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Abstract

Bangladesh, with two-thirds of its land area less than five meters above sea level, is one of the most climate-vulnerable countries in the world. Low-lying coastal districts along the Bay of Bengal are particularly vulnerable to sea level rise, tidal flooding, storm surges, and climate-induced increases in soil and water salinity. This paper investigates the impact of drinking water salinity on infant mortality in coastal Bangladesh. It focuses on the salinity of drinking water consumed during pregnancy, which extensive medical research has linked to maternal hypertension, preeclampsia, and post-partum morbidity and mortality. The study combines spatially-formatted salinity measures for 2001–09 provided by Bangladesh with individual and household survey information from the Bangladesh Demographic and Health Surveys for 2004 and 2007. It uses probit and logit analyses to estimate mortality probability for infants less than two months old. Controlling for many other determinants of infant mortality, the analysis finds high significance for salinity exposure during the last month of pregnancy and no significance for exposure during the preceding months. The estimated impact of salinity on infant mortality is comparable in magnitude to the estimated effects of traditionally-cited variables such as maternal age and education, gender of the household head, household wealth, toilet facilities, drinking water sources, and cooking fuels.

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Drinking Water Salinity and Infant Mortality in Coastal Bangladesh

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Introduction

The potential impacts of climate change on coastal regions include progressive inundation from sea level rise, heightened storm damage, loss of wetlands, and increased salinity from saltwater intrusion. Worldwide, about 600 million people currently inhabit low-elevation coastal zones and will be affected by progressive salinization (Wheeler 2011; CIESIN 2010). Recent research suggests that the sea level may rise by one meter or more in the 21st century, which would increase the vulnerable population to about one billion by 2050 (Hansen and Sato 2011; Vermeer and Rahmstorf 2009; Pfeffer, et al. 2008; Rahmstorf 2007; Dasgupta, et al. 2009; Brecht, et al. 2012).

While most research has focused on inundation and losses from heightened storm surges, increased salinity from saltwater intrusion may pose another serious threat through its impact on household water supplies. Understanding the significance and magnitude of this threat may be critical for long-term development and poverty alleviation in countries with vulnerable coastal regions (Brecht, et al. 2012).

Bangladesh provides an excellent setting for investigation; with two-thirds of its land area less than 5 meters above sea level, it is one of the countries most threatened by sea level rise and saltwater intrusion. About 30% of the cultivable land of Bangladesh is in coastal areas where salinity is affected by tidal flooding during the wet season, direct inundation by storm surges, and movement of saline groundwater during the dry season (Haque, 2006). In consequence, the potential impact of salinity has become a major concern for the Government of Bangladesh and affiliated research institutions.[4] Recently, the Bangladesh Climate Change Resilience Fund (BCCRF) Management Committee and the

[4] Prior research on salinity intrusion has been conducted or co-sponsored by the Ministry of Environment and Forests (World Bank 2000) and two affiliated institutions: the Center for Geographic and Environmental Information Services (Hassan and Shah 2006) and the Institute of Water Modeling (IWM 2003; UK DEFR 2007). Additional research has been conducted by the Bangladesh Center for Advanced Studies (World Bank 2000; Khan, et al. 2011), the Bangladesh Agricultural Research Council (Karim, et al. 1982, 1990), and the Bangladesh Soil Resources Development Institute (SRDI 1998a,b; Peterson and Shireen 2001).

World Bank have highlighted salinity intrusion in coastal Bangladesh as a critical part of adaptation to climate change (Dasgupta et al. 2014a and Dasgupta et al. 2014b).[5]

Resources will remain scarce, and mobilizing a cost-effective response will require an integrated spatial analysis of salinity diffusion, its impacts, and the costs of prevention, adaptation and remediation. This paper attempts to contribute by addressing two critical components of the problem: salinity changes in the coastal region of Bangladesh, and their consequences for maternal and child health in the region. The paper focuses on the salinity of drinking water consumed during pregnancy, which extensive medical research has linked to maternal hypertension, preeclampsia and post-partum morbidity and mortality.[6]

Methods

Previous Research

Recent micro-level research on drinking water salinity in the coastal region of Bangladesh and its impact on hypertension in pregnant women (Khan, et al. 2008, Khan, et al. 2011) draws on numerous international observational studies and clinical trials that establish a strong link between higher salt intake and elevated blood pressure (Alderman 2000; Calabrese and Tuthill 1981; Hallenbeck, et al. 1981; He and MacGregor 2007; Midgley, et al. 1996; Welty, et al. 1986). The current state of the art has been established by Khan, et al. (2011), who focus on the links between drinking water salinity and

[5] Sarwar (2005) and SRDI (1998a,b, 2000, 2010) have documented changes in salinity that have accompanied coastal subsidence and thermal expansion of the ocean. Detailed assessments of salinization have employed two principal methods. One approach focuses on simulation of salinity change in rivers and estuaries, using hydraulic engineering models whose results are compared with actual measures (Bhuiyan and Dutta 2011; Mohal et al. 2006; Aerts, et al. 2000; Nobi and Das Gupta 1997). Another approach focuses on local salinity impacts, using surveys and descriptive statistics (Mahmood, et al. 2010; Khan, et al. 2008, 2011; Haque 2006; Sarwar 2005; Rahman and Ahsan 2001; Hassan and Shah 2006; Karim, et al. 1982, 1990). In the most comprehensive study to date, Dasgupta, et al. (2014a) develop detailed projections of river salinity through 2050 in Bangladesh's coastal region.

