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Heterogeneity in Population and Values and Water Pollution Clean-up: The Ganges in Kanpur and Varanasi, India[1]

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Abstract

We utilize the public good features of Ganges water pollution clean-up and conduct a game-theoretic analysis of an economy consisting of two Indian cities, Kanpur and Varanasi, through which the Ganges flows. We show how heterogeneity in the two cities in *population* and the *value* placed on pollution clean-up determines whether clean-up ought to be centralized or decentralized. Under decentralization, in several scenarios, it is optimal for only one city to clean-up pollution. Under centralization, this exclusive clean-up of pollution is suboptimal but the amount of pollution cleaned up can be larger or smaller than the amount cleaned up under decentralization. We note the broader environmental and public health implications of pollution control and contend that the two differences between Kanpur and Varanasi and the use of majority voting are key factors to consider when pondering how much pollution to clean up in this economy and in other settings.

Keywords: Clean-up, Ganges River, Population Difference, Values Difference, Water Pollution

JEL Codes: Q53, Q56, D81

1. Introduction

The rivers of India play a significant role in the lives of the people of this nation. *Inter alia*, these rivers provide drinkable water, relatively inexpensive transportation, hydroelectric power, and a whole host of ecosystem services such as flood protection and nutrient recycling. Therefore, as pointed out by Vaidyanathan and Mitra (2011), many of India's cities are located on the banks of these rivers. Examples include Kanpur and Varanasi that are located on the Ganges river, Guwahati which is located on the Brahmaputra river, Ahmedabad which is located on the Sabarmati river, and Jabalpur which is located on the Narmada river. The work of Sanyal (2013) tells us that seven major rivers along with their tributaries, comprise the main system of rivers in India. Some important rivers such as the Ganges and the Brahmaputra empty into the Bay of Bengal and others such as the Narmada and the Sabarmati empty into the Arabian Sea.

Sharma *et al*. (2021) point out that in contemporary times, many of India's rivers are polluted. Even though this is factually true, when it comes to river water pollution, it is fair to say that the extremely polluted status of the Ganges, arguably the most important river in India, dominates public discussion about river water pollution.[4] In this regard, Black (2016) notes that more than a billion gallons of waste are deposited into the Ganges every day. In addition, we learn that the problem of waste deposition into the Ganges arises at various points along the river.

The contributions of Gallagher (2014), Black (2016), Jain and Singh (2020) and Batabyal *et al*. (2023a) tell us that as far as the flow of water and pollution in the Ganges are concerned, three problems deserve particular attention. The first problem is water pollution from the tannery or leather producing industry, which is situated mainly in the city of Kanpur in the state of Uttar

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4 See Markandya and Murty (2004) and Jani *et al*. (2018) for a more detailed validation of this claim.

Pradesh (see Figure 1). The magnitude of the pollution problem caused by tanneries in Kanpur can be gauged by recognizing that in 2015, for instance, one-half of the 26 million liters of tannery

Figure 1 about here

refuse was left untreated and a significant portion of this refuse ended up in the Ganges.[5] The significance of the tannery industry in Kanpur explains why this city is occasionally referred to as India's "leather city."[6] The second problem is waste deposited into the Ganges in the city of Varanasi (sometimes called Benares), also in the state of Uttar Pradesh, which is, as shown in Figure 1, situated to the south-east of and about two hundred miles downstream from Kanpur. A lot of the pollution in Varanasi, inarguably the spiritual center of Hinduism, is the result of Hindu religious activities. In this regard, Dhillon (2014) notes that 32,000 bodies are cremated every year in Varanasi and that this practice results in 300 tons of ash and 200 tons of half-burnt human flesh being deposited into the Ganges.[7] The third problem is that the climate change phenomenon is reducing water flows in the Ganges[8] and this factor has decreased the river's natural capacity to absorb pollutants that are deposited into it.[9]

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Go to https://www.bqprime.com/business/why-kanpurs-tanneries-are-at-the-centre-of-a-fight-to-save-the-ganga for additional details on this point. Accessed on 22 February 2024.

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Go to https://mahileather.com/blogs/news/the-world-s-most-famous-leather-markets for a more detailed discussion of this point. Accessed on 22 February 2024.

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See Wohl (2010) for more details on how these damaging impacts exacerbate the Ganges water pollution problem.

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Go to https://www.indiawaterportal.org/articles/impacts-water-infrastructure-and-climate-change-hydrology-upper-ganges-river-basin for more details and for a quantitative discussion of this point. Accessed on 22 February 2024.

