5 Conclusion

Adaptation to environmental stress, and water scarcity in particular, can take many forms. Within the agricultural domain, farmers may be able to adapt farming practices and technologies that would allow them to maintain their production even while reducing their water usage. Alternatively, farmers may also choose to shift away from agriculture and migrate from areas that face severe water decline.

In this study, we find evidence to suggest that the primary modes of adaptation pursued by socially advantaged (dominant castes) farmers in an increasingly water-scarce region of India are migration to cities and employment shifts away of agriculture. The ability to migrate and to shift income sources may have been instrumental in avoiding some of the more pessimistic predictions about the eventual impacts of water depletion, for which we find no evidence in the study area (but we do not claim to be able to provide an accurate assessment of the wealth or welfare of the household we surveyed).

The sort of environmental stress we study here is a gradual process, not a short-term shock. The fact that young farmers are choosing to migrate rather than to adapt agricultural practices may be an indication that such adaptation strategies are not readily available to them. Furthermore, our results suggest that migration opportunities may be largely available only to the dominant land-holding castes that have access to enough social and economic capital to transition away from agriculture. When and if groundwater depletion occurs over a larger geographical scale, migration possibilities may be crowded out, and the implications for agricultural production may be substantially negative. This case study does not allow us to predict the general equilibrium effects of such a process, but it can be a source of concern from the broader policy perspective on food security in India. In particular, we note that the great majority of migrant land-owners were reported to lease out their land, rather than sell it. This raises the concern that increasing amounts of land will be cultivated by individuals with few incentives to invest in that lands productivity or in agricultural infrastructure. The full impacts of migration on agricultural productivity are, however, beyond the scope of this seed study.

The difficulty of assessing the welfare impacts of groundwater depletion and of associated migration make it difficult to draw conclusive policy lessons from our study. Economists mostly consider the permanent movement from the agricultural sector into the non-agricultural sector and from rural to urban areas as an essential aspect of economic development (Todaro, 1969; Harriss and Todaro, 1970). However, among developing countries, India stands out for its remarkably low levels of occupational and geographic mobility. The World Development Report (2009) argues that policy barriers to internal mobility in India are imposed by omission rather than by commission and that negative attitudes held by government and ignorance of the benefits of population mobility have caused migration to be overlooked as a force in economic development. Indeed, the government of Gujarat, for example, declares the reduction of rural to urban migration to be a prominent policy goal, and attempts to achieve it through infrastructural investments in rural areas.

Our results suggest that government policies to sustain irrigation in the region may have indeed reduced the rates of migration to cities and economic diversification. If it were not for the state governments long standing subsidization of electricity for groundwater pumping, falling water tables would have most likely constrained agriculture in the area years ago (Columbia Water Center 2010). Similarly, current plans already under implementation to bring surface irrigation canals to this area through energy intensive lift irrigation programs may also relieve water scarcity. Our results suggest these policies, in addition to the high energy related costs they incur, may also slow down processes that are usually considered to be integral to economic growth. However, an estimate of the impacts of migration and diversification rates on overall growth is beyond the scope of this study and additional research will be needed in order to rigorously evaluate them.

6 Bibliography

Banerjee, B. (1983). Social Networks in the Migration Process: Empirical Evidence on Chain Migration in India. The Journal of Developing Areas, Vol. 17, No. 2 (Jan., 1983), pp. 185-196

Brown, Lester R. (2004). New flows of environmental refugees.

Burke, J., Moench, M. (2000). Groundwater and Society: Resources, Tensions, Opportunities. Sales no. E.99.II.A.1. United Nations, New York.

Chopra, K., Gulati, S.C. (2001). Migration, Common Property Resources and Environmental Degradation.Sage, New Delhi.

Coffey, D., Papp, J. and Spears, D. (2012). Dual Economies or Dual Livelihoods? Short-Term Migration from Rural India and Non-Agricultural Employment.RICE Working Paper.

Columbia Water Center (2011). Addressing the Water Crisis in Gujarat, India. Columbia Water Center White Paper.

Deshingkar, P. (2006). Internal migration, poverty and development in asia. Technical report,ODI Briefing Paper.

Deshingkar, P. and E. Anderson (2004). People on the move: New policy challenges for increasingly mobile populations. Natural Resources Perspectives 92.

Fishman, R. M., Siegfried, T., Raj, P., Modi, V. and Lall, U. (2011), Over-extraction from shallow bedrock versus deep alluvial aquifers: Reliability versus sustainability considerations for India's groundwater irrigation, Water Resources Research, Vol 47.

Fishman, R.M. (2011), Falling Water Tables in India ? a Review of the Evidence, Columbia Water Center Working Paper.

Foster, A., and M. Rosenzweig (2004). Agricultural Productivity Growth, Rural Economic Diversity, and Economic Reforms: India, 19702000. Economic Development and Cultural Change 52.3 (2004): 509-542.