[6] This is a serious public health issue because hypertension in pregnancy is associated with numerous maternal and infant health threats, including impaired liver function, intrauterine growth retardation, preterm birth, and maternal and perinatal deaths (Sibai, 2002).

hypertension during pregnancy in Dacope Upazilla, Khulna. The study infers the impact of salinity on maternal health from three information sources: monthly measurements of salinity in shallow and deep groundwater tubewells at various sites in the Khulna region and along the Passur River during the period 1998-2000; urine samples and blood pressure measures for 343 pregnant Dacope women during the 2009-2010 dry season (October 2009 through March 2010); and hospital-based measures of the prevalence of hypertension for 969 pregnant women during the period July 2008 - March 2010. The study has three principal findings: (1) The salinity of tubewell water in the study area was far higher during dry season months in 1998-2000. (2) Pregnant women who drank tubewell water during the dry season of 2009-2010 had significantly higher urinary sodium than women from the sample group who drank rainwater during that period. However, the study does not establish a significant link between urinary sodium and hypertension. (3) Hospital-based blood pressure measures during wet and dry seasons during the period 2008-2009 revealed a significantly higher incidence of hypertension during the dry season.

This pioneering inferential study yields valuable insights into the relationship between salinity and maternal health in Bangladesh. However, its restricted geographic coverage, limited temporal span, and temporal mismatch of data sources have left a significant gap between its findings and the results that could be delivered by the longitudinal study that we described above.

Extensions in This Paper

In this study, we attempt to narrow the research gap by mobilizing information that features a larger sample population, broader geographic coverage, a longer temporal span, and temporally-matched data. Monitoring household-specific drinking water and health indicators was beyond the scope of our research. Instead, we relied on (1) proxies for drinking water salinity: monthly spatially-formatted data from 41 soil salinity monitoring stations for the period 2001-2009, provided by the Bangladesh Soil

Research Development Institute; (2) spatially-formatted Bangladesh Demographic and Health Surveys (DHS) conducted during the same period. The 2004 Bangladesh DHS includes information on 11,440 women age 10-49 and 4,297 men age 15-54 from 10,500 households, covering 122 urban and 239 rural clusters (NIPORT, et al. 2005). The 2007 Bangladesh DHS includes information on 10,996 women age 15-49 and 3,771 men age 15-54 from 10,400 households in 134 urban and 227 rural clusters (NIPORT, et al. 2009).

The Bangladesh DHS surveys do not include hypertension measures for the women surveyed. However, their information on cluster location allows us to construct monthly indicators of drinking water salinity for each surveyed woman during a nine-year period (2001-2009). The surveys also include temporally-specific information on mortality events for children in the surveyed households. The data therefore permit estimation of a reduced-form model that relates mothers' consumption of saline water during pregnancy to post-natal mortality outcomes for their children.[7]

Model Specification

We focus on the relationship between drinking water salinity during pregnancy and mortality during the first two months of life. Using data for individual children, we estimate equations for mortality events with the following general form:

(1) $P_{ijkl} = \alpha_0 + \sum_{e=1}^{m} \beta_e C_{eijkl} + \sum_{f=1}^{n} \beta_f M_{fjkl} + \sum_{g=1}^{s} \beta_g H_{gkl} + \sum_{h=1}^{T} \beta_h S_{l,t-h} + \varepsilon_{ijkl}$

where, for child i, mother j, household k, DHS cluster l and birth month t:

P = Event probability
C = Child characteristics
M = Mother characteristics
H = Household characteristics
S_{t-h} = Drinking water salinity index, lagged h months from the child's birth month
Ɛ = Random error term