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In the state of Uttar Pradesh, the severity of the Ganges water pollution problem is highest in Kanpur and Varanasi. Go to https://www.indiatimes.com/news/india/ganga-river-water-not-fit-for-drinking-even-bathing-toxicity-worst-in-varanasi-kanpur-368279.html for more details on this point. Accessed on 22 February 2024.

The question of regulating water pollution[10] in the Ganges caused by tanneries in Kanpur has recently been studied from a variety of perspectives by Batabyal and Yoo (2022), Batabyal (2023), and Batabyal *et al*. (2023b). Similarly, the topic of how pollution in the Ganges in Varanasi ought to be managed has received attention in the literature from Batabyal and Beladi (2017, 2019, 2020), Xing and Batabyal (2019), Matta *et al*. (2020), and Nazir *et al*. (2022). Finally, Batabyal *et al*. (2023b) have analyzed the impact that climate change has on the regulation of pollution caused by the activities of tanneries in Kanpur.[11] These studies show how static, microeconomic modeling along with comparative statics (sensitivity analysis) and probabilistic modeling including modeling with the theory of Poisson processes, can be gainfully utilized to shed light on several aspects of the regulation of Ganges water pollution in Kanpur and Varanasi.

At this stage, we would like to emphasize two points. First, the studies mentioned in the preceding paragraph have certainly enhanced our understanding of aspects of the complex problem of water pollution clean-up in the Ganges. Second, the preceding point notwithstanding, it is important to understand that in India, centralized planning has been the norm in water resources management for many decades. Therefore, Das and Tamminga (2012) are certainly right when they point out that this feature has been a problem for municipalities. Why? Because these municipalities lack the funds they typically need to operate and maintain large sewage disposal and treatment facilities that are controlled and financed by the central or federal government. More

10 For additional perspectives on this specific issue, see Kumar *et al*. (2022), Younas *et al.* (2022), and Kumar *et al.* (2023).

11 In addition to the papers mentioned in this paragraph, the Ganges has been studied from multiple perspectives by a variety of authors. Specifically, Salman and Uprety (1999) have analyzed what they call water politics in the context of the Ganges, Bhaduri and Barbier (2008a, 2008b) have analyzed transboundary water sharing involving Ganges water, Islam and Gnauck (2009) have analyzed threats to mangrove wetland ecosystems in the Ganges basin, Kedzior (2017) has analyzed environmental awareness and participation in Ganges water quality policy in India, and Lee and Mitchell (2019) have analyzed water related conflicts with reference to the Ganges basin. More generally, sustainability considerations, broadly construed, in the context of rivers have been studied by Ferrer *et al.* (2022), Xu *et al.* (2022), and Anh *et al.* (2022).

recently, new forms of urban governance have called for decentralization resulting in the transfer of responsibilities from the state to local or community institutions.

In the context of water pollution clean-up in the Ganges, there is no gainsaying the fact that "[e]fforts to clean the Ganges have, so far, fallen far short of their stated goals" (Das and Tamminga, 2012, p. 1649). Why has this been the case? According to Das and Tamminga (2012, p. 1649), this saturnine situation is the consequence of water pollution clean-up in the Ganges being unduly *centralized* with pollution abatement programs "imposed from the top…" with little or no attempts being made to collaborate with local institutions.

As a result of the observations stated above, Batabyal and Beladi (2023) have demonstrated how *spatial spillovers* from water pollution clean-up in the Ganges affect whether this clean-up ought to be centralized or decentralized. Our goal in this paper is to continue to study the subject of Ganges water pollution clean-up in the cities of Kanpur and Varanasi that are situated in the state of Uttar Pradesh in India. That said, our paper breaks new ground in the existing literature in three salient ways. First, we cast the question of how much Ganges water pollution to clean up in Kanpur and Varanasi in a *strategic or game-theoretic* setting. That said, the reader should note that we do not propose or use any "mixed methods" in the analysis we undertake in this paper. Second, we investigate how two kinds of heterogeneity, in *population* differences between Kanpur and Varanasi and in the *values* placed on cleaning up Ganges water pollution in Kanpur and Varanasi, determine whether pollution clean-up ought to be centralized or decentralized. Finally, we concentrate on optimal but counterintuitive solutions to the question about how much water pollution clean-up to undertake in these same two cities. In these three ways we show how our theoretical approach in this paper sheds valuable light on an applied problem---Ganges water pollution clean-up---of considerable significance.

