When Water Runs Out: Adaptation to Gradual Environmental Change in Indian Agriculture *

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Abstract

Increasing water scarcity will affect hundreds of millions of smallholder farmers in coming decades, but little is known about likely forms of adaptation. We exploit a natural experiment, in which heterogeneous geological formations affect the rate of groundwater depletion across villages in Gujarat, India. We find that greater water scarcity leads to declines in irrigated agriculture and enhanced migration to cities, but only among dominant socio-economic groups. We find no evidence of substantial compensating investments in water efficient technologies or in human capital, despite farmers having been long aware of the decline in water levels.

Keywords: Adaptation, Water Scarcity, Irrigation, Migration

JEL: O13, O15, Q15, Q25, Q56

1 Introduction

Anthropogenic environmental change of un-precedented scale is gradually affecting large populations around the world. Despite this, there is still very limited empirical evidence on the manner in which agents respond to or adapt to such slow-occurring changes. A fundamental question is whether the build-up of awareness or exposure to environmental pressure triggers, of itself, a response that can mitigate major economic or social impacts.

In this paper, we explore this question empirically in the context of water scarcity. Water scarcity is expected to increasingly affect hundreds of millions of smallholder farmers in semi-arid, developing countries who depend on irrigation for their livelihoods (Vörösmarty et al., 2000). Projections of the impacts on farmers' welfare and their responses, however, remain mostly speculative or anecdotal. The more optimistic among these point to the large technological potential for improving water use efficiency in developing countries and thus for managing (maintaining production) with less water. For example, in India, only 5% of farmers and 10% of the potential cropped area have made use of water efficient micro-irrigation systems as of 2013. [1] According to these views, increasing scarcity will trigger technological adaptation that will substantially reduce its economic impacts.

More pessimistic views predict that water scarcity and climate change may uproot hundreds of millions of environmental refugees (Parry et al., 2007; Brown, 2008; Mundial, 2009; Warner, 2010). For example, Brown (2012) predicts that

> ...water refugees are likely to become commonplace. They will be most common in arid and semiarid regions where populations are outgrowing the water supply and sinking into hydrological poverty.

[1] Source: 5th Minor Irrigation Census: `http://mowr.gov.in/sites/default/files/5th-MICensusReport_0.pdf`

> Villages in northwestern India are being abandoned as aquifers are depleted and people can no longer find water. Millions of villagers in northern and western China and in northern Mexico may have to move because of a lack of water. [2]

Empirical evidence that can bear on this, and similar debates, remains scarce. A major challenge is the typical absence of useful variation in exposure that one could examine for causally interpretable correlations with adaptive behaviour. By its very nature, exposure to slow moving environmental change does not exhibit high frequency temporal variation (unlike weather shocks, for example), meaning that the researcher must rely on spatial variation in the rate and intensity of such changes. However, cross sectional associations with adaptive behaviour are usually challenging to interpret causally because of concerns about confounding variables, especially when, as is often the case, spatial variation in exposure occurs over large spatial scales (recent notable contributions in this regard include Burke et al. (2016), who use 'long-differencing' to study agricultural adaptation to rising temperatures in the U.S., and Taraz (2017), who uses decadal variation in monsoon rainfall to study agricultural adaptation in India).

Here, we utilise a unique natural experiment to contribute novel evidence to the literature on adaptation. The widespread depletion of groundwater in India likely represents the single greatest threat to the growth of Indian agriculture in the coming decades (Shah, 2010). Water levels are declining in many of the country's most productive areas, and in a few locations scarcity has become a binding constraint to cultivation (Fishman et al., 2011). In one of these locations, in the state of Gujarat, we have identified plausibly exogenous variation in the rate of groundwater depletion that occurs on unusually small spatial scales,

[2] http://www.earth-policy.org/books/pb2/pb2ch6_ss6

including across neighbouring villages.

The variation derives from the irregular presence of a geological formation, typically around 500 feet below the surface. The formation consists of a particularly impermeable layer of clay, which severely restricts the downward seepage of water into the aquifers that lie below it, and hence the rate at which they are naturally recharged. Over time, water tables declined, forcing farmers to drill ever deeper wells. Eventually, wells belonging to farmers whose land happened to overlie this clay layer have become reliant on water from the relatively slower-recharging and therefore faster-depleting aquifers that lie below it. These farmers would gradually face more severely constrained water flows from their wells.

This feature of the local hydro-geology forms the basis of our empirical strategy. It is documented in the geological literature (Bradley and Phadtare, 1989; Kavalanekar et al., 1992) and is common knowledge amongst local well-drillers and government geologists. These drillers and geologists have first made us aware of it and have supplied us with geological village-level data on the presence of the clay layer, as we describe in detail in section 3.1. Our analysis consists of comparisons of primary household and village level data between villages that overlie this formation to those that do not. We first confirm that hydrological indicators of water scarcity experienced by farmers are indeed more severe in villages that overlie the formation: well failures are more frequent, and water flows are weaker. We then proceed to examine whether and how this exogenously derived variation translates into differences in cultivation practices, labor allocation and migration rates.

We find that farmers in villages overlying the clay formation attempt to deepen their wells and increase pumping effort in order to "chase the water table", but even though they spend about 30% more energy per unit land to pump water, aquifers are depleted to such an extreme extent that this effort fails to compensate for physical water depletion. [3] The net result is that cultivated areas shrink. While we find evidence that some farmers use more efficient irrigation technologies or shift cultivation to less water demanding crops, these efforts are modest in scale and far from sufficient to maintain the extent of cultivation. Instead, the prominent response seems to be a rise of migration rates to cities by young male household members, but only among the dominant well-to-do castes. We find very weak evidence, if any, for labor shifts away from farming within the village. We also do not find evidence for greater investment in human capital as a means of adapting to the loss of water.

Much of the literature on environmental migration is based on correlations, qualitative investigations and case studies relying on self-reported drivers of migration (Warner et al., 2009; Feng et al., 2010). Even a systematic correlation between water scarcity and migration would not establish a causal connection. Both migration and rapid water mining (leading to greater scarcity) could be driven by some other unobservable factor, such as wealth or access to capital. Migration could itself lead to scarcity if, for example, outside employment provides capital that is used to increase pumping effort. Moreover, rents received from more rapid extraction of groundwater may themselves be facilitating the investments required for migration.

Our identification strategy is based on the assumption that the presence of the deep geological formation that accelerates groundwater depletion is uncorrelated with other factors that may be driving water scarcity, cultivation decisions or migration. As we show below, the presence of this formation is spatially heterogenous within a relatively small area (the study area is almost entirely located within two sub-districts) that is otherwise homogenous in terms

[3] In many other aquifers in India in which water tables are declining, but aquifers are abundant and not yet physically exhausted, this strategy seems to be more effective (Fishman et al., 2011).

of economic characteristics, agro-ecology, climate, institutions, water and energy policies and centralized infrastructure such as power grids and access to markets. Moreover, our results are robust to the inclusion of observable geographical factors such as soil composition, distance to towns and roads.

Before wells have gone deep enough to encounter the 500 feet deep geological formation, which we estimate to have occurred in the mid to late 1990s, it seems highly plausible to assume that its existence was unknown to local farmers[4] and would therefore have no impacts on the rural economy. We do not possess data going back far enough in time, before differences in water scarcity would have begun to emerge, to directly test for 'balance'. However, both administrative and self-reported recall survey data from the early 2000s, when long-term impacts of scarcity are unlikely to have manifested, suggests that differences between the two types of villages were mostly non-existent or smaller at those times.

Several other recent studies provide causal quantitative evidence on environmental stress and migration. Hornbeck (2012) shows that the "dust bowl" of the 1930s in the American midwest resulted in large and long-term population declines in affected areas, by comparing outcomes across counties with different levels of soil erosion. Other studies utilize temporal variation in weather. Feng et al. (2010) find that weather induced production shocks result in increased immigration from Mexico to the U.S., Feng et al. (2012) find a similar result for internal migration from the U.S. corn belt and Cai et al. (2016) find international migration responds to temperature fluctuations especially in agriculturally dependent countries. Bohra-Mishra et al. (2014) find that climatic fluctuations in Indonesia increase rates of permanent internal migration. Henderson et al.

[4]The lithologic data we use to identify the presence of dark clay formations is obtained from drinking water wells that were mostly drilled in the 2000s. Prior to that, even government geologists would have no indication of this presence other than through what farmers had encountered in their own wells.

(2017) find that dryness in the Sahel leads to more rapid urbanization but only in cities with industrial bases. Our results differ from these studies in an important way, since our results describe a response to a gradual, anticipated process of environmental change ("slow onset"), rather than to a temporary shock (like a weather shock) or a permanent but sudden and un-anticipated change (like the "dust bowl"). Henderson et al. (2017) study the effects of slower, decadal scale variation in dryness, but even that variation can be oscillatory and can shift in any given year. In our context, farmers have been aware of the ongoing persistent decline in the water table for decades, and have a clear idea of its eventual impact, potentially allowing them to better prepare. However, we find no evidence for such preparation.

A long theoretical literature, starting with the seminal Dasgupta-Heal-Solow-Stieglitz model of resource substitution (Solow, 1974; Dasgupta and Heal, 1974; Stiglitz, 1974) analyses the optimal depletion of a natural resource and the degree to which investments in reproducible capital can help maintain production. Our study can be conceptualized within a framework based on this model. Agents anticipating water resources to be depleted can invest in human capital, an input to non-agricultural production; and agricultural capital, such as efficient irrigation technology, that can help maintain agricultural production with lower water supply. When water depletes, agents allocate labor between the agricultural and non-agricultural sectors (a more complete description of the model is presented in Appendix B). We think of the two types of investments as representing *anticipatory* adaptation within and outside of agriculture, and of the re-allocation of labor from agriculture as a form of *responsive* adaptation that takes place after water stress is realized. Our analysis investigates the extent to which households pursue these three types of adaptations (adoption of efficient irrigation equipment, education and migration from the village). [5] We

[5] Much of the theoretical literature on the topic investigates the optimal rate of resource

note that the distinction we make between anticipatory and responsive adaptation is only relevant in a context of slow moving change in which households can predict the future state of the environment (the resource stock). Responses to transient weather shocks are, by nature, only responsive (or consist of stable levels of precautionary investments).

Our results are also related to the literature on the impact of changes in agricultural productivity on the local non-agricultural economy. Hornbeck and Keskin (2015) finds that boosts to agricultural incomes in areas overlying the Ogallala aquifer in the U.S. post WWII did not lead to long-term expansion in non-agricultural sectors. Foster and Rosenzweig (2004) find that in India, rural industry grew faster where crop yields grew more slowly. In contrast, Asher and Novosad (2012) find, also in India, that declines in output induced by rainfall shocks reduce capital availability for investments in small scale rural industry. Here, we find no evidence that reductions in agricultural productivity resulting from groundwater depletion result in higher non-agricultural employment.

The remainder of this paper is organized as follows. Section 2 provides background on India's groundwater depletion crisis. Section 3 describes our empirical strategy. Section 4 describes the data, section 5 presents results and section 6 concludes.

2 Background and the Study Area

The depletion of groundwater resources is a major global driver of increased water scarcity (Konikow and Kendy, 2005; Wada et al., 2010). India, the world's

use and investment. We do not claim that depleting groundwater resources is dynamically sub-optimal. Rather, we study empirically how farmers adapt to this depletion, regardless of whether it is efficient or not. Our data also does not put us in a position to make claims about the welfare impacts of resource depletion, since we are unable to track migrants. Regardless of migrants' welfare outcomes, however, our results may suggest that increasing water scarcity poses serious threats to India's food production even though technologies exist that could avert this threat. Of course, a more complete answer to this question would require an estimation of general equilibrium effects, which is beyond the scope of the present analysis.

largest consumer of groundwater, is the country probably most vulnerable to this threat. Over-extraction of groundwater (in excess of natural recharge) and falling water tables are widespread across India, especially in most agriculturally productive regions of North-Western and Southern India (Rodell et al., 2009; World Bank, 1998; Livingston, 2009; Shah, 2010; Fishman et al., 2011; Sekhri, 2013) and goes hand in hand with increasing use of heavily subsidized electricity for pumping (Fishman et al., 2016; Badiani et al., 2012).

The importance of irrigation to agricultural productivity and rural development is widely acknowledged (Viala, 2008), and Sekhri (2014) provides evidence that difficulty in accessing groundwater leads to increased poverty in parts of Eastern India where water tables are still quite shallow. There is also evidence that short-term temporal variation in water tables leads to reductions in agricultural production (Fishman et al., 2011; Sekhri, 2011), but despite widespread concerns in Indian policy circles about the consequences of long-term groundwater depletion, there is little evidence that can help assess the eventual impacts of India's vast alluvial aquifers "drying up".

