Article

Centralized versus Decentralized Cleanup of River Water Pollution: An Application to the Ganges

Amitrajeet A. Batabyal [1,*] and **Hamid Beladi** [2]

1   Department of Economics and Sustainability, Rochester Institute of Technology, 92 Lomb Memorial Drive, Rochester, NY 14623-5604, USA
2   Department of Economics, University of Texas at San Antonio, One UTSA Circle, San Antonio, TX 78249-0631, USA; hamid.beladi@utsa.edu
*   Correspondence: aabgsh@rit.edu

Abstract: We exploit the public good attributes of Ganges water pollution cleanup and theoretically analyze an aggregate economy of two cities—Kanpur and Varanasi—through which the Ganges flows. Our specific objective is to study whether water pollution cleanup in these two cities ought to be provided in a centralized or in a decentralized manner. We first determine the *efficient* cleanup amounts that maximize the aggregate surplus from making the Ganges cleaner in the two cities. Second, we compute the optimal amount of water pollution cleanup in the two cities in a *decentralized* regime in which spending on cleanup is financed by a uniform tax on the city residents. Third, we ascertain the optimal amount of water pollution cleanup in the two cities in a *centralized* regime subject to equal provision of cleanup and cost sharing. Fourth, we show that if the two cities have the *same* preference for pollution cleanup, then centralization is preferable to decentralization as long as there is a spillover from pollution cleanup. Finally, we show that if the two cities have *dissimilar* preferences for pollution cleanup, then centralization is preferable to decentralization as long as the spillover exceeds a certain threshold.

Keywords: Ganges; pollution cleanup; spillover; uncertainty; water pollution

JEL Classification: Q53; Q56; D81

1. Introduction

1.1. Preliminaries

The Ganges (Ganga in Hindi) river in the Indian subcontinent is unique in the sense that it is both the longest and the most significant river in this nation.[1] This notwithstanding, Black (2016) [2] notes that more than one billion gallons of waste are deposited into the Ganges every day. Although the problem of waste deposition into the Ganges occurs at various points along the river, by way of background and consistent with the work of Gallagher (2014) [3], Black (2016) [2], and Jain and Singh (2020) [4], we note that with regard to the flow of water and pollution in this river, three problems deserve particular emphasis.

The first problem is water pollution from the tannery industry which is located primarily in the city of Kanpur in the state of Uttar Pradesh (see Figure 1). The significance of the tannery industry in Kanpur explains why this city is sometimes referred to as India's "leather city".[2] The second problem is waste deposited into the Ganges in the city of Varanasi, also in the state of Uttar Pradesh, which is, as shown in Figure 1, located to the south-east of and approximately two hundred miles downstream from Kanpur. A lot of the pollution in Varanasi, the spiritual center of Hinduism, is the outcome of Hindu religious activities. In this regard, Dhillon (2014) [5] points out that 32,000 bodies are cremated every year in Varanasi and that this process results in 300 tons of ash and 200 tons of half-burnt human flesh being deposited into the Ganges. The third problem is that the phenomenon

of climate change is diminishing water flows in the Ganges and this factor, along with other factors, has, most likely, reduced the river's natural capacity to absorb pollutants that are deposited into it. Additionally, by way of background, we would like to point out that the question of regulating water pollution in the Ganges caused by tanneries in Kanpur has recently been studied from a variety of perspectives by Madhulekha and Arya (2016a, 2016b) [6,7], Nazir et al. (2022) [8], and Batabyal (2023) [9].

Figure 1. Flow of the Ganges and the locations of Kanpur and Varanasi.

The above papers have certainly increased our understanding of many aspects of the complex problem of water pollution cleanup in the Ganges. Even so, it is important to comprehend that "despite increased funding and much lip service, the [Ganges] is more polluted than before" (Shah et al., 2018, p. 503) [10]. Given this unhappy state of affairs, it is instructive to ponder the perspectives offered by Das and Tamminga (2012, p. 1649) [11].

These researchers point out that "[e]fforts to clean the Ganges have, so far, fallen far short of their stated goals." More importantly, Das and Tamminga (2012, p. 1649) [11] contend that this is the result of water pollution cleanup in the Ganges being excessively centralized with pollution abatement programs "imposed from the top…" with little or no attempts being made to collaborate with local institutions.[3]

A similar point has been made by Alley (1996, p. 352) [14]. She argues that "centralization has exaggerated the administrative and fiscal problems that have burdened urban institutions since the colonial period." She then goes on to say that in the context of pollution prevention programs, "city municipalities are finding difficulty raising the revenue to operate and maintain sewage disposal and treatment infrastructure developed under centrally directed and financed schemes" (p. 352).