Foster, A. and M. Rosenzweig (2002). Household division and rural economic growth. The Review of Economic Studies 69 (4), 839-869.

Foster, A. and M. Rosenzweig (2008). Economic development and the decline of agricultural employment. Handbook of Development Economics 4, 3052-3083.

Harris, J. and M. P. Todaro (1970). Migration, unemployment and development: A two sector analysis. American Economic Review 60 (1), 126142.

Hornbeck R. (2012) The Enduring Impact of the American Dust Bowl: Short- and Long-run Adjustments to Environmental Catastrophe. American Economic Review [Internet]. 2012;102(4):1477-1507.

Hornbeck, R., and Keskin P. (2012) Does Agriculture Generate Local Economic Spillovers? Short-run and Long-run Evidence from the Ogallala Aquifer. No. w18416. National Bureau of Economic Research.

Konikow, L. F., and Kendy, E. (2005) "Groundwater depletion: A global problem." Hydrogeology Journal 13.1: 317-320.

Kundu, A. (2011) Politics and Economics of Urban Growth. Economic and Political Weekly, Vol. XLVI, No. 20, 10:12.

McLeman, R. and Smit, B. (2006). Migration as an Adaptation to Climate Change. Climatic Change. 76: 31-53.

Mitra, A. and Murayama, M. (2008), Rural to Urban Migration: a district level analysis for India IDE Discussion Paper No. 137, Institute of Developing Economies, Japan.

Moench, M. (1992). Drawing down the buffer. Economic and Political Weekly, XXVII (13): A7A14.

Moench, M. H. (1992). Chasing the Watertable: Equity and Sustainability in Groundwater Management." Economic and Political Weekly: 171-177.

Moench, M. (1993). Preface to Groundwater Management: The Supply Dominated Focus of Traditional, NGO and Government Efforts. VIKSAT, Ahmedabad.

Moench, M. (2002). Water and the potential for social instability: Livelihoods, migration and the building of society, Natural Resource Forum, 26(2002), page 195-204.

Moench, M., Burke, J., Moench, Y. (2001). Through a Different Lens: The Question of Groundwater, Food Security, Uncertainty, Variability and Risk. FAO, Rome.

Munshi, K. and Rosenzweig, M. (2007). Why is Mobility in India so Low? Social Insurance, Inequality and Growth, IPC Working Paper Series Number 68, University of Michigan.

Pohle, A. and Knerr, B. (2010). Exploring Interactions between Water Resource Depletion and Remittances from Labour Migration: The Case of Kerala, Tropentag, September 14-16, Zurich

Postel, S. (1999). Pillar of Sand: Can the Irrigation Miracle Last? Norton, New York.

Prakash, A. (2005). The dark zone: groundwater irrigation, politics and social power in North Gujarat. Orient Blackswan

Rhoda, R. (1983) Rural Development and Urban Migration: Can we keep them down on the Farm? International Migration Review, 17 (1) (Spring): 34-64.

Shah, T. (2010), Taming the anarchy: Groundwater governance in South Asia, Resources for the Future Press Washington, DC

Sreedhar, K. S., Reddy, A. V. and Srinath, P. (2010). Is it Push or Pull? Recent Evidence from Migration in India. SANEI Report 10-04.

Todaro, M.P. (1969). A model of labor migration and urban unemployment in less developed countries, The American Economic Review, Vol 59: 138-49

United Nations Development Programme (1976) .Ground-water surveys in Rajasthan and Gujarat, United Nations Development Programme.

Vrsmarty, C. J., et al. (2000). Global water resources: vulnerability from climate change and population growth. science 289.5477 (2000): 284.

World Bank (2009). World Development Report: Reshaping Economic Geography, Washington, DC: World Bank.

World Bank (2010). Deep wells and prudence: Towards pragmatic action for addressing groundwater overexploitation in India. World Bank Technical Report.

World Bank and GOI (1998). India-Water Resources Management Sector Review: Groundwater Regulation and Management Report. World Bank, Washington, DC

Wada, Yoshihide, et al. (2010) Global depletion of groundwater resources. Geophysical Research Letters 37.20 (2010): L20402.

Warner, K. (2010). Global environmental change and migration: Governance challenges. Global Environmental Change 20.3 (2010): 402-413.