Water scarcity is driven by both hydrological and energy constraints. Even though in most of India power for pumping groundwater is provided to farmers at highly subsidised flat rates, the daily duration of agricultural power supply is restricted, limiting the amount of water that can be extracted. As water tables drop, the limited supply of energy enables the extraction of reduced amounts of water, but farmers may still deepen their wells and increase the power of their pumps in order to 'chase the water table' and maintain a stable extraction level, especially where aquifers still hold large amounts of water (Fishman et al., 2011). [6]

Our study was carried out in a region of Northern Gujarat known for its

[6] The situation in shallow, hard rock aquifers can be different. In such aquifers, common around central India, aquifers with limited storage capacity can follow a more transient oscillation in water availability which depends on rainfall patters (Fishman et al., 2011)

extreme levels of groundwater depletion (Prakash, 2005; Bhatia, 1992; Dubash et al., 2002). In comparison to other parts of India that rely on deep, alluvial aquifers for irrigation, the area is extreme in terms of the advanced stage of depletion, already observed in the 1970s (United Nations Development Programme, 1976; Postel, 1999; Moench, 1992a,b), and seems to have reached the point in which enhanced energy use cannot substitute for binding hydrological scarcity (the actual physical depletion of aquifers). As suggested by Shah (2007), impacts observed in this area may therefore be informative on what may be expected to follow in other groundwater depleting parts of the country.

Figure 1 contrasts the depth of the water table, as recalled by respondents in surveys in the region, [7] and as measured in government observation wells. The plot indicates an extremely high average rate of decline of 3 meters per year over the last four decades. It also shows that farmers are not only aware of the worsening water situation and the declining depth of the water table, but have also been tracking it for years. Figure 2 plots well depth against the year of drilling for a collection of borewells in the study area, obtained from the same surveys, and illustrates the ongoing deepening of wells to "chase the water table".

Prakash (2005) offers a particularly relevant in-depth ethnography of the groundwater economy in a village in the vicinity of our study area that describes, amongst others, the caste-differentiated response to the boom and bust of the local groundwater economy. Several other observational and ethnographic studies found increased out-migration from areas where water and other natural resources are becoming degraded (Chopra and Gulati, 2001; Moench, 2002; Burke and Moench, 2000). [8] More recent surveys conducted in the study area

[7] The data is obtained from a separate survey conducted in a smaller number of villages in the same area (Narula et al., 2011)

[8] 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

(Narula et al., 2011) found that almost all respondents expected the water table to continue to decline, and the average expected time until water "runs out in their wells" was six years. Once that happens, farmers indicated they will deepen their wells (30%), migrate (30%) or restrict the extent of irrigated cultivation (20%). The analysis below will find causal evidence consistent with both the ethnographic evidence and these self-reported adaptations to water scarcity.

3 Empirical Strategy

3.1 Regional Hydro-Geology and Dark Clay Formations

Our empirical strategy relies on a natural experiment that creates geologically induced, fine scale variation across local villages in the rate at which local aquifers are depleted. To explain our approach, we present here a basic, simplified hydro-geological framework and some key related facts about the regional hydro-geology.

The yield (water flow) of a groundwater bore-well is determined by a complex combination of factors. These include the depth of the well, the power of the pump, and characteristics of the aquifer the well is tapping. However, as

shocks. Work on rural-urban migration which is focused on "pull" factors often builds upon the Harris-Todaro model (Harris and Todaro, 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 (1983) found that caste networks play an important role in facilitating migration to Delhi from other parts of India. Munshi and Rosenzweig (2009) 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 (2013) explore circular migration and find that rates of migration are higher among the poor and more socially marginalized, especially in drought prone regions. In a survey of seasonal migrants in 70 villages in Gujarat, Rajasthan, and Madhya Pradesh, Coffey et al. (2011) 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 et al. (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.

aquifers become depleted (which is manifested in a decline in the water table in unconfined aquifers and a drop in pressure in confined aquifers), the yield of a given well tends to decline.

Over time, changes in aquifer storage (the volume of water stored in the aquifer) are determined by the net balance of recharge and discharge. Therefore, for the same given level of groundwater extraction, differences in the rate of natural recharge can lead to substantial differences in the rate at which the aquifer is depleted. In the case of the deep, ancient aquifers tapped by wells in our study area, most discharge occurs as a result of water extraction through borewells, and most recharge takes place through vertical infiltration of water from the surface or from other aquifers overlying the aquifer in question (Bradley and Phadtare, 1989). The rate of this natural recharge is determined by the permeability of the strata confining the aquifer. In particular, the presence of highly impermeable layers in the strata can impede the rate of natural recharge of the aquifers that underlie them, leading to accelerated rates of depletion of these aquifers.

Geo-hydrological research in 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 (Bradley and Phadtare, 1989). For example, Kavalanekar et al. (1992), state that (see Figure 3):

> 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.

Permeable layers, such as sands, store greater amounts of water and allow for a relatively free flow of water, whereas non-permeable layers, such as clays, only allow water to flow through at extremely slow rates. Local geologists working in the study area have pointed to the presence of a particularly impermeable layer of dark clay in certain locations as the single most important factor determining variation in water conditions across different villages. The dark color of this clay reflects its ancient origins, and aquifers confined by it tend to be older aquifers that receive less natural recharge and may also be more likely to be saline. Wells drilled in locations that overlie these dark clay formations, and which are deep enough to penetrate them, will tap into these aquifers, and because of the low rate of natural recharge, will tend to deplete them more rapidly, leading to a faster decline in the yield of the well than would have occurred in the absence of the clay. [9]

To illustrate our empirical strategy, consider a thought experiment that involves two farmers, otherwise similar, except that one of whose land overlies a dark clay formation. Initially, before reaching the depths at which dark clay layers tend to occur (depths that mostly exceed 300 feet), the two farmers, if they are using similar wells and pumps, would be tapping similar aquifers and would be able to extract similar amounts of water. As they gradually deplete the shallower aquifers and continue increasing their pumping 'effort' (deepening their wells and increasing the power of their pumps) in an attempt to maintain water extraction, their wells eventually reach the depth at which one of them penetrates the dark clay layer. From that point onwards, that well will begin tapping an aquifer with a lower rate of recharge, and will therefore deplete it more rapidly. The farmer owning that well will therefore begin to experience a more rapid decline in water flow and potentially, also reductions in water quality. Initially, increases in 'effort' (deeper wells and more powerful pumps) may be able to compensate for these differences, but over time, physical water scarcity will lead to permanent differences in the quantity and quality of water extractable by the two farmers.

[9] Private communication with D.S.Chaudhary, Hydro-Geologist, Gujarat Water Supply and Sewerage Board (GWSSB), Mehsana (Gujarat) office

This thought experiment, while highly simplified, illustrates the logic underlying our empirical strategy. We assume that before wells reached the depths at which dark clay tends to occur, local farmers were not aware of the presence of the dark clay layer and it had no direct impact on their agricultural practices. However, once wells reached those depths, those villages that happen to overlie these spatially heterogenous formations would have gradually begun to experience a faster rate of decline in water flows and other manifestations of physical water scarcity. Our analysis makes use of this natural experiment to identify the impacts of variation in the rate of groundwater depletion and scarcity.

Even though we are unable to observe the time at which wells in different villages would have reached the dark clay layer, an examination of Figure 2 suggests this would have occurred roughly in the mid to late 1990s. [10] Depending on the exact hydro-geological characteristics of the strata, it may be a matter of several years before these diverging trends would manifest in substantial differences in water availability.

3.2 Lithologic Data

To obtain physical data on localized geological characteristics, we approached the Gujarat Water Supply And Sewerage Board (GWSSB). GWSSB drills drinking water wells in most villages in the area and in some cases, maintains handwritten records of *lithologs* obtained in the course of drilling these wells. These lithologs detail the type of strata encountered at different depths in the subsurface, including an indication of the presence and depth of dark clay layers. We were able to obtain 164 lithologs of drinking water wells in 145 sites, 107 of which were identified in census records. Sixty six of the lithologs indicated the presence of dark clay, at an average depth of 520 feet (standard deviation

[10] The dark clay layers typically occur at depth ranging from 400-600 feet. An examination of the relationship between the time wells were drilled and their depth (Figure 2) suggests typical wells would cross the dark clay layer in the mid to late 1990s.

of 150 feet). In 12 villages, we obtained multiple lithologs (31 in total), and in 9 of these 12 cases, all of them were in agreement about the presence of dark clay, suggesting that there is relatively little variation in dark clay occurrence at sub-village scales.

Figure 4 displays a map of the study area, in which black (green) dots indicate the presence (absence) of dark clay and grey dots indicate villages for which we have no lithologic data. Large dots indicate villages that were included in the household survey (described in the next section). We have household data for 40 of the villages for which we have lithologic data and these villages form the main sample of the study (we became aware of the lithologic data after the survey was completed). Of these, dark clay is detected in 18 villages. The figure suggests that dark clay tends to occur in a band running from southeast to northwest but with substantial spatial variation. Note that the typical extent of the entire study area is only about 50 square kilometers.

There are a number of potential concerns about the lithologic data that could undermine the basis of our empirical strategy and are important to consider.

First, one may be concerned that the drinking wells from which we obtain our lithologic data are drilled in locations that are systematically different than those of farmers' private irrigation wells, or that there is a great deal of variation in lithologic data within villages, making the lithologs of drinking water wells relatively uninformative for our purposes. However, as we have seen above, variation in the presence of dark clay across lithologs obtained from the same village is quite low. Moreover, we found that the lithologic data was in near perfect agreement with assessments made by commercial irrigation well drillers on the presence of dark clay in a given village (these interviews were made before we obtained the lithologic data). Also, as we will see below, lithologic data is highly predictive of various indicators of water scarcity in the village.

A second potential concern is that dark clay could be mechanically more likely to be found in the lithologs of deeper drinking water wells, simply because of their depth. If the depths of these drinking water wells are also correlated with those of farmers' irrigation wells, themselves likely correlated with the degree water scarcity, the presence of dark clay would be mechanically correlated with various indicators of water scarcity, leading us to misinterpret our results. To examine this possibility, we compared the depths of wells that found dark clay to those that did not. Lithologs that did not report dark clay were obtained from wells that were, on average, 690 feet deep. Those that did encounter dark clay were obtained from wells that were only ten feet deeper, a difference that is insignificant both statistically (standard error = 40 feet) and in magnitude.

A third concern might be that the presence of dark clay happens to be correlated with other geological features, closer to the surface, that may have impacted agriculture in dark clay areas even before wells have reached the dark clay itself. However, we found no significant correlations between the presence of dark clay and the composition of shallower layers. For example, villages in which dark clay were detected are no more likely to have any kind of clay layer at depths below 165 or 330 feet.

3.3 Empirical Specification

Our empirical strategy is straightforward and consists of estimating differences between households and individuals who live in villages overlying dark clay and those that do not. We will be estimating regressions of the form

$$I_{v,i} = \omega G_v + \alpha Z_v + \beta X_i + e_{i,v} \tag{1}$$

where I is an outcome of interest for household i in village v. The variable G_v indicates whether the local geology of village v contains a dark clay layer [11] and the coefficient of interest is ω. The regression also controls for household or individual characteristics X_i (see below).

Even though the presence of dark clay is unlikely to impact agricultural or economic outcomes other than through its impact on water availability, it may potentially be correlated, by chance, with other geographical variables which could be impacting the outcomes of interest and result in biased estimates (recall that the sample is somewhat small in terms of the number of villages). We therefore conduct robustness checks that also control for various village level geographical variables Z_v that include longitude and latitude, sub-district fixed effects, soil type fixed effects, and the distance to the nearest main road and town.

It is also worth noting that the relatively small geographical extent of the study area means variation in climatic and agro-ecological conditions is negligible. In addition, the possibility of sorting taking place after the water situation is 'revealed' to farmers, which would change the interpretation of our results, is very unlikely, as land markets in the area are extremely thin.