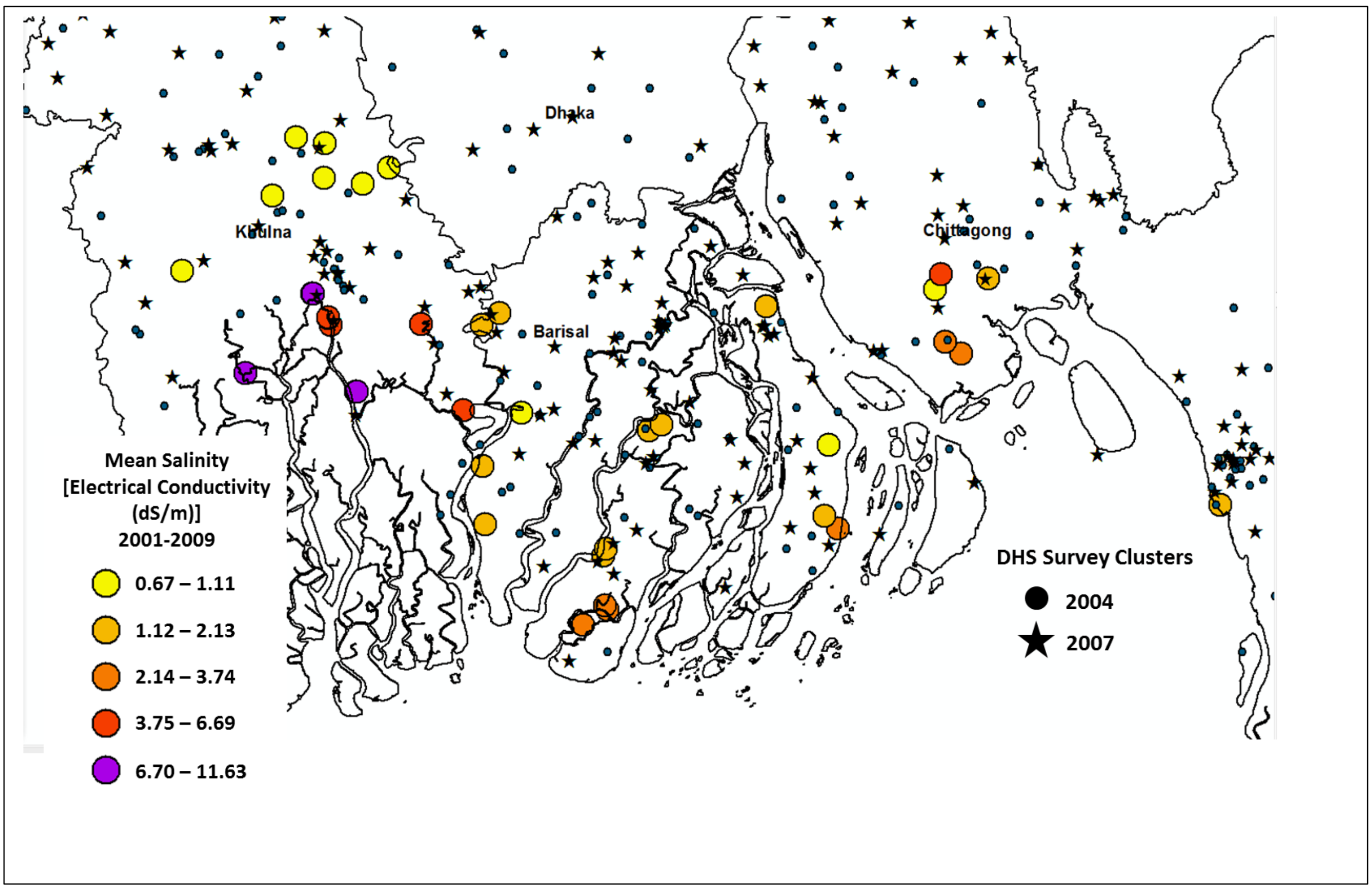
[7] We should emphasize that this is an exercise in statistical control, not direct experimental control. A quasi-experimental approach might test for significance using an arbitrary segmentation of sample-population mothers into "exposed" and "unexposed" groups residing in "low-salinity" and "high-salinity" areas. In contrast, our regression-based approach estimates the size and significance of incremental effects using continuous measures of exposure. Although our sample population resides solely in the coastal region, our salinity monitoring data indicate that salinity exposure for this population varies from negligible to very high.

Database Construction

Cluster Estimates of Soil Salinity

Figure 1 displays our study area, which comprises four regions of southern Bangladesh: Barisal, Chittagong, Dhaka and Khulna. Monitoring stations are color-coded by their mean soil salinity measure in 2001 - 2009.[8] Figure 1 and Table 1 illustrate the substantial variation in measured salinity across monitors, years and seasons within years. In Figure 1, clusters of monitors with low and high mean readings are particularly noticeable in north and central Khulna. Seasonal variation is clear in Table 1, with minimum and maximum measures often differing by several multiples in the same year. Cross-monitor variations are also evident, particularly for maximum readings.

Figure 1: Soil salinity monitoring stations and DHS survey clusters in Khulna, Dhaka, Barisal and Chittagong



[8] The standard sample-based measure for soil salinity is electrical conductivity (in dS/m -- deciSiemens per meter).