The remainder of this paper is organized as follows: Section 2 describes our static, game-theoretic model.[12] In this model, the *size* of the populations in Kanpur and Varanasi and the *value* that the citizens in these two cities place on undertaking Ganges water pollution clean-up in their cities, are dissimilar. Section 3 solves for the *decentralized* Nash equilibrium levels of water pollution clean-up when Kanpur is both larger---which it is in reality---and places a higher value on Ganges water pollution clean-up.[13] Section 4 studies the decentralized clean-up of water pollution in the counterfactual case where Varanasi is assumed to be larger but the value it places on water pollution clean-up is lower than the corresponding value in Kanpur. Section 5 examines the *centralized* clean-up of water pollution in the aggregate economy of Kanpur and Varanasi with majority voting. Section 6 describes the social *welfare* effects of centralization, first when Varanasi is assumed to be larger and then when Kanpur is larger. Finally, section 7 concludes and then suggests two ways in which the research delineated in this paper might be extended.

2. The Game-Theoretic Framework

Consider a stylized, aggregate economy of two cities Kanpur and Varanasi in India. As shown in Figure 1, both cities lie on the Ganges, both cities are located in the state of Uttar Pradesh, and they are denoted by the subscript $i = K, V$. There are n_i identical citizens in city i. The first of two kinds of *heterogeneity* in our model arises from the specification that $n_K \neq n_V$.

We work with three goods in our model. The first is a private good that is denoted by z. The second and the third goods are the amounts of water pollution in the Ganges cleaned up in the two cities and these amounts are denoted by $w_K \geq 0$ and $w_V \geq 0$. It is now well known that

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Because our model is *static*, the reader should understand that it does not make sense to describe the various activities that are occurring in the model in terms of a flow over time.

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The population of Kanpur exceeds that of Varanasi. Go to https://geographyhost.com/top-10-largest-cities-in-uttar-pradesh-by-population/ for additional details on this point. Accessed on 22 February 2024.

pollution clean-up shares the characteristics of public goods in the sense that this clean-up is both non-excludable and non-rivalrous.[14] In the setting of our paper, non-excludable means that if water pollution is cleaned up in Kanpur and in Varanasi then no citizen in either of these two cities can be excluded from benefiting from the clean-up. Non-rivalry means that the benefit obtained by any one citizen of either Kanpur or Varanasi from the amount of water pollution cleaned up does not diminish the benefit obtained by any other citizen of these same two cities. Therefore, in the remainder of this paper, we shall think of water pollution clean-up in Kanpur and Varanasi as public goods that are substitutable for all intents and purposes.

Each citizen in the aggregate economy under study possesses a fixed amount of the private good and this fixed amount can be converted into water pollution clean-up at marginal cost equal to unity. The utility function of each citizen in city i is

$$U_i = z_i + \zeta_i \log(w), \tag{1}$$

where we have temporarily dropped the subscript on the amount of polluted water cleaned up or w and $\zeta_i > 0$ is a measure of the *value*[15] that each citizen in city i places on the amount of water pollution cleaned up in his or her city. The reader will note that the utility function in equation (1) is quasi-linear because it is linear in z_i but non-linear in w. The second of two kinds of heterogeneity in our model arises from the stipulation that $\zeta_K \neq \zeta_V$. Our next task is to solve for

14 Go to https://resources.environment.yale.edu/kotchen/pubs/pgchap.pdf and to https://plato.stanford.edu/entries/public-goods/ for a more detailed corroboration of this claim. Accessed on 22 February 2024. See Hindriks and Myles (2013, pp. 147-190), for a textbook discussion of public goods.

15 Later on, in sections 5 and 6 of the paper, we shall refer to this ζ_i or *value* parameter as a *preference* parameter. In other words, the utility function in equation (1) can also be thought of as a preference *function* and ζ_i is a value or preference *parameter* of the preference function.

the decentralized Nash equilibrium[16] levels of water pollution clean-up in the two cities when Kanpur is both *larger* and places a *higher* value on pollution clean-up.