Since the presence of dark clay is measured at the level of the village, we allow for flexible correlation of the errors $e_{i,v}$ for observations within the same village, and determine statistical significance using the small sample t-distribution (using $G - 1 = 39$ degrees of freedom, where $G = 40$ is the number of clusters). Given the somewhat small number of clusters, there is still a possibility of over-rejecting the null hypothesis, and we follow the recommendations of Cameron et al. (2008) by also checking statistical significance using a wild-cluster boot-

[11] There are two villages in our sample in which multiple lithologs gave mixed results, and we consider these villages as having dark clay. In regressions, we code the dark clay variable as the fraction of lithologs that found dark clay, but we note that our results are insensitive to modifying these codes or omitting the two villages from the sample.

strap to estimate the distribution of the test statistic. The resulting p-values enable us to reject the null hypotheses at very similar confidence levels reported in our main tables for all the principal outcomes of interest (results not shown). Because the presence of dark clay exhibits spatial correlation, in a robustness test we will also estimate standard errors that are adjusted for spatial correlation (Conley, 2008) across neighboring villages (5 KM)[12].

4 Data

4.1 Household Data

In 2012, we conducted household surveys in 62 randomly selected villages in the area (Figure 4). In each village, an average of 25 households were randomly selected to be surveyed from village rosters . The surveys included questions on agricultural practices, access to irrigation, assets and household demographics, and on the primary activities and places of residence of each of the sons and brothers of the household head. We focused on the activities and places of residence of male family members because female family members' migration patterns were mostly driven by marriage considerations. Using these data, we calculated household level indicators of migration that include the number of migrant sons and brothers of the household head (males above the age of 16 who are residing away from the village), and binary indicators of whether the household head has at least one migrant son or one migrant brother. Parallel indicators were constructed for engagement in non-farming activity (males above the age of 16 residing in the village whose primary activity isn't farming).

In addition, we make use of another set of surveys that were executed by a separate field team from the *Columbia Water Center* (CWC) in 84 villages, and

[12]We use code provided by Solomon Hsiang at `http://www.solomonhsiang.com/computing/stata-code`

consisted of interviews with village heads and a small number of "prominent" farmers. We also make use of administrative data from the *3rd Minor Irrigation Census*, run by the Ministry of Water Resources, which collected information about the properties of minor irrigation structures at the village level in 2001, as well as administrative data on the adoption of drip irrigation, a water efficient irrigation technology, obtained from the *Gujarat Green Revolution Company.*

As explained above, we only became aware of the presence of the lithologic data after the surveys were concluded and were able to obtain such data for 40 of the 62 villages that took part in the household survey. These 40 villages form the main sample used in the analysis. We have survey data for about 1,020 households in these villages.

4.2 Summary Statistics

Table 1 summarizes some of the characteristics of agriculture, labor and migration gathered in our household surveys. These surveys were conducted in 2012, but we refer to their data as representing the "current" situation for brevity. Respondents were asked to report the present and past values of these characteristics, using the 2001 Gujarat earthquake as a temporal reference point. A comparison of these responses paints a clear picture of increasing water scarcity.

To cope with falling water tables, farmers have mostly resorted to deepening wells and using more powerful pumps: respondents report current wells to be more than 240 feet deeper than they were in 2001, and pumps to be more powerful by more than 20 HP. Despite these investments, water flow has eventually reduced. For example, the time required to irrigate a parcel of a fixed size (during the wheat crop), a good indicator of water flow from a well, [13] has increased from 3.3 to 5.5 hours over the last decade. The amount of energy required to

[13]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

irrigate such a parcel has more than doubled, and so has the fraction of farmers that only rely on rainfall for cultivation (i.e. have no access to irrigation).

Among farmers with access to irrigation, the decreased availability of water seems to have arrested the increase in cropping intensity, defined as the number of crops grown on a unit of land per year, which critically depends on the ability to irrigate crops during the dry parts of the year (roughly October to May). Since 2001, cropping intensity has not risen and has even declined modestly, in clear contrast to India-wide trends.

The data also points to an increase in migration and non-farming activity. Twenty four percent of households have at least one son (above the age of 16) who is residing in the village, but whose primary activity isn't farming. The corresponding figure for the previous generation, i.e. the group consisting of the household head and his brothers, is 18%. Even though the comparison is not strictly valid, because of the different ages of the two samples, it is consistent with an increase of off-farm employment in the villages. Similarly, 27% of households have at least one migrant son (above the age of 16), whereas the corresponding figure for the previous generation is only 17%.

The simultaneous increase in water stress, migration and exit from agriculture may suggest that exit from agriculture is an adaptation strategy pursued by households in order to decouple their income from the constraints of irrigated agriculture. The analysis that follows will attempt to examine the evidence for a causal link between these trends.

4.3 Balance Tests

Since we do not have access to data from periods that definitely predate the emergence of dark clay impacts, and since most indicators on which we have data can, in principle, be outcomes of the 'treatment' (i.e. the presence of dark clay), we are unable, strictly speaking, to perform a proper balance test between 'treated' (dark clay) and 'non-treated' villages. Our identification relies on the plausible assumption that prior to wells reaching the depths at which dark clay occurs, these formations would have little economic or other impacts, and farmers would have no knowledge of their presence. Nevertheless, we report such comparisons for certain variables that may be less likely to be impacted by the presence of dark clay. Most of these variables pertain to 2001. By then, differences in water scarcity between the two sets of villages may have potentially begun to manifest, but it seems unlikely they would have affected longer term non-agricultural outcomes.

Table 2 reports such 'balance' tests for several household properties. The number of sons and brothers of the household head are well balanced between the two groups of villages. In both sub-samples, a household head tends to have 1.6 sons and 1.4 brothers (meaning that his own cohort consists of 2.4 sons per household). However, households in villages that have dark clay are 15% more likely to belong to the Patel caste, the dominant land-owning caste in North Gujarat (column 3). When sub-district fixed effects are included in the comparison (column 4), the difference is smaller and statistically insignificant. Nevertheless, we control for this caste indicator in all household regressions that follow.

We next turn to examine non-agricultural asset holdings as recalled by our respondents for the year 2001, noting that such data are prone to recall bias, and should be interpreted with care. We focus on non-agricultural assets because their accumulation is less likely to respond to water scarcity differentials as rapidly as agricultural indicators (we examine impacts on agriculture in section 5.4). We do not find evidence for imbalance in any of the asset categories, other than for the probability of a household reporting having been landless in 2001, which is 15% higher in dark clay villages. Present landlessness could potentially be an outcome of the treatment, and could influence reporting of past landlessness. Nevertheless, it could also reflect pre-treatment differences between the two types of villages, and we test the robustness of all of our regressions to the inclusion of controls for past landlessness. As we will see below, this has little effect on our estimates.

In Table A1 we report comparisons of village level irrigation indicators collected from the 2001 *Minor Irrigation Census* which provides data on the numbers and properties of all types of minor irrigation unit, including wells of various types. [14] In all villages in our study area, the census only indicates the presence of basically one type of irrigation units, namely deep borewells. The properties of these wells are generally consistent with results from our household surveys and well balanced between the two types of villages. [15] In Table A2 we report comparisons of the labor force composition using village level data from the 2001 demographic census and here, too, find the two types of villages to be quite similar. These comparisons are generally re-assuring about the assumptions underlying our identification strategy.

In Table A3 we compare the study villages in terms of their geographical characteristics. We find that treated and control village are similar in elevation and soil characteristics, and in distance to the main city of Ahmedabad, but exhibit a small but significant difference in distance to towns and major roads (two variables that are significantly correlated). We find little reason to expect

[14] We were able to obtain this data for 34 of the 40 villages in our sample.

[15] There are about 30 wells per village; the great majority of which are still functional in 2001, and basically none use drip or sprinkler irrigation (technologies that enable more efficient use of water, which become more prevalent in the dark clay villages later on, see below). Basically all wells use electrical pumps (most of which have power exceeding 18 HP, the highest category used in the census), and run for about 7.5 hours per day at peak season. Wells in the dark clay sample are slightly older, and irrigate more area during the rainy season. However, irrigated areas during the key irrigation seasons of the winter and summer are well balanced. Most wells report power limitations as the main constraint, and none report physical water limitations (although the two are related), consistent with expectations from our conceptual hydrological framework for that time.

such modest differences in distance to towns to matter for migration outcomes. The overwhelming migration destination for young men is the state capital of Ahmedabad which is located about a 1.5 hours drive away. Nevertheless, we now control for these two variables in all of our regressions (under Column 5 in all household regression tables) and find that they have little impact on the results. It is worth noting that 2001 census data reports all villages in our sample were reachable by paved road and had power supply and drinking water facilities.

5 Results

Estimates of regression 1 are organized into three groups of outcomes: indicators of water availability and irrigation use, agricultural practices, and migration and occupation. Estimates for each group of outcomes are presented in a separate table. All tables have the same format: each row reports results of regressions in which the dependent variable is indicated in the leftmost column and the independent variable is an indicator of the presence of dark clay in the local village geology. Column 1 reports the mean value of the dependent variable in the non dark clay villages. The next six columns report estimates of regressions with different sets of additional controls, with emphasis on variables that are not well balanced across the two types of villages (as discussed above).

All regressions control for belonging to the Patel caste. Column 2 reports the basic OLS estimate. In column 3, sub-district fixed effects are included. In column 4, geographical controls (latitude and longitude and the distances to the nearest town and main road) are added. In column 5, fixed effects for each of the dominant soil types reported by prominent farmers in the villages are added. In column 6 we add controls for household level land scarcity: an indicator of landlessness in 2001, and the total land size divided by the number of sons of the household heads. In column 7, standard errors are adjusted for spatial correlation (Conley, 2008) with a radius of 5 KM.

In addition to our main estimates, which make use of household data, we also report results of regressions that use related primary and secondary village level data. These regressions are similar to regression 1 except that all variables are defined at the village level.

5.1 Access to Irrigation and Water Availability

We begin by comparing indications of water scarcity across dark clay and non-dark clay households. These comparisons test the validity of our empirical strategy, which relies on the proposition that the presence of dark clay creates differences in water scarcity.

Table 3 reports estimated impacts of dark clay on various indicators of water availability and access to irrigation at the household level. We find that well failures (wells drying up) have been substantially more common in dark clay villages over the past decade. Respondents in dark clay villages reported 0.6 more well failures than in non-dark clay villages, where the mean number of failures was 1.7. There is also evidence that farmers make use of substantially fewer irrigation wells in dark clay villages (it is typical for farmers to obtain water from multiple wells if their plots are not all served by a single well), a reduction of 0.46 wells in comparison to the 1.22 wells used by farmers in non-dark clay villages.

We also find some evidence that wells are deeper and pumps are more powerful in dark-clay villages, but these results are not precisely estimated. However, despite the increase in drilling 'effort', the time required to irrigate a plot of wheat of fixed size, a measure of the water flow from a well (water is allowed to flow into a plot until the plot is completely covered in water, so that the time required for irrigation varies inversely with the strength of the flow) is 1-2 hours longer in dark clay villages. The combined effect of these difference is that about 30% more energy (about 100 KwH/Acre) is required to irrigate a plot of wheat of fixed size in dark clay villages. The amount of energy used to irrigate a fixed plot is a useful summary measure of irrigation water scarcity, and the difference we estimate in this measure between the two types of villages is both highly significant and robust to alternative specifications

There are also indications that farmers in dark clay villages are more likely to be dependent on rain-fed cultivation (likely because they have no access to irrigation), and while the effect is large - eight percentage points, which amounts to a 2-3 fold increase - it is somewhat less precise and robust to alternative specifications.

We also examine whether village heads and prominent farmers report greater water scarcity in villages that have dark clay. Table A4 reports estimates of regression 1 for similar indicators of water scarcity reported by these respondents for the village as a whole. These include the average depth of wells in the village, the average power of pumps, the time required to irrigate one plot, and the fraction of farmers who are strictly rain-fed. The first panel reports regressions of responses by village heads, and the second panel reports regressions of the the average response of the three prominent farmers in the village (identified by the village head). We find results that are consistent with our household estimations. Both village heads and prominent farmers in dark clay villages report larger shares of farmers that are rain-fed, deeper wells, more powerful pumps and longer times required to irrigate a fixed plot (even though not all estimates are precisely estimated). Prominent farmers also report a higher number of failed wells per working well (an imprecisely estimated coefficient) and a larger number of columns per well, which is a more direct measure of the depth of the water table than that provided by the depth of the well (we did not collect this information in our household surveys).

Overall, the results provide confirmation that villages with dark clay exhibit more severe water shortages and more restricted irrigation supply, and confirm the hydrological impacts of dark clay that form the basis of our empirical strategy.

5.2 Agriculture

We now turn to an examination of the impacts of dark clay on crop cultivation. We examine impacts at both the extensive (the extent of cultivated land) and intensive (amount of water applied per unit of land) margins.