Very recently, in their review of alternate approaches to the cleanup of water pollution in the Ganges, Sigdel et al. (2023) [15] have also criticized excessively centralized approaches. Specifically, these researchers contend that "[a]lternative frameworks need to be considered that work from a bottom-up approach rather than a top-down polity" (p. 138). They go on to say that "[g]ood policy is not only implemented by the state but also originates from *community-led initiatives* where citizens work hand in hand with researchers to take charge of their own futures" (p. 138, emphasis added). These community level initiatives are important because a variety of researchers working in and out of India have noted that many efficacious river pollution remediation and planning techniques can take place at smaller scales. Here are five examples of such initiatives. First, Metzger and Lendvay (2006) [16] showed how community-based water monitoring can involve citizens and stimulate advocacy. Second, Cronin and Guthrie (2011) [17] chronicled how community-led resettlement efforts can ameliorate problems in the case of disaster-prone waterways. Third, Peplow and Augustine (2012) [18] studied how participatory action research programs can assist in improving awareness about water pollution. Fourth, the arsenic pollution reduction efforts discussed by Chakrabarti et al. (2018) [19] are dependent on community-engaged actions such as the reinstitution of traditional water filtration methods and a return to dug wells. Finally, Davis et al. (2022) [20] described how mycofiltration can be used to remove organic pollutants from the Ganges.

Echoing the common theme mentioned in the preceding three paragraphs and concentrating on tanneries in Kanpur, Singh and Gundimeda (2021, p. 73) [21] point out that "[e]nvironmental regulations in the Indian leather industry have been restricted to [command-and-control] policies, with mandatory uniform pollution control norms across all the tanneries". Supporting this viewpoint, Das and Tamminga (2012, p. 1649) [11] argue persuasively that for pollution cleanup in the Ganges to be effective, it needs to be *decentralized*, "with the transfer of responsibilities from the state to local or community institutions".

1.2. Objective

The above discussion, which summarizes the critiques of several researchers about excessively centralized approaches to pollution control, emphasizes the significance of answering the following salient, policy-oriented question: When should water pollution cleanup in the Ganges be centralized, and when should it be decentralized? To the best of our knowledge, this question has *not* been studied *theoretically* in the literature to date. Therefore, our central objective in this paper is to analyze this question. However, before we move to the specifics of the paper itself, it is important to point out that we wish to connect our study of the centralization versus decentralization matter to the notion of *spillovers* from water pollution cleanup in the Ganges.

To understand the significance of spillovers, it is important to recall that because Varanasi is located about 200 miles *downstream* from Kanpur, pollution cleanup undertaken in upstream Kanpur will benefit Varanasi residents because these residents will now be less exposed to contaminated river water flowing down from Kanpur. In other words, some of the benefits of pollution cleanup in Kanpur will spill over to Varanasi residents. Similarly, given Varanasi's status as the spiritual center of Hinduism, pollution cleanup carried out in

Varanasi will benefit some (mainly Hindu) Kanpur residents because when they travel to Varanasi to, inter alia, bathe in the Ganges, perform religious rites, and cremate their dead, they will benefit from cleaner river water in Varanasi. In sum, there are spillovers from water pollution cleanup in the Ganges and these spillovers have also not been studied in the literature thus far. As such, to reformulate our central objective stated above, we wish to study the role that spillovers play in determining when water pollution cleanup in the Ganges ought to be centralized or decentralized.

The remainder of this paper is organized as follows: Section 2 delineates our theoretical model of two cities Kanpur (K) and Varanasi (V) that is adapted from the discussion in Batabyal and Beladi (2019) [22].[4] That said, we would like to point out that, consistent with our observation in note 7 below, the model we construct and analyze in this paper is a "fiscal federalism" model. As such, our model builds on the theoretical foundations provided in early research by Oates (1972) [24] that has since been expanded upon and discussed thoroughly in standard textbooks such as Hindriks and Myles (2013, chapter 19) [25]. Section 3 computes the efficient pollution cleanup amounts that maximize the total surplus from cleaning water pollution in the Ganges in Kanpur and Varanasi. Section 4 calculates the amount of pollution cleanup made available in Kanpur and Varanasi in a decentralized regime in which spending on pollution cleanup is financed by a uniform tax on the residents of the two cities. Section 5 determines the amount of pollution cleanup in Kanpur and Varanasi in a centralized regime subject to the condition that pollution cleanup and the sharing of costs are both the same in the two cities. Section 6 demonstrates that if Kanpur and Varanasi have identical preferences for pollution cleanup then centralization is preferable to decentralization as long as there is a spillover from pollution cleanup in the Ganges. Section 7 shows that if Kanpur and Varanasi have non-identical preferences for pollution cleanup then centralization is, once again, preferable to decentralization but only if the spillover exceeds a certain threshold. Section 8 concludes and then suggests several ways in which the research described in this paper might be extended.[5]

2. The Theoretical Framework

Consider the stylized aggregate economy of the two cities, Kanpur and Varanasi. 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 $i = K, V$. These two cities are assumed to have the same population size. In addition, the population in each city i is represented by a continuum of individuals with a mass of unity. There are three goods that we work with in our model. The first is a private good that is denoted by x. The second and the third goods are the amounts of water pollution cleaned up in the two cities; these amounts are denoted by w_K and w_V.