3. Water Pollution Clean-up with a Dominant Kanpur

By "dominant," we mean that the conditions $\zeta_K > \zeta_V > 0$ and $n_K > n_V > 0$ both hold simultaneously. Now, each city independently decides how much water pollution to clean up. This means that the common level of water pollution clean-up is the sum of the two clean-up amounts undertaken in Kanpur and in Varanasi or $w = w_K + w_V$. Let us denote the fixed endowment of the private good of each citizen in Kanpur by $\hat{z}$. Also, let us think of the ratio $1/n_V$ as the per citizen marginal cost of cleaning up water pollution in Varanasi. Then, the utility of a Varanasi citizen as a function of the pollution clean-up amounts w_V and w_K is

$$U_V(w_K, w_V) = \hat{z} - \frac{w_V}{n_V} + \zeta_V \log(w_K + w_V). \tag{2}$$

Differentiating the utility function in equation (2) with respect to w_V, the first-order necessary condition for an optimum is

$$\frac{\partial U_V(w_K, w_V)}{\partial w_V} = \frac{\zeta_V}{w_K + w_V} - \frac{1}{n_V} = 0. \tag{3}$$

Simplifying equation (3), the best response---sometimes called reaction---function of a Varanasi citizen is

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In a Nash equilibrium, every player in a game is doing the best that he or she can for himself or herself given that all the other players in this game are also doing the best that they can for themselves. For a technical definition of and more details about a Nash equilibrium, see Gibbons (1992) or Tadelis (2013).

$$w_V = \zeta_V n_V - w_K. \quad (4)$$

Using a similar line of reasoning, the utility function of a Kanpur citizen as a function of the amounts of water pollution cleaned up w_V and w_K is

$$U_K(w_K, w_V) = \hat{z} - \frac{w_K}{n_K} + \zeta_K \log(w_K + w_V), \quad (5)$$

where, as in the case of Varanasi, we shall think of the ratio $1/n_K$ as the per citizen marginal cost of cleaning up water pollution in Kanpur. Differentiating equation (5) with respect to w_K, we get

$$\frac{\partial U_K(w_K, w_V)}{\partial w_K} = \frac{\zeta_K}{w_K + w_V} - \frac{1}{n_K} = 0. \quad (6)$$

Simplifying equation (6), the best response or reaction function of a Kanpur citizen is

$$w_K = \zeta_K n_K - w_V. \quad (7)$$

The two inequalities $\zeta_K > \zeta_V$ and $n_K > n_V$ together tell us that $\zeta_K n_K > \zeta_V n_V$. Inspecting this last inequality along with the two best response functions in equations (4) and (7), it follows that the optimal amounts of water pollution cleaned up in a Nash equilibrium are given by

$$w_V = 0 \; and \; w_K = \zeta_K n_K. \quad (8)$$

To understand the result in (8), the reader should recall two points from our previous discussion in this paper. First, the marginal cost of cleaning up water pollution is lower in Kanpur $\{n_K > n_V \Rightarrow (1/n_V) > (1/n_K)\}$ and the value placed on water pollution clean-up in Kanpur is also higher $(\zeta_K > \zeta_V)$. Second, there is perfect substitutability between the amounts of water pollution cleaned up in Kanpur and Varanasi. These two points together tell us that in this case, it is optimal for *only* Kanpur to clean up water pollution in our aggregate economy. From a practical perspective, in the scenario studied in this section, Varanasi does *not* clean up water pollution at all and it basically free rides on the Ganges water pollution cleaned up by Kanpur.

As pointed out in footnote 10, the condition $n_K > n_V$ is factually accurate. That said, as stated in footnote 6, Ganges water pollution is a serious problem in both Kanpur and Varanasi. This notwithstanding, to the best of our knowledge, there are no data that will tell us whether the citizens of Kanpur value Ganges water pollution clean-up more or less than the citizens of Varanasi. As such, excluding the knife-edge case in which $\zeta_K = \zeta_V$, one reasonable scenario to study is the one in which $\zeta_K > \zeta_V$. Now, putting the previous two inequalities together, we have formally demonstrated that when Kanpur is larger, it places a higher value on water pollution clean-up, and the water pollution clean-up amounts in the two cities are perfect substitutes, it is optimal for Kanpur to clean up water pollution *exclusively*.

In this section, we have studied the case of a "dominant" Kanpur meaning that the inequalities $\zeta_K > \zeta_V$ and $n_K > n_V$ both hold simultaneously. That said, we are also very interested in studying the clean-up of water pollution in the Ganges in our aggregate economy when the preceding two inequalities *do not both* hold simultaneously. That is why in section 4 below, we study the counterfactual case of what we call a "less dominant Kanpur." In this specific instance, our assumption about the relative *values* placed on water pollution clean-up is unchanged ($\zeta_K >$

ζ_V) but the population in Varanasi is now assumed to be larger than the population in Kanpur ($n_V > n_K$).