Estimates that make use of household level data are reported in Table 4. We begin, in the first row, with cropping intensity, a summary measure of the number of crops grown on a plot of land in a year. The local seasonal calendar consists of three seasons, the rainy season (June-September), the winter season (November-February) and the summer (March-May). Hardly any precipitation occurs outside of the rainy season, and basically all cultivation during the winter and summer months must rely on irrigation. A value of 3 for the cropping intensity would indicate the entire area cultivated in the rainy season is cultivated again in both the winter and summer seasons, and a value of 1 would indicate there is no cultivation outside the rainy season. In dark clay villages, we find a robust drop in cropping intensity of about 0.3 from a mean value of 2.14 in non-dark clay villages. Decomposing the data into the seasonal extent of cultivated land (reported in acres), we see the the reduction in cultivation occurs mostly during the dry winter and summer seasons (about a 30% decrease, in comparison to a 10% decline during the rainy season), even though the reduction in winter is more precisely estimated.

The total number of irrigations applied annually (totalled over the three seasons) does not exhibit a significant or sizeable difference between dark clay and other villages. The results suggest that farmers respond to water scarcity on the extensive margin, rather than the intensive margin, consistent with field observations and interviews with farmers that indicated that they stick to a prescribed irrigation schedule for their crops and adjust the amount of cultivation in order to respond to water availability as they assess it before the season starts. Consistent with this, we also do not find evidence for differences in the yields (per unit land) of the primary seasonal crops.

In Table 5 we examine whether farmers in dark clay villages attempt to adapt to greater scarcity through a switching of crops. Unfortunately, we did not collect crop level cultivated area, but only asked farmers to indicate the major crop they cultivate in each season. We find evidence of modest shifts to crops with somewhat lower water requirements, but only during the summer season, when crop water requirement are highest: a switch from Millet (Bajri) to Sorghum (Jowar). However, these crop changes unlikely to lead to substantial differences in water use (summer Millet is only slightly more water demanding of the two crops), and as we saw above, are unable to maintain the overall extent of cultivated area.

In Table A5 we report related estimates from village level data. Village-level cropping intensity reported by village heads does not show any significant differences between dark clay and non-dark clay villages. However, cropping intensity and seasonal land use reported by prominent farmers are significantly lower in dark clay villages, in magnitudes consistent with results from the household data. The village head survey also included questions about land purchase and rental prices. Data on land prices seems to be very noisy, with highly imprecise estimates of varying signs by specification. Land markets in this area, and in

India in general, are very thin, so data on land purchase value is probably unreliable. In addition, land value is unlikely to be a good measure of the present discounted value of future agricultural profits because other factors, such as non-agricultural demand, seem to be stronger determinants of land value and transactions in these areas. Short term rental rates may provide a more accurate measure of the agricultural productivity of land, and these seem to be significantly lower in dark clay villages.

Finally, we examine evidence for adaptation to water scarcity through the purchase of drip irrigation, an efficient irrigation technology that can enable farmers to irrigate the same amount of land with about half as much water. We use administrative data obtained from the *Gujarat Green Revolution Company* (GGRC), a government agency in charge of distributing drip irrigation in the state. We use Poisson regressions to estimate the effect of dark clay on the number of drip irrigation purchases made in a village during 2006-2012 through GGRC, and find a positive impact of dark clay. This provides evidence for agricultural technological adaptation to water scarcity. However, we note that there were only about 5 drip irrigation systems installed in an average non-dark clay village from 2006-2012. The increase in drip irrigation usage in dark clay villages, while substantial in percentage terms, is still unlikely to have a real effect on overall water balance, or, as we have seen, on the extent of irrigated cultivation in the village, which shrinks considerably in dark clay villages.

5.3 Migration, Education and Exit from Agriculture

Having established an impact of the dark clay layer on water availability and irrigated agriculture, we now turn to an examination of migration and labor shift responses. In Table 6, we report estimates of linear probability models for a household head having at least one son, above the age of 16, who has:

migrated (does not reside in the village); migrated for educational purposes; or has remained in the village but engages in a non-agricultural activity as his main income generating activity. We also report estimates of the number of sons in the household who satisfy these criteria.

We find robust evidence for increases in the incidence of migration from dark clay villages. The probability of having at least one migrant son is higher by about 11% in dark clay villages, in comparison to a mean value of 20% in non-dark clay villages. There are also 0.22 more migrant sons per household in dark clay villages. These impacts are precisely estimated across all models.

However, we do not find evidence for an increase in the incidence of educational migration, or in exit from farming within the village. The estimates are imprecise, and small in magnitude (in comparison to the mean). Educational migration is generally quite rare in both types of villages, so while we do not find significant evidence of any impact, we are unable to reject a relatively large effect in proportional terms.

In Table A6 we estimate another group of regressions, similar to regression 1, in which the unit of observation is an individual son, rather than the entire household. All regressions control for caste and for the son's age.

We begin by examining the educational investments. We do not find evidence of higher educational investments in dark clay villages, as measured by years of education, or by indicators of secondary, higher-secondary or higher education (for which samples are limited to individuals of appropriate ages). Primary education is not included because it is nearly universal for children above the age of 6 in our sample. It does not appear as though households in dark clay villages made higher investments in educating their sons as a means of adapting to shrinking agriculture.

In row 5 we estimate the probability of migration, and find that sons in dark clay villages are about 10% more likely to migrate, consistent with the result we found using household level data. In rows 6-8 we break the sample by education levels and re-estimate the impact of dark clay on the probability of migration for each of those groups. Even though these regressions are not well identified, strictly speaking, since education is endogenous, it is noteworthy that we find statistically similar results across all educational groups. Increased migration from dark clay villages is not restricted to highly educated individuals.

In Table A7 we examine migration differences using village level responses by village heads and prominent farmers. Village heads were asked to indicate if they felt that amongst the young men in the village, the majority are (1) "Living in the village and engaged in farming"; (2) "Living in the village but not engaged in farming"; or (3) "Migrated". Answers by both village heads and prominent farmers indicate a large decrease in the likelihood of the first response (farming in the village) in dark clay villages; a large (but less precise) increases in the likelihood of the third response (migration); and only a small and insignificant impact on the likelihood of the second response (exit from agriculture within the village). These patterns are consistent with results from the household surveys even though the two sets of surveys were independently carried out by separate teams.

5.4 Comparing Current and Past Impacts

In section 4.3 we examined differences in non-agricultural asset holding in 2001 (benchmarked to the great Gujarat earthquake) between dark clay villages and non-dark clay villages. Even though the impacts of dark clay formations on water availability may have become apparent as far back as the mid 1990s, it would seem less likely for these differences to impact the accumulation of non-agricultural assets in such short time periods.

It may be less implausible for differences in water scarcity to begin and impact agricultural outcomes by that time, but even so, one would expect these impacts to be smaller in magnitude in comparison to the present. Our surveys collected both current (2012) and past (2001) responses on several irrigation and agricultural indicators, allowing us to test this hypothesis and examine how differences between dark clay and other villages might have evolved over time. We interpret these tests with caution because recall data may potentially suffer from recall bias and lower precision. On the other hand, we note that farmers are quite confident and consistent in their estimation of past water tables and well properties.

The top panel of Table 7 contrasts estimated coefficients on some of our main cultivation outcomes as reported at present (i.e. 2012, column 2) and recalled in 2001(column 3). Even though our sample size does not allow us to compare these estimates to one another with sufficient precision, the overall pattern confirms differences in most outcomes were smaller and less precise in 2001 than they are at present, consistent with our hypothesis. For example, the energy required to irrigate a plot of land, while exhibiting a large difference between dark clay and non-dark clay villages at present, was virtually identical between the two types of villages in the past. The same is true of the share of rain-fed farmers. The estimated difference in cropping intensity between dark clay and non-dark clay villages is twice as large at present as it was in 2001, but the difference in 2001 is still statistically significant.

To compare the current and past impacts of dark clay on migration, we asked household heads about the place of residence and work and the primary activity of each of their brothers, as well as sons. The bottom panel of Table 7 compares the impacts of dark clay on the income generation and migration of these two generations. To compare the rates of migration of sons and brothers, we constructed indicators of migration by brothers that took place more than 20 years ago. This would make the age period in which migration could have taken place roughly comparable. Using these indicators, we do not find evidence for an impact of dark clay in the previous generation. The likelihood of at least one brother of the household head (himself included) to have migrated from the village 20 years ago was only an insignificant 2% higher in dark clay villages, whereas the corresponding difference for the current generation is 11%.

Unfortunately, unlike for migration, we did not collect information on the year in which non-farming household head brothers stopped farming. We are therefore unable to construct a comparable indicator of exit from agriculture by young males, as we did for migration. When we compare the incidence of exit from farming among the two generations, using the present activity of the household head brothers, we do find a larger, and statistically significant impact of dark clay on the probability of at least one of the brothers exiting agriculture, estimated at 9%. We hypothesize that this effect is driven by relatively recent responses to water scarcity by older individuals for whom migration to cities is more difficult than it is for young males, but without information on the date of these transitions, we are unable to directly test this hypothesis.

5.5 Heterogeneous Impacts by Caste

A small number of village-level studies document the inequality surrounding groundwater use in Northern Gujarat (Bhatia, 1992; Prakash, 2005; Moench, 1992b), particularly between the dominant *Patel* caste and other social groups. In his ethnography of a village in the vicinity of our study site, Prakash (2005) argues that not only did the Patels appropriate most rents from groundwater use, but when the resource began to be exhausted, they had greater capacity to adapt: first by investing in more powerful wells and pumps, and when that strategy was exhausted, by shifting away from agriculture and migrating away from the village. According to this argument, both the intensive use of groundwater and its depletion enhance inequality in an already unequal society. Qualitative interviews in our study area also suggested that young men from socio-economically weaker castes did not have the same opportunity - in terms of capital as well as social networks - to leave the village and migrate to the city like their peers from the Patel caste.

Table A8 reports average differences between Patels and others in terms of irrigation practices, asset holdings and migration and labor shifts. While there is no significant difference in irrigation practices, Patels have larger asset holdings in almost every category (except buffaloes). Moreover, Patels of both the current and previous generations are more likely to have migrated, and Patels from the current generation are more likely to have exited agriculture.

To examine heterogeneous impacts of water scarcity on Patels and the rest of the population, we report, in Table 8, results of regressions like the ones estimated above, except that they are estimated separately for Patels and others. In column 1 we repeat the estimation for the entire sample, for ease of reference. In column 2, we report estimates for the Patel sample, and in column 3 for the non-Patel sample. Column 4 reports the estimate of an interaction term between dark clay formations and an indicator of belonging to the Patel caste, in a regression that contains the full sample.

Even though both groups seem to be experiencing similar increases in water scarcity in dark clay villages (as measured by borewell failures and the time required to irrigate a plot), the results confirm that Patels are more likely to engage in a range of adaptive responses to increased scarcity. In dark clay villages, it is mostly the Patels who invest in deeper wells and more powerful pumps in an attempt to maintain water supplies. [16] However, these attempts

[16] However, we note the possibility that non-Patels, who are less likely to be owning the well

seem to have had limited and short-lived impacts, as witnessed by a similar level of current water flow and a similar decline in cropping intensity for the two groups.

We also find a clear divergence in the ways both groups respond to the difficulties of maintaining agriculture. Patels are migrating to cities in large numbers, whereas there is no evidence for migration amongst the non-Patels. The latter are finding themselves more likely to be rain-fed farmers, share croppers and even landless (although, as we have discussed above, we do not claim the latter is necessarily a result of water scarcity). These results are remarkably consistent with the ethnographic description by Prakash (2005) . However, we acknowledge that our analysis does not determine the mechanism that creates these differences in adaptive approaches between the two groups. Both the ethnographic literature from the area and anecdotal evidence suggests that the strong social networks maintained by members of the Patel castes, including in cities, facilitate enhanced migration, but we cannot exclude the possibility that greater wealth, access to finance or some other difference between the Patels and the rest of the population is responsible for these differences.

6 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 scarcity.

In this study, we find evidence to suggest that the primary mode of adapta-

that they use, may not be as aware of the depth and HP of the well they are using.

tion pursued by socially advantaged (dominant castes) farmers in an increasingly water-scarce region of India, where the continual increases in pumping effort are no longer effective, is migration to cities. For these farmers, the ability to migrate and to shift income sources may have been instrumental in avoiding some of the more pessimistic predictions, voiced for several decades now, about the eventual economic impacts of water depletion. However, amongst the socio-economically weaker castes, the dominant form of adaptation seems to be switching to rain-fed farming. This suggests that migration opportunities are only open to those farmers who have sufficient social and economic capital to enable a smooth transition away from agriculture.