A Tables

Table 1: Changes in Irrigation Indicators (2001-Present)

	N	Now	Past	Diff.	p
Time to Irrigate a Parcel (Hours)	1088	5.8	3.5	2.3***	0.00
Days between irrigations	1080	16.3	11.8	4.5***	0.00
Bore HP	985	53.2	33.2	20.0***	0.00
Bore Depth (100 ft)	1034	5.8	3.6	2.2***	0.00
Bores Used	1062	1.7	1.6	0.0	0.72
Land Cultivated, Rainy (Bg)	1166	6.9	7.0	-0.1	0.77
Land Cultivated, Winter (Bg)	1166	5.2	5.6	-0.4	0.11
Land Cultivated, Summer (Bg)	1166	2.3	2.8	-0.5***	0.00
No. Irrigations, Rainy	1022	5.8	5.5	0.3**	0.02
No. Irrigations, Winter	1068	6.1	6.4	-0.2*	0.09
No. Irrigations, Summer	837	6.5	6.8	-0.3	0.11

Table 2: Agricultural Correlates of Water Tables (Proxied by Depth of Wells), Per 100 ft.

	N	OLS		Taluka FE		Spatial Controls		Soil FE	
Time to irrigate a plot	1018	-0.28**	(0.13)	0.12**	(0.06)	0.03	(0.11)	-0.27*	(0.14)
Days between water access	1011	0.59***	(0.11)	0.52***	(0.12)	0.68***	(0.18)	0.61***	(0.13)
Pump HP	977	7.82***	(0.60)	4.86***	(0.62)	4.10***	(0.82)	7.60***	(0.77)
Cropping Intensity	1020	-0.02*	(0.01)	-0.02*	(0.01)	-0.03	(0.02)	-0.03**	(0.01)
Number of Irrigations	791	-0.20**	(0.10)	-0.16	(0.15)	-0.26	(0.21)	-0.18	(0.12)
Bore Failures	954	0.09***	(0.03)	0.09**	(0.04)	0.13**	(0.05)	0.10***	(0.03)

Standard errors in parentheses

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Table 3: Respondent's Sons vs. Brothers

	N	Uncles	N	Sons	Diff.
Number of sons	7645	1.38	4587	1.58	-0.20***
Migrated	2086	0.16	2334	0.16	-0.01
Not Farming	1745	0.08	1859	0.18	-0.10***
Years Migrated	288	17.65	405	7.58	10.07***
Migrated due to Land Scarcity	271	0.09	381	0.12	-0.03
Migrated due to Water Scarcity	271	0.03	381	0.09	-0.07***
Migrated due to Emloyment Opportunity	271	0.85	381	0.72	0.13***

Table 4: Probability of Having a Non-Farming Son or Uncle (OLS)

	Sons				Uncles			
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Well Depth, Now	0.018***	0.019***	0.026***	0.025*	-0.001	-0.001	-0.003	-0.003
	(0.005)	(0.006)	(0.008)	(0.015)	(0.004)	(0.004)	(0.005)	(0.008)
Land Holding		0.009	0.008	0.007		0.000	-0.000	0.000
		(0.007)	(0.007)	(0.007)		(0.001)	(0.001)	(0.001)
Relatives in City		0.098	0.096	0.073		0.033	0.033	0.025
		(0.081)	(0.082)	(0.067)		(0.039)	(0.039)	(0.034)
Did Any Brothers Exit Agri.?		0.143*	0.129	0.112				
		(0.084)	(0.084)	(0.085)				
Land per Son		-0.014	-0.014	-0.013				
		(0.008)	(0.009)	(0.009)				
Land Owning Caste		0.092*	0.090**	0.038		0.003	0.004	-0.016
		(0.046)	(0.044)	(0.066)		(0.026)	(0.030)	(0.033)
Constant	0.147***	0.072*	0.055	0.015	0.086***	0.082***	0.094**	0.001
	(0.030)	(0.042)	(0.063)	(0.418)	(0.023)	(0.025)	(0.038)	(0.272)
Taluka FE	No	No	Yes	No	No	No	Yes	No
Village FE	No	No	No	Yes	No	No	No	Yes
Observations	671	458	458	458	690	681	681	681
R^2	0.015	0.050	0.068	0.180	0.000	0.002	0.011	0.113

Standard errors in parentheses

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Table 5: Probability of Having a Migrant Son or Uncle (OLS)

	Sons				Uncles			
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Well Depth, Now	0.025***	0.026***	0.022***	0.005	0.009	0.005	0.002	-0.007
	(0.007)	(0.005)	(0.006)	(0.011)	(0.006)	(0.006)	(0.008)	(0.009)
Land Holding		0.017***	0.017***	0.017***		0.001	0.002	0.001
		(0.004)	(0.004)	(0.004)		(0.002)	(0.002)	(0.002)
Relatives in City		0.180***	0.174***	0.182***		0.325***	0.315***	0.321***
		(0.056)	(0.056)	(0.044)		(0.059)	(0.060)	(0.039)
Did Any Brothers Migrate?		0.130***	0.125***	0.116***				
		(0.042)	(0.043)	(0.042)				
Land per Son		-0.022***	-0.022***	-0.022***				
		(0.006)	(0.006)	(0.006)				
Land Owning Caste		0.204***	0.202***	0.168***		0.041	0.020	0.010
		(0.039)	(0.041)	(0.047)		(0.035)	(0.037)	(0.040)
Constant	0.094**	-0.100***	-0.212***	0.944**	0.159***	0.093**	0.127	0.057
	(0.043)	(0.028)	(0.049)	(0.374)	(0.033)	(0.041)	(0.087)	(0.380)
Taluka FE	No	No	Yes	No	No	No	Yes	No
Village FE	No	No	No	Yes	No	No	No	Yes
Observations	795	600	600	600	799	788	788	788
R^2	0.030	0.229	0.237	0.330	0.004	0.125	0.136	0.237