4. Water Pollution Clean-up with a Less Dominant Kanpur

Some thought about the structure of our model ought to convince the reader that when the conditions $\zeta_K > \zeta_V$ and $n_V > n_K$ hold simultaneously, there are three possibilities to consider. The first possibility arises when the condition $\zeta_K n_K > \zeta_V n_V$ holds. When this happens, the amount of water pollution that is cleaned up is the same as that analyzed above in section 3. The second possibility arises when $\zeta_V n_V > \zeta_K n_K$. When this condition is satisfied, the logic of the section 3 analysis still holds but the Nash equilibrium is upturned in the sense that we now have

$$w_K = 0 \; and \; w_V = \zeta_V n_V. \tag{9}$$

This means that Kanpur ought not to be cleaning up any water pollution in the Ganges and it is now optimal for Varanasi to undertake *exclusively*, the task of cleaning up water pollution in the Ganges. From a practical standpoint, in this counterfactual case, Varanasi alone cleans up water pollution while the city of Kanpur free rides on Varanasi's clean-up efforts.

The third and last possibility arises when the condition $\zeta_K n_K = \zeta_V n_V$ holds. In this case, we obtain a symmetric Nash equilibrium. In a symmetric Nash equilibrium, all the players use the same strategy in the equilibrium (Tadelis, 2013, p. 230). From equation (4) we get $w_V - w_K = \zeta_V n_V$. Similarly, simplifying equation (7), we get $w_K - w_V = \zeta_K n_K$. Since the right-hand-sides (RHSs) of the preceding two equations are equal in this third case, we get $w_V - w_K = w_K - w_V \Rightarrow 2w_V = 2w_K \Rightarrow w_V = w_K$. In other words, in the symmetric Nash equilibrium under study, the amounts of water pollution that are cleaned up satisfy the conditions

$$w_K = w_V \; and \; w_K + w_V = \zeta_K n_K. \tag{10}$$

The reader will observe that of the three possibilities that we have analyzed in this fourth section, it is optimal for *both* Kanpur and Varanasi to undertake water pollution clean-up only when an equality condition that we can think of as a knife-edge condition given by $\zeta_K n_K = \zeta_V n_V$ holds. Practically speaking, only when the above equality condition holds do we see *no* free riding, with both cities cleaning up pollution. Next, in section 5, we depart from the decentralized clean-up of water pollution in the Ganges and examine the *centralized* clean-up of water pollution in the aggregate economy of Kanpur and Varanasi with majority voting.[17]

5. Centralized Provision of Water Pollution Clean-up

In this case, the decision about how much water pollution to clean up is made *jointly* for Kanpur and Varanasi by a central authority such as the Uttar Pradesh Pollution Control Board (UPPCB)[18] at the state level or by the National Ganga River Basin Authority (NGRBA)[19] at the national level. In addition, we suppose that majority voting determines the actual amount of water pollution that is cleaned up in the two cities. In other words, the amount of water pollution cleaned up is based on the *preference* of the median or larger city, which turns out to be Kanpur in section 3 and Varanasi in section 4. The reader should understand that even though the centralized clean-up of Ganges water pollution results in spreading the cost of cleaning up pollution more widely, at the same time, the *preference* of the citizen in the larger city is imposed on the citizens living in the smaller city.

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See Hindriks and Myles (2013, pp. 350-361) for a textbook discussion of majority voting.

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Go to http://www.uppcb.com/ for more details on the UPPCB. Accessed on 22 February 2024.

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Go to https://nmcg.nic.in/ngrbaread.aspx for additional details on the NGRBA. Accessed on 22 February 2024.

Let us now determine the optimal amount of water pollution that is cleaned up in this centralized setting. As in section 3, when Kanpur is the larger city, it chooses the amount of water pollution to clean up or w based on the preference of the median citizen in Kanpur and this is given by ζ_K. So, the appropriate optimization problem now involves choosing w to solve

$$max_{\{w\}}\, \hat{z} - \frac{w}{n_K+n_V} + \zeta_K \log(w), \tag{11}$$

and it is understood that the cost of cleaning up water pollution is now spread over the entire population $n_K + n_V$ in our aggregate economy. Differentiating equation (11) with respect to w and then setting this derivative equal to zero gives us the first order necessary condition for an optimum. We get

