THE CONSEQUENCES OF INDUSTRIALIZATION: EVIDENCE FROM WATER POLLUTION AND DIGESTIVE CANCERS IN CHINA

Avraham Ebenstein*

Abstract—China's rapid industrialization has led to a severe deterioration in water quality in the country's lakes and rivers. By exploiting variation in pollution across China's river basins, I estimate that a deterioration of water quality by a single grade (on a six-grade scale) increases the digestive cancer death rate by 9.7%. The analysis rules out other potential explanations such as smoking rates, dietary patterns, and air pollution. I estimate that doubling China's levy rates for wastewater dumping would save roughly 17,000 lives per year but require an additional $500 million in annual spending on wastewater treatment.

I. Introduction

During the 1980s and 1990s, China's rapid economic growth transformed the country and lifted millions of its citizens out of poverty. The economic boom, however, has been accompanied by environmental degradation, including a severe deterioration in the water quality of the country's rivers and lakes. Extensive use of fertilizers by farmers and industrial wastewater dumping by manufacturing firms have rendered the water in many lakes and rivers unfit for human consumption. China's water monitoring system indicates that roughly 70% of the river water is unsafe for human consumption, although many farmers in rural areas still rely on these sources for drinking water (World Bank, 2006).

Concurrent with the decline in water quality in China's lakes and rivers, the country experienced an increase in rural cancer rates during the 1990s (see figure 1). Stomach cancer and liver cancer now represent China's fourth and sixth leading causes of death and, in combination with other digestive tract cancers (such as esophageal), account for 11% of all fatalities and nearly 1 million deaths annually in China (World Health Organization, 2002). The media have reported incidents of contaminated river water from industrial activity leading to outbreaks of cancer in rural villages in China (Kahn & Yardley, 2007; Griffiths, 2007), but systematic analysis of these trends is lacking. As the World Bank (2006) notes, establishing the true public health cost of China's water pollution has been a challenge, and this may help explain the continued resistance to enforcing tighter environmental standards on the country's industrial firms.

Researchers have found connections between water quality and acute waterborne diseases such as typhoid (Cutler & Miller, 2005) and diarrhea (Jalan & Ravallion, 2003), and access to cleaner water may lower infant mortality (Galiani, Gertler, & Schargrodsky, 2005). The connection between water quality and cancer, however, has not been fully explored. A limited but growing literature has linked water pollution to particular cancer types such as liver cancer (Lin et al., 2000) or gastric cancer (Morales-Suarez-Varela et al., 1995). However, as Cantor (1997) described, the literature is incomplete regarding the causal link between water contaminants and cancer: "The epidemiologic data are not yet sufficient to draw a conclusion." Without further estimation of the impact of degraded water on cancer rates, the literature fails to provide the information required to fully carry out the benefit-cost analysis surrounding the environmental health issue in this context.

China represents an excellent context to investigate a causal association between contaminated water and digestive cancers. First, in most developing countries, reliable data on pollution and mortality are unavailable. However, China's efforts in the late 1980s to begin carefully monitoring both mortality and water pollution provide reliable data on these patterns in areas where millions of inhabitants still rely on well water and lake water as their primary drinking sources. Second, since water quality is not randomly assigned to individuals, researchers must also pay attention to why a particular set of inhabitants live in an area of polluted water and the time frame that survey respondents were exposed. In China, however, for most of the exposure window, mobility was extremely limited by government regulations. Therefore, the location of residents at the time of observation in the data will likely reflect their true lifetime surface water pollution exposure.[1] Third, China's high rates of cancer, high rates of pollution, and dramatic regional variation in water quality, driven in part by plausibly exogenous rainfall patterns, allow more precise measurement of the causal effect of contaminated water on digestive cancer incidence.[2] Finally, parameter estimates of water pollution's effect on human health are of critical interest to policymakers in China, who must attempt to balance the interests of industrial firms and those of the large, rural population without access to clean drinking water (World Bank, 2006).

In this paper, I exploit rich data on water quality, air quality, and cause-specific death rates to estimate the causal

Received for publication November 12, 2009. Revision accepted for publication June 14, 2010.

* University of Jerusalem.

I acknowledge the detailed and useful input by the editor and three anonymous referees. I also thank Joan Fang, Wallace Forman, Alison Flamm, Eyal Frank, Charlene Neo, Dan Pam, and Nir Regev for excellent research assistance, and Scott Walker for invaluable help using the Hydro packages in ArcGIS. Special thanks to Jostein Nygard, Tamer Rabie, and Nicholas Bowden of the World Bank for helpful comments and generous access to environmental data. I also thank Rodney Andrews, Jing Cao, David Card, Richard Crump, Janet Currie, Simon Galed, Alexander Gelber, Gopi Shah Goda, Jonathan Gruber, Ann Harrison, Larry Katz, Anna Levine, Ronald Lee, David Levine, Sanny Liao, Kevin Stange, and Ebonya Washington for helpful suggestions.

A supplemental appendix is available online at http://www.mitpressjournals.org/doi/suppl/10.1162/REST_a_00150.

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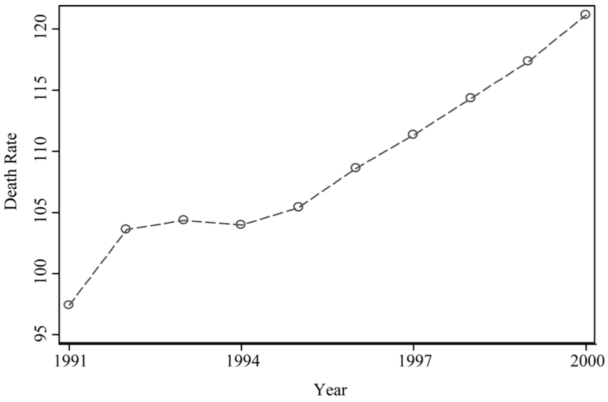
[1] This will be true provided water pollution exhibits time persistence. This is generally true across China's river systems, and is discussed in detail in section III.

[2] Northern China has a shorter rainy season than southern China, and as a consequence exhibits higher levels of pollutants in its surface water. This is discussed further in the next section.

The Review of Economics and Statistics, February 2012, 94(1): 186–201

FIGURE 1.—TRENDS IN CANCER DEATH RATES IN RURAL CHINA, 1991–2000



Source: China Disease Surveilance Points (1991–2000).

The graph was created using STATA lowess smoother. Death rates are per 100,000 persons and are age and sex adjusted using the population distribution in China's 2000 Census.

association between exposure to polluted water and cancer rates. Using a sample of 145 Disease Surveillance Points (DSP) in China and water quality measures from China's nationwide monitoring system, I examine the relationship between water quality and cancer incidence. At each DSP site, I observe cause-specific death rates and the average water grade among monitoring stations in the same river basin.[3] Using geographic information system (GIS) software, I am able to examine several other environmental features of the river basins, such as the average air quality observed from satellite imagery and the long-term average of monthly precipitation.[4]

By comparing DSP sites with better and worse water quality, I estimate using OLS that a deterioration of water quality by a single grade (on a six-grade scale) increases the incidence of digestive cancers by 9.7% in my preferred specification, which includes control variables for air quality and other potential confounding factors also associated with industrialization, such as whether the site is urban, the share of people employed in farming, and region.[5] Furthermore, the largest effect of water quality on digestive cancer rates is observed in areas where households are less likely to have access to tapwater (which can be treated), consistent with the paper's hypothesis that the rural cancer epidemic is in part due to a lack of safe drinking water. By exploiting plausibly exogenous variation in rainfall and the DSP site's distance from the river's headwaters, I estimate 2SLS models, which provide further support for a causal link between digestive cancer and surface water quality. I also rule out other factors that might confound the effect of water quality on cancer, such as smoking or diet, by demonstrating that there is no strong relationship in China between regional variation in smoking rates or dietary patterns and water quality.

In light of the potentially large health consequences of China's water pollution, I present an analysis of the benefits and costs of wastewater treatment in China. Industrial firms in China are subject to a system of levies for wastewater that fails to meet discharge standards, and I exploit regional variation in the policy's effective levy rate (yuan collected per ton discharged) to estimate the potential impact of revisions to China's current rates. Using provincial data from China's environmental yearbooks (1992–2002), I estimate that industrial cleanup (in tons) rises by 0.82% and spending on wastewater treatment (in yuan) rises by 0.14% with respect to a 1% increase in the effective levy rate. I also find that water quality is responsive to total industrial dumping: a doubling of wastewater that fails to meet discharge standards increases the water grade within the basin by .22 units. In combination, these estimates imply that a doubling of China's levy rates would avert roughly 17,000 deaths per year but require firms to spend roughly $500 million more per year on treatment, yielding a cost per averted death of roughly $30,000.[6] In addition, since these estimates do not include the potential benefits of cleaner water in reducing the incidence of other causes of disease and death, they potentially understate the full benefits of tighter environmental regulations. Policymakers should recognize that cleanup efforts could yield large improvements in public health in a relatively cost-effective manner.

The next section provides background information on China's waterways and regional variation in industrial dumping and water quality. Section III describes the data in more detail and summarizes the patterns observed in the data in water quality, industrial dumping, and cause-specific mortality. Section IV reports the empirical results of the analysis. Section V concludes.

II. Background

The pollution levels in China's water bodies have little historical precedent and are believed to be the highest in human history. Despite recent efforts to reduce water dumping by manufacturing firms, roughly 70% of China's surface water has been found unfit for human use, and 115 million rural inhabitants still rely on surface water as their main source of drinking water (World Bank, 2006). In this section, I provide background information on environmental factors that affect

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[3] The river basins are identified by the U.S. Geological Survey project, which uses satellite imagery to divide China into basins, or watersheds, which can be presumed to have similar water quality levels near the DSP site. This is described in greater detail in the data section.

[4] Air quality is proxied by average optical depth observed from NASA satellite imagery for 2002–2007. Precipitation is measured for 1961–1990 by the Global Precipitation Climatology Center (2008).

[5] The water grade is measured on a six-point scale established by the Chinese government based on purpose of use: drinkable water (grade I or grade II), undrinkable but suitable for human contact (grade III), appropriate for general industrial water supply and recreational waters in which there is not direct human contact with the water (grade IV), appropriate only for agricultural water supply and general landscape requirements (grade V), and essentially useless (grade VI).