Standard errors in parentheses

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Table 6: Probability of Education (OLS)

	(1) secondary	(2) higher_secondary	(3) higher
Well Depth, Now	0.002	0.005	0.003
	(0.006)	(0.007)	(0.007)
Land Holding	0.001	-0.003	-0.004
	(0.002)	(0.004)	(0.003)
Relatives in City	0.016	0.013	0.032
	(0.021)	(0.052)	(0.046)
Did Any Brothers Exit Agri.?	-0.064	0.000	-0.004
	(0.053)	(0.075)	(0.063)
Land per Son	0.001	0.012*	0.015**
	(0.003)	(0.007)	(0.006)
Land Owning Caste	0.070***	0.309***	0.284***
	(0.025)	(0.053)	(0.046)
Constant	0.878***	0.538***	0.435***
	(0.045)	(0.060)	(0.058)
Taluka FE	Yes	Yes	Yes
Observations	561	516	516
R^2	0.041	0.204	0.226

Standard errors in parentheses

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Table 7: Agricultural Impacts of a Dark Clay Layer

	N	OLS		Taluka FE		Spatial Controls		Soil FE	
Depth of Wells	606	1.34*	(0.78)	1.34**	(0.64)	0.95*	(0.55)	1.88**	(0.91)
Time to irrigate a plot	648	0.65*	(0.32)	0.82***	(0.26)	0.48	(0.32)	0.76*	(0.38)
Days between water access	647	2.11**	(0.79)	1.90**	(0.71)	1.09	(0.68)	1.85*	(0.97)
Pump HP	561	11.23*	(6.64)	11.83**	(5.39)	8.97***	(3.10)	15.95**	(7.02)
Cropping Intensity	691	-0.30***	(0.08)	-0.33***	(0.08)	-0.24**	(0.09)	-0.28***	(0.10)
Number of Irrigations	476	-0.87	(1.07)	-0.60	(1.12)	0.42	(1.86)	-0.90	(1.37)
Bore Failures	595	0.80***	(0.16)	0.76***	(0.17)	0.60***	(0.13)	0.74***	(0.19)

Standard errors in parentheses

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Table 8: Probability of Having a Non-Farming Son or Uncle (OLS)

	Sons			Uncles		
	(1)	(2)	(3)	(4)	(5)	(6)
Clay Layer	0.101**	0.048	0.044	0.042	0.036	0.048
	(0.044)	(0.042)	(0.043)	(0.039)	(0.036)	(0.036)
Land Holding		0.022***	0.022***		-0.002	-0.002
		(0.007)	(0.007)		(0.003)	(0.003)
Relatives in City		0.108	0.111		0.023	0.018
		(0.085)	(0.086)		(0.037)	(0.036)
Did Any Brothers Exit Agri.?		0.294***	0.296***			
		(0.093)	(0.094)			
Land per Son		-0.026***	-0.026***			
		(0.009)	(0.009)			
Land Owning Caste		0.063	0.057		-0.027	-0.024
		(0.052)	(0.050)		(0.035)	(0.036)
Constant	0.225***	0.127***	0.125***	0.086***	0.101***	0.079***
	(0.027)	(0.033)	(0.039)	(0.020)	(0.025)	(0.027)
Taluka FE	No	No	Yes	No	No	Yes
Observations	565	358	358	598	584	584
R^2	0.012	0.078	0.079	0.004	0.008	0.017

Standard errors in parentheses

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Table 9: Probability of Having a Migrant Son or Uncle (OLS)