It is now well known that pollution cleanup shares the characteristics of public goods in the sense that this cleanup is both non-excludable and non-rivalrous.[6] In the setting of our paper, non-excludable means that if water pollution cleanup is provided in Kanpur and Varanasi, then no resident of either of these two cities can be excluded from benefiting from the cleanup. Non-rivalry means that the benefit obtained by any one resident of either Kanpur or Varanasi from the amount of water pollution cleaned up does not diminish the benefit obtainable by any other resident of these same two cities. Therefore, in the remainder of this paper, we shall think of water pollution cleanup in Kanpur and Varanasi as public goods for all intents and purposes.[7]

One unit of either $w_K \geq 0$ or $w_V \geq 0$ requires $c > 0$ units of the private good to produce. The residents of Kanpur and Varanasi are *heterogeneous* in the sense that they differ in their preference for water pollution cleanup. Thus, a resident of type θ who lives in city i has a utility function given by

$$u_\theta(x, w_i, w_{-i}) = x + \theta\{(1-\delta)log(w_i) + \delta log(w_{-i})\}, \tag{1}$$

where $\delta \in [0, 1/2]$ measures the extent of the inter-city spillover from cleaning up water pollution in the Ganges. As explained in Section 1.2, this means that pollution cleanup in Kanpur leads to a spillover in Varanasi and vice versa. The two extreme cases are given by the endpoints of the closed interval $[0, 1/2]$. Specifically, when $\delta = 0$, there is no inter-city spillover, and the residents of city i care only about pollution cleanup in their own city. In contrast, when $\delta = 1/2$, the residents in our aggregate economy care equally about pollution cleanup in the two cities under study.

In each city i, residents with preference type θ are assumed to be distributed in accordance with a cumulative distribution function $F_i(\theta)$ that is defined on the interval $[0, \overline{\theta}]$, and has mean denoted by $\zeta_i < \overline{\theta}/2$.[8] Now, consistent with the discussion in the preceding paragraph of the heterogeneity of the residents in the two cities, we suppose that compared to Varanasi, Kanpur displays a stronger mean preference for water pollution cleanup. In symbols, this means that $\zeta_K > \zeta_V$. This concludes the description of our theoretical framework. We now compute the efficient or idealized pollution cleanup amounts that maximize the total surplus from cleaning up pollution in the Ganges in Kanpur and Varanasi.

3. Efficient Pollution Cleanup Amounts

We begin by denoting the income of a type θ resident of city i by $M_{\theta_i} \geq 0$. We can now express the *total* welfare in city i as

$$U_i = \int_0^{\overline{\theta}} dF_i(\theta) \left[x_{\theta_i} - cw_i + \theta\{(1-\delta)log(w_i) + \delta log(w_{-i})\} \right]. \tag{2}$$

The aggregate welfare in the two cities under study can be written as $W = U_K + U_V$. We also have an aggregate budget constraint, and this constraint tells us that we must have

$$\int_0^{\overline{\theta}} dF_K(\theta) x_{\theta_A} + \int_0^{\overline{\theta}} dF_V(\theta) x_{\theta_B} = \int_0^{\overline{\theta}} dF_K(\theta) M_{\theta_A} + \int_0^{\overline{\theta}} dF_V(\theta) M_{\theta_B} - c(w_K + w_V). \tag{3}$$

In order to maximize the welfare of our aggregate economy, we need to set $\partial W/\partial w_i = 0$, $i = K, V$.[9] So, let us use Equations (2) and (3), and then differentiate $W(\cdot)$ with respect to w_K. This gives us

$$\frac{\partial\{U_K + U_V\}}{\partial w_K} = \int_0^{\overline{\theta}} dF_K(\theta) \left\{ \frac{\theta(1-\delta)}{w_K} - c \right\} + \int_0^{\overline{\theta}} dF_V(\theta) \frac{\theta\delta}{w_K} = 0 \tag{4}$$

and we obtain a similar equation when setting $\partial\{U_K + U_V\}/\partial w_V = 0$. We can now use standard expressions from statistics for the expected value of a random variable—see Taylor and Karlin (1998, pp. 9–15) [26]—to simplify the two first-order necessary conditions for an optimum. This gives us

$$\frac{\zeta_i(1-\delta)}{w_i} + \frac{\zeta_{-i}\delta}{w_{-i}} = c, \quad i = K, V. \tag{5}$$

Solving the system of two equations described by (5) in the two unknowns w_K and w_V, we obtain the efficient pollution cleanup amounts that maximize the total surplus in our aggregate economy consisting of Kanpur and Varanasi. Let us denote these *efficient* levels by w_i^E, $i = K, V$. Then, we obtain

$$w_i^E = \frac{\zeta_i(1-\delta) + \zeta_{-i}\delta}{c}, \quad i = K, V. \tag{6}$$

Inspecting Equation (6), we see that the efficient pollution cleanup amounts depend *positively* on the mean preference for pollution cleanup (ζ_i, ζ_{-i}) in the two cities and *negatively* on the number of units of the private good (c) needed to produce and provide the two efficient cleanup amounts. Our next task is to determine the pollution cleanup

amounts in Kanpur and Varanasi in a decentralized setting in which spending on water pollution cleanup is financed by a uniform tax on the residents of the two cities.