$$\frac{\zeta_K}{w} - \frac{1}{n_K+n_V} = 0. \tag{12}$$

Simplifying equation (12), the majority voting equilibrium amount of water pollution that is cleaned up is

$$w = \zeta_K(n_K + n_V) > \zeta_K n_K. \tag{13}$$

Comparing equation (13) with equation (8) we see that relative to the decentralized Nash equilibrium in section 3, *more* water pollution is now cleaned up in the centralized setting. Observe that this result comes about because Kanpur---which values water pollution clean-up more than Varanasi---ends up being decisive in the majority voting equilibrium and, in addition, the cost of cleaning up water pollution is spread over all the citizens of the two cities in our aggregate economy.

In the scenario studied in section 4, we had $\zeta_K > \zeta_V$ and $n_V > n_K$. Now focusing on the centralized clean-up of water pollution with majority voting, Varanasi chooses how much water pollution to clean up. In this case, Varanasi will select w based on the preference of the median citizen in Varanasi and this is given by $\zeta_V < \zeta_K$. Therefore, the optimization problem now involves choosing w to solve

$$max_{\{w\}} \hat{z} - \frac{w}{n_K+n_V} + \zeta_V \log(w), \qquad (14)$$

where, once again, the cost of cleaning up water pollution is spread over the entire population of Kanpur and Varanasi or n_K+n_V in our aggregate economy. Differentiating equation (14) with respect to w, the first-order necessary condition for an optimum and the majority voting equilibrium amount of water pollution cleaned up is given by

$$w = \zeta_V(n_K + n_V). \qquad (15)$$

To compare the centralized equilibrium clean-up of water pollution described in equation (15) with the decentralized clean-up of water pollution discussed in section 4, it will be necessary to consider the three possibilities discussed in that section. First, if $\zeta_K n_K > \zeta_V n_V$ then the centralized Nash equilibrium is identical to the equilibrium discussed in section 4 and this tells us that

$$w = w_K = \zeta_K n_K. \tag{16}$$

Comparing equations (15) and (16), we see that with centralization, the optimal clean-up of water pollution can decline if the following inequalities hold

$$\zeta_V(n_K + n_V) < \zeta_K n_K \Leftrightarrow \zeta_V n_V < n_K(\zeta_K - \zeta_V). \tag{17}$$

The second possibility is that $\zeta_V n_V > \zeta_K n_K$. In this case, the centralized Nash equilibrium is given by

$$w = w_V = \zeta_V n_V. \tag{18}$$

In this second instance, equations (15) and (18) tell us that for the amount of water pollution cleaned up to decline with centralization, we must have the inequality $\zeta_V(n_K + n_V) < \zeta_V n_V$, which is clearly impossible.

The third and final possibility is that $\zeta_K n_K = \zeta_V n_V$. In this case, the centralized Nash equilibrium amount of water pollution cleaned up is given by

$$w = w_K + w_V = \zeta_K n_K. \tag{19}$$

For the amount of water pollution cleaned up in the centralized Nash equilibrium to be lower than the amount cleaned up in the decentralized Nash equilibrium, we must have the inequality $\zeta_V(n_K + n_V) < \zeta_K n_K$, which is also impossible. Consequently, the central policy related finding that arises from our discussion of the three possibilities is that the optimal amount of water pollution cleaned up in our aggregate economy can decline with centralization if and only if the condition in (17) holds. Our final task in this paper is to delineate the social welfare effects of centralization when, first, Varanasi is assumed to be larger in terms of population and, second, when Kanpur is larger, also in terms of population.

6. Social Welfare Impacts of Centralization

Consider first the case in which Varanasi is, by assumption, larger than Kanpur. In symbols, we have $n_V > n_K$. We know from equation (15) that the optimal amount of water pollution cleaned up under centralization is $w = \zeta_V(n_K + n_V)$. As such, the social welfare from cleaning up Ganges water pollution in our aggregate economy is

$$U_K(w) + U_V(w) = 2\left\{\hat{z} - \frac{\zeta_V(n_K+n_V)}{n_K+n_V}\right\} + (\zeta_K + \zeta_V)\log\{\zeta_V(n_K + n_V)\}. \qquad (20)$$

Canceling the $(n_K + n_V)$ terms in the first expression in the curly brackets on the RHS of equation (20), this equation simplifies to

$$U_K(w) + U_V(w) = 2(\hat{z} - \zeta_V) + (\zeta_K + \zeta_V)\log\{\zeta_V(n_K + n_V)\}. \qquad (21)$$