Table 1: Soil salinity monitor measures (dS/m): 2001, 2005, 2009

				2001		2005		2009	
District	Upazila	Union	Local No.	Min	Max	Min	Max	Min	Max
Bagerhat	Mongla	Burirdanga	1	7.50	13.10	4.70	23.10	5.70	23.90
Bagerhat	Mongla	Burirdanga	2	6.80	16.40	1.70	14.70	4.80	22.20
Bagerhat	Morrelganj	Boloibunia	1	2.50	5.60	2.00	17.20	1.10	9.10
Barguna	Amtali	Amtali Paurashava	1	0.59	2.40	0.63	2.46	1.09	2.85
Barguna	Amtali	Amtali Paurashava	2	0.71	1.89	0.85	1.86	0.96	2.10
Bhola	Bhola Sadar	Illisha	1	0.99	6.56	0.18	4.00	0.21	1.09
Bhola	Charfesson	Aslampur	1	0.81	10.07	0.50	8.42	0.36	2.28
Bhola	Charfesson	Betua	1	0.90	2.80	0.40	11.54	1.24	12.18
Bhola	Tazumuddin	Shambhupur	1	0.64	2.38	0.26	3.94	0.25	1.93
Chittagong	Sadar	Patenga	1	1.12	4.13	0.35	3.13	0.80	3.00
Jessore	Abhoynagar	Noapara Paurshava	1	0.40	0.60	0.30	0.90	1.04	2.31
Jessore	Keshabpur	Sagardari	1	0.70	1.00	0.40	0.90	1.18	2.78
Khulna	Batiaghata	Batiaghata	1	2.20	6.80	2.20	11.50	1.40	22.50
Khulna	Batiaghata	Batiaghata	2	1.00	8.30	2.10	8.90	1.50	17.80
Khulna	Batiaghata	Batiaghata	3	2.00	11.10	2.20	21.90	1.20	14.60
Khulna	Batiaghata	Batiaghata	4	2.20	17.40	2.50	17.20	1.20	13.50
Khulna	Batiaghata	Jalma	1	1.60	10.10	1.80	11.30	1.10	19.00
Khulna	Batiaghata	Jalma	2	1.60	9.80	1.80	8.40	1.10	12.80
Khulna	Dumuria	Gutudia	1	1.20	25.20	4.70	28.90	1.40	19.70
Khulna	Dumuria	Gutudia	2	1.30	6.80	9.60	29.10	2.20	15.30
Khulna	Paikgacha	Paikgacha Paurshava	1	5.40	37.40	2.60	22.50	1.30	43.30
Narail	Lohagara	Kotakul	1	0.60	0.90	0.70	1.00	0.80	2.78
Narail	Sadar		1	0.60	0.80	0.50	1.10	0.92	1.18
Narail	Sadar	Tularampur	1	0.60	0.90	0.70	1.30	0.92	2.04
Narail	Kalia	Babra Hachla	1	0.50	0.80	0.40	1.50	1.04	2.78
Narail	Sadar	Singasolpur	1	0.60	0.90	0.60	1.20	0.92	1.18
Noakhali	Sadar		1	1.60	11.50	0.60	14.20	0.20	4.60
Noakhali	Sadar		2	1.40	3.40	0.30	2.70	0.10	1.20
Noakhali	Sadar	Noakhali Paurashava	1	1.50	6.60	0.20	15.20	0.10	1.20
Noakhali	Subarnachar	Char Bata	1	1.90	24.50	0.50	19.90	0.20	9.50
Noakhali	Subarnachar	Char Jubilee	1	1.40	8.80	0.10	15.30	0.10	3.20
Patuakhali	Dumki	Lebukhali	1	0.86	1.98	0.65	2.20	0.91	2.49
Patuakhali	Dumki	Lebukhali	2	0.86	2.00	0.73	2.30	0.87	2.24
Patuakhali	Kalapara	Kalapara Paurashava	1	1.10	4.11	1.00	4.14	1.00	5.31
Patuakhali	Kalapara	Kalapara Paurashava	2	1.17	4.39	2.00	4.76	2.22	4.10
Patuakhali	Kalapara	Nilganj	1	1.25	8.47	1.60	5.73	1.71	6.74
Pirojpur	Bhandaria	Nudmulla	1	0.22	0.86	0.24	1.82	0.18	1.14
Pirojpur	Mathbaria	Sapleza	1	0.50	5.78	0.47	3.14	0.24	2.83
Pirojpur	Mathbaria	Tushkhali	1	0.79	1.73	0.36	3.10	0.24	9.80
Pirojpur	Nazirpur	Nazirpur	1	0.61	4.17	0.72	4.50		
Pirojpur	Nazirpur	sekhmatia	1	1.24	3.86	0.70	3.90	0.54	6.46

Cluster locations for the DHS surveys are identified in Figure 1 by circles for 2004 and stars for 2007.[9] They are sited at widely-varying distances from salinity monitors, with some clusters close to several monitors. Using the information illustrated by Figure 1, we estimate salinities for DHS clusters using two basic assumptions. First, we assume that the soil salinity measure for an area provides a useful proxy indicator for drinking water salinity. This seems reasonable on two grounds. First, runoff from fields and subsurface diffusion should produce higher water source salinity in areas with more saline soils. As Yu (2010) shows, soil composition in coastal Bangladesh is particularly conducive to vertical diffusion of salinity from the surface to groundwater. Second, in cases where soil monitors are near more scattered river monitors, Dasgupta, et al. (2011a) show that neighboring soil and water salinity readings are highly correlated.[10] This provides further evidence of diffusion from runoff. Although we believe that local soil salinity provides a useful proxy indicator for drinking water salinity, we recognize that this assumption introduces random measurement error of unknown magnitude.