	Sons					Uncles			
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Dark Clay	0.158***	0.091**	0.085*	0.091*	0.130***	0.091*	0.056	0.022	0.006
	(0.045)	(0.042)	(0.042)	(0.048)	(0.044)	(0.053)	(0.036)	(0.039)	(0.038)
Land Holding		0.028***	0.028***	0.026***	0.024**	0.028***		0.005	0.005*
		(0.010)	(0.010)	(0.009)	(0.009)	(0.007)		(0.003)	(0.003)
Relatives in City		0.111*	0.107*	0.132*	0.095	0.111***		0.355***	0.358***
		(0.062)	(0.063)	(0.071)	(0.072)	(0.020)		(0.059)	(0.059)
Did Any Brothers Migrate?		0.121**	0.122**	0.151***	0.155**	0.121***			
		(0.050)	(0.052)	(0.055)	(0.057)	(0.009)			
Land per Son		-0.034***	-0.035***	-0.034***	-0.031***	-0.034***			
		(0.011)	(0.011)	(0.011)	(0.010)	(0.002)			
Land Owning Caste		0.217***	0.233***	0.235***	0.235***	0.217***		-0.019	-0.020
		(0.048)	(0.046)	(0.044)	(0.050)	(0.012)		(0.034)	(0.033)
Constant	0.198***	0.027	0.064	62.261***	51.475***	0.027	0.214***	0.137***	-0.050**
	(0.026)	(0.039)	(0.044)	(16.177)	(16.188)	(0.037)	(0.023)	(0.029)	(0.020)
Taluka FE	No	No	Yes	Yes	Yes	No	No	No	Yes
Spatial Controls	No	No	No	Yes	Yes	No	No	No	No
Soil FE	No	No	No	No	Yes	No	No	No	No
Observations	701	503	503	430	407	503	713	698	698
Clustering	Vil	Vil	Vil	Vil	Vil	20K	Vil	Vil	Vil

Standard errors in parentheses

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Table 10: Probability of Having a Non-Farming Son (OLS)

	(1) secondary	(2) higher_secondary	(3) higher
Clay Layer	0.014	0.004	0.016
	(0.027)	(0.042)	(0.035)
Land Holding	0.004	0.007	0.003
	(0.004)	(0.008)	(0.008)
Relatives in City	0.011	0.051	0.057
	(0.020)	(0.057)	(0.050)
Did Any Brothers Exit Agri.?	0.002	0.009	0.012
	(0.046)	(0.071)	(0.066)
Land per Son	-0.002	0.002	0.006
	(0.005)	(0.012)	(0.011)
Land Owning Caste	0.092***	0.309***	0.304***
	(0.025)	(0.053)	(0.049)
Constant	0.819***	0.154*	0.086
	(0.031)	(0.082)	(0.068)
Taluka FE	Yes	Yes	Yes
Observations	451	412	412
R^2	0.051	0.194	0.223