[6] I estimate that China's firms would need to increase spending on wastewater treatment by 14% from the level reported in 2001 of roughly $3.7 billion, or an extra $500 million in compliance costs.

water quality, geographic variation in these factors, and the variation in water quality that the analysis exploits to estimate its effect on digestive cancer rates. In this paper, I focus on digestive cancers due to their high relevance in China, where two-thirds of cancer cases are digestive, and because they are less likely to be affected by concurrent changes in smoking patterns that are occurring in China (Yang, 1997). I also attempt to improve on existing cancer studies by examining data in a nationally representative sample, whereas the existing epidemiological literature is often focused on case studies of small subpopulations. Since I aim to examine the benefit of tighter environmental standards in China on human health, this strategy may provide parameter estimates more appropriate for this purpose.

Water pollution is classified as either point source or nonpoint source pollution. Point source pollution is wastewater from domestic sewage and industrial wastes that is discharged from a single point. Nonpoint source pollution, such as urban and agricultural runoff, enters rivers and lakes at multiple points. China's experience following industrialization has led to the increase in both: farmers have attempted to increase yields through widespread fertilizer use (nonpoint source), and manufacturing firms have dumped inorganic compounds into water as part of their production processes. When these chemicals drain into waterways, they stimulate a river's algal growth beyond its natural speed (a process known as eutrophication), which simulates the formation of carcinogenic compounds and chemicals. Through eutrophication, the water becomes populated by cyanobacteria (blue-green algae), leading to the formation of microcystins, which have been linked directly to liver cancer (Codd, 2000). Additionally, water pollution introduces nitrate into bodies of water, which, when digested, can undergo endogenous reduction to nitrite on contact with bacteria in the gastrointestinal tract, forming highly carcinogenic N-nitroso compounds (Barrett et al., 1998; Gulis, Czompolyova, & Cerhan, 2002; Weyer et al., 2001). Further, chlorine in water used to treat bacteria also poses a risk because it reacts with organic particles in river water to form halogenated hydrocarbons such as trihalomethane, a carcinogen.

In this paper, I build on a growing body of empirical evidence that cancer may be linked to polluted drinking water. The presence of nitrate, a chemical observed in China's water monitoring stations, in drinking water is linked to cancer increases in several studies (Armijo & Coulson, 1975; Morales-Suarez-Varela et al., 1995; Gulis et al. 2002). Tao, Zhu, and Matanoski (1999) find that halogenated hydrocarbons, a by-product of chlorine, cause higher rates of esophageal cancer in men in Shanghai, China. Laboratory tests have also demonstrated that hexavalent chromium (Cr^{+6}) in drinking water for rats and mice leads to carcinogenic activity in the oral and intestinal cavities (Beaumont et al., 2008). In a recent study, Beaumont et al. (2008) found high levels of Cr^{+6} dumped by a ferrochromium factory in Liaoning province. In the exposed population, they find that stomach and lung cancer rates are significantly higher than in an unaffected areas.[7] As I will discuss further in section IV, I also find large effects of polluted water on both digestive and lung cancer, consistent with these findings that a range of cancers is affected by polluted water.[8] Also note that the relationship between water pollution and cancer rates may operate through several channels. While drinking polluted water may lead to the formation of carcinogens, it may also lead to other infections, which eventually become carcinogenic (Gersten & Wilmoth, 2002). One known cause of digestive cancer is infectious *Helicobacter pylori*, a gastric bacterium. The analysis presented in this paper examines the reduced-form relationship between water pollution and cancer rates without identifying the exact mechanisms.

The deterioration of China's rivers and lakes over the past decades has been regionally bound, with water quality in northern regions declining more severely due to lower levels of precipitation. The rainy season may last as long as six to seven months in some southern areas and be as short as two or three months in more arid northern regions (World Bank, 2006). As such, northern river systems have a lower capacity to absorb contaminants. In a thorough review of monitoring data for 1991 to 2005, the World Bank (2006) reported that 40% to 60% of the northern region's water is continuously in the nonfunctional water classification categories (grades V and VI) and therefore is unfit even for agricultural use. The Hai River basin, located in northern China, is the most polluted basin in the country, with 57% of monitored sections failing to meet grade V, and therefore far below drinkable standards. The Yangtze River basin, has exhibited a far smaller deterioration in water quality in spite of industrialization. Regional differences in water quality induced by rainfall patterns provide for observation of areas of China with similar levels of industrialization but different levels of pollution.

In China, the degradation of waterways has also led areas without industrial activity to experience a decline in water quality. This occurred recently in Anhui, which has very low industrial activity of its own but is downstream of a major industrial zone located in the Huai river basin. According to Elizabeth Economy in her book *The River Runs Black* (2004), "Heavy rain flooded the [Huai] river's tributaries, flushing more than 38 billion gallons of highly polluted water into the Huai. Downstream, in Anhui Province, the river water was thick with garbage, yellow foam, and dead fish." In this way,

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[7] While the epidemiological literature often focuses on subpopulations, my estimates are broadly consistent with their findings. Gulis et al. (2002) estimate overall cancer incidence to increase by a factor of 1.14 and stomach cancer by 1.24 in high- versus low-nitrate areas of Slovakia. Beaumont et al. (2008) estimated a 1.82 relative risk ratio for stomach cancer in areas where the drinking water was contaminated by hexavalent chromium. My preferred OLS estimate for digestive cancers implies a relative risk ratio of 1.097 per water grade, and polluted water is roughly 2.5 grades worse than drinkable water, implying a relative risk ratio of 1.24. My preferred estimate is therefore somewhat higher than Gulis et al. (2002) and lower than Beaumont et al. (2008), but this back-of-the-envelope calculation suggests that my estimates are plausible relative to the existing estimates.

[8] Another chemical that has been tied to both digestive tract cancers as well as lung cancer is arsenic. Arsenicosis has been linked to cancer of the lung (Yu, Sun, & Zhang, 2007) and bladder (Smith et al., 1998).

regions without industrial firms can suffer from the same, or more serious, water pollution as those directly engaged in wastewater discharge, and in these rural areas, the inhabitants have experienced the environmental costs of industrialization without realizing the economic benefits.[9] As such, analysis is warranted to estimate the national benefits and costs to tighter regulations, which may induce a welfare transfer from the affected firms to the rural population forced to bear the health burden of the industrial waste.

The water quality available to villagers is also partly determined by whether a village is located along a tributary versus a main river segment. Tributaries in China often have more pollution than main river system segments (World Bank, 2006). Smaller streams have more eutrophication, partly due to slower stream flow, which leads to greater algal bloom. If water flows slowly, pollutants are not transported away quickly, and the added time of exposure leads to greater algae growth and, consequently, worse water quality (Zhong et al., 2005). The World Bank (2006) also reports that cleanup efforts have generally focused on main stream segments, leaving many tributaries with very poor water quality. In 2001, while the main river segment of the Yangtze had no monitoring points graded at V or VI, these high levels of pollution were observed at 48% of the water in the tributaries. In the next section, I describe how I will exploit both regional variation in water quality and the placement of the DSP site along a river system to estimate the causal link between water quality and cancer incidence.

China's environmental conditions have continued to worsen in spite of long-running regulatory efforts to punish firms for dumping untreated wastewater. In 1982, China established a nationwide system of levies assessed on the tonnage of untreated wastewater emitted by factories. By 1998, Chinese regulators had collected about 40 billion RMB ($4.9 billion) in levies, with both private and state-owned enterprises being subject to the policy (Wang & Wheeler, 2005). Though China's environmental regulatory agencies have gained increasing clout in administrative decisions nationally, incentive conflicts with local administrators who rely primarily on local industries for tax revenue have limited the effectiveness of the program (Ma & Ortolano, 2000). However, when enforced, the levies have been found to induce reductions in chemical dumping by firms and higher spending on wastewater treatment facilities (Wang & Wheeler, 1996; Wang, 2002).[10] In my empirical analysis, using more recent data, I find that the levy system continues to be an effective policy measure at inducing firms to modify their behavior and limit the discharge of untreated wastewater.

TABLE 1.—AGE-ADJUSTED DEATH RATES (PER 100,000) BY CAUSE IN CHINA, 1991–2000

	Males		Females	
	Rural (1)	Urban (2)	Rural (3)	Urban (4)
Death Rates by General Cause				
All causes	726	599	600	463
Cancer	133	150	78	85
Digestive cancers	94	79	49	38
Lung cancers	26	50	12	21
Other cancer	14	21	18	25
Heart	133	100	134	91
Stroke	125	125	107	100
Respiratory illnesses	126	72	120	58
Accidents, violence	91	49	59	31
Other	118	102	100	97
Death Rates for Types of Digestive Cancer				
Esophageal cancer	21	11	11	4
Stomach cancer	32	22	17	11
Liver cancer	33	31	14	11
Other digestive Cancers	9	15	7	12

Source: Chinese Disease Surveillance Points Mortality Registration System (DSP).
$N = 145$. Age adjustment is performed by calculating age-specific death rates and creating weighted averages using the population structure in China's 2000 Census. Other digestive cancers include colon cancer, intestinal cancer, and pancreatic cancer. The reported death rates are the average rates for the 145 sites, weighted by the population at each site. These calculations exclude roughly 3,000 deaths (of the 500,000 deaths) in the sample where I am missing information on the age or sex of the decedent.

III. Data

The analysis of mortality patterns in China is based on China's Disease Surveillance Point system (DSP). The DSP is a set of 145 sites chosen to form a nationally representative sample of China's population and selects sites across different levels of wealth and urbanization. The coverage population was also chosen to reproduce geographic dispersion in China's population relative to patterns in China's 1990 Census. The DSP records all deaths among the coverage population of 10 million residents at the points and, due to careful sample selection of the DSP sites, yields an annual sample of deaths that mirrors patterns in the country nationwide (Yang et al., 2005).[11] This paper relies on the data taken from roughly 500,000 deaths recorded at DSP sites between 1991 and 2000, and population counts by age and sex that are used to convert the recorded deaths into death rates.[12] A summary of cause-specific death rates during the sample period is shown in table 1.