Our second assumption is that we can use spatial interpolation to compensate for the locational mismatch between monitors and DHS clusters in our database. We apply spatial interpolation in two steps. First, we select monitors within a constant distance from each DHS cluster. Then, for each month and year, we estimate cluster salinity as the weighted average of monitor salinity readings, where the weights are inversely proportional to squared distances. To test for robustness, we create three sets of cluster estimates for bounding distances of 20, 30 and 40 km. We face an unavoidable tradeoff in setting the bound: Greater distance permits salinity estimation for more DHS clusters, but it may also

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[9] The indicated locations are cluster centroids supplied by the DHS, which randomly displaces GPS latitude/longitude positions to ensure confidentiality for respondents. DHS-supplied urban centroids are within 2 km of actual centroids; 99% of rural cluster centroids are within 5 kilometers of actual centroids and 1% are within 10 km.

[10] This study uses the soil salinity monitors because they provide many more observations for estimation. Soil monitors substantially outnumber river monitors in the databases available for this study. The soil monitors are also more widely scattered geographically, so they are relatively close to many more DHS clusters than the river monitors.

introduce more spatial interpolation error. We explore the implications in our discussion of the estimation results.

DHS Variables

Many studies have investigated the determinants of mortality risk for infants in Bangladesh and other low-income countries (Amouzou and Hill 2004; Bicego and Ahmad 1996; Chowdhury 2013; Das Gupta 1990; Hobcraft, et al. 1984, 1985; Jain 1985; Majumder, et al. 1997; Martin, et al. 1983; Murphy and Wang 2001; World Bank 1993). This paper draws on their findings to identify potentially-significant variables that are provided by the Bangladesh DHS. They include numerous variables for children (e.g., gender); parents (e.g., age, education); and households (e.g., gender of household head, wealth status, sanitation facilities, drinking water sources, cooking fuels).

Model Estimation

To maximize degrees of freedom, we estimate our model using a combined sample from DHS 2004 and 2007 that contains information on 39,150 children. We perform all estimations using standard and robust estimators for both probit and logit models. The results across all four estimators are effectively identical, so we report only the standard probit estimates in this paper.[11]

DHS Variable Selection

We identify potentially-significant child, parent and household variables in the DHS data for full sample estimation for infant mortality, excluding salinity because inclusion drastically reduces degrees of freedom by restricting the sample to clusters within 40 km of salinity monitors in the coastal region. Variables included in this step are gender of child; age and education of the mother; gender of household head and household wealth; and selected dummy variables for toilet facilities (flush toilets, pit latrines), water sources (tubewells, springs and other surface water) and cooking fuels (clean fuels - electricity and

[11] The other estimates are available from the authors on request. We have not estimated spatial variants of these models because the appropriate estimators are not yet available in Stata.

gas). The dummy variables provide tests against excluded dummies for inferior toilet facilities (none), superior water sources (pipes and public taps), and inferior cooking fuels (principally charcoal, wood, straw and dung).[12]

Results

Results for DHS Variables

We present our full-sample results for the DHS variables in the first column of Table 2.[13] These results are of independent interest, since they provide new insight into the determinants of infant mortality in Bangladesh.[14] All of the significant parameters have the expected signs: The probability of death is significantly lower for infants whose mothers are older, more highly educated, and live in female-headed households with access to piped or tap water and flush toilets or pit latrines. We find no significance in the full sample for child gender, household wealth, tubewell water sources or clean cooking fuels.[15]

Results for Salinity

Columns (2) - (4) of Table 2 summarize an extensive exploration of lagged salinity impacts that is illustrated for the 40 km distance bound in Table 3. Using the selected DHS variables, we successively introduce lagged values of our salinity indicator, starting with the first month before each child's birth. Our standard and robust probit and logit estimators all yield the same strong result: Only salinity in the

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[12] Appendix A provides more detailed information on variable selection for toilet facilities, drinking water sources and cooking fuels.

[13] It is important to note that these are regression results for data on individuals, not statistics for sub-groups in the population. Employment of the latter would require sample weighting. As the illustration in Table 4 shows, our microeconometric results can be used to construct estimates for arbitrarily-segmented sub-groups.

[14] The term "infant mortality" is commonly understood to mean mortality of infants less than twelve months old. For expositional simplicity in this paper, we use the term for mortality of infants less than two months old.

[15] Previous micro-level research by the authors on fuel use and indoor air pollution in Bangladesh (Dasgupta, et al. 2006) finds a significant relationship between cooling fuels and indoor levels of harmful particulate air pollution. However, the results also show that structural conditions (e.g., building materials, kitchen locations) play a more significant role. In addition, the previous work does not test the impact of indoor particulate pollution on infant survival probability. Our weak results in the current research suggest that robust inferences about the impact of cooking fuel choice on infant health require much more detailed structural and environmental data than are available for this exercise.

first month before birth is significant. Accordingly, we include this variable in the final estimates that are reported in Table 2. All of our estimates include monthly dummy variables (excluded from the tables for brevity) to ensure that our results for salinity (which varies greatly between wet and dry seasons) are not simply reflections of other seasonal factors that affect the incidence of infant mortality.