Standard errors in parentheses

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

B Figures

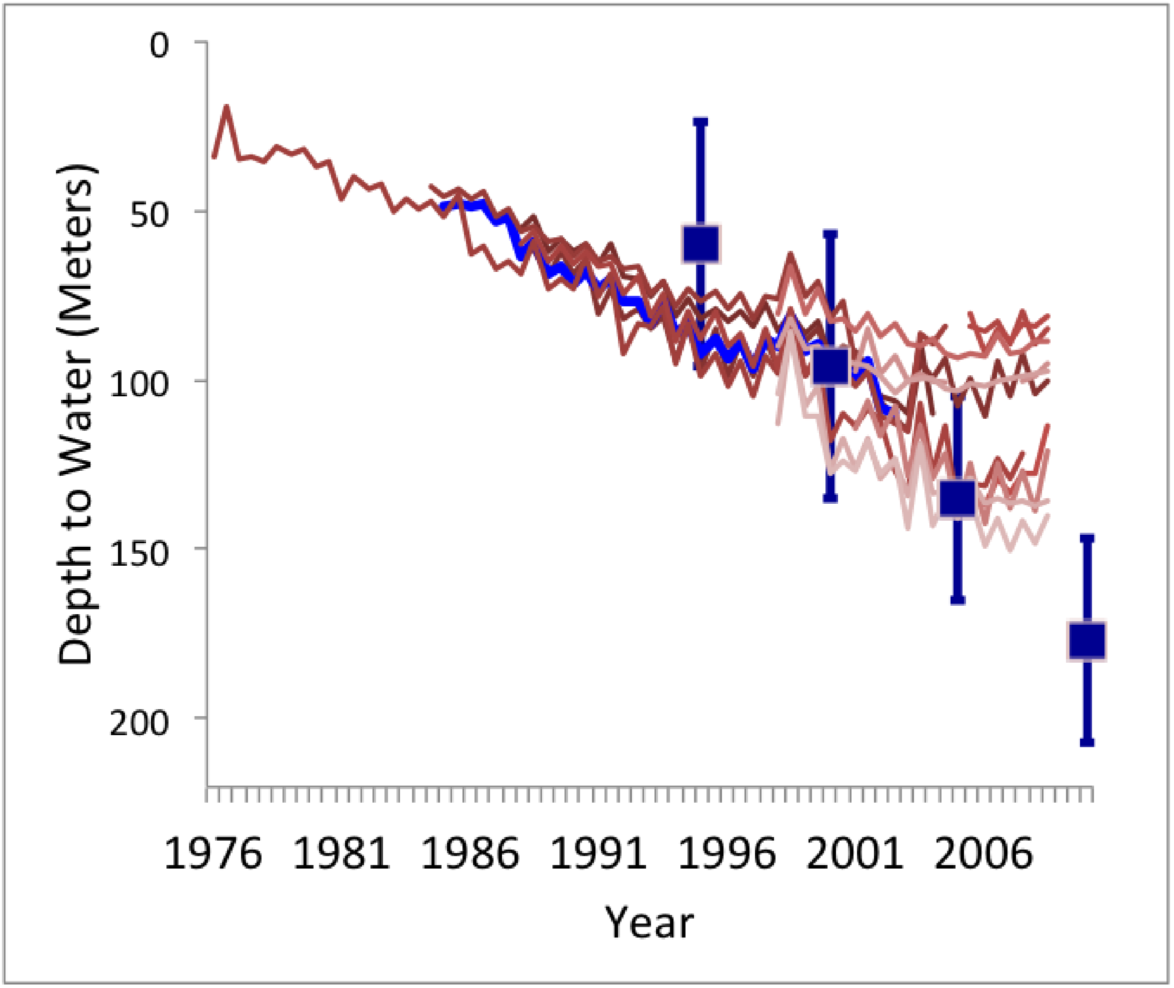

Figure 1: Depth to water, over time (red curves), in a collection of observation wells located in the study area (Vijapur Taluka). Blue error bars represent farmers recall of the depth to water currently, and 5, 10, and 15 years ago.

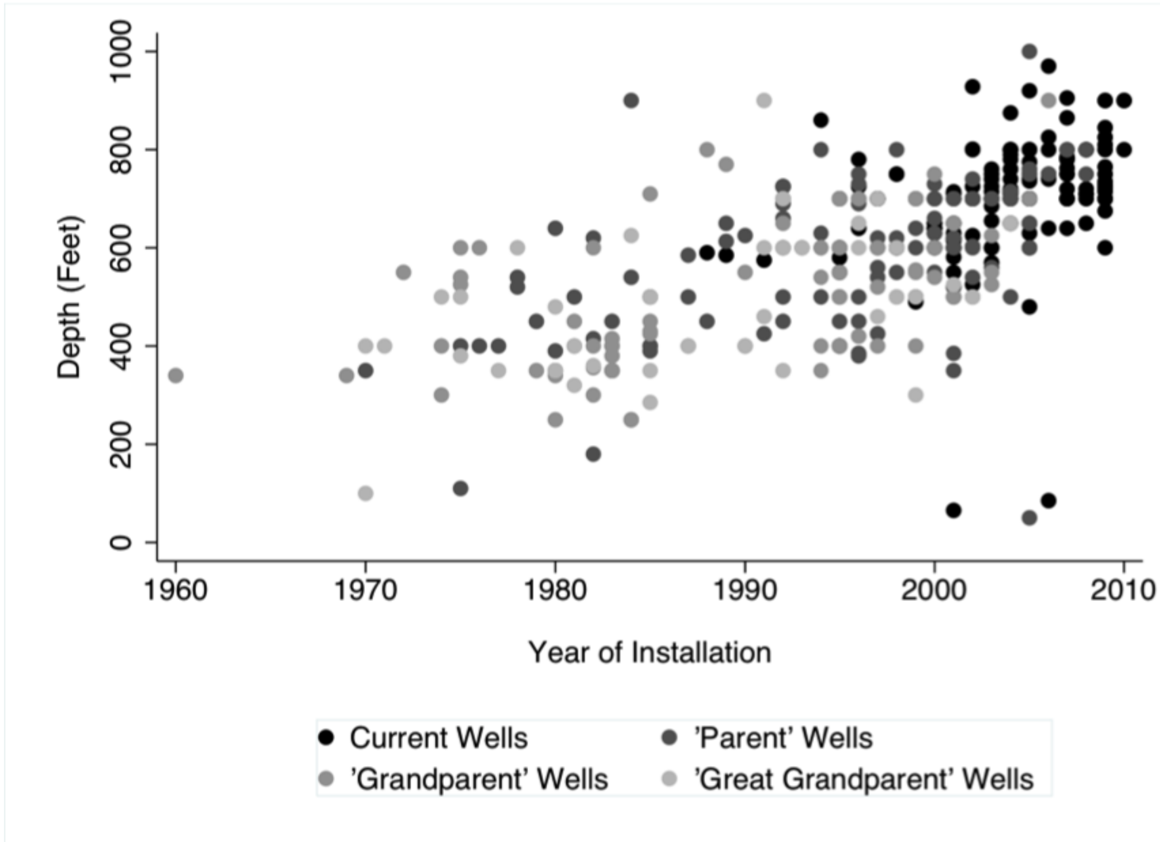

Figure 2: Depth of wells in the study area vs. their year of drilling. Respondents were asked to specify the depth and drilling year of their current wells and up to three "generations" of their previous wells ("father", "grandfather" and "great grandfather").