4. Decentralized Provision of Pollution Cleanup

In the decentralized regime, each city *independently* chooses water pollution cleanup amount w_i to maximize the total city welfare U_i. Public spending on pollution cleanup in each city is financed by a uniform tax on the residents of the city. This means that if the *i*th city provides pollution cleanup of amount w_i then each resident of city i pays a tax given by $t_i = cw_i$. Given these changes, the expression for U_i is now given by

$$U_i = \int_0^{\bar{\theta}} dF_i(\theta) \left[M_{\theta_i} - cw_i + \theta\{(1-\delta)log(w_i) + \delta log(w_{-i})\} \right]. \tag{7}$$

The first order necessary conditions for an interior optimum are given by setting $\partial U_i / \partial w_i = 0$, $i = K$, V. Doing this and then simplifying the resulting expressions gives us the two optimal pollution cleanup amounts under decentralization. Denoting these two amounts by w_i^D, $i = K$, V, we obtain

$$w_i^D = \frac{\zeta_i(1-\delta)}{c}, \ i = K, \ V. \tag{8}$$

Inspecting Equation (8), we see that like the efficient pollution cleanup amounts case analyzed in Section 3 and described by Equation (6), the optimal decentralized pollution cleanup amounts also depend *positively* on the mean preference for pollution cleanup (ζ_i) in the two cities and *negatively* on the number of units of the private good (c) needed to provide the two decentralized pollution cleanup amounts. That said, subtracting the right-hand-side (RHS) of Equation (8) from the RHS of Equation (6), we see that

$$w_i^E - w_i^D = \frac{\zeta_{-i}\delta}{c} > 0 \tag{9}$$

as long as $\delta > 0$.

Equation (9) tells us that as long as there is a pollution cleanup related spillover between Kanpur and Varanasi, the efficient or idealized pollution cleanup amounts that are provided are *greater* in magnitude than the pollution cleanup amounts provided in the decentralized regime. Put differently, decentralized regulation gives rise to *lower* pollution cleanup amounts. Furthermore, in the special case in which there is no spillover and therefore $\delta = 0$, the efficient and the decentralized pollution cleanup amounts coincide. We now ascertain the amount of pollution cleanup that is made available in a centralized regime subject to the condition that cleaning up water pollution in the Ganges and the sharing of costs are the same in Kanpur and Varanasi.

5. Centralized Provision of Pollution Cleanup

In the centralized regime, the pertinent pollution cleanup amounts in the two cities are chosen by a central authority with two specific conditions. First, there is the equal provision of pollution cleanup requirement and this means that $w_K = w_V = w$. Second, there is equal cost sharing of the pollution cleanup that is provided and this means that each resident in either city pays $t_i = c(w_K + w_V)/2$. These two conditions together ensure that the central authority displays no favoritism towards either Kanpur or Varanasi. With these two changes, the expression for U_i is now

$$U_i = \int_0^{\bar{\theta}} dF_i(\theta) \left[M_{\theta_i} - cw + \theta log(w) \right]. \tag{10}$$

To determine the optimal pollution cleanup amount or w, we need to solve for $d\{U_K + U_V\}/dw = 0$. Using Equation (10) and then differentiating with respect to w, we obtain

$$\frac{d\{U_K + U_V\}}{dw} = \int_0^{\bar{\theta}} dF_K(\theta)\left\{\frac{\theta}{w} - c\right\} + \int_0^{\bar{\theta}} dF_V(\theta)\left\{\frac{\theta}{w} - c\right\} = 0. \tag{11}$$

Using standard expressions from statistics for the expected value of a random variable—see Taylor and Karlin (1998, pp. 9–15) [12]—we can simplify the RHS of Equation (11). This gives us

$$\frac{\zeta_K + \zeta_V}{w} - 2c = 0. \tag{12}$$

Denoting the optimal pollution cleanup amount in the centralized setting by w^C, we obtain

$$w^C = \frac{\zeta_K + \zeta_V}{2c}. \tag{13}$$

Inspecting Equation (13), we see that like the cases analyzed in Sections 3 and 4, the optimal centralized pollution cleanup amount depends *positively* on the mean preference for pollution cleanup in the two cities (ζ_K, ζ_V) and *negatively* on the number of units of the private good (c) needed to provide the centralized pollution cleanup amount. Subtracting the right-hand-side (RHS) of Equation (13) from the RHS of Equation (6), we see that

$$w_i^E - w^C = \frac{(\zeta_i - \zeta_{-i})(1 - 2\delta)}{2c}. \tag{14}$$

Now recall that the spillover parameter $\delta \in [0, 1/2]$ and that $\zeta_K > \zeta_V$. Using these two pieces of information along with the result contained in Equation (14), we deduce that

$$w_K^E \geq w^C \geq w_V^E. \tag{15}$$

The result in (15) contains an interesting but negative finding about the centralized provision of pollution cleanup in the two cities under study. Specifically, we see that in the centralized regime, pollution cleanup will be *underprovided* in the city (Kanpur) that has a stronger mean preference for pollution cleanup $(w_K^E \geq w^C)$ and *overprovided* in the city (Varanasi) that has a weaker mean preference for pollution cleanup $(w^C \geq w_V^E)$. We now want to show that if Kanpur and Varanasi have identical preferences for pollution cleanup then centralization is preferable to decentralization as long as there is a spillover—of any magnitude—from cleaning up water pollution in the Ganges.