While we find some evidence of attempts to shift crops and adapt more efficient irrigation practices, these attempts are modest and very limited in scale, and unless they are expanded considerably, have little chance of maintaining the extent of cultivation at a village scale. The fact that young farmers are choosing to migrate rather than to adapt agricultural practices may be an indication that agricultural adaptation strategies, while they exist 'on paper', are not readily available or sufficiently attractive to smallholder farmers as a means of mitigating the impact of water scarcity and managing with less water.

Our analysis is based in fine scale variation of the rate of water depletion in a relatively small geographical area. As such, it does not enable us to assess general equilibrium effects or the responses that would take place when such severe groundwater depletion occurs over a larger geographical scale in India (which seems plausible given the pervasiveness of water table declines). In such a scenario, migration possibilities may be 'crowded out' and become less attractive. On the other hand, food prices may increase and encourage technological adaptation within agriculture. Nevertheless, our results 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 land's productivity or in agricultural infrastructure. The full impacts of migration on agricultural productivity are, however, beyond the scope of this study.

The inability of tracking migrants limits our ability to assess the welfare impacts of water depletion. One may be inclined to conclude that migration that is caused by water depletion must be welfare reducing, given that it does not occur without this "push" factor. The question is related to the debate on the nature of the agricultural productivity gap in developing countries. While evidence on the size of this gap is mixed (Gollin et al., 2013; Hicks et al., 2017), Bryan et al. (2014) provide experimental evidence that credit and risk barriers limit the extent of welfare enhancing migration, making it difficult to reject the possibility that the "push" offered by water depletion could improve wages. Additional evidence on this question in the context of water depletion would be a valuable goal for additional research.

The debate on the merit of migration extends to policy discussions. While 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, many policy makers view such migration as un-desirable (Mundial, 2009). 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 government's 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, 2011). 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 analysis indicates that such 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 rates on overall growth is beyond the scope of this study and an important subject for future research.

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7 Tables and Figures

Table 1: Summary Statistics and Trends in Time

Irrigation and Cultivation	**At Survey (2012)**	(S.E.)	**Recalled (2001)**	(S.E.)
Well Depth (100 feet)	6.54	(0.10)	4.10	(0.07)
Pump HP	62.52	(0.93)	38.59	(0.70)
Time to irrigate a plot (hours)	5.51	(0.17)	3.32	(0.08)
Energy used to irrigate a plot (Kwh/Bigha)	399.85	(8.79)	159.72	(4.31)
Share of Rainfed Farmers	0.06	(0.01)	0.03	(0.01)
Cropping Intensity	2.03	(0.02)	2.14	(0.02)
Number of Irrigations	12.32	(0.37)	12.91	(0.37)

Migration and Exit from Agriculture	**Current Generation**	(S.E.)	**Previous Generation**	(S.E.)
At Least One Non-Farmer	0.24	(0.02)	0.18	(0.01)
Number of Non-Farmers	0.33	(0.02)	0.22	(0.02)
At Least One Migrant	0.27	(0.02)	0.17	(0.01)
Number of Migrants	0.42	(0.03)	0.23	(0.02)

Summary statistics comparing present and past irrigation, cultivation, assets and migration and labor shift indicators. The top panel (Irrigation and Cultivation) compares mean values reported at present and recalled for 2001, the time of the Gujarat earthquake. The bottom panel (migration and exit from agriculture) compares the mean migration and farming status of the sons (current generation) and brothers (past generation) of the household heads. The sample consists of 1,070 households in 40 villages. Migration and labor variables are only defined for households who have sons above the age of 16 (of which there are 737).

Table 2: Balance tests, Household Indicators

	(1)	(2)	(3)	(4)
	No Dark Clay	Dark Clay	Difference	Sub-Dist.
Patel Caste	0.27	0.42	0.15*	0.12
	(0.06)	(0.05)	(0.08)	(0.08)
Number of Brothers	2.40	2.35	-0.04	-0.08
	(0.06)	(0.06)	(0.08)	(0.09)
Number of Sons	1.60	1.57	-0.03	0.01
	(0.04)	(0.06)	(0.07)	(0.07)
Asset Holdings in 2001 (Recall)				
Landless	0.25	0.40	0.15 ***	0.15 ***
	(0.03)	(0.05)	(0.05)	(0.05)
Land (Bigha)	6.47	6.69	0.21	0.16
	(0.41)	(0.63)	(0.74)	(0.71)
Land per Son	4.47	4.28	-0.19	-0.18
	(0.34)	(0.50)	(0.60)	(0.61)
House of Permanent Material	0.48	0.60	0.12	0.10
	(0.06)	(0.05)	(0.08)	(0.08)
Ceiling Fans	2.08	2.03	-0.05	-0.07
	(0.07)	(0.13)	(0.15)	(0.15)
MotorCycles	0.16	0.11	-0.05	-0.05
	(0.02)	(0.02)	(0.03)	(0.03)
Cars	0.02	0.02	-0.01	-0.01
	(0.01)	(0.01)	(0.01)	(0.01)
Sample Size	533	487		

'Balance' Tests, Household Level. Columns 1-2 report mean values of household variables less likely to be impacted by the presence of dark clay (see text) in villages that have it (column 1) and those that do not (column 2). Column 3 reports OLS estimates of the difference between the two samples, and column 4 reports estimates that also control for sub-district fixed effects. Standard errors, clustered at the village level, are reported in parentheses. Stars in columns 3 and 4 indicate statistical significance. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Table 3: Household Level Impacts on Irrigation

	(1) Mean (Control)	(2) OLS	(3) Sub-District	(4) Geog. Cont.	(5) Soils	(6) Land Holding	(7) Spatial Clustering
Bore Failures	1.68	0.60***	0.54***	0.56***	0.67***	0.58***	0.60**
		(0.17)	(0.16)	(0.16)	(0.15)	(0.20)	(0.24)
Borewells, Has Access to	1.22	-0.46**	-0.48**	-0.42**	-0.70***	-0.39*	-0.46**
		(0.17)	(0.18)	(0.18)	(0.17)	(0.22)	(0.22)
Well depth (100 feet)	6.11	1.16	1.09	1.39**	1.82**	1.55**	1.16*
		(0.84)	(0.71)	(0.61)	(0.84)	(0.73)	(0.62)
Pump HP	59.70	8.48	7.78	11.42***	13.26**	9.01	8.48
		(6.94)	(4.80)	(3.80)	(5.60)	(6.96)	(7.46)
Time to irrigate a plot (hours)	4.94	1.53	1.06**	1.55**	1.31***	1.86	1.53
		(1.11)	(0.45)	(0.71)	(0.32)	(1.19)	(1.16)
Energy used to irrigate a plot (Kwh / Bigha)	362.00	102.12**	94.26**	112.74**	152.78***	106.47**	102.12**
		(47.34)	(34.90)	(43.27)	(32.90)	(48.54)	(46.87)
Share of rainfed farmers	0.03	0.08*	0.08*	0.07*	0.11***	0.08*	0.08
		(0.04)	(0.05)	(0.04)	(0.03)	(0.04)	(0.07)

The impact of dark clay formations on household irrigation outcomes. Each row reports results of regressions in which the dependent variable is indicated in the leftmost column and the independent variable is an indicator of the presence of dark clay in the local village geology. Column 1 reports the mean value of the dependent variable in villages without dark clay. The next six columns report regression estimates. Column 2 reports a simple OLS estimate. In column 3, sub-district fixed effects are included in the regression. In column 4, geographical controls (a linear function of latitude and longtitude and the distances to the nearest town and main road) are added. In column 5, fixed effects for each of the possible prominent soil types in the village are added. In column 6, an indicator for whether the household was landless in 2001 and the household land holding size, divided by the number of sons, are added. In column 7, the calculation of standard errors takes into account potential spatial clustering in a radius of 5 km around each village. Standard errors, clustered by village, are reported in parentheses. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. The sample consists of 1040 households in 40 villages.

Table 4: Household Level Impacts on Agriculture

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
	Mean (Control)	OLS	Sub-District	Geog. Cont.	Soils	Land Holding	Spatial Clustering
Cropping Intensity	2.14	-0.28**	-0.32***	-0.24**	-0.36***	-0.26**	-0.28*
		(0.11)	(0.11)	(0.10)	(0.10)	(0.11)	(0.16)
Land Cultivated, Rainy Season, Now	0.40	-0.04	-0.03	-0.04	-0.03	-0.00	-0.04
		(0.04)	(0.03)	(0.03)	(0.03)	(0.02)	(0.03)
Land Cultivated, Winter Season, Now	0.32	-0.11**	-0.10**	-0.11**	-0.11***	-0.08**	-0.11***
		(0.04)	(0.04)	(0.04)	(0.03)	(0.03)	(0.04)
Land Cultivated, Summer Season, Now	0.12	-0.03	-0.03	-0.02	-0.04*	-0.02	-0.03
		(0.02)	(0.02)	(0.02)	(0.02)	(0.02)	(0.02)
Number of Irrigations	12.43	0.15	0.61	0.36	0.90	0.78	0.15
		(1.89)	(2.05)	(1.60)	(2.09)	(2.19)	(1.95)
Yield, Rainy Season, Now	20.99	-1.51	-0.24	-1.71	-0.46	-2.27*	-1.51
		(1.54)	(1.39)	(1.68)	(1.58)	(1.31)	(1.64)
Yield, Winter Season, Now	55.44	-7.77	-5.15	-12.41	-12.00	-7.23	-7.77
		(14.66)	(13.09)	(16.28)	(18.60)	(15.35)	(13.57)
Yield, Summer Season, Now	31.40	0.40	0.40	-0.18	1.01	0.94	0.40
		(2.36)	(2.46)	(2.24)	(2.69)	(2.75)	(2.10)

The impact of dark clay formations on household cultivation outcomes. Each row reports results of regressions in which the dependent variable is indicated in the leftmost column and the independent variable is an indicator of the presence of dark clay in the local village geology. Column 1 reports the mean value of the dependent variable in villages without dark clay. The next six columns report regression estimates. Column 2 reports a simple OLS estimate. In column 3, sub-district fixed effects are included in the regression. In column 4, geographical controls (a linear function of latitude and longtitude and the distances to the nearest town and main road) are added. In column 5, fixed effects for each of the possible prominent soil types in the village are added. In column 6, an indicator for whether the household was landless in 2001 and the household land holding size, divided by the number of sons, are added. In column 7, the calculation of standard errors takes into account potential spatial clustering in a radius of 5 km around each village. Standard errors, clustered by village, are reported in parentheses. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. The sample consists of 1040 households in 40 villages.

Table 5: Impacts on Crop Choice

Season	Cotton	Castor	Wheat	Potato	Sorghum	Millet	Other
Rainy	0.04	0.00	N.A.	N.A.	-0.02	0.03	-0.03
Winter	0.01	-0.00	0.01	-0.02	0.00	0.00	0.01
Summer	N.A.	0.03**	N.A.	N.A.	0.33***	-0.37***	0.01

The impact of dark clay formations on household seasonal crop choice. Each entry reports an estimate of the impact of the presence of a dark clay layer on the probability that the household reports a given crop (column headings) as its main crop in a given season (rainy, winter and summer, indicated in the separate rows). In each regression the dominant soil type in the village is also controlled for. Standard errors, clustered by village, are reported in parentheses. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. The sample consists of 1020 households in 40 villages.

Table 6: Household Level Impacts on Migration and Labor

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
	Mean (Control)	OLS	Sub-District	Geog. Cont.	Soils	Land Holding	Spatial Clustering
At Least One Migrant Son	0.20	0.11**	0.11**	0.11**	0.13**	0.13**	0.11**
		(0.05)	(0.05)	(0.05)	(0.06)	(0.06)	(0.05)
Number of Adult Sons Who Have Migrated	0.29	0.22**	0.21**	0.21**	0.27***	0.28**	0.22***
		(0.08)	(0.08)	(0.09)	(0.09)	(0.11)	(0.08)
At Least One Son Migrated for Educational Purposes	0.01	0.02	0.02	0.02	0.02	0.03	0.02
		(0.01)	(0.01)	(0.01)	(0.02)	(0.02)	(0.01)
At Least One Non-Farming Son (Residing in Village)	0.24	-0.00	0.01	-0.01	0.05	0.00	-0.00
		(0.04)	(0.04)	(0.04)	(0.04)	(0.05)	(0.03)
Number of Adult Sons Who Are Not Farming (Residing in Village)	0.31	0.01	0.01	0.01	0.05	0.03	0.01
		(0.06)	(0.06)	(0.06)	(0.05)	(0.07)	(0.06)

The impact of dark clay formations on household migration and labor outcomes. Each row reports results of regressions in which the dependent variable is indicated in the leftmost column and the independent variable is an indicator of the presence of dark clay in the local village geology. Column 1 reports the mean value of the dependent variable in villages without dark clay. The next six columns report regression estimates. Column 2 reports a simple OLS estimate. In column 3, sub-district fixed effects are included in the regression. In column 4, geographical controls (a linear function of latitude and longtitude and the distances to the nearest town and main road) are added. In column 5, fixed effects for each of the possible prominent soil types in the village are added. In column 6, an indicator for whether the household was landless in 2001 and the household land holding size, divided by the number of sons, are added. In column 7, the calculation of standard errors takes into account potential spatial clustering in a radius of 5 km around each village. Standard errors, clustered by village, are reported in parentheses. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. The sample consists of 1040 households in 40 villages.