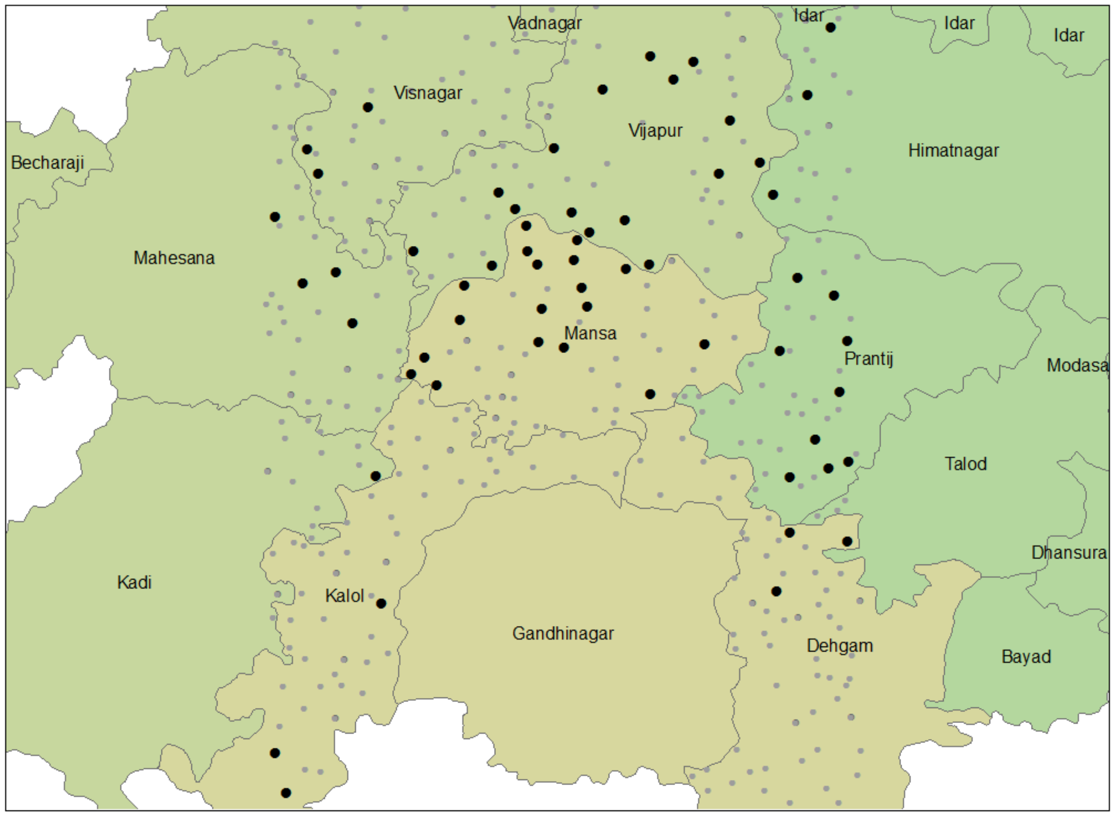

Figure 3: Map of the surveyed villages (larger dark dots). Smaller dots indicate other villages in the region. Shades indicate the three districts covered and lines indicate sub-district boundaries.