6. Identical Preferences for Pollution Cleanup

We model the identical preferences for pollution cleanup in Kanpur and Varanasi by supposing that $\zeta_K = \zeta_V$. Additionally, since the spillover from the cleanup of water pollution in the Ganges is positive, we have $\delta > 0$. The welfare of the ith city in the decentralized regime is given by Equation (7); therefore, Equation (8) gives us the optimal pollution cleanup amounts in this regime. So, using this last result and denoting the total income in the ith city by M_i, we can now write

$$U_i^D = M_i - \zeta_i(1 - \delta) + \zeta_i\left[(1 - \delta)log\left\{\frac{\zeta_i(1 - \delta)}{c}\right\} + \delta log\left\{\frac{\zeta_{-i}(1 - \delta)}{c}\right\}\right]. \tag{16}$$

Given Equation (16), the welfare in our aggregate economy of the two cities, Kanpur and Varanasi, can be written as

$$W^D = M - (\zeta_K + \zeta_V)(1 - \delta) + (\zeta_K + \zeta_V)log\left\{\frac{1 - \delta}{c}\right\} + \{\zeta_K(1 - \delta) + \zeta_V\delta\}log(\zeta_K) + \{\zeta_K\delta + \zeta_V(1 - \delta)\}log(\zeta_V), \tag{17}$$

where we have used $M = M_K + M_V$ to denote the total income in our aggregate economy.

When water pollution is cleaned up in Kanpur and Varanasi in the centralized regime, the welfare of the ith city is given by Equation (10), and the optimal amount of pollution cleaned up or w^C is given by Equation (13). Using these two pieces of information, we can write the welfare of the ith city as

$$U_i^C = M_i - \frac{\zeta_i + \zeta_{-i}}{2} + \zeta_i log\left\{ \frac{\zeta_i + \zeta_{-i}}{2c} \right\}, \tag{18}$$

and the welfare of our aggregate economy as

$$W^C = M - (\zeta_K + \zeta_V) + (\zeta_K + \zeta_V)log\left\{ \frac{\zeta_K + \zeta_V}{2c} \right\}. \tag{19}$$

Because $\zeta_K = \zeta_V = \zeta$, the two aggregate welfare expressions in Equations (17) and (19) simplify to

$$W^D = M - 2\zeta(1 - \delta) + 2\zeta log\left\{ \frac{1 - \delta}{c} \right\} + 2\zeta log\{\zeta\} \tag{20}$$

and

$$W^C = M - 2\zeta + 2\zeta log\left\{ \frac{\zeta}{c} \right\}. \tag{21}$$

Subtracting the RHS of Equation (20) from the RHS of Equation (21), we are able to confirm that

$$W^C - W^D = -2\zeta\{\delta + log(1 - \delta)\} > 0, \tag{22}$$

as long as $\delta \in [0, 1/2]$. We have just demonstrated that when there is an inter-city spillover from the provision of pollution cleanup, relative to decentralization, the centralized provision of pollution cleanup gives rise to a *higher* level of welfare. In contrast, when there is no spillover, hence, $\delta = 0$, the two city welfare levels under centralization and decentralization are *identical*. We now proceed to our final task in this paper and that is to demonstrate that if the two cities, Kanpur and Varanasi, have non-identical preferences for pollution cleanup then, once again, centralization is preferable to decentralization as long as the spillover δ from cleaning up pollution in the Ganges exceeds a certain threshold.

7. Dissimilar Preferences for Pollution Cleanup

We account for the dissimilar preferences for pollution cleanup in Kanpur and Varanasi by supposing that the inequality $\zeta_K > \zeta_V$ holds. Next, we write the expression corresponding to Equation (22) in the case where the two cities have dissimilar preferences for pollution cleanup. After some algebraic steps, we obtain

$$\begin{aligned} W^C - W^D = &-\delta(\zeta_K + \zeta_V) - (\zeta_K + \zeta_V)log(1 - \delta) + (\zeta_K + \zeta_V)log\left\{ \frac{\zeta_K + \zeta_V}{2} \right\} \\ &- [\{\zeta_K(1 - \delta) + \zeta_V\delta\}log(\zeta_K) + \{\zeta_K\delta + \zeta_V(1 - \delta)\}log(\zeta_V)] \end{aligned} \tag{23}$$

Focusing for the moment on the parameter $\delta \geq 0$ denoting the spillover associated with cleaning up pollution in the Ganges, we can rewrite the expression on the RHS of Equation (23) as

$$W^C - W^D = \Delta W(\delta), \tag{24}$$

where Δ denotes the change in welfare.

Evaluating $\Delta W(\delta)$ at $\delta = 0$, we obtain

$$\Delta W(0) = (\zeta_K + \zeta_V)log\left\{ \frac{\zeta_K + \zeta_V}{2} \right\} - \zeta_K log(\zeta_K) - \zeta_V log(\zeta_V). \tag{25}$$

After some algebraic steps, the RHS of Equation (25) can be simplified and signed. In particular, because $\zeta_K > \zeta_V$, this process gives us

$$\Delta W(0) = \zeta_K \left[log \left\{ \frac{1}{2} \left(\frac{\zeta_V}{\zeta_K} + 1 \right) \right\} + \frac{\zeta_V}{\zeta_K} log \left\{ \frac{1}{2} \left(\frac{\zeta_K}{\zeta_V} + 1 \right) \right\} \right] < 0. \tag{26}$$