Next, consistent with reality, we consider the case where Kanpur is larger so that we have $n_K > n_V$. The optimal amount of water pollution cleaned up under centralization is $w = \zeta_K(n_K + n_V)$ and we also have $\zeta_K(n_K + n_V) > \zeta_V(n_K + n_V)$. Therefore, social welfare in our aggregate economy of Kanpur and Varanasi is

$$U_K(w) + U_V(w) = 2(\hat{z} - \zeta_K) + (\zeta_K + \zeta_V)\log\{\zeta_K(n_K + n_V)\}. \tag{22}$$

We now want to express the difference in the social welfare in our aggregate economy, i.e., the social welfare when Varanasi is decisive (is in the majority) less the social welfare when Kanpur is decisive (is in the majority). This difference is given by subtracting the RHS of equation (22) from the RHS of equation (21). Doing this, we get

$$2(\zeta_K - \zeta_V) + (\zeta_K + \zeta_V)\{\log(\zeta_V) - \log(\zeta_K)\}. \tag{23}$$

Now recall that we have the inequality $\zeta_K > \zeta_V$. This tells us that the first term in (23) is positive and that the second term is negative. The alternating signs of these two terms in the expression in (23) describe the tradeoff between what we can describe as "preference matching" on the one hand and the "duplication of costs" on the other. The general ambiguity of the expression in (23) notwithstanding, it is possible to shed more light on this expression in some special instances. To illustrate this point, we now concentrate on one specific instance. Suppose that

$$\frac{\zeta_K - \zeta_V}{\zeta_K + \zeta_V} > \left|\frac{1}{2}\log\left(\frac{\zeta_V}{\zeta_K}\right)\right|. \tag{24}$$

In words, the ratio on the left-hand-side (LHS) of the inequality in (24) is larger in magnitude than the absolute value of the logarithmic term on the RHS. In this instance, the difference in social welfare is *positive* when Varanasi, which places a lower value on water pollution clean-up but is larger, is decisive and therefore can impose its preference about water pollution clean-up, on the aggregate economy. This completes our game-theoretic analysis of heterogeneity and Ganges water pollution clean-up in Kanpur and Varanasi in India.

7. Conclusions

In this theoretical paper, we analyzed how two kinds of heterogeneity concerning population and values affected the *decentralized* and the *centralized* clean-up of water pollution in the Ganges in an aggregate economy consisting of Kanpur and Varanasi, two cities where this kind of pollution is a very serious problem. In particular, the *size* of the populations in Kanpur and Varanasi and the *value* citizens in these two cities placed on cleaning up water pollution in their cities, were dissimilar. Two main results flow from our analysis. First, under decentralization, it was optimal for only one city to undertake water pollution clean-up in several circumstances. Second, under centralization, this exclusive clean-up of water pollution was generally not optimal but the amount of water pollution cleaned up could be larger or smaller than the amount cleaned up under decentralization.

Clearly, cleaning up water pollution not only in the Ganges but also in polluted rivers elsewhere in the world has broader environmental and public health benefits. In addition, our research tells policymakers to be mindful of two salient points. First, when pondering the clean-up of Ganges water pollution in Indian cities such as Kanpur and Varanasi, it is important to pay careful attention to the *administrative level* at which the clean-up *decision* is made. When water pollution clean-up is centralized, majority voting makes sense but the use of this procedure will, for all practical purposes, “shut out” the wishes of the smaller (in population) city. Second, when water pollution clean-up is decentralized, counterintuitive “corner solutions” can arise in which one city undertakes no water pollution clean-up and therefore free rides on the efforts of the other city. In fact, a scenario in which we have a “corner solution” in which Varanasi does not clean up water pollution at all is likely to be of considerable practical concern. This is because this kind of situation may be indicative of a mindset among citizens that Ganges water pollution caused by the deleterious activities of religious tourists is either not important enough to clean up in and of itself, or not important enough to clean up compared to the seriousness of water pollution caused by the upstream tanneries in the city of Kanpur.