We obtain strong results for salinity despite our monthly controls because, as Table 1 shows, salinity exhibits substantial independent variation, both over time within locations and across locations at each point in time. In any case, the risk of seasonal correlation is minimal, since our salinity variable is separately lagged for each child relative to birth month, not calendar month.

To test robustness and parameter stability, we present results for cluster salinity generated from distance bounds of 40, 30 and 20 km.[16] As Table 2 shows, reducing the bound has a very large impact on degrees of freedom: Available observations fall from 8,183 at 40 km to 4,847 at 30 km and 2,072 at 20 km. These sharp reductions have consequences for the statistical significance of all estimated parameters, as would be expected. In the 40 km estimate, salinity in the month before birth is one of the five variables that have statistical significance of 95% or higher (the others are male household head, mother's age, wealth[17] and spring water source). In the 30 km estimate, salinity is one of three variables with significance of 95% or higher. In the 20 km estimate, none of the variables has 95% significance. In the transition from 40 km to 20 km, the parameter estimates for salinity remain stable at .02 or slightly higher.

[16] These three distance bounds are sufficient to establish the clear relationship linking geographic proximity, sample size and estimation robustness. Our impact estimates for salinity are effectively identical for bounds of 40, 30 and 20 km. However, as Table 2 shows, estimated standard errors rise (and t-statistics fall) as degrees of freedom fall sharply with progressive reduction of the distance bound.

[17] The DHS surveys include self-reported wealth in five twenty-percentile classes. Prior experimentation revealed significant effects for the top two classes separately, but no significant difference in magnitudes. We have therefore combined the two classes into "Top 40%" for the final estimates reported in this paper.

Table 2: Probit estimation results (controlling for birth month)

Dependent variable: Child death before age 2 months

	(1)	(2)	(3)	(4)
	Full Sample	Cluster Distance Bound (km) 40	30	20
Observations	39,150	8,183	4,847	2,072
Pre-natal salinity (month before birth)		0.020 (2.21)*	0.023 (2.07)*	0.024 (1.52)
Female child	-0.025 (1.09)	-0.024 (0.43)	-0.062 (0.86)	-0.083 (0.74)
Male household head	0.123 (2.71)**	0.400 (3.10)**	0.462 (2.58)**	0.484 (1.71)
Age of mother	-0.012 (6.10)**	-0.014 (2.97)**	-0.011 (1.79)	-0.005 (0.54)
Mother education (years)	-0.019 (5.63)**	-0.007 (1.05)	-0.010 (1.02)	-0.016 (0.97)
Wealth - top 40%	-0.001 (0.05)	-0.183 (2.50)*	-0.188 (1.94)	-0.206 (1.36)
Sanitation (no toilet facility excluded)				
Flush toilet	-0.100 (2.14)*	-0.226 (1.95)	-0.188 (1.26)	-0.095 (0.41)
Pit latrine	-0.061 (2.06)*	-0.106 (1.43)	-0.069 (0.71)	-0.012 (0.08)
Water source (tap and piped water excluded)				
Tubewell	0.069 (1.85)	-0.041 (0.48)	-0.065 (0.58)	-0.084 (0.49)
Spring	0.386 (5.01)**	0.425 (2.69)**	0.482 (2.38)*	0.503 (1.62)
Surface	0.235 (2.32)*	-0.187 (0.72)	-0.168 (0.52)	-0.101 (0.22)
Cooking fuel (dirty fuels excluded)				
Electricity or gas	-0.067 (1.23)	0.196 (1.66)	0.204 (1.36)	0.202 (0.88)
Constant	-1.459 (17.31)**	-1.803 (8.52)**	-1.957 (6.94)**	-2.158 (4.89)**

Absolute value of t statistics in parentheses
*** significant at 5%; ** significant at 1%**

Table 3: Probit estimates (40 km): Impact on incidence of infant mortality - salinity exposure by month before birth