Next, we want to evaluate $\Delta W(\delta)$ at $\delta = 1/2$. This gives us

$$\Delta W \left(\frac{1}{2} \right) = (\zeta_K + \zeta_V) log \left\{ \frac{\zeta_K + \zeta_V}{2} \right\} - \frac{(\zeta_K + \zeta_V)}{2} - (\zeta_K + \zeta_V) log \left(\frac{1}{2} \right) - \frac{(\zeta_K + \zeta_V)}{2} \{ log(\zeta_K) + log(\zeta_V) \}. \tag{27}$$

After a couple of steps of algebra, the RHS of Equation (27) can also be simplified and signed. This time, we obtain

$$\Delta W \left(\frac{1}{2} \right) = (\zeta_K + \zeta_V) \left[log \left\{ \frac{\zeta_K + \zeta_V}{\sqrt{\zeta_K \zeta_V}} \right\} - \frac{1}{2} \right] > 0. \tag{28}$$

Let us now differentiate the expression for $\Delta W(\delta)$ in Equation (23) with respect to the spillover parameter δ. This gives us

$$\frac{d\{\Delta W(\delta)\}}{d\delta} = (\zeta_K + \zeta_V) \frac{\delta}{1 - \delta} + (\zeta_K - \zeta_V) log \left(\frac{\zeta_K}{\zeta_V} \right) > 0, \tag{29}$$

as long as $\zeta_K > \zeta_V$. Our analysis thus far in this section leads to three results. First, we showed that $\Delta W(0) < 0$. Second, we pointed out that $\Delta W(1/2) > 0$. Finally, since differentiability implies continuity,[10] we have shown that $d\{\Delta W(\delta)\}/d\delta$ is both continuous and monotonically increasing in δ. These three results and the mean value theorem [11] together tell us that there exists a *threshold* $\delta^* \in (0, 1/2)$ such that $\Delta W(\delta^*) = 0$ and $\Delta W(\delta) > 0$ for $\delta \in (\delta^*, 1/2]$.

Our analysis of the provision of pollution cleanup in the aggregate economy consisting of Kanpur and Varanasi shows that there is a clear *tradeoff* between the centralization and the decentralization regimes. As shown in the second column of Table 1, when preferences for water pollution cleanup are *identical* in Kanpur and Varanasi, as long as there is a spillover, of any magnitude, centralized cleanup leads to *higher* welfare. On the other hand, when there is no spillover ($\delta = 0$), it does not matter whether water pollution cleanup is centralized or decentralized.

Table 1. Comparison of identical and dissimilar preference cases.

Spillover	Identical Preferences for Pollution Cleanup	Dissimilar Preferences for Pollution Cleanup
Any spillover ($\delta > 0$)	Centralized cleanup leads to higher welfare	
Strong spillover ($\delta > \delta^*$)		Centralized cleanup leads to higher welfare
No spillover ($\delta = 0$)	Centralized and decentralized cleanup lead to same welfare	Centralized cleanup leads to lower welfare

Under centralization, an excessively *high* amount of pollution cleanup is provided in the city with a *lower* preference for pollution cleanup (Varanasi) and an insufficiently *low* amount of pollution cleanup is provided in the city with a *higher* preference for pollution cleanup (Kanpur). In addition, if the inter-city spillover from cleaning up pollution in the Ganges is sufficiently strong ($\delta > \delta^*$), then the extra utility obtained by the residents of the city with a stronger preference for the pollution cleanup provided in the city with a weaker preference for such cleanup compensates them for the *loss* of utility stemming from the *underprovision* of pollution cleanup in their own city. As a result, total welfare in this last

instance with pollution cleanup being provided in a centralized manner is *higher* than what it would be with decentralized provision.

The third column of Table 1 shows us that when preferences for water pollution cleanup are *dissimilar* in Kanpur and Varanasi, centralized cleanup of pollution again leads to *higher* welfare but now it is not enough for the spillover to be positive. In particular, the magnitude of the spillover must exceed the threshold value denoted by δ^*. Finally, from (26) and as shown in the last row of Table 1, when there is no spillover ($\delta = 0$), we observe that centralized cleanup of water pollution leads to lower welfare. This completes our analysis of the optimal provision of Ganges water pollution cleanup in an aggregate economy consisting of the two cities, Kanpur and Varanasi.

8. Conclusions

In this paper, we exploited the public good features of pollution cleanup and theoretically analyzed an aggregate economy of two cities, Kanpur and Varanasi, in which pollution cleanup could be provided in either a decentralized or a centralized manner. We first determined the efficient pollution cleanup amounts that maximized the aggregate welfare from cleaning water pollution in the Ganges in Kanpur and Varanasi. Second, we computed the optimal amounts of pollution cleanup in the two cities in a decentralized regime in which spending on pollution cleanup was financed by a uniform tax on the city residents. Third, we ascertained the optimal amount of pollution cleanup in the two cities in a centralized regime subject to the equal provision of pollution cleanup and cost sharing. Fourth, we showed that if the two cities have the same preference for pollution cleanup, then centralization was preferable to decentralization as long as there was a spillover from cleaning water pollution in the Ganges. Finally, we showed that if the two cities have dissimilar preferences for pollution cleanup, then centralization was, once again, preferable to decentralization as long as the spillover exceeded a critical threshold.