The analysis in this paper does have some limitations and hence this analysis can certainly be extended in a number of different directions. First, the aggregate economy we study in our model consists of two cities even though in actuality, the Ganges flows through many cities across the Indo-Gangetic plain in north India. Therefore, it would be useful to analyze the question of Ganges water pollution clean-up in an aggregate economy model with at least three cities---for instance, Kanpur, Prayagraj (formerly called Allahabad), and Varanasi---and where the citizens of these three cities are able to migrate between them when they believe that there are substantive differences in Ganges water quality. Second, we have studied heterogeneity of two kinds stemming from differences in population and values about pollution control, in our two cities. As such, it would be helpful to examine city attributes in addition to differential population sizes and pollution clean-up valuations to see how these additional attributes---such as the tax base and average incomes in each city---affect the regulatory objective of keeping the Ganges as clean as possible. Studies that analyze these aspects of centralized versus decentralized water pollution clean-up in the Ganges will provide additional insights into two issues. First, the broader environmental and public health benefits of river water pollution clean-up. Second, the complex interactions between alternate sources of pollution (tanneries, religious tourism) on the one hand and the clean-up of water pollution by regulators on the other.

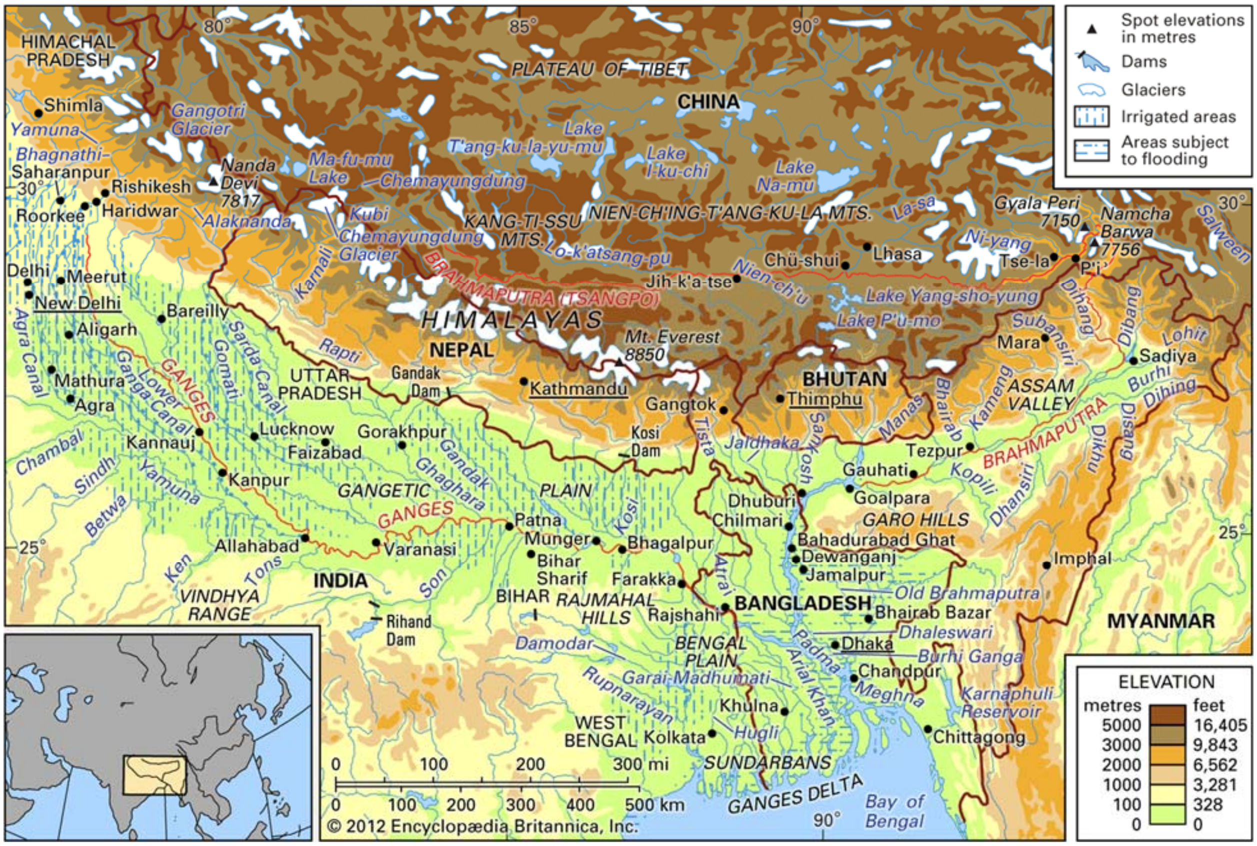

Figure 1: Flow of the Ganges and the Locations of Kanpur and Varanasi

Source: https://www.britannica.com/place/Ganges-River

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