Table 7: Comparison of Present and Past Impacts

Cultivation and Irrigation	At Time of Survey (2012)	Recalled (2001)
Well depth (100 feet)	1.16	0.76
	(0.84)	(0.51)
Pump HP	8.48	4.79
	(6.94)	(4.52)
Time to irrigate a plot	1.53	-0.13
	(1.11)	(0.34)
Energy used to irrigate a plot	102.12**	8.60
	(47.34)	(14.07)
Share of rainfed farmers	0.08*	0.02
	(0.04)	(0.02)
Cropping Intensity	-0.28**	-0.15*
	(0.11)	(0.08)
Migration and Labor Shifts	**Current Generation**	**Previous Generation**
At Least One Migrant	0.11**	0.02
	(0.05)	(0.02)
Number of Migrants	0.22**	0.03
	(0.08)	(0.03)
At Least One Non-Farmer	-0.00	0.09*
	(0.04)	(0.05)
Number of Non-Farmers	0.01	0.08
	(0.06)	(0.06)

A comparison of the present and past impacts of dark clay formations on household outcomes. Each row reports results of OLS regressions in which the dependent variable is indicated in the leftmost column and the independent variable is an indicator of the presence of dark clay in the local village geology. All regressions control for the caste type of the household (see text). **Top Panel: Irrigation and Cultivation Outcomes.** Columns 1 and 2 reports estimates for the same outcome variable, as reported at present and recalled for 2001 (the time of the great Gujarat earthquake), respectively. **Bottom Panel: Migration and Exit from Agriculture.** Column 1 reports estimates for the migration and farming status of the sons of the household head. Column 2 reports estimates for parallel outcomes reported by the household heads for himself and his brothers. Farming status is reported at present. The migration status takes into account migration that has taken place up to 20 years back (see text for details). Standard errors, clustered by village, are reported in parentheses. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. The sample consists of 1040 households in 40 villages.

Table 8: Heterogenous Impacts of Dark Clay by Caste

	(1)	(2)	(3)	(4)
	All	Patel	non-Patels	Difference
Bore Failures	0.60***	0.69***	0.49**	0.20
	(0.17)	(0.21)	(0.23)	(0.29)
Well depth (100 feet)	1.16	2.18**	-0.06	2.24***
	(0.84)	(0.89)	(0.89)	(0.81)
Pump HP	8.48	15.26*	-0.01	15.27*
	(6.94)	(8.10)	(7.61)	(8.48)
Time to irrigate a plot	1.53	1.86	1.17	0.69
	(1.11)	(1.30)	(1.33)	(1.41)
Energy used to irrigate a plot	102.12**	151.52**	40.81	110.71
	(47.34)	(59.07)	(51.72)	(66.06)
Share of rainfed farmers	0.08*	0.00	0.15**	-0.15*
	(0.04)	(0.04)	(0.07)	(0.07)
Cropping Intensity	-0.28**	-0.30**	-0.27*	-0.04
	(0.11)	(0.12)	(0.14)	(0.14)
Landless, Present	0.20***	0.03	0.29***	-0.26***
	(0.05)	(0.05)	(0.06)	(0.07)
Share Cropper, Present	0.06*	0.01	0.11*	-0.10
	(0.03)	(0.02)	(0.06)	(0.07)
At Least One Migrant Son	0.11**	0.21**	0.04	0.17*
	(0.05)	(0.09)	(0.04)	(0.09)
At Least One Non-Farming Son	-0.00	-0.02	0.01	-0.03
	(0.04)	(0.06)	(0.05)	(0.07)

Each row reports results of OLS regressions in which the dependent variable is indicated in the leftmost column and the independent variable is an indicator of the presence of dark clay in the local village geology. Column 1 reports OLS regression results for the full sample whereas columns 2 and 3 reports estimates of regressions restricted to the Patel and other caste households. Column 4 reports estimates of an interaction term between adverse geology and belonging to the Patel caste in a regression which contain the full sample. Standard errors, clustered by village, are reported in parentheses. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. The sample consists of 1020 households in 40 villages.

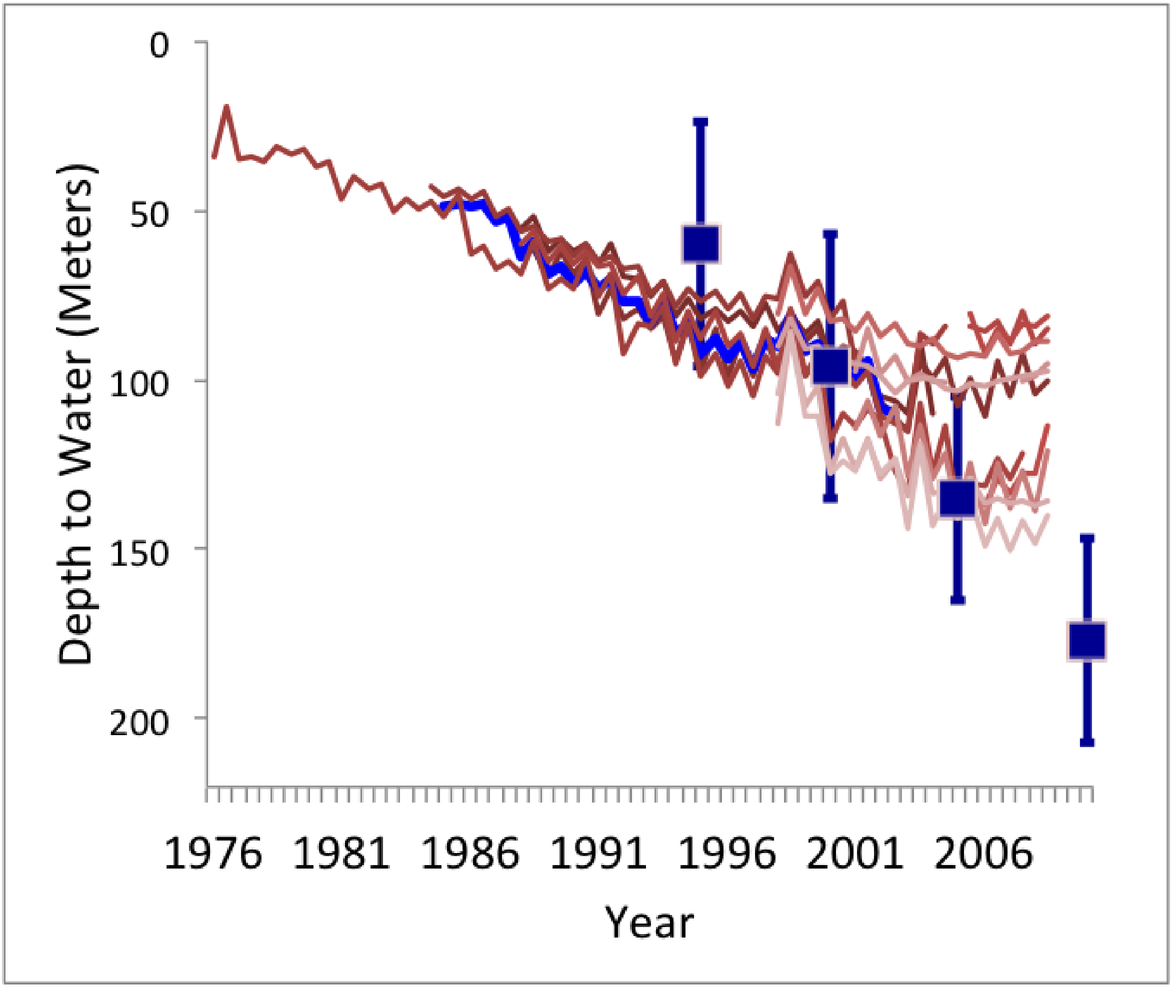

Figure 1: Depth to water, over time (red curves), in a collection of observation wells located in the study area (Vijapur Taluka). Blue error bars represent farmers' recall of the depth to water currently, and 5, 10, and 15 years ago.

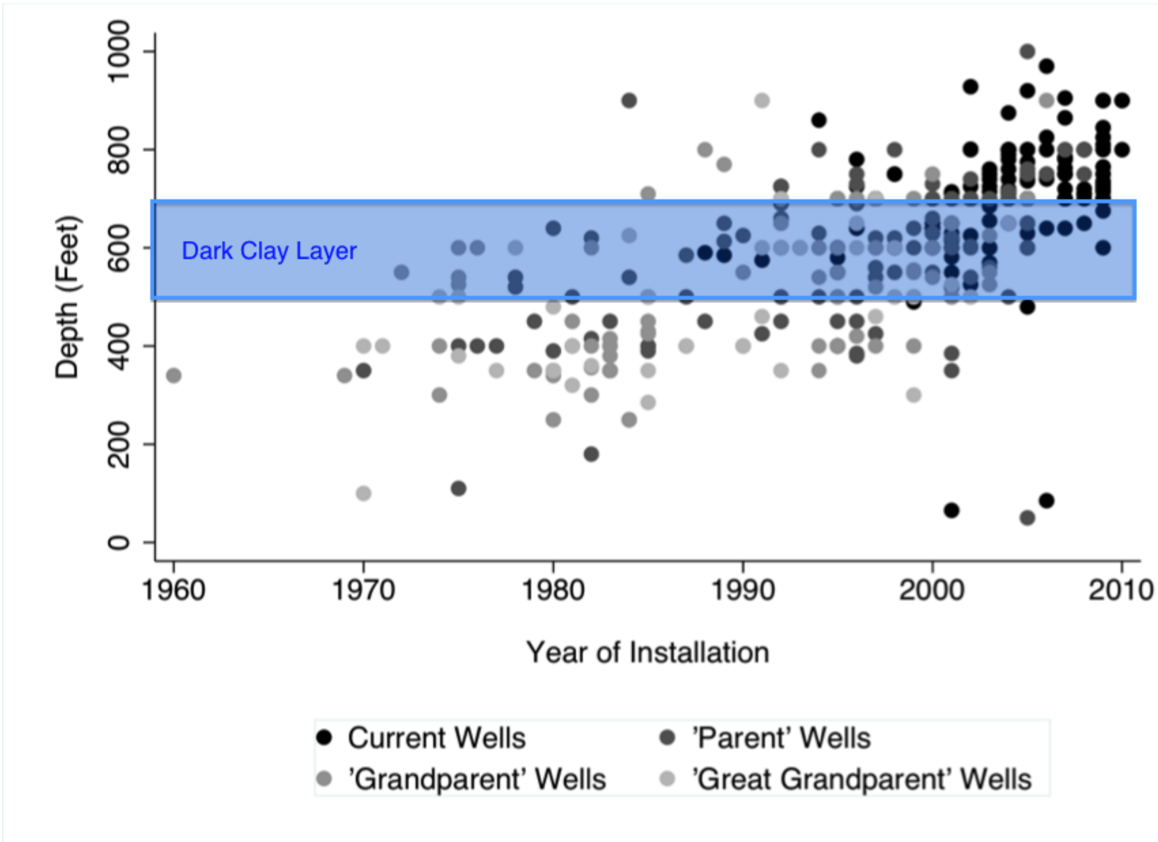

Figure 2: Depth of wells in the study area vs. their year of drilling. Respondents were asked to specify the depth and drilling year of their current wells and up to three “generations” of their previous wells (“father”, “grandfather” and “great grandfather”). The shaded area represent the typical range of depths at which dark clay tend to occur.