The analysis in this paper can be extended in several different directions. In what follows, we suggest five potential extensions. First, consistent with our objective and, as stated clearly in Section 1.2, we conducted a theoretical analysis of centralized versus decentralized water pollution cleanup in the context of the Ganges. Even though our goal was not to conduct an empirical analysis of centralized versus decentralized water pollution cleanup, one could collect data about actual water pollution cleanup in Kanpur and Varanasi and use this data along with alternate values of the parameters δ and ζ to examine the impact of contemporary water pollution control programs in these two cities. Second, we did not conduct an ecological–economic analysis of the interactions between ecosystem service provision on the one hand and water pollution cleanup on the other. As such, in an ecological–economic analysis that is both dynamic and stochastic, we can ask how cleaning water pollution in the Ganges in Kanpur and Varanasi affects the provision of specific ecosystem services such as water for drinking, water for irrigation, the cycling of nutrients, and the maintenance of populations and habitats.

Third, in our analysis, we did not compare and contrast the properties of alternate pollution control instruments such as taxes on water pollution and quotas on specific pollutants. Therefore, in either a centralized or a decentralized regime, it would be helpful to determine the relative merits of using price versus quantity control instruments to clean up pollution in the Ganges. Fourth, to expand the analysis we undertook in this paper, we could examine how alternate ways of cleaning up water pollution in the Ganges might be used to bring about enhancements in the governance and the sustainability of the tannery industry in Kanpur and religious tourism in Varanasi. Finally, in addition to the heterogeneity in the preference for pollution cleanup (the ζ_i parameter), one could also introduce heterogeneity into the model, along other dimensions such as the income of the residents in the two cities, Kanpur and Varanasi. When this has been carried out, one would have to analyze a more complex model in which two heterogeneity parameters capturing the preference for pollution cleanup and income interact with the spillover parameter to jointly determine the optimal levels of pollution cleanup in centralized and decentralized

settings. Studies that analyze these aspects of the acute water pollution problem in the Ganges will provide additional insights into the nexuses between the ecological health of the Ganges and the welfare of the millions of people who live in the basin of this river.

Notes

1. See Markandya and Murty (2004) [1] for a more detailed corroboration of this claim.

2. Go to https://mahileather.com/blogs/news/the-world-s-most-famous-leather-markets for a more detailed discussion of this point. Accessed on 20 September 2023.

3. In general, the term *centralization* refers to the concentration of authority at the top level of an organization. It is the systematic and consistent reservation of authority at the central points in an organization. In a centralized organization, managers at lower levels have a very limited role in decision-making. In other words, their job is to execute the decisions made at the top level of the organization. In contrast, the term *decentralization* refers to the dispersal of authority within an organization. It refers to a systematic effort to delegate to the lowest levels of the organization, all decisions except those which can be made more effectively at the central points. Put differently, decentralization is the distribution of authority throughout an organization. Therefore, in a decentralized organization, the authority to make major decisions is vested with the top management and the remaining authority is delegated to the middle and to the lower levels of this same organization. See Aiyar and Kapur (2019) [12] and Varma et al. (2022) [13] for more details on this dichotomy.

4. See Sheehan and Kogiku (1981) [23] for a general discussion of the role of game-theoretic modeling in the context of water resource problems.

5. We note that even though our paper, which is an economics paper, does not explicitly follow the "IMRaD structure" in which many scientific papers are written, the paper does implicitly follow this structure. To see this, observe that our Section 1 corresponds to the "Introduction" part in the IMRaD structure, our Section 2 corresponds to the "Methods" part in the IMRaD structure, and Sections 3–7 correspond to the "Results" and "Discussion" parts in the IMRaD structure.

6. 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 20 September 2023. See Hindriks and Myles (2013, pp. 147–190) [25], for a textbook discussion of public goods.

7. It is important to comprehend that even though we are thinking of Ganges water pollution cleanup in Kanpur and Varanasi as public goods, strictly speaking, they are *local public goods* which means that in order to enjoy the benefits of water pollution cleanup in, say, Kanpur, one must be resident in the Kanpur area. Therefore, the model we construct and analyze in this paper is *not* a "standard public goods model" as this term is understood in well-known public economics textbooks such as Hindriks and Myles (2013, chapter 6) [25]. Finally, our model is better thought of as a "fiscal federalism" model where fiscal federalism, speaking broadly, "is the division of revenue collection and expenditure responsibilities among different levels of government" (Hindriks and Myles, 2013, p. 635) [25]. Finally, we stress that consistent with our observation in Section 1.2, this paper is the *first* to study the merits of centralized versus decentralized approaches to water pollution control in the Ganges.

8. We assume that the mean is equal to the median in both cities under study. This means that the preference type distribution functions are symmetrical in nature.