	1	2	3	4	5	6	7	8	9
Pre-natal salinity	0.020	0.007	0.005	-0.003	0.003	-0.017	-0.005	0.000	-0.002
	(2.21)*	(0.64)	(0.45)	(0.27)	(0.33)	(1.48)	(0.58)	(0.01)	(0.23)
Female child	-0.024	-0.020	-0.018	-0.021	-0.021	-0.062	-0.038	-0.040	-0.006
	(0.43)	(0.36)	(0.33)	(0.37)	(0.37)	(1.08)	(0.67)	(0.69)	(0.10)
Male household head	0.400	0.406	0.406	0.412	0.410	0.408	0.397	0.388	0.497
	(3.10)**	(3.15)**	(3.14)**	(3.19)**	(3.17)**	(3.13)**	(3.03)**	(2.97)**	(3.34)**
Mother age	-0.014	-0.015	-0.015	-0.015	-0.015	-0.021	-0.020	-0.019	-0.022
	(2.97)**	(3.04)**	(3.05)**	(3.09)**	(3.05)**	(4.07)**	(3.85)**	(3.73)**	(4.12)**
Mother education (years)	-0.007	-0.007	-0.007	-0.008	-0.008	-0.004	-0.003	-0.004	-0.001
	(1.05)	(1.05)	(1.05)	(1.08)	(1.10)	(0.62)	(0.48)	(0.60)	(0.18)
Wealth index - top 40%	-0.183	-0.167	-0.167	-0.158	-0.162	-0.159	-0.154	-0.163	-0.137
	(2.50)*	(2.28)*	(2.28)*	(2.16)*	(2.20)*	(2.14)*	(2.07)*	(2.16)*	(1.79)
Flush toilet	-0.226	-0.227	-0.224	-0.224	-0.217	-0.190	-0.209	-0.196	-0.316
	(1.95)	(1.96)	(1.93)	(1.93)	(1.86)	(1.62)	(1.77)	(1.66)	(2.53)*
Pit latrine	-0.106	-0.103	-0.100	-0.096	-0.087	-0.110	-0.126	-0.123	-0.173
	(1.43)	(1.38)	(1.33)	(1.28)	(1.17)	(1.45)	(1.65)	(1.60)	(2.22)*
Tubewell water	-0.041	-0.034	-0.030	-0.025	-0.037	-0.050	-0.060	-0.068	0.015
	(0.48)	(0.40)	(0.35)	(0.29)	(0.43)	(0.58)	(0.69)	(0.77)	(0.16)
Spring water	0.425	0.437	0.436	0.455	0.463	0.474	0.482	0.399	0.334
	(2.69)**	(2.75)**	(2.74)**	(2.85)**	(2.87)**	(2.92)**	(2.95)**	(2.35)*	(1.78)
Surface water	-0.187	-0.151	-0.142	-0.118	-0.152	-0.072	-0.111	-0.140	-0.048
	(0.72)	(0.58)	(0.55)	(0.45)	(0.59)	(0.28)	(0.43)	(0.54)	(0.18)
Clean cooking fuel	0.196	0.187	0.185	0.183	0.185	0.089	0.105	0.114	0.106
	(1.66)	(1.59)	(1.57)	(1.55)	(1.56)	(0.71)	(0.83)	(0.90)	(0.79)
Constant	-1.803	-1.773	-1.769	-1.754	-1.765	-1.541	-1.637	-1.642	-1.715
	(8.52)**	(8.36)**	(8.32)**	(8.26)**	(8.30)**	(7.12)**	(7.49)**	(7.44)**	(7.36)**
Observations	8,183	8,108	8,020	7,956	7,881	7,816	7,730	7,634	7,526

Absolute value of t statistics in parentheses
*** significant at 5%; ** significant at 1%**

Overall, we opt for the 40 km results because they incorporate many more degrees of freedom, while exhibiting no deviation from the 30 and 20 km results in signs and little deviation in magnitudes. The results for salinity are particularly stable.

Assessment of Implications for Public Health in the Coastal Region

To illustrate the implications, we use our 40 km results to predict mortality probabilities for the case presented in Table 4: a female child, one month old, of a mother with no formal education living in a poor, male-headed household with no toilet facilities, access to a community water tap and wood fuel for cooking. We predict probabilities with salinity at the 5th and 95th percentile measures for the sample (0.52 and 7.83 dS/m, respectively), and for maternal ages 30 and 17. As the table shows, increasing salinity from the 5th to 95th percentile increases the child's mortality probability by about 30% (33.3% for maternal age 30 and 29.1% for age 17). In comparison, the 13-year difference in age accounts for a change of about 40% in mortality probability (43.3% for 5th-percentile salinity; 38.8% for 95th-percentile salinity).

Table 4: Salinity impact illustration

Child		Household	
Gender:	Female	Head:	Male
Age:	1 month	Wealth class:	Bottom 60%
Birth month:	June	Toilet facility:	None
		Water access:	Community tap
Mother		Cooking fuel:	Wood
Education (years):	0		

		Mortality Probability (%)			
		Mother Age			
Salinity Percentile	Salinity (dS/m)	30	17	Diff.	% Ch.
5	0.52	6.0	8.6	2.6	43.3
95	7.83	8.0	11.1	3.1	38.8
Diff		2.0	2.5		
% Ch.		33.3	29.1		

Experimentation with a wide variety of individual, maternal and household characteristics reveals similarly-large percent increases in infant mortality when salinity is increased from the 5th to the 95th percentile. Overall, our results suggest that the impact of salinity variation on infant health in coastal Bangladesh is comparable to the impact of other variables that have been assigned major importance by previous research (e.g., maternal age and education, gender of household head, wealth, toilet facilities, drinking water sources and cooking fuel).