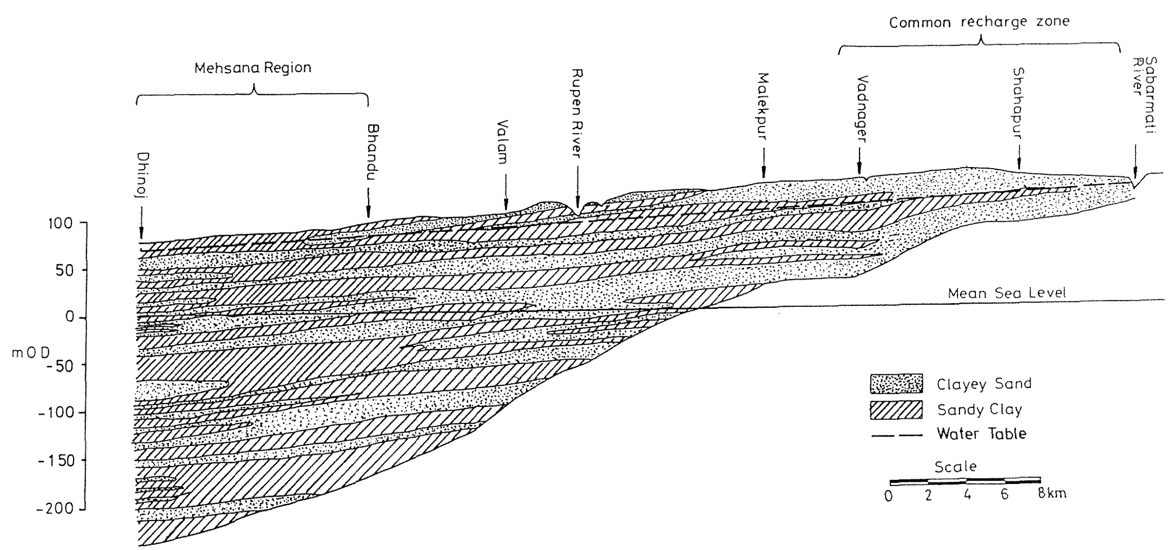

Figure 3: Schematic diagram of the complex aquifer system of North Gujarat. Source: Kavalenkar and Sharma (1992)

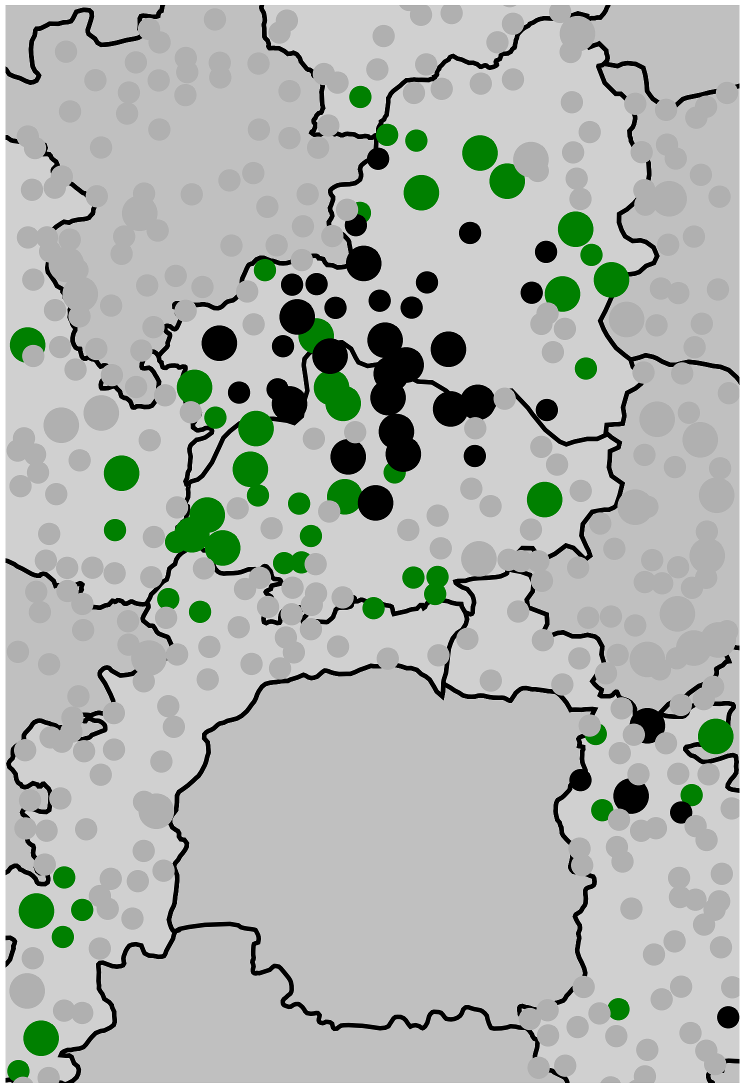

Figure 4: Map of the study area. Larger dots indicate villages that were included in the household surveys. Smaller dots indicate other villages in the region. Black dots indicate the presence of dark clay, green dots indicate its absence, and grey dots indicate villages for which we were unable to obtain lithologic data. Lines indicate sub-district boundaries. Darker shades indicate sub-districts for which no lithologic data was accessible. The empty sub-district is Gandhinagar subdistrict, which was excluded from the survey and the analysis because it is dominated by the administrative capital city of Gandhinagar.

A Appendix

Table A1: Balance tests, Village Level Irrigation (Minor Irrigation Census, 2001)

	(1)	(2)	(3)
	No Dark Clay	Dark Clay	Difference
Number of Deep BoreWells	29.65	33.31	3.16
	(4.89)	(4.79)	(8.22)
Mean Year of Construction	1996	1997	0.62
	(0.42)	(0.51)	(0.66)
Functional Wells (Percent)	0.99	0.96	-0.02
	(0.01)	(0.02)	(0.02)
Percent Deep Wells w Drip, 2001	0.00	0.00	0.00
	(.)	(0.00)	(0.00)
Percent Deep Wells w Sprinkler, 2001	0.00	0.00	0.00
	(.)	(.)	(.)
Wells Using Electric Pump (Percent)	0.99	1.00	0.01
	(0.01)	(.)	(0.01)
Daily Hours of Pumping at Peak Season	7.51	7.51	-0.02
	(0.44)	(0.51)	(0.68)
Wells with Powerful (18 HP) Pumps (Percent)	0.95	0.88	-0.07
	(0.05)	(0.08)	(0.09)
Area Irrigated per well, Rainy Season (Ha)	2.36	3.68	1.32*
	(0.40)	(0.71)	(0.75)
Area Irrigated per well, Winter (Ha)	7.26	7.18	-0.09
	(0.68)	(0.59)	(0.96)
Area Irrigated per well, Summer (Ha)	1.81	1.74	-0.09
	(0.57)	(0.59)	(0.85)
Wells Constrained by Power Shortage (Percent)	0.98	0.99	0.01
	(0.02)	(0.01)	(0.02)
Wells Constrained by Water Shortage (Percent)	0.00	0.00	0.00
	(.)	(.)	(.)
Sample Size	20	14	

Comparisons of village level indicators from the 2001 Minor Irrigation Census. Columns 1-2 report mean values of indicators of interest in villages that have it (column 1) and those that do not (column 2). Column 3 reports OLS estimates of the difference between the two samples. Standard errors are reported in parentheses. Stars in columns 3 and 4 indicate statistical significance. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Table A2: Balance tests, Village Labor Composition (2001 Census)

	(1)	(2)	(3)
	No Dark Clay	Dark Clay	Difference .
Share, Workers (01)	0.38	0.39	0.02
	(0.02)	(0.02)	(0.03)
Share, Cultivators (01)	0.32	0.27	-0.05
	(0.03)	(0.01)	(0.03)
Share, Ag. Laborers (01)	0.23	0.26	0.03
	(0.03)	(0.02)	(0.04)
Share, HH Industry (01)	0.01	0.01	0.00
	(0.00)	(0.00)	(0.00)
Share, Other Workers (01)	0.44	0.45	0.01
	(0.03)	(0.02)	(0.04)
Share, Males (01)	0.52	0.52	0.00
	(0.00)	(0.00)	(0.00)
Sample Size	22	18	

Comparisons of village level labor force composition indicators from the 2001 Demographic Census. Columns 1-2 report mean values of indicators of interest in villages that have it (column 1) and those that do not (column 2). Column 3 reports OLS estimates of the difference between the two samples. Standard errors are reported in parentheses. Stars in columns 3 and 4 indicate statistical significance. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Table A3: Balance tests, Geographical Indicators

	(1)	(2)	(3)
	No Dark Clay	Dark Clay	Difference
Elevation (m)	103.6	111.6	8.2
	(5.1)	(2.7)	(6.2)
Soil: Bulk Density (kg/cm)	1649.8	1652.4	2.9
	(2.7)	(4.0)	(4.6)
Soil: Clay Contect (Percent)	29.9	29.1	-0.8
	(0.4)	(0.3)	(0.6)
Soil: Organic Carbon Content (g/kg)	103.1	106.1	3.0
	(1.4)	(3.2)	(3.1)
Soil: Soil PH (h20)	78.1	78.4	0.3
	(0.2)	(0.2)	(0.3)
Distance to Nearest Waterway (km)	6.9	8.7	1.8
	(0.9)	(1.1)	(1.4)
Distance to Nearest Main Road (km)	7.2	5.1	-2.3*
	(0.8)	(0.8)	(1.2)
Ditance to Nearest Town (km)	13.7	10.6	-3.4*
	(1.1)	(1.2)	(1.7)
Distance to Main City (km)	64.7	69.0	4.2
	(3.9)	(2.4)	(4.8)
Travel Time to Main City (min)	87.6	89.0	1.0
	(3.5)	(2.3)	(4.5)
Sample Size	22	18	

Balance Tests of Village Level Geographical Indicators: Surface elevation (source: 30 meter Shuttle Radar Topography Mission globally accessed using the get_elev_raster function in R); Soil characteristics at the surface, including bulk density, clay content, organic carbon content and acidity (source: SoilGrids.org, a collection of updatable soil property and class maps of the world at 250 m spatial resolutions produced); Distance to the nearest main road and waterway (source: Inland water shape file which maps rivers, canals, and lakes and the Roads shape file, both available at 1:1,000,000 scale from Digital Camera of the World (http://www.diva-gis.org/gdata)); and distance to the nearest town (source: 2001 India Demographic Census). Columns 1-2 report mean values of indicators of interest in villages that have it (column 1) and those that do not (column 2). Column 3 reports OLS estimates of the difference between the two samples. Standard errors are reported in parentheses. Stars in columns 3 and 4 indicate statistical significance. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Table A4: Village Level Impacts on Irrigation

	(1)	(2)	(3)		(4)		(5)		(6)	
	N	Mean	OLS	(SE)	Sub-District	(SE)	Geography	(SE)	Soils	(SE)
Survey of Village Heads										
Shut wells per Working well	41	0.13	-0.00	(0.07)	-0.01	(0.08)	-0.03	(0.10)	0.03	(0.09)
Well Depth	42	642.12	171.19**	(78.60)	181.58***	(47.54)	116.11**	(49.12)	187.90***	(52.73)
Well Columns (Depth to Water)	42	49.69	17.14**	(6.25)	17.88***	(4.45)	11.65**	(4.59)	19.41***	(4.34)
Pump HP	43	58.96	10.53	(7.26)	13.45**	(5.40)	3.34	(4.63)	14.96**	(6.61)
Time to Irrigate a Plot	42	4.44	1.34**	(0.53)	1.31**	(0.58)	1.62**	(0.70)	0.95	(0.62)
Fraction of Farmers, Rainfed	39	28.80	15.63	(10.50)	15.33	(11.54)	18.79	(14.73)	10.05	(12.74)
Survey of Prominent Farmers										
Shut wells per Working well	38	0.09	0.07	(0.07)	0.08	(0.07)	0.04	(0.10)	0.16*	(0.09)
Pump HP	41	59.17	19.46**	(8.21)	16.60**	(7.13)	6.88	(8.21)	23.16**	(9.28)
Time to Irrigate a Plot	41	4.57	1.48**	(0.69)	1.72**	(0.67)	2.00*	(0.99)	1.67*	(0.86)
Fraction of Farmers, Rainfed	36	33.64	14.90	(9.45)	16.65*	(8.17)	20.75*	(10.34)	19.53*	(10.52)

Standard errors in parentheses

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

The impact of dark clay formations on village level irrigation outcomes. Each row reports results of regressions in which the dependent variable is indicated in the leftmost column and the independent variable is an indicator of the presence of dark clay in the local village geology. Column 1 reports the sample size (number of villages). Column 2 reports the mean value of the dependent variable in the non dark clay villages. The next eight columns report regression estimates, with standard errors reported in parentheses. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. Column 3 reports a simple OLS estimate. In column 4, sub-district fixed effects are included in the regression. In column 5, geographical controls (a linear function of latitude and longtitude and the distance to the nearest irrigation canal) are added. In column 6, fixed effects for the prominent soil type in the village are added.