9. We assume that the resulting solution is an interior solution.

10. See Theorem 5.2 in Rudin (1976, p. 104) [27] for additional details.

11. See Rudin (1976, pp. 107–108) [27] for a textbook exposition of the mean value theorem.

References

1. Markandya, A.; Murty, M.N. Cost-benefit analysis of cleaning the Ganges: Some emerging environment and development issues. *Environ. Dev. Econ.* **2004**, *9*, 61–81.
2. Black, G. Purifying the goddess. *New Yorker* **2016**, *92*, 46–53.
3. Gallagher, S. India: The Toxic Price of Leather. *Pulitzer Center*. 4 February 2014. Available online: https://pulitzercenter.org/reporting/india-toxic-price-leather-0 (accessed on 20 September 2023).
4. Jain, C.K.; Singh, S. Impact of climate change on the hydrological dynamics of river Ganga, India. *J. Water Clim. Chang.* **2020**, *11*, 274–290.
5. Dhillon, A. Ganga Management. *South China Morning Post*. 14 September 2014. Available online: http://www.scmp.com/magazines/post-magazine/article/1589301/ganga-management (accessed on 20 September 2023).
6. Madhulekha; Arya, S. Assessment of water pollution of river Ganga by tannery effluent using fish as a bio-indicator in Kanpur, India. *Biochem. Cell. Arch.* **2016**, *16*, 120–123.
7. Madhulekha; Arya, S. Evaluation of Water Quality in River Ganga Due To Contaminant of Heavy Metals, Kanpur, India. *Int. J. Innov. Trends Eng.* **2016**, *20*, 97–100.
8. Nazir, A.; Khan, M.A.; Ghosh, P. Assessment of variations in metal concentrations of the Ganges river by using multivariate statistical techniques. *Limnologica* **2022**, *95*, 125989.
9. Batabyal, A.A. Tanneries in Kanpur and pollution in the Ganges: A theoretical analysis. *Reg. Sci. Policy Pract.* **2023**, *15*, 1114–1123.
10. Shah, T.; Ray, C.; Lele, U. How to clean up the Ganges? *Science* **2018**, *362*, 503. [CrossRef]
11. Das, P.; Tamminga, K.R. The Ganges and the GAP: An assessment of efforts to clean a sacred river. *Sustainability* **2012**, *4*, 1647–1668.
12. Aiyar, Y.; Kapur, A. The centralization vs decentralization tug of war and the emerging narrative of fiscal federalism for social policy in India. *Reg. Fed. Stud.* **2019**, *29*, 187–217.
13. Varma, V.G.; Jha, S.; Raju, L.H.K.; Kishore, R.L.; Ranjith, V. A review on decentralized wastewater treatment systems in India. *Chemosphere* **2022**, *300*, 134462. [CrossRef] [PubMed]
14. Alley, K.D. Urban institutions at the crossroads: Judicial activism and pollution prevention in Kanpur. *Urban Anthropol. Stud. Cult. Syst. World Econ. Dev.* **1996**, *25*, 351–383.
15. Sigdel, R.; Carlton, G.; Gautam, B. Resolving the Ganges pollution paradox: A policy-centric systematic review. *River* **2023**, *2*, 126–141. [CrossRef]
16. Metzger, E.S.; Lendvay, J.M. Seeking environmental justice through public participation: A community-based water quality assessment in Bayview Hunters Point. *Environ. Pract.* **2006**, *8*, 104–114.
17. Cronin, V.; Guthrie, P. Community-led resettlement: From a flood-affected slum to a new society in Pune, India. *Environ. Hazards* **2011**, *10*, 310–326. [CrossRef]
18. Peplow, D.; Augustine, S. Community-led assessment of risk from exposure to mercury by native Amerindian Wayana in Southeast Suriname. *J. Environ. Public Health* **2012**, *2012*, 674596. [CrossRef]
19. Chakraborti, D.; Singh, S.; Rahman, M.; Dutta, R.; Mukherjee, S.; Pati, S.; Kar, P. Groundwater arsenic contamination in the Ganga river basin: A future health danger. *Int. J. Environ. Res. Public Health* **2018**, *15*, 180.
20. Davis, L.J.; Milligan, R.; Stauber, C.E.; Jelks, N.T.O.; Casanova, L.; Ledford, S.H. Environmental injustice and Escherichia coli in urban streams: Potential for community-led response. *Wiley Interdiscip. Rev.* **2022**, *9*, e1583.
21. Singh, A.; Gundimeda, H. Measuring technical efficiency and shadow price of water pollutants for the leather industry in India: A directional distance function approach. *J. Regul. Econ.* **2021**, *59*, 71–93. [CrossRef]
22. Batabyal, A.A.; Beladi, H. The optimal provision of information and communication technologies in smart cities. *Technol. Forecast. Soc. Chang.* **2019**, *147*, 216–220. [CrossRef]
23. Sheehan, M.; Kogiku, K.C. Game theory analyses applied to water resource problems. *Socio-Econ. Plan. Sci.* **1981**, *15*, 109–118. [CrossRef]
24. Oates, W.E. *Fiscal Federalism*; Harcourt Brace Jovanovich: New York, NY, USA, 1972.
25. Hindriks, J.; Myles, G.D. *Intermediate Public Economics*, 2nd ed.; MIT Press: Cambridge, MA, USA, 2013.
26. Taylor, H.M.; Karlin, S. *An Introduction to Stochastic Modeling*, 3rd ed.; Academic Press: San Diego, CA, USA, 1998.
27. Rudin, W. *Principles of Mathematical Analysis*, 3rd ed.; McGraw Hill, Inc.: New York, NY, USA, 1976.