Yamuna River Project Climate Change Initiative, Phase I:

Baseline Greenhouse Gas Emissions & Systems Model Design

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Executive Summary

Implementing the goals and designs of the Yamuna River Project (YRP) may have positive implications for both greenhouse gas emissions and for climate change vulnerability in the National Capital Region. Changes in wastewater treatment, solid waste management, and land use in the Yamuna River floodplain could reduce net emissions of key greenhouse gases (GHGs), namely carbon-dioxide, methane, and nitrous oxide. The same measures could also produce benefits and co-benefits in the form of enhanced ecosystem services such as protection from flooding, aesthetic and recreational value, and improved nutritional and health outcomes for residents.

To quantify these potential effects, the YRP's Climate Change research team is undertaking a two-phase effort. In the first phase, reported here, we estimate GHG emissions from and associated with the land use, water treatment, and waste management processes that are the primary subject of the YRP. In the second phase, we will construct a forward-focused systems model for exploring scenarios for changes in those processes envisioned by the YRP as well as those already described or implemented by other processes.[1] This model will encourage experimentation, communication, and dialog about how various efforts can contribute to reductions in net GHG emissions, reduced vulnerability to climate change.

Because the model needed to simulate GHG emissions and climate vulnerability must work though or otherwise connect to various environmental, social, and economic outcomes (e.g., water quality and quantity, greenspace, and outputs of production systems like floodplain agriculture and formal/informal solid waste management), the effort will also provide a tool to assess and communicate the multiple benefits of Yamuna River restoration and conservation. Namely, the model will describe relationships among management decisions, GHG emissions, water quality, aesthetics, food and energy production, human health, and economic activity while tracking indicators of the same.

Building, testing, and running that comprehensive systems model is to be the subject of Phase II of the Climate Initiative. Phase II also includes collaborative work with researchers, policy makers, and diverse stakeholders both to develop the model and to use the model in strategic communications efforts to gain the financial, institutional, and political support for accelerating Yamuna River restoration project elements and/or related changes in land use, infrastructure, and environmental management.

The Phase I effort, reported here, is designed to lay the groundwork for achieving that Phase through three elements:

1. Develop quantitative baseline estimates of GHG emissions associated with the main subsystems that are the subjects of the YRP to date.
2. Scope the comprehensive systems