Table A5: Village Level Impacts on Agriculture

	(1)	(2)	(3)		(4)		(5)		(6)	
	N	Mean	OLS	(SE)	Sub-District	(SE)	Geography	(SE)	Soils	(SE)
Survey of Village Heads										
Cropping Intensity	42	2.17	-0.01	(0.14)	0.01	(0.15)	-0.04	(0.20)	0.17	(0.15)
Irrigated Land, Rainy Season (Percent)	42	95.56	-0.35	(5.52)	0.13	(5.93)	-0.97	(7.99)	1.18	(7.03)
Irrigated Land, Winter (Percent)	42	72.59	-3.68	(8.51)	-2.43	(8.73)	-3.08	(10.97)	7.14	(8.64)
Irrigated Land, Summer (Percent)	42	44.44	3.10	(6.99)	3.24	(7.47)	-1.26	(9.76)	10.24	(7.79)
Land Price (Million Rs./Acre)	43	2.53	-0.23	(0.79)	0.02	(0.41)	-0.27	(0.50)	0.15	(0.48)
Land Rental Price (Thousand Rs./Acre)	42	7.69	-2.77**	(1.25)	-3.00**	(1.15)	-3.14*	(1.55)	-3.30**	(1.43)
Agricultural Labor Wage (Rs./day)	43	135.37	-8.94	(12.92)	-2.94	(12.47)	9.21	(14.44)	-5.51	(10.59)
Survey of Prominent Farmers										
Cropping Intensity	40	2.15	-0.32**	(0.14)	-0.33**	(0.13)	-0.31	(0.19)	-0.30	(0.18)
Irrigated Land, Rainy Season (Percent)	41	99.14	-10.35***	(3.19)	-9.95***	(3.43)	-9.77*	(5.10)	-9.59**	(4.05)
Irrigated Land, Winter (Percent)	41	72.32	-17.94**	(8.57)	-19.23**	(8.44)	-21.30	(12.55)	-19.35	(11.37)
Irrigated Land, Summer (Percent)	40	42.52	-14.02**	(5.67)	-13.43**	(5.39)	-9.77	(7.41)	-10.89	(7.39)
Purchases of Drip Irrigation (2005-2013)										
Drip Irrigation Purchases	89	4.66	0.88***	(0.08)	0.38***	(0.10)	0.53***	(0.15)	0.53***	(0.17)

Standard errors in parentheses

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

The impact of dark clay formations on village level cultivation outcomes. Each row reports results of regressions in which the dependent variable is indicated in the leftmost column and the independent variable is an indicator of the presence of dark clay in the local village geology. Column 1 reports the sample size (number of villages). Column 2 reports the mean value of the dependent variable in the non dark clay villages. The next eight columns report regression estimates, with standard errors reported in parentheses. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. Column 3 reports a simple OLS estimate. In column 4, sub-district fixed effects are included in the regression. In column 5, geographical controls (a linear function of latitude and longtitude and the distance to the nearest irrigation canal) are added. In column 6, fixed effects for the prominent soil type in the village are added.

Table A6: Impacts on Individuals' Education, Migration and Labor

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
			Sub-Dist.	Geog.		Land	Spatial
	Mean	OLS	F.E	Cont.	Soils	Holding	Clustering
Years of Education	9.78	-0.05	-0.15	0.02	-0.02	0.48	-0.05
		(0.33)	(0.31)	(0.33)	(0.29)	(0.40)	(0.31)
Secondary Education	0.88	-0.02	-0.03	-0.03	-0.02	0.03	-0.02
		(0.03)	(0.02)	(0.03)	(0.02)	(0.03)	(0.02)
Higher Secondary Education	0.46	0.00	-0.02	0.01	-0.01	0.11**	0.00
		(0.04)	(0.03)	(0.04)	(0.03)	(0.05)	(0.04)
Higher Education	0.25	0.02	0.01	0.02	-0.00	0.08*	0.02
		(0.03)	(0.03)	(0.04)	(0.03)	(0.05)	(0.02)
Migrated	0.17	0.09**	0.09**	0.10**	0.12**	0.12**	0.09**
		(0.04)	(0.04)	(0.05)	(0.05)	(0.06)	(0.04)
Migrated, Secondary Ed.	0.19	0.08*	0.08*	0.09*	0.12**	0.11*	0.08**
		(0.04)	(0.04)	(0.05)	(0.05)	(0.06)	(0.04)
Migrated, Higher Secondary Ed.	0.25	0.14**	0.13**	0.12**	0.14**	0.14*	0.14***
		(0.06)	(0.05)	(0.05)	(0.05)	(0.07)	(0.05)
Migrated, Higher Ed.	0.38	0.07	0.05	0.03	0.05	0.07	0.07**
		(0.06)	(0.06)	(0.06)	(0.07)	(0.06)	(0.03)

The impact of dark clay formations on individual sons' education, migration and occupation. Each row reports results of regressions in which the dependent variable is indicated in the leftmost column and the independent variable is an indicator of the presence of dark clay in the local village geology. Column 1 reports the mean value of the dependent variable in villages without dark clay. The next six columns report regression estimates. Column 2 reports a simple OLS estimate. In column 3, sub-district fixed effects are included in the regression. In column 4, geographical controls (a linear function of latitude and longtitude and the distance to the nearest irrigation canal) are added. In column 5, fixed effects for each of the possible prominent soil types in the village are added. In column 6, an indicator for whether the household was landless in 2001 and the household land holding size, divided by the number of sons, are added. In column 7, the calculation of standard errors takes into account potential spatial clustering in a radius of 5 km around each village. Standard errors, clustered by village, are reported in parentheses. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.The sample consists of 1520 individuals in 38 villages.

Table A7: Village Level Impacts on Migration and Labor Outcomes

	(1)	(2)	(3)		(4)		(5)		(6)	
	N	Mean	OLS	(SE)	Sub-District	(SE)	Spatial	(SE)	Soil	(SE)
Survey of Village Heads										
Young Men Mostly Live in Village, Farming	43	0.734	-0.317**	(0.131)	-0.299**	(0.145)	-0.159	(0.187)	-0.223	(0.135)
Young Men Mostly Live in Village, Not Farming	43	0.544	-0.100	(0.147)	-0.116	(0.146)	-0.179	(0.192)	-0.031	(0.144)
Young Men Mostly Migrated	43	0.165	0.194	(0.147)	0.233	(0.138)	0.232	(0.155)	0.225**	(0.108)
Survey of Prominent Farmers										
Share of Young Men In Village, Farming	37	78.258	-12.475	(7.876)	-13.330	(8.734)	-19.831**	(9.030)	-26.986***	(5.350)
Share of Young Men In Village, Not Farming	28	26.346	0.089	(5.657)	2.290	(5.421)	1.452	(6.795)	4.380	(5.796)
Share of Young Men Migrated	35	34.950	13.766	(8.925)	12.819	(9.084)	17.326	(11.214)	19.666*	(9.807)

Standard errors in parentheses

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

Each row reports results of regressions in which the dependent variable is indicated in the leftmost column and the independent variable is an indicator of the presence of dark clay in the local village geology. Column 1 reports the sample size (number of villages). Column 2 reports the mean value of the dependent variable in the non dark clay villages. The next eight columns report regression estimates, with standard errors reported in parentheses (* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$). Column 3 reports a simple OLS estimate. In column 4, sub-district fixed effects are included in the regression. In column 5, geographical controls (a linear function of latitude and longtitude and the distance to the nearest irrigation canal) are added. In column 6, fixed effects for the prominent soil type in the village are added.

Table A8: Comparisons of Patels and non-Patels

	(1)	(2)	(3)
	non-Patels	Patels - non-Patels	(S.E.)
Water Use			
Pump HP	52.84	1.00	(1.85)
Well depth	5.78	-0.01	(0.19)
Time to irrigate a plot	5.88	-0.14	(0.25)
Number of Irrigations	12.91	-0.46	(0.46)
Assets			
Land Holding	5.72	3.25***	(0.52)
Permanent House	0.44	0.50***	(0.02)
Ceiling Fans	1.93	0.82***	(0.07)
Cows	0.91	0.52**	(0.23)
Buffaloes	1.26	0.04	(0.10)
MotorCycles	0.33	0.43***	(0.03)
Tractors	0.04	0.12***	(0.02)
Cars	0.04	0.11***	(0.02)
Migration and Labor Shifts			
Did Any Sons Migrate?	0.12	0.31***	(0.02)
Did Any Sons Exit Agri.?	0.22	0.10***	(0.03)
Did Any Brothers Migrate?	0.15	0.17***	(0.03)
Did Any Brothers Exit Agri.?	0.10	-0.00	(0.02)

A comparison of the irrigation practices, asset holdings and migration and labor shifts between Patels and other castes. Column 1 reports the mean value of each variable for the non-Patel castes (others). Column 2 reports the difference between Patels and others. The standard error of the estimate is reported in column 3. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$.

B Conceptual Framework

Our conceptual framework borrows the basic elements of the Dasgupta-Heal-Solow-Stieglitz (DHSS) model of resource substitution (Solow, 1974; Dasgupta and Heal, 1974; Stiglitz, 1974). The DHHS model considers a natural resource dependent production function $Y = F(K, W, L)$ where K is reproducible capital, W is the extraction of an exhaustible natural resource with initial stock S, and L is labor. In each period, agents chooses the levels of resource use W and investment in K in order to maximise the discounted utility of consumption. The DHHS model investigates the conditions under which investments in K can *substitute* for (the inevitable) reductions in W in order to prevent output from declining to zero.

We consider a simple variant in which the production function consists of two parts: a resource-intensive sector, as above, $Y_W = F(K, W, L)$ and a non-resource intensive sector $Y_H = G(H, L)$. In our context, the resource intensive sector represents agriculture and the non-resource intensive sector represents off-farm (urban) employment. Capital used in agriculture K represents water efficient irrigation technology that has the potential to substitute for lower water availability, and H represents human capital.

There are two periods, representing two generations. In period 1, we assume the household only engages in resource intensive production and that $K_1 = 0$. The household chooses the amount of water to use, W_1, and then divides production between consumption and investments in irrigation and human capital:

$$Y_1 = F(W_1, 0, L) = C_1 + K + H \tag{2}$$

In period 2, the household uses the remaining water in storage $W_2 = S - W_1 + r$, where r is the rate of natural recharge. We assume r is known in advance with certainty. The household also allocates its labor between the resource intensive and non-resource intensive sectors: $L = L_W + L_H$ to produce (and consume)

$$Y_2 = F(W_2, K, L_W) + G(H, L_H) \tag{3}$$

The choice of W_1 represents conservation, or mitigation of future environmental stress. Investments in K and H represent *anticipatory* adaptations, and our framework makes a distinction between adaptation within agriculture (K) and outside of agriculture (H). The re-allocation of labor away from the resource intensive sector is a form of *responsive* adaptation that takes place after water stress is realized. The distinction between the two forms of adaptation (anticipatory investment and responsive labor shifts, or migration) is only relevant in a context of slow moving change in which households can predict the future state of the environment (the resource stock). Responses to transient weather shocks are only responsive (or consist of stable levels of precautionary investments).

Let the household equilibrium choices be W^*, K^*, H^*, L_H^*. We are interested in testing whether the household responds to lower recharge, i.e. greater expected future water scarcity, by increasing its engagement in adaptation of various types. Formally, we wish to test for:

- **Mitigation**: $\frac{\partial W^*}{\partial r} < 0$.
- **Anticipatory adaptation within agriculture**: $\frac{\partial K^*}{\partial r} < 0$.
- **Anticipatory adaptation outside of agriculture**: $\frac{\partial H^*}{\partial r} < 0$.
- **Responsive adaptation outside of agriculture**: $\frac{\partial L_H^*}{\partial r} < 0$.

Our primary interest is in adaptation. In our context, households do not seem to reduce water extraction efforts in anticipation of depletion. As we will see later, we do not find evidence for difference in the power or duration of operation of pumps around the year 2000, when the rate of water table decline was already observable to households. This should not be surprising given the common property nature of the groundwater resource. Survey results in the area have shown that farmers are well aware of the fact the reductions in water extraction will not stabilise water tables unless the other farmers in the area make similar reductions (results not shown).

Our empirical analysis will be focused on investments in water efficient irrigation K, educational attainment H and labor shifts outside of agriculture, including migration, L_H, of the younger generation in the household. Note also that it is possible for adaptation outside of agriculture to be either anticipatory or responsive or both. For example, it is in principle possible for households to allocate labor outside of farming without having made any prior investments in human capital.