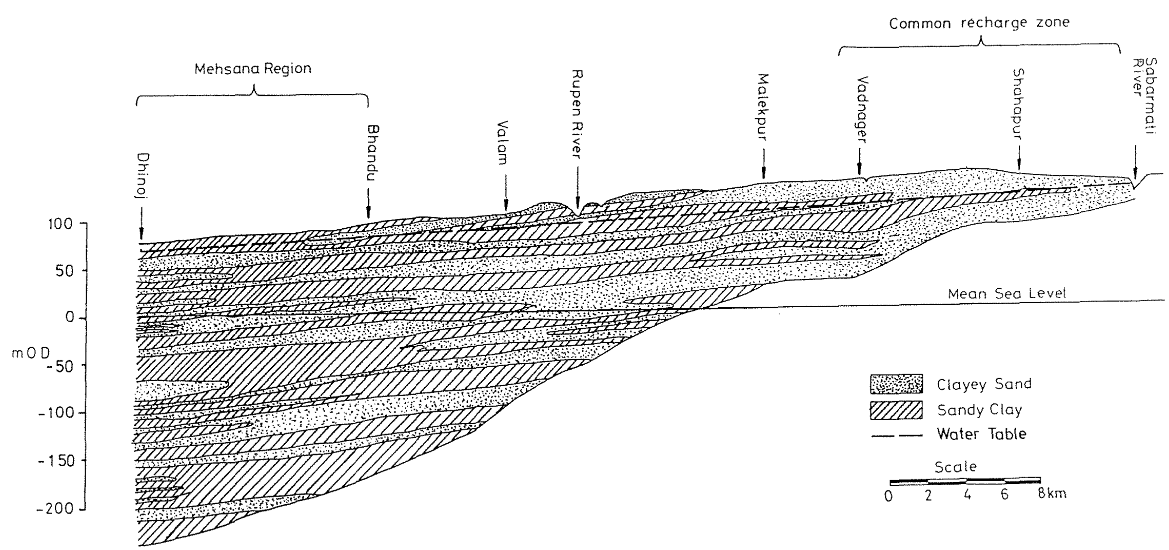

Figure 4: Schematic diagram of the complex aquifer system of North Gujarat. Source: Kavalenkar and Sharma (1992)

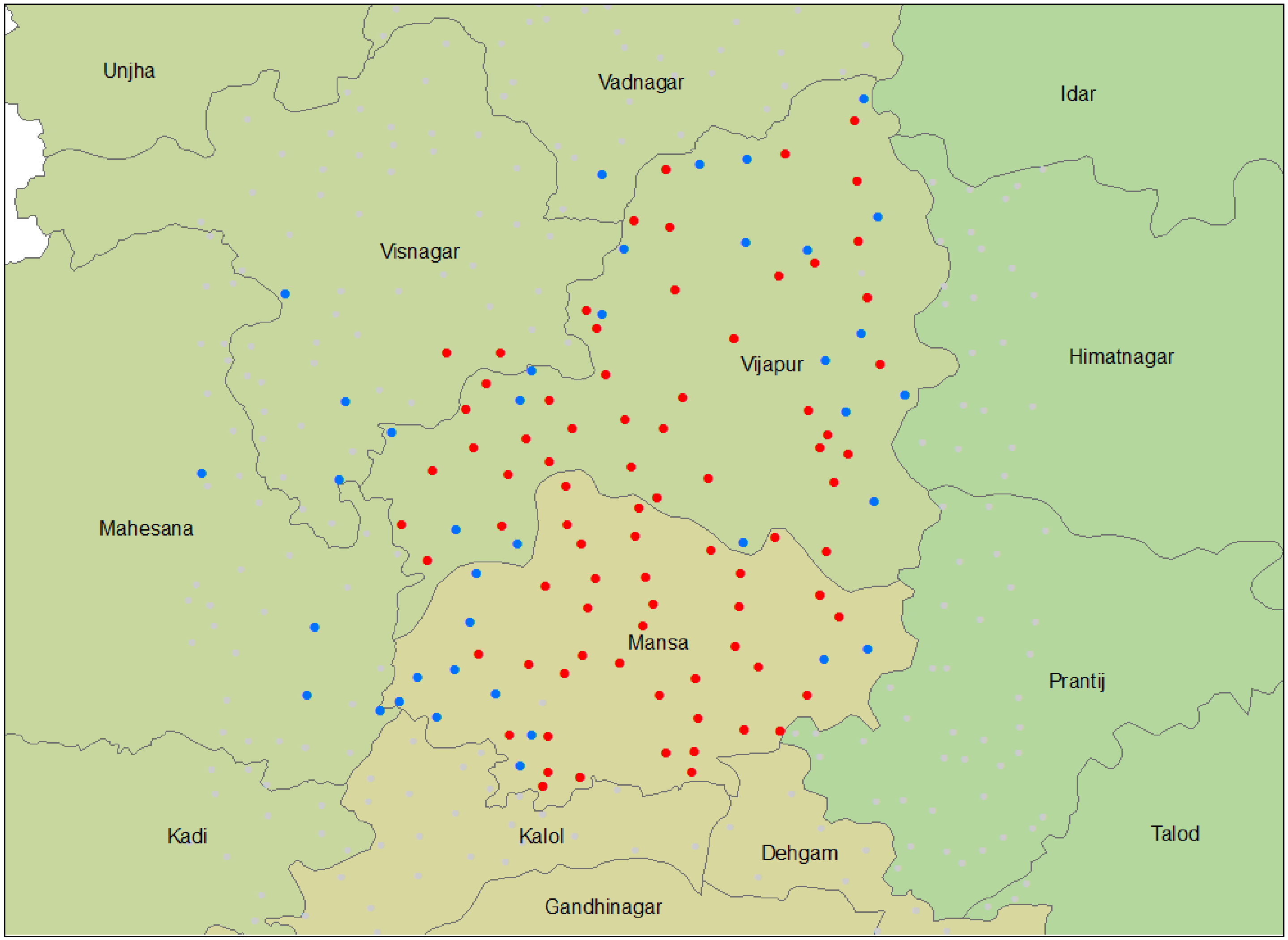

Figure 5: Villages in the study area labeled in blue (no dark clay layer) or red (dark clay layer).