Conclusions

In this paper, we have used new monitoring data to investigate the impact of drinking water salinity on infant mortality in coastal Bangladesh. Our work also incorporates many determinants of mortality and morbidity that have been identified by previous research. We use probit and logit analysis to estimate mortality probability models for infants whose age is less than two months. Our database combines spatially-formatted individual and household survey information from the Bangladesh Demographic and Health Surveys for 2004 and 2007 with spatially-formatted salinity measures for 2001-2009 provided by the Bangladesh Soil Research Development Institute. Our approach is based on extensive medical research that has established significant links between the salinity of drinking water consumed during pregnancy, hypertension and preeclampsia in pregnant women, and postpartum infant morbidity and mortality. We focus particularly on testing the post-natal impact of pre-natal salinity exposure during each month of pregnancy.

Controlling for many other determinants, our probability model estimation for infant mortality finds high significance for salinity exposure during the last month of pregnancy and no significance for exposure during the preceding months. The implied impact is comparable in magnitude to the estimated effects of traditionally-cited variables such as maternal age and education, gender of the household head, household wealth, toilet facilities, drinking water sources and cooking fuels.

To summarize, our results strongly suggest that drinking water salinity is a significant determinant of infant mortality in coastal Bangladesh. They also provide some new insights about the relationship between post-natal impacts and the timing of pre-natal ingestion of saline drinking water. However, we should add a cautionary note: Although our research has benefitted from unprecedented access to spatially-formatted salinity monitoring information, our estimation exercise is not based on direct, household-specific measures of drinking water salinity. We have constructed salinity estimates for each DHS cluster using spatial interpolation of information from salinity monitors that lie within 40 km of the cluster. In addition, our monitoring information is for soil salinity, not the salinity of drinking water sources. We provide a rationale for our approach in the paper, but we readily acknowledge the possibility that the resulting measures proxy actual drinking water salinity with substantial random error.

In closing, we believe that our results are sufficiently strong to encourage further empirical work on this issue. An ideal longitudinal study would track health outcomes for women and their children over an extended period, while measuring the salinity of their drinking water at frequent intervals. The study would also track other determinants of maternal and child health outcomes (e.g., mother's education, household wealth, access to sanitation, drinking water sources and cooking fuels). Such a study might well seem infeasible as a stand-alone exercise, but we believe that a relatively low-cost expedient could contribute valuable information. Once sampling clusters are identified for future Bangladesh Demographic and Health Surveys, an independently-financed team could undertake monthly sampling of drinking water salinity in those clusters, both before and during the survey period. This would provide sufficient information to support more robust and detailed short-run analyses of health impacts and, if repeated in successive surveys, would ensure the growth of a spatially-formatted database for long-term analysis. In light of the apparent strength of our results, we believe that the potential value of such an exercise would justify the cost of fielding the requisite team.

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Table A1: Drinking water sources (Bangladesh DHS 2004, 2007)

Water Sources	DHS Description	Freq.	%
Dummy variables included			
Tubewell	Tube well or borehole	33,369	85.28
Spring	Protected spring	441	1.13
	Unprotected spring	270	0.69
Surface	River/dam/lake/pond/stream/canal/irrigation	444	1.13
Dummy variables excluded (for comparison)			
Piped	Piped into dwelling	1,548	3.96
	Piped to yard/plot	930	2.38
Tap	Public tap/standpipe	150	0.38
Excluded (Insufficient data)			
Well	Protected well	21	0.05
	Unprotected well	126	0.32
Other	Rainwater	3	0.01
	Cart with small tank	6	0.02
	Bottled water	3	0.01
	Other	18	0.05
	Not a de jure resident	1,794	4.59
Total		39,123	100

Table A2: Toilet facilities (Bangladesh DHS 2004, 2007)

Facility Type	DHS Description	Freq.	%
Dummy variables included			
Flush toilet	Flush to piped sewer system	2,496	6.38
	Flush to septic tank	2,646	6.76
	Flush to pit latrine	870	2.22
	Flush to somewhere else	690	1.76
	Flush, don't know where	36	0.09
Pit latrine	Ventilated improved pit latrine	3,192	8.16
	Pit latrine with slab	9,846	25.16
	Pit latrine without slab/open pit	11,466	29.31
	Pit latrine, other	465	1.19
Dummy variables excluded (for comparison)			
No toilet facility	No facility/bush/field	3,453	8.83
Excluded (ambiguous definition or insufficient data)			
	Bucket toilet	12	0.03
	Hanging toilet/latrine	2,160	5.52
	Not a de jure resident	1,794	4.59
	Total	39,126	100

Table A3: Cooking fuels (Bangladesh DHS 2004, 2007)

Cooking Fuel Type	**DHS Description**	**Freq.**	**%**
Dummy variables included			
Electricity or gas	Electricity	24	0.06
	Lpg	1,761	4.5
	Natural gas	1,449	3.7
	Biogas	102	0.26
Dummy variables excluded (for comparison)			
Charcoal	Charcoal	7,452	19.04
Biomass	Wood	9,780	24.98
	Straw/shrubs/grass	8,559	21.87
	Agricultural crop	5,037	12.87
Dung	Animal dung	1,248	3.19
Excluded (insufficient data)			
Kerosene	Kerosene	9	0.02
Coal	Coal, lignite	9	0.02
	Other	123	0.31
	Not a de jure resident	3,591	9.17
	Total	39,144	100