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[9] Lipscomb and Mobarak (2007) deal with a set of related political economy issues in Brazil and find that pollution is higher near county boundary points, where neighboring counties incur a larger share of the pollution's cost.

[10] Wang and Wheeler (1996), in an analysis of provincial data from 1987 to 1989 and 1992 to 1993, estimate an elasticity of roughly −1 for the discharge of chemical oxygen demand (COD) pollution intensity (discharge/output) with respect to the effective levy rate. Wang (2002), using plant-level data, estimates an elasticity of .65 for firm spending on operating expenses and .27 for firm investment in wastewater treatment facilities.

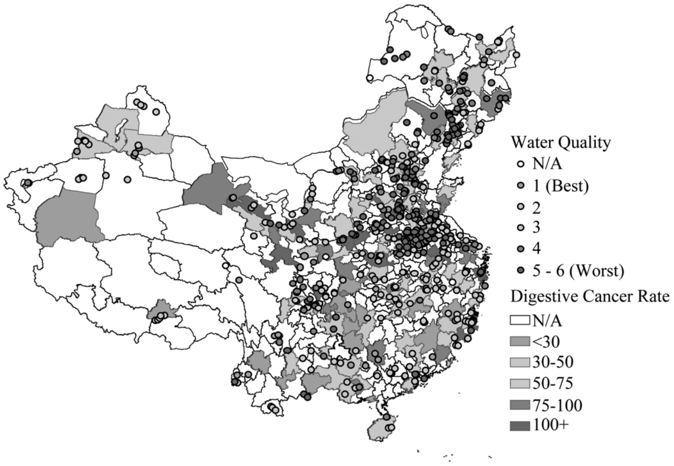
[11] The DSP mortality collection is based on the location of the decedent. Migration is a potential problem if migrants are recorded where they die rather than where they spent most of their lives, since their assigned pollution measures will be incorrect. It is worth noting that migration in China is a recent phenomenon, and migrants are generally young. China's 2000 Census indicates that the median age of a migrant is 34, and over 90% of migrants are below 64 years of age, the median age of death from digestive cancer. As such, it is unlikely that the results are affected greatly by migration. It is worth noting, however, that recent fieldwork indicates that while most migrants are registered, some are not and would presumably be excluded from the migrant census sample (Park & Wang, 2010). Therefore, the results should be interpreted with due caution.

[12] While the DSP data provides information on cancer mortality rather than incidence, the difference is slim in the case of digestive cancers. Physical signs of gastric cancer are rarely presented in time for curative treatment, and the five-year survival rate for patients presented with stage III cancer (likely the vast majority of cases in China) is only 10% to 15% (Cabebe & Mehta, 2008).

China's severe problems with water pollution began in the 1980s, following economic reforms in the late 1970s that led to an industrial boom. The national water monitoring system was established during the late 1980s and collects annual readings of chemical content at a set of sites across China. The World Bank produced a comprehensive assessment of water quality patterns in China from 1991 to 2005 using data collected by the monitoring system. The analysis presented here relies on the 2004 readings, which report water quality readings for 484 geographic points across China's nine river systems. The analysis presented here is cross-sectional in nature. The analysis will rely on the relationship between measures of water pollution by location in 2004 and mortality rates by cause and location from 1991 to 2000.[13] The DSP and water quality data are geographically overlaid by using data on China's river basins created by the Hydro1k project, conducted by the U.S. Geological Survey (see figure 2). The project provides a suite of geo-referenced data sets that are created using a Digital Elevation Model (DEM) in which China can be separated into a set of 989 basins, and a smaller set of larger basins. Satellite imagery is exploited to assess regional variations in air quality that might also affect cancer rates.

Using NASA estimates of optical depth from aerosol imagery, I proxy for the impact of air quality on digestive cancer rates. The measure is taken between 0 and 1, with higher numbers representing higher optical depth and implying the presence of more particulates and worse air quality (see figure 3). I assign to each river basin a measure of the average particulates over the basin's region between 2002 and 2007 to reduce annual fluctuations in the data.[14] In order to examine how precipitation may affect water quality, I include measures of monthly rainfall collected by the Global Precipitation Climatology Center for 1961 to 1990. These measures are calculated by river basin in a manner similar to how I calculate average air quality, where I use GIS software and average the rainfall measure across the area in the same basin as the DSP site (see figure 4). Summary statistics are shown for the water quality measures assigned to each DSP site and other characteristics of the decedents at the points in table 2. The characteristics reported are split between DSP sites along polluted rivers versus cleaner rivers. The data indicate that water quality measures are statistically significantly different along these rivers, but other observable features of the decedents (such as average education) are similar, suggesting no obvious correlation between water quality and observables. While it is difficult to rule out the possibility that water quality is correlated with unobservable features of areas that affect cancer rates, the similarity along observable dimensions is suggestive that the omitted variables bias associated with calculations using water quality may be small (Altonji, Elder, & Taber, 2005).

FIGURE 2.—WATER QUALITY AND DIGESTIVE CANCER RATES IN SELECT LOCATIONS, 1991–2000



Source: China Disease Surveillance Points (1991–2000), China National Water Monitoring System (2004).

Rates reported per 100,000 persons and are age and sex adjusted using the China 2000 Census population structure.

The river basin data from the Hydro1k project are coded using a consistent numerical scheme that allows for inference regarding water flows within the network of basins (see figure 1 in the appendix). The Pfafstetter coding system, designed in 1989 by Otto Pfafstetter, assigns watershed identification numbers based on the topology of the land surface. Since it is hierarchical, it is possible to identify the flow dynamics of rivers from the numerical scheme of the basins (see figure 2 in the appendix). For each DSP site, I observe the nearest river and the flow length to the river's headwaters. The flow length is informative regarding whether the DSP site is along a tributary or main stem (lower values are found along tributaries), and since rivers are more polluted along tributaries than main river stems, this distance is predictive of the water

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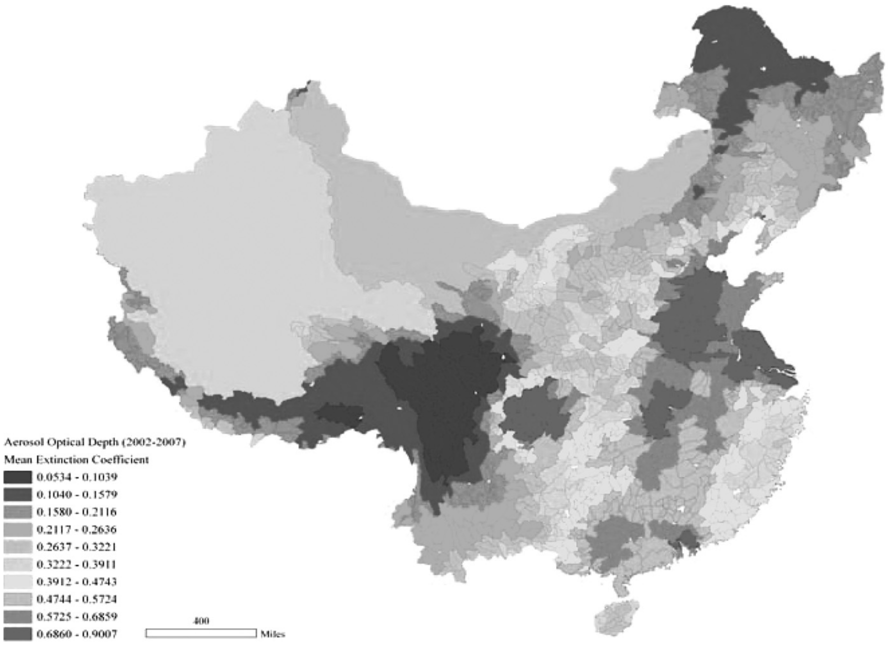
[13] Data on water quality for China in GIS format are available only for 2004. Ideally, a longer series of water quality would be used to examine the relationship between water quality and digestive cancer. Cancer incidence is thought to peak ten to twenty years following exposure to a carcinogen, as is observed between rises in smoking rates and lung cancer rates. As a robustness check, I examine the relationship between industrial output in each river basin between 1970 and 1990 and the digestive cancer rate at the DSP point. The results (shown in table 6 in the online appendix) reflect that industrial output during the twenty years before the DSP sampling frame is correlated with digestive cancer rates, and the results are statistically significant and similar to those using observed water quality in 2004. In addition, data on water grade averages by river system are available in the 1990s. The correlation between the water grade average between 1991 and 2000 and my 2004 measure for seven major river systems is .92, suggesting that the pollution measure in 2004 is capturing variation in water pollution levels that has presumably persisted for many years. Insofar as my 2004 data are not perfectly correlated with water pollution for the appropriate period, such as 1970–1990, the coefficient estimates can be potentially attenuated or biased. As such, the magnitudes of my coefficients should be interpreted with some degree of caution.

[14] The NASA data on optical aerosol levels are available beginning only in 2002. Ideally, a comprehensive air quality measure would be available for the window prior to and overlapping with the DSP collection (1991–2000). Unfortunately, measures for China during this period are available only by city. However, China's industrialization exhibits a high degree of spatial concentration that suggests that the air quality during the available window is a reasonable proxy for air quality at the DSP points following China's large boom in manufacturing (Hanink, Ebenstein, & Cromley, 2010). Also, China's air pollution data by city during this period reflect a time persistence implying the proxy I use is reasonable (Almond et al., 2009).

FIGURE 3.—AIR QUALITY PATTERNS IN CHINA



Source: NASA satellite imagery.

quality at the DSP site.[15] The river basin coding allows me to assign both current and historical industrial output in each basin.[16]

China's *Environmental Yearbook* is produced by the State Environmental Protection Agency (SEPA) and provides the necessary data to examine the responsiveness of dumping to regulatory incentives. China's environmental regulations require manufacturing firms to register all emissions, and each yearbook contains province-level totals for the tonnage of discharge of wastewater that fails to meet standards, and the total levies collected as a result of these infractions, in a consistent format for 1992 to 2002. The data also contain information on the tonnage of dumping and treatment by chemical, allowing more detailed analysis of the statistical relationships between firm behavior and water pollution graded by chemical. Finally, the yearbooks contain reported spending by firms in wastewater treatment in each year in terms of both equipment investments and operating expenses. During the 1990s, many provinces began to ratchet up enforcement of water discharge standards, leading to an increase in the levy collections as well as a decline in industrial dumping of untreated wastewater relative to output (see figure 5). Using variation across provinces in the timing of these increases, I am able to assess how firm spending on cleanup responds to the environmental regulations, which reflects the marginal cost to firms of compliance with respect to levy rate increases. The industrial dumping data are also used to assess the responsiveness of water quality to dumping within a river basin. Dumping within a basin is imputed using provincial dumping and the industrial mix of counties within a province.

IV. Empirical Results

A. Main Results

In table 3, I report the main results of the paper, where I examine OLS models of water quality and digestive cancer rates, measured in logs:

$$\ln(DeathRate_i) = \beta_0 + \beta_1 WaterQuality_i + \Gamma X_i + \varepsilon_i. \quad (1)$$

I estimate models where the log of the death rate from digestive cancer at site i is a linear function of the water quality (that is, grade) and demographic features of the residents X_i.[17] Note that water quality is graded on a six-point scale, where

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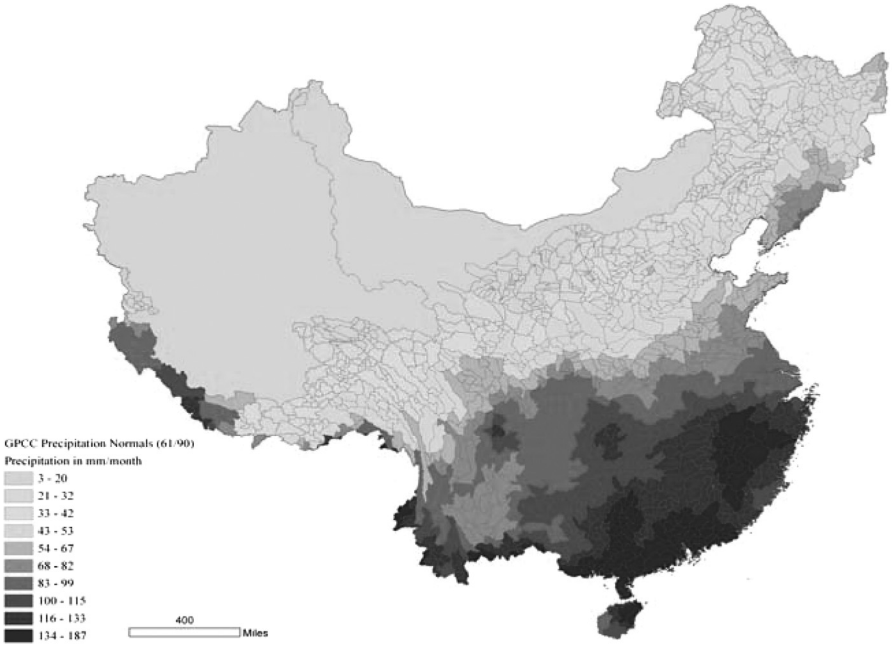
[15] The flow length is calculated using ArcGIS 9.2 and calculates the length of the longest flow path within a given basin. Since tributaries are closer to the river stem's headwaters, longer flow lengths will correspond to DSP sites on the main stem of a river. More information regarding this calculation is available from the ArcGIS 9.2 help documentation.

[16] While water quality data are not available during the 1970s or 1980s, I am able to assign a comprehensive series of gross industrial output in each river basin for this period using provincial data. This is presumably correlated with industrial water pollution and provides variation in the total length of exposure to polluted water among inhabitants of any particular river basin. In the online appendix, I demonstrate a correlation between historical industrial output (1970–1990) and cancer rates in the DSP (1991–2000).

[17] Alternative specifications for the functional form are discussed in the next section. Also see in the appendix, table 3 which reflects that the results are similar when broader categories of water quality (drinkable water, somewhat polluted, very polluted) are used. It is worth noting that since water quality is measured in an ordinal manner, the units of my analysis should be interpreted with caution. I choose the linear functional form due to the ease of presentation and because it allows for a more transparent calculation of the benefits and costs of cleanup than nonlinear specifications.

FIGURE 4.—MONTHLY PRECIPITATION PATTERNS IN CHINA, 1961–1990



Source: Global Precipitation Climatology Center.

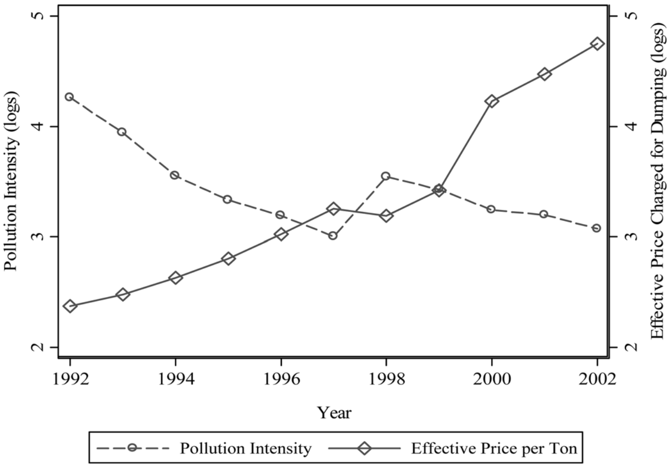
TABLE 2.—SAMPLE MEANS FOR DISEASE SURVEILLANCE POINTS BY RIVER SYSTEM

Statistic	Points along Polluted Rivers (1)	Points along Cleaner Rivers (2)	Differences (3)
Digestive cancer rate	79.6	63.3	16.34**
Overall water grade	4.58	3.13	1.45***
Ammonia nitrogen	3.88	2.52	1.36***
Biological oxygen demand	3.74	1.58	2.16***
Lead	1.16	1.08	0.08*
Oils	3.14	1.69	1.45***
Permanganate	4.12	2.27	1.85***
Volatile phenol	2.33	1.29	1.04***
Average years of education	3.96	4.30	−0.34
Share in farming	0.70	0.63	0.07
Urban site (1 = yes)	0.24	0.23	0.01
Share in manufacturing	0.07	0.10	−0.03
Air pollution reading	0.54	0.49	0.05
Monthly rainfall (mm)	52.6	97.6	−45.1***
Share of households with tapwater	0.51	0.48	0.026
County income level (1 = poor, 4 = rich)	3.02	2.85	0.170
Number of sites	59	86	27

Source: Chinese Disease Surveillance Points Mortality Registration System (DSP), China National Monitoring Center (2004), Global Precipitation Climatology Center (2008).

All sites along rivers with average water grade higher than 4.0 are in column 1, which includes the Huai, Hai, Yellow, and Songhua rivers. Sites along all other rivers, including the Yangtze and Pearl, are in column 2. Higher grades reflect lower water quality (1 = best, 6 = worst) and a greater concentration of the listed pollutants. The water grade measure at each DSP site reflects the average water grade among monitoring sites in the same river basin. The air pollution reading is taken from satellite imagery and takes on values from 0–1, with higher values reflecting more particulates in the air, and is reported as the average reading in the river basin containing the DSP site. The rainfall measure is the average monthly rainfall in millileters in the river basin containing the DSP site from 1961–1990. The DSP survey defines each site by the income level of the coverage population of rural counties into four categories (1 = poor, 4 = rich). The sample means are the average values (such as average education) among decedents at each site restricted to deaths among persons age 20 and older. Sample means are reported weighted by the population at each site. *Significant at 10%, **5%, ***1%.

FIGURE 5.—POLLUTION INTENSITY AND THE EFFECTIVE PRICE CHARGED FOR DUMPING



Source: *China Environmental Yearbooks* (1993–2003).

Pollution intensity is the ratio of dumping in tons to 10,000 yuan of industrial output. The effective price is the value of collected yuan per 100 tons not meeting wastewater discharge standards.

I (1) is the best water and VI (6) indicates that the water is unfit even for agricultural use.[18] In the first regression, I examine the partial correlation of digestive cancer with the overall water quality grade and find that an increase in the water grade by one level (say, IV to V) increases the digestive cancer rate by 12.2%. The coefficients are 32%, 12%, and 8%

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[18] Water that is severely polluted can be unsafe for watering crops, and its use can lead to damage to agriculture. The World Bank (2007) describes one of the challenges in quantifying the public health impact of water pollution as identifying the full impact through food chain effects and cite estimates that the cost of water pollution in 2003 was .05% of GDP.

TABLE 3.—ORDINARY LEAST SQUARES REGRESSIONS OF LOG OF DIGESTIVE CANCER RATES ON WATER GRADE

	No Controls				With Controls			
Statistic	Digestive (All) (1)	Esophageal (2)	Stomach (3)	Liver (4)	Digestive (All) (5)	Esophageal (6)	Stomach (7)	Liver (8)
Water grade (1 = best, 6 = worst)	0.122**	0.315***	0.120*	0.080*	0.097**	0.274***	0.105	0.050
	(0.052)	(0.108)	(0.065)	(0.045)	(0.044)	(0.093)	(0.062)	(0.032)
Average education					−0.016	−0.014	−0.080	0.012
					(0.044)	(0.109)	(0.066)	(0.031)
Share in farming					0.029	0.719	0.510	−0.484***
					(0.293)	(0.991)	(0.415)	(0.175)
Urban (1 = yes)					−0.260	0.109	0.060	−0.588***
					(0.194)	(0.667)	(0.254)	(0.128)
ln(Air Pollution)					0.232*	0.647**	0.070	0.253**
					(0.127)	(0.263)	(0.181)	(0.120)
County income controls					Yes	Yes	Yes	Yes
Region controls	No	No	No	No	Yes	Yes	Yes	Yes
R^2	0.083	0.121	0.048	0.045	0.267	0.227	0.213	0.315

Source: China Disease Surveillance Points Mortality Registration (DSP), China National Monitoring Center (2004).

$N = 145$. The first four columns represent OLS regressions of the logarithm of the death rate of a cause on the average water grade of the river basin in which the DSP site is located. I add covariates for columns 5–8, which are the average values among decedents at each site restricted to deaths among persons age 20 and older. Standard errors are robust and clustered at the province level. The water grade measure at each DSP site reflects the average water quality among monitoring sites in the same river basin. County income controls are fixed effects for the four income classifications of rural DSP sites. Region controls are fixed effects for whether the site is located in an eastern, middle, or western province (see the data appendix for details). Regressions are weighted by the population at each DSP site. *Significant at 10%, **5%, ***1%.

for the impact of water quality on esophageal, stomach, and liver cancer, respectively, with the coefficients statistically significant at the 5% level for all but liver cancer, which is significant at the 10% level.

In a second set of specifications, I assess the impact of water quality on the same set of dependent variables, but with a rich set of controls for factors that might also affect digestive cancer rates. Controls are included for whether the DSP site is urban, the average education of decedents at the site above the age of 20, the share of people who were employed in farming and manufacturing, an imputed measure of ambient air quality (where a higher number reflects more particulates), region dummies, county income category dummies, and each site is weighted by the total population.[19] Region dummies are based on the survey's classification of the 145 DSP sites into three main regions: eastern, middle, and western.[20] The DSP sites are also classified by income: rural counties included in the sample were stratified into four classifications of wealth (1 = poorest, 4 = richest), and these categories are included as dummies to attempt to control for variation in cancer due to income differences. With these controls, results are somewhat lower, with the estimates implying that water quality erosion by one grade induces a 9.7 percentage point increase in the digestive cancer rate. The estimated impact of a decline in water quality of one grade is associated with increases in esophageal, stomach, and liver cancer of 27, 11, and 5 percentage points, respectively. It may be unsurprising that the coefficients are not dramatically changed by including controls, since table 2 reflects that water quality variation is not highly correlated with observable features of a location, such as rates of urbanization or air quality. Table 3 also indicates that air quality has a positive and statistically significant relationship with digestive cancer rates, with an increase in the particulate index variable (that varies from 0–1) by 1%, inducing a .23% increase in the digestive cancer rate.[21] This may reflect a causal link between contaminants in the air and the likelihood of tumors forming in digestive organs (Jerret et al., 2005), or it may reflect a correlation between air quality and other carcinogenic environmental factors, such as water dumping or exposed carcinogenic chemicals. Quantitatively, since the standard deviation of the log of air pollution measure is .447, the coefficient on air pollution implies that the log of the digestive cancer rate increases by roughly 10.4% (.447 × .232) in places with air pollution 1 standard deviation above the mean. As a point of reference, a 1 standard deviation increase in water grade is associated with a 13.9% (.096 × 1.38) increase in digestive cancer rates. The results suggest that pollutants can lead to a general increase in cancer rates, though it is difficult to completely separate the two effects in light of factors that may affect both water pollution and air pollution.[22]

In table 4, I present an additional set of OLS regressions in which I examine whether the relationship between water quality and digestive cancers observed differs by sex and by the share of households within the county that have access to tapwater. Note that tapwater is much more likely to be treated and consequently cleaner than water taken directly

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[19] The results are robust to the inclusion or exclusion of weights. Results without population weights are slightly weaker. In unweighted calculations with the full set of controls, a one-grade increase in the water grade is associated with a 6.7% increase in the digestive cancer rate. These results are included in the appendix. I proceed with the weighted calculations, since the DSP weights were designed to produce a nationally representative sample, and the benefit-cost analysis is at the national level.

[20] While fixed effects by province would be preferable, they do not provide sufficient degrees of freedom. Since $N = 145$ and there are thirty provinces, in many cases there are only two or three DSP sites per province.

[21] The air quality measure has a mean of .48 and a standard deviation of .19 in the sample of DSP sites.

[22] Since rainfall reduces both water pollution and air pollution, it may be difficult to separately identify the effect of water and air pollution. However, the empirical issue may be mild since the correlation between water grade and the air pollution measure is .1134 (p-value = .174), suggesting a sufficient number of DSP points with either air or water pollution and providing an opportunity to identify the impact of each separately.

Table 4.—OLS Regressions of Log of Digestive Cancer Rates on Water Grade by Sex and Access to Tapwater

	Men (1)	Women (2)	Low Tap-water Share (3)	High Tap-water Share (4)
Digestive (all)	0.090**	0.111**	0.131**	0.033
	(0.043)	(0.048)	(0.057)	(0.057)
Esophageal	0.262***	0.252**	0.271**	0.222***
	(0.092)	(0.122)	(0.136)	(0.086)
Stomach	0.109*	0.100	0.122	0.037
	(0.062)	(0.065)	(0.078)	(0.073)
Liver	0.035	0.086**	0.105***	0.000
	(0.033)	(0.035)	(0.040)	(0.045)
Observations	145	145	74	71

Source: China Disease Surveillance Points Mortality Registration (DSP), China National Monitoring Center (2004), China 2000 Census.

Each reported coefficient represents a separate regression, with water grade as the independent variable and the log of the death rate of the listed cause as the dependent variable. Columns 1 and 2 represent regressions where the dependent variable is the log of the death rate of the listed cause among men and women respectively. Columns 3 represent regressions for the 74 DSP sites located in counties where a majority of households do not have access to tapwater, and column 4 represents regressions for the 71 DSP sites where a majority have tapwater according to the 2000 Census. All regressions include the controls shown in columns 5–8 of table 3. *Significant at 10%, **5%, ***1%.

from rivers or wells.[23] The results in columns 1 and 2 of table 4 reflect a consistency between the estimated impact for men and women. For example, an increase in the water grade by one unit is associated with a 9.0 percentage point increase in the digestive cancer rate for men and a 11.1 percentage point increase for women. The impact of overall water quality on esophageal cancer is also positive and similar by gender (26.2 percentage points for men, 25.2 percentage points for women), and this holds for stomach cancer as well (10.9 percentage points for men, 10.0 percentage points for women), though it is less similar for liver cancer. The results in columns 3 and 4 reflect that water quality and digestive cancer rates are highly correlated in areas without tapwater, but much less strongly linked in areas with tapwater, suggesting that living near polluted rivers is less dangerous when households have access to tapwater. For all digestive cancers, I estimate that a one-unit increase in water grade is associated with a 13.1 percentage point increase in areas without tapwater, but only a 3.3 percentage point increase in areas with tapwater. This result is also observed for stomach and liver cancer, where I observe a stark difference in the elasticity of cancer rates to water quality in areas with and without tapwater. This result is much weaker for esophageal cancer, however, where the coefficients are similar in areas with and without tapwater.[24]

These findings are compelling evidence that environmental factors are responsible for the correlation between water quality and digestive cancer rates. In particular, if water quality did not directly affect digestive cancer rates but was instead reflecting an unobserved correlation between water quality and omitted factors, such as occupational exposure to carcinogens, one would expect to find larger elasticities for men, who are more likely to work in mines and other hazardous occupations. However, the similarity by gender is suggestive instead that factors shared by men and women are responsible for the correlation, such as water quality. Likewise, the lack of an effect in areas with tapwater is compelling evidence that drinking water is responsible for the correlation between surface water quality and digestive cancer rates.

In table 5, I consider whether the OLS results could be explained by unobserved correlation between water quality and other potential risk factors for digestive cancer, such as smoking rates and dietary patterns. Using province-level information on smoking rates and dietary practices from household survey data (China Household Income Survey, 1995, and China Health and Nutrition Survey, 1989–2006), I examine whether either smoking or diet patterns covary with water quality.[25] The results indicate that smoking rates are similar across the water quality readings, suggesting that the estimated impact of water quality is not being confounded by smoking patterns.[26] Likewise, no large difference in diet is observed across sites with better and worse quality, suggesting that regional differences in diet are not responsible for the correlation between water quality and digestive cancer. So although diet is a known risk factor for digestive cancers, it is uncorrelated with water quality and therefore unlikely to be biasing the estimated effect of water quality on cancer.

Although dietary patterns in China are known to vary by region, it is unlikely to explain the patterns in cancer mortality I observe in the data, which reflect high digestive cancer rates among northern areas with lower rainfall (and consequently worse surface water quality). First, while salty and pickled foods are thought to be associated with higher digestive cancer rates (Kono & Hirohata, 1996), southern China is not very different from northern China in this dietary dimension. In fact, the principal difference between northern and southern China in terms of diet is the South's rice culture versus the northern wheat culture. Carbohydrates are thought to be a risk factor for Asian men with high rates of this disease (Ji et al., 1998) but inhabitants of both regions consume large amounts of carbohydrates. Since regional differences in diet are not thought to be risk factors for digestive cancer, it is

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[23] Other research in China has found a link between the source from which people draw water and local cancer rates. In a prospective cohort study, Chen et al. (2005) found high rates of colon and rectal cancer among those who relied on wellwater relative to those relying on municipal water in Jiashan County, Zhejiang Province, China.

[24] The lack of a sharp distinction between esophageal cancer's relationship to water quality between areas with and without tapwater may indicate that a mechanism other than polluted drinking water is responsible for my results on esophageal cancer. As I discuss in the paper, it may be that water pollution increases digestive cancers through mechanisms other than through its effect on drinking water (such as increasing the rate of infections that lead to cancer). It is worth noting, however, that the results in table 4 on tapwater rates fail the placebo test for esophageal cancer.

[25] Regressions of water grade on smoking rates or dietary patterns fail to reveal statistically significant relationships. Results available on request.

[26] National surveys reflect that smoking rates for men are in excess of 75%, but fewer than 8% of women smoke (Yang, 1997). The age profile of smoking rates was very similar in both the national smoking survey of 1984 and a follow-up survey in 1996, suggesting that smoking patterns are unlikely to be responsible for the recent increase in China's digestive cancer rate.

TABLE 5.—SMOKING AND DIETARY HABITS BY WATER GRADE IN CHINA

	Smoking Rates			Dietary Patterns					
Water Grade	Men (1)	Women (2)	Number of DSP Sites (3)	Caloric Intake (4)	% Carbo-hydrates (5)	% Fat (6)	% Protein (7)	Other (8)	Number of DSP Sites (9)
Level I (best)	0.732	0.034	2	2,172	15.21	2.89	2.86	79.04	3
Level II	0.685	0.065	15	2,376	15.12	2.96	2.84	79.08	7
Level III	0.697	0.025	28	2,303	14.75	3.06	2.92	79.28	23
Level IV	0.704	0.035	20	2,238	15.38	2.75	2.97	78.90	9
Level V	0.704	0.059	18	2,311	16.13	2.41	2.99	78.47	5
Level VI (worst)	0.710	0.046	20	2,316	15.19	2.82	2.92	79.06	8

Source: Smoking rates are taken from the China Household Income Survey (CHIS, 1995). The diet information is taken from the China Health and Nutrition Survey (CHNS, 1989–2006).

The smoking rates are shown for the DSP sites that were in the nineteen provinces in the CHIS (1995), which includes 103 of the 145 DSP sites. Information on diet is shown for DSP sites located in the nine provinces included in the CHNS, which includes 55 of the 145 sites. Statistical tests reflect no significant correlation between water grade and either smoking rates or dietary patterns.

TABLE 6.—OLS REGRESSIONS OF LOG OF DEATH RATES BY CAUSE IN CHINA ON WATER GRADE

	All (1)	Men (2)	Women (3)
All causes	0.019	0.016	0.023
	(0.02)	(0.02)	(0.02)
Cancer (all types)	0.090***	0.087**	0.099***
	(0.03)	(0.03)	(0.03)
Digestive	0.097**	0.091**	0.110**
	(0.04)	(0.04)	(0.05)
Lung	0.114***	0.086***	0.167***
	(0.03)	(0.03)	(0.03)
Other	0.034	0.030	0.044
	(0.02)	(0.03)	(0.03)
Noncancer (all types)	0.009	0.005	0.014
	(0.03)	(0.02)	(0.03)

Source: Chinese Disease Surveillance Points Mortality Registration System, China National Monitoring Center (2004).

$N = 145$. Each reported coefficient represents a separate regression, with water grade as the independent variable and the log of the death rate of the listed cause as the dependent variable. All regressions include the controls shown in table 3. *Significant at 10%, **5%, ***1%.

unlikely that unobserved differences in diet are confounding the regression analysis.[27]

In table 6, I perform a falsification exercise where I attempt to assess whether water quality's correlation with cancer is an artifact of a correlation between water quality and higher death rates in general. As shown in the table, water quality appears largely unrelated to other causes of death but is strongly correlated with cancer rates. A deterioration of water quality by a single grade induces a 9.0 percentage point increase in the cancer rate (significant at 5%) but has a small and statistically insignificant relationship to the death rate from causes other than cancer. The results also indicate that the correlation between water quality and cancers of all types is similar to what is found between digestive cancers alone (9.7%). Since digestive cancers represent nearly two-thirds of all cancers, this is perhaps unsurprising, but it reflects that nondigestive cancers, such as lung cancer, are also positively correlated with water pollution and may be causally linked to water pollution as well. Table 6 reflects that the regression coefficient of water grade's effect on lung cancer is 11.5%, potentially implicating water pollution in rising lung cancer rates observed in China. Water pollution has been blamed by local residents for the outbreak of throat and lung cancer in some of China's "cancer villages" (Voss, 2008) and has been linked to the incidence of certain respiratory tract cancers in China (Yu et al., 2007).[28] While the analysis here focuses on digestive cancers, the link between water quality and cancer incidence may exist across a broader class of cancer types, lung in particular, and represents an area for further research.[29] As a consequence of the large impact on cancer rates, which represent roughly one-sixth of all deaths, the 9.0 percentage point increase in cancer deaths results in a roughly 1.7% increase in the total death rate, while other causes are largely unaffected.[30]

B. *Robustness Checks*

In Table 7, I examine whether rainfall can be used as an instrument for water quality. Rainfall has a large impact on surface water quality through three primary channels. First, areas with more rainfall have pollution diluted by the relatively clean water from the atmosphere. Second, areas with more rainfall have faster river currents. If water flows slowly, pollutants are not transported away quickly, and the added time of exposure leads to greater algae growth and, consequently, worse water quality (Zhong et al., 2005). Third, areas with insufficient rainfall may attempt to compensate by

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[27] In an empirical study in China regarding the potential connection between variation in diet and cancer rates, Wong et al. (1998) examine data on rice and wheat intake across eight major cities in China and fail to find any relationship between gastric cancer and dietary patterns.

[28] Voss (2008) documents high rates of cancer and poor water quality in Shenqiu County (Henan Province).

[29] A comparison of cancer rates in China relative to the United States reveals that in spite of China's high male smoking rate, roughly three times the American, lung cancer is less common in China and represents a smaller share of total cancer deaths (see appendix table 4). The table suggests that the causal links between behavior, environment, and cancer incidence may operate differently in China than in the United States.

[30] Work by Honoré and Lleras-Muney (2006) highlights the potential role of declining mortality rates for causes other than cancer in explaining changes in the cancer rate. In the context of my analysis, one potential explanation between a correlation between water pollution and digestive cancer rates is that declining mortality rates for other illnesses in areas with more water pollution could lead to increases in the digestive cancer rate. The results in table 6 are suggestive that this is not the explanation for my results, since the impact on overall death rates from water pollution is roughly equal to cancer's share of deaths times the increase in the cancer death rate, which would suggest that higher cancer rates do not simply represent a substitution from other causes of death to cancer deaths. However, it is difficult to rule out the role of falling rates for other causes of death on the cancer rate in China in the absence of longitudinal data of trends in China for mortality rates by cause and water pollution.

TABLE 7.—OLS REGRESSIONS OF LOG OF CAUSE-SPECIFIC DEATH RATES ON MONTHLY RAINFALL (MM) BY ACCESS TO TAPWATER

	Low Tapwater Share (1)	High Tapwater Share (2)
All causes	0.001	−0.001
	(0.0011)	(0.0015)
Cancer	−0.006***	0.000
	(0.0018)	(0.0018)
Digestive (all)	−0.008***	0.000
	(0.0026)	(0.0022)
Lung	−0.007***	−0.001
	(0.0020)	(0.0017)
Other Cancer	0.001	0.002
	(0.0026)	(0.0019)
Noncancer (all types)	0.002	−0.002
	(0.0012)	(0.0015)
Observations	74	71

Source: China Disease Surveillance Points Mortality Registration (DSP), China National Monitoring Center (2004), China 2000 Census.

Each reported coefficient represents a separate regression, with monthly rainfall as the independent variable and the log of the death rate of the listed cause as the dependent variable. Column 1 represents regressions for the 74 DSP points located in counties where a majority of households do not have access to tapwater, and column 2 represents the 71 DSP points where a majority have tapwater according to the 2000 Census. All regressions include the controls shown in table 3. *Significant at 10%, **5%, ***1%.

the overuse of fertilizer. This leads to excessive runoff and degrades the surface water quality further. Although rainfall has a large impact on water quality, its suitability as an instrument is debatable. Rainfall affects many other factors, including income and crop types, and these may directly affect cancer rates. In order to assess whether rainfall satisfies the exclusion restriction of affecting only cancer rates through its effect on surface water quality, I present the reduced-form relationship between cause-specific death rates and monthly rainfall within the river basin, while including the complete set of control variables (air quality, county income, and so on). I also stratify the 145 DSP sites by whether a majority of residents of the county have access to tapwater since areas without tapwater are more likely to experience negative health consequences of surface water pollution. The results indicate that areas with more rainfall have significantly lower cancer rates, but rainfall has only a very weak relationship with mortality rates for other causes. Furthermore, rainfall's impact on the cancer rate of the DSP site is significant only in counties with low rates of tapwater use. I find that an increase in monthly rainfall by 1 milliliter decreases cancer mortality by 0.60% among those without access to tapwater, significant at the 1% level. The effect on digestive (0.80) and lung cancer (0.60) is particularly large, and both estimates are significant at the 1% level. In contrast, I find almost no relationship between rainfall and cancer rates in areas with high rates of tapwater use and almost no relationship with rainfall and other causes of death. While rainfall affects many facets of life, the results suggest that the reduced-form relationship between rainfall and cancer rates is consistent with an interpretation that drinking water quality in rivers and wells is affected by the amount of rainfall and the dilution of chemicals in the waterways. Also, the scientific literature on identifying a causal link between cancer rates and rainfall patterns is extremely limited, suggesting no obvious mechanism by which rainfall would be affecting cancer rates other than through affecting drinking water quality.[31]

In table 8, I present a set of 2SLS estimates of water quality's relationship with digestive cancer rates. A potential concern may arise if the control variables in the DSP do not appropriately account for factors correlated with industrial pollution that could also affect health, such as higher income levels which mitigate the health impact of the pollution. As such, in this section I exploit plausible exogenous variation in water quality due to differences in precipitation across the DSP sites and variation in the distance from the DSP site to the nearest river's headwaters to estimate 2SLS models. As discussed earlier, regional differences in water quality are induced by rainfall patterns, since additional rainfall dilutes the pollutants and contributes to flow speed, which makes the river less prone to eutrophication. The second instrument, distance from a river's headwaters, is correlated with water quality variation within a region and in fact within a river basin, since the tributaries of a river system are generally more polluted than main river segments.

In the first column, I examine the first-stage relationship between monthly rainfall in milliliters and distance in kilometers (in 000s) from the river's headwaters and the observed water grade within the river basin. The coefficient implies that an increase by 100 milliliters lowers the water grade by 1.6 levels, significant at the 1% level, which suggests that large variation in surface water quality is induced by variation in rainfall patterns. The water grade is declining with respect to distance from the river's headwaters, consistent with an expectation that tributaries will have worse water quality than main stem river segments. Each additional 1,000 kilometers of river flow reduces the water grade by .40 units. An F-test of the joint significance of the two instruments is 11.53, which is highly significant as well. I estimate a Cragg-Donald F-statistic value of 12.06, which implies that I can reject the null hypothesis that the maximal size of the test of significance of the 2SLS coefficient estimate is 15% but cannot reject the null that the maximal size is 10%.[32] This suggests that caution is warranted in interpreting the significance of the results of the 2SLS estimates below.

In column 2, I exploit this variation and regress the log of the death rate from digestive cancer on the predicted water quality reading from the first stage and the covariates included from columns 5 to 8 of table 3 (urban, years of education, and so on). The 2SLS estimates are larger than the OLS estimates and imply that increasing the water quality grade by one level

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[31] One plausible mechanism by which rainfall could affect cancer rates (other than through surface water quality) is through its impact on diet. This is discussed in the section IVA, where I present evidence that this is not responsible for the variation in cancer rates I observe in the data.

[32] The Cragg-Donald F-statistic is used when there are concerns that the instruments may only be weakly correlated with the endogenous regressor. In this case, the sampling distribution of IV statistics is in general nonnormal, which implies that standard IV point estimates and hypothesis tests may be unreliable. See Stock, Wright, and Yogo (2002) for a thorough discussion.

TABLE 8.—TWO-STAGE LEAST SQUARES REGRESSIONS OF LOG OF DIGESTIVE CANCER RATES ON WATER GRADE USING MONTHLY RAINFALL AND DISTANCE FROM HEADWATERS

	First Stage	Two-Stage Least Squares			
Statistic	Water Grade (1)	Digestive (All) (2)	Esophageal (3)	Stomach (4)	Liver (5)
Monthly rainfall (mm)	−0.016***				
	(0.00)				
Distance from headwaters (km × 10^3)	−0.401***				
	(0.11)				
Water grade (1 = best, 6 = worst)		0.221**	0.851***	0.365**	−0.023
		(0.096)	(0.238)	(0.136)	(0.095)
Average education	0.148	−0.025	−0.054	−0.098	0.017
	(0.118)	(0.045)	(0.120)	(0.074)	(0.034)
Share in farming	−1.067	0.046	0.798	0.545	−0.494**
	(1.09)	(0.30)	(0.96)	(0.55)	(0.22)
Urban (1 = yes)	−1.186	−0.213	0.326	0.158	−0.616***
	(0.79)	(0.19)	(0.59)	(0.33)	(0.16)
ln(Air Pollution)	0.863**	0.181	0.409	−0.038	0.283**
	(0.323)	(0.136)	(0.313)	(0.191)	(0.133)
F-test of instruments	11.53***				
Cragg-Donald F-statistic	12.06				
Hansen's J-statistic		1.757	2.859*	1.784	0.716
Chi squared p-value		(0.18)	(0.09)	(0.18)	(0.40)

Source: China Disease Suveillance Points Mortality Registration (DSP), China National Monitoring Center (2004), Global Precipitation Climatology Center (2008).

$N = 145$. The first column is the first-stage relationship between water grade at the DSP site, the covariates and two instrumental variables: average monthly rainfall in millileters in the basin and distance from the river's headwaters in thousands of kilometers. This is calculated as the longest path from the DSP point's nearest stream node and the drainage basin divide. The regressions in columns 2 through 5 represent 2SLS regressions where the dependent variable is the logarithm of the death rate of a cause on the predicted average water grade from column 1 and the other covariates. Dummies for county income level and region are included and suppressed. Standard errors are robust and clustered at the province level. Regressions are weighted by the population at each DSP site. The Cragg-Donald F is a test of weak identification. The Hansen J-statistic is an overidentification test of the instruments. *Significant at 10%, **5%, ***1%.

increases the digestive cancer rate by 22%. The estimates for esophageal cancer and stomach cancer imply that increasing the water-quality grade by one level increases the incidence of these diseases by 85% and 37% respectively, statistically significant at the 1% and 5% levels, respectively. The 2SLS estimate for liver cancer is 2% and not statistically significant.[33] The results of the overidentification test (Hansen's J-statistic) imply that I fail to reject the null hypothesis that the instruments are valid at the 5% level for three of the four cases and at the 10% level in all four cases. Overall, the 2SLS results support the claim of a causal link between water quality and digestive cancers, though the point estimates are somewhat larger than what I find using OLS in table 3.

The larger coefficient estimates using 2SLS require discussion, since these point estimates are nearly two and a half times larger than the OLS results. This may reflect that measurement error in water grade is attenuating the OLS estimates and the true effect is understated by OLS. Another possibility is that the controls in the DSP are not sufficient to account for higher incomes found in industrialized areas and inhabitants are able to mitigate the health consequences of pollution, which would also partly explain why 2SLS results would be larger than OLS estimates. Alternatively, water quality and digestive cancer may be related nonlinearly with respect to grade. When I use broader categorical measures of water quality, I find that digestive cancer rates are 19% higher in areas with medium water quality (grade III) and 33% higher in areas with very poor water (grade IV+) relative to areas with potable surface drinking water (grades I and II). If the instruments are exploiting variation in water quality where the water quality–digestive cancer gradient is steeper than the average slope, the 2SLS estimates will be larger than OLS. In the benefit-cost analysis performed in the next section, I rely on the OLS per grade estimates since these are more conservative and will be more likely to understate (rather than overstate) the true health benefit to cleanup. While it is unclear whether the 2SLS estimates are closer to the average causal effect of water grade on digestive cancer incidence than my OLS estimates, the results are consistent with a direct impact of water quality on digestive cancer rates.

C. *Estimating the Cost of Averting a Death through Cleanup*

Digestive cancers are responsible for nearly 1 million deaths annually in China (World Health Organization, 2002), and policy efforts to lower the incidence of these diseases can have large benefits in terms of population health and life expectancy. Digestive cancers represent 20% of deaths in China among those age 40 to 60 and are more common at these ages than other leading causes of death, such as stroke (see figure 6). The conservative estimate of the impact of improving China's water grade is that almost 93,000 deaths could be averted annually, since nearly 1 million people (980,000) die each year of these diseases, and each water grade improvement is associated with 9.7% fewer digestive cancer deaths. As such, it is of great policy interest to know the cost of improving China's waterways by a single grade.

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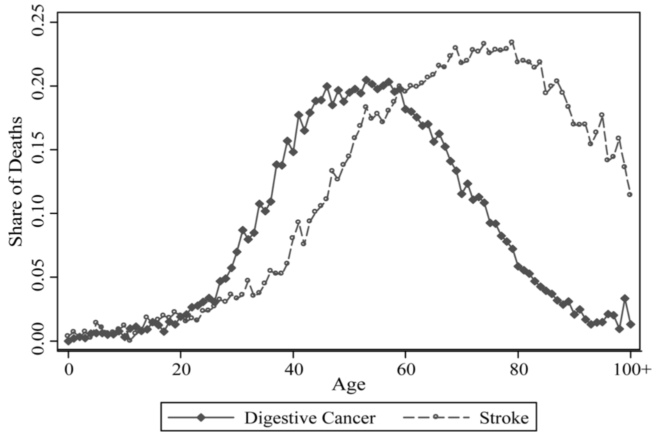
[33] While I fail to find an effect for liver cancer using 2SLS, this may be due to differences that exist by sex and whether households have access to tapwater. Interestingly, Chiu et al. (2004) find that liver cancer is responsive to water pollution among women but not men and, in particular, in areas without tapwater. This is similar to what I find in table 4 and may explain why the 2SLS results, which are not disaggregated by sex or tapwater access, are not significant for liver cancer.

FIGURE 6.—AGE DISTRIBUTION OF DIGESTIVE CANCER AND STROKE DEATHS



Source: China Disease Surveillance Points (1991–2000).

TABLE 9.—OLS REGRESSIONS EXAMINING WATER QUALITY, INDUSTRIAL DUMPING, AND FIRM RESPONSE TO POLLUTION LEVIES

	Water Grade (1)	Log of Total Industrial Cleanup (tons) (2)	Log of Spending on Cleanup (100 million yuan) (3)
Log of total untreated waste water (tons)	0.220^{***}		
	(0.08)		
Monthly rainfall (mm)	-0.019^{***}		
	(0.004)		
Total area (billions of km^2)	-4.868^{**}		
	(2.18)		
Log of effective fine levy		0.815^{***}	0.137^{*}
		(0.21)	(0.08)
Period available	2003–2004	1992–2002	1992–2002
R^2	0.241	0.706	0.902
N	125	319	319

Source: China National Monitoring Center (2004), China Environmental Yearbooks (1993–2003), China Manufacturing Census (2003).

In the first column, the dependent variable is the average water grade of monitoring stations, and the independent variable is the log of the number of tons of industrial wastewater not meeting discharge standards within the level 4 river basin. The number of observations corresponds to the total number of level 4 river basins in which water quality readings are available. Controls (not shown) include monthly rainfall and the total area of the river basin. In the second and third columns, the dependent variable is the log of the total tons of reported cleanup and the log of spending on cleanup, respectively, and the independent variable is the effective fine levy. The effective fine levy is yuan collected per ton of wastewater discharge failing to meet regulatory standards. Cleanup and spending on cleanup are reported for all registered manufacturing firms by province and year. The regressions in columns 2 and 3 include province and year fixed effects, and the standard errors are robust and clustered at the province level. Regressions are weighted by the population of each province. *Significant at 10%, **5%, ***1%.

In combination with my estimates of the potential benefit in averted cases of digestive cancer, it provides information regarding the trade-offs associated with tighter wastewater regulations in China.

In order to assess the cost of improving China's water, in table 9, I examine three relationships: the relationship between China's surface water quality and industrial dumping, the relationship between industrial dumping and the levy rates, and the relationship between levy rates and firm spending on wastewater treatment facilities.[34] In column 1 of table 9, I report the relationship between the overall water grade and the total dumping of untreated wastewater within a river basin, which indicates that an increase in dumping by 10% would induce a .022 unit increase in water grade, and the result is statistically significant at the 1% level.[35] I also report the impact of rainfall and the size of the river basin, which reflect that larger basins and basins with more rainfall have lower water grades, for a given level of industrial dumping. In columns 2 and 3, I examine how China's levy rates affected firm dumping behavior for 1992 to 2002, the window for which China's environmental yearbooks contain the necessary data on industrial wastewater treatment (in tons) and total spending by firms in wastewater treatment.[36] Raising levy rates by 1 percent increases the tonnage of cleanup by 0.82% (significant at the 1% level) and spending on cleanup by 0.14% (significant at the 10% level). This is estimated with province and year fixed effects that absorb province- or year-specific variation in levies, and the standard errors are clustered at the province level. Since China's levy rates have been generally rising, this strategy essentially exploits the timing of levy increases across China and is robust to either time-invariant or province-invariant factors driving levy rates and dumping behavior. These coefficients indicate that the marginal cost of abatement in China is much lower than the average cost, since wastewater treatment is anticipated to increase by almost six times as much as the total spending on cleanup, implying that during the 1990s many provinces could have induced large increases in cleanup by raising levy rates.[37]

In table 10, I synthesize the preceding analysis to calculate the anticipated savings (in lives) of raising China's levy rate and the compliance costs required of firms in wastewater treatment spending. A full 100% increase in China's levy rate is predicted to reduce untreated dumping by 82%, which in turn improves the water grade by 22% (from table 9) of 82%, yielding a predicted improvement in water quality of

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[34] Summary statistics of the industries with the largest share of industrial pollution are presented in appendix table 5. Firms classified as producing chemicals or chemical products were responsible for 19% of the dumping of untreated wastewater, the largest share among the 21 industrial categories.

[35] Dumping is assigned to each river basin using data on the industrial mix within the river basin and county-level data on industrial production. Details regarding this calculation are in the appendix.

[36] Since the Chinese levy system relies on self-reporting by firms, it may be that emissions are underreported. If underreporting is correlated with the effective levy rate, it may be that my analysis exaggerates the impact of levy rates on dumping if firms respond by lowering reported emissions without changing their behavior. As such, the coefficient on the elasticity of emissions to the effective levy rate may be biased and could potentially lead to an overly optimistic prediction regarding the benefit of tighter levy rates. Though I am unable to independently examine this issue, Wang and Wheeler (2005) describe in detail the punishments on firms for false reporting and suggest that the levy system is generally effective at inducing firms to report emissions.

[37] An alternate interpretation is that the province and year fixed effects are overcontrolling for the relevant incentives. The simple correlation between the levy rate and spending on cleanup is roughly 0.43, which would imply marginal costs roughly three times larger than the preferred estimate of 0.14, but much of this variation is absorbed by the province and year fixed effects. In terms of the cost to avert a death by increasing the levy rates, this would yield an estimate three times larger than what I present in table 9.

TABLE 10.—ESTIMATED BENEFITS AND COSTS OF RAISING LEVY RATES

				Benefits and Costs of Doubling Fine Rates			
	$\frac{\partial \ln DeathRate_i}{\partial WaterQuality_i}$ (1)	$\frac{\partial WaterQuality_i}{\partial \ln Dumping_i}$ (2)	$\frac{\partial \ln Dumping_i}{\partial \ln TaxRate_i}$ (3)	Deaths Averted per Year (4)	Extra Compliance Cost per Year ($) (5)	Cost per Averted Death (6)	Cost per Year of Life (7)
				$(1) \times (2) \times (3) \times (980,000)$	(Costs) $\times$ (0.137)	(5)/(4)	(6)/20.12
Overall Grade	0.097^{**}	0.220^{***}	0.815^{***}	17,044	$504,888,032	$29,622	$1,472
	(0.044)	(0.075)	(0.21)				

Source: China Disease Surveillance Points Mortality Registration (DSP), China National Monitoring Center (2004), China Environmental Yearbooks (1993–2003), World Health Organization (2002).

In column 1, I report the relationship between the log of the digestive cancer rate on the overall water grade (see table 3). In column 2, I report the relationship between the water grade and the log of total dumping (see table 9). In column 3, I report the relationship between the log of total dumping and the log of the effective fine levy on water dumping (see table 9). In column 4, I predict the number of lives saved by raising the levy rate, using the fact that the total annual deaths due to digestive cancers is roughly 980,000 (World Health Organization, 2002). In column 5, I predict the cost of compliance of raising the levy rate, using the fact that total reported compliance costs in 2000 was roughly $3.7 billion (China Environmental Yearbook, 2001), and the estimated elasticity of spending on cleanup of .137 (see table 9). In column 6, I present the cost to firms in additional spending required to avert one additional death from digestive cancer. In column 7, I report this cost in terms of extra years of life expectancy, using the projection that decedents have on average 20.12 years of remaining life expectancy. *Significant at 10%, **5%, ***1%.

.18 units (.82 × .22).[38] In the preferred OLS specification in table 3, each unit decrease in water grade is associated with roughly 9.7% fewer deaths due to digestive cancer, or roughly 95,000 deaths due to digestive cancer. Since water quality is expected to improve by .18 units, the proposed levy increase would avert roughly 17,000 deaths. In terms of the anticipated compliance costs, I estimate that China's firms would need to increase spending on wastewater treatment by 14% from the level reported in 2001 of 29 billion yuan, or roughly $3.7 billion on wastewater treatment, which implies an anticipated extra $500 million in compliance costs.[39] This implies a cost per death averted of roughly $30,000 ($500 million/17,000 deaths averted). Since each digestive cancer death imposes a cost of slightly more than twenty years in life expectancy (20.12), this amounts to a cost of roughly $1,500 per year.[40]

This estimate is low relative to conventional valuation placed on a human life, even in low-income countries. According to surveys conducted in China by the World Bank in 2005, estimates based on the contingent valuation method indicate a mean value of a statistical life among the participants of 1.4 million yuan, or $175,000 (World Bank, 2007).[41] While it is difficult to measure the full cost in quality and length of life of contracting digestive cancer, the simple back-of-the-envelope calculation here suggests that the cost of compliance with higher pollution levies is justified by their benefit. My estimates suggest that even if the cost per averted death was much higher than the estimated $30,000, the cost of saving a life through cleanup would still be justified by the benefit in improved health outcomes.

In addition, my estimate of the potential health benefit of raising levies may be very conservative. First, the preferred OLS estimate of 9.7% is smaller than point estimates without regional control variables (12%) or estimates from 2SLS (27%), which serves to understate the impact of improving water quality. Second, because I am focusing on a narrow measure of the health benefits of cleanup, the estimate presented here can be thought of as a lower bound of the full impact on mortality. Third, these calculations count only the cost of a death, when in fact digestive cancer is also associated with years of poor health and distress preceding death. Finally, China's rapid income increases have led to large reductions in infant mortality and the incidence of infectious diseases. As the population ages, reducing the prevalence of digestive cancer will avert an increasing number of deaths, since the disease's share of deaths is higher among those in middle and old age (see figure 6).

V. Conclusion

Despite an increase in cleanup efforts in recent years, the overall degradation of China's waterways continues. While the capacity of wastewater treatment facilities has grown, it has not kept pace with the growth of industrial output. The pollution intensity of China's industrial firms has declined

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[38] The calculation performed here examines the relationship between spending per year on water treatment and averted deaths per year due to improved water quality, and so it is essentially a calculation entirely in terms of flows. Rivers clean themselves quickly since pollution has a short residence time, whereas lakes may take years to become clean even after the cessation of emissions. My analysis of the elasticity of water pollution to industrial dumping is based on China's main river basins, so the flow-based calculation seems to be a reasonable approximation. However, for some of China's largest lakes, there may be a large stock of pollutants, and so the results should be interpreted with caution.

[39] The environmental yearbook estimate for 2000 (in the 2001 yearbook) is the most recent year in which China's environmental yearbook reported both operating expenses and equipment value. This calculation also assumes an exchange rate of 8 yuan per dollar.

[40] This is calculated as the weighted average of remaining life expectancy, where the weights are defined by the share of digestive cancer deaths that occur at that age in the DSP. Alternatively, I have calculated that life expectancy at birth would be increased by 1.5 years through the elimination of this cause from a standard life table. The life expectancy at birth in the DSP sample (1991–2000) is 73.9 years, and is 75.4 years when the death rate from digestive cancer is set to 0 and the death rates from other causes are assumed to equal their distribution in the DSP. Results available on request.

[41] The World Bank (2007) reports that the survey was administered in Chongqing and Shanghai (twice) and the survey questionnaire, with minor changes, was identical to those administered in the United States, Canada, United Kingdom, France, Italy, and Japan. See Krupnick et al. (2006) for more information regarding the surveys in China.

(discharge per yuan of output), but the tonnage of water dumping has continued to increase (World Bank, 2007).

Although China's economy has grown rapidly and brought with it many benefits, the adverse health effects of pollution threaten to mitigate the health benefits of the country's newly found wealth. The results presented here highlight one channel by which China's industrial growth has led to deterioration in health outcomes. The dumping of untreated wastewater in densely populated areas has contributed to China's increasing cancer rate, and cancer is now the country's leading cause of death (Chinese Ministry of Health, 2008). The cost of industrial pollution is also disproportionately borne by the millions of Chinese farmers who are unable to access safe drinking water and are least able to share in the benefits of China's urban manufacturing boom. Estimates by the World Bank (2006) indicate that as many as half of China's inhabitants still lack access to safe drinking water. In 2005, China's Ministry of Water Resources announced ambitious plans to reduce the number of residents without access to clean drinking water by one-third by 2010 and to provide safe access to drinking water to all rural residents by 2030. Recent reports suggest that much progress on this front has been made.[42] Even if these goals are met, the need to curb industrial dumping of untreated wastewater in the near future is clear and pressing. India is also facing similar struggles due to industrialization, with heavily polluted rivers, a large exposed population, and an environmental regulation regime that has struggled to contain emissions (Maria, 2003).

The analysis reveals a relatively low cost to averting deaths by water cleanup of roughly $30,000, suggesting that dumping regulations need to be more aggressively enforced. The gaps in enforcement of China's regulations reveal inexpensive opportunities to avert deaths relative to the value of life that Chinese citizens report in contingent valuation surveys. These surveys indicate average valuations of roughly $175,000 for the value of a statistical life (Krupnick et al., 2006). Protests by villagers who are justifiably angered by the contamination of the water supply also suggest that the current Chinese policy may represent an ongoing threat to political stability in China. The government reported 50,000 environmental protests in 2005 alone (Magnier, 2006), providing further motivation for tightening environmental standards on China's industrial firms. Wastewater dumping is in part responsible for China's emerging cancer epidemic, and addressing this problem through stricter levy enforcement may yield large improvements in public health and life expectancy at a reasonable cost. Failure to act could prove costly for the millions of rural Chinese farmers who continue to rely on surface water for their drinking supply.

This paper examines the health consequences of industrialization by focusing narrowly on water pollution and digestive cancers in China, but this issue has salience in other developing countries that face similar challenges. Like many other developing countries, China's ability to industrialize has preceded its ability to deal with the resultant waste. Developing countries such as China and India must design environmental policy that balances the interests of industry and those it employs against the interests of the population vulnerable to the health risks of industrial waste. As this analysis demonstrates, tighter regulations may yield large human health benefits with relatively low economic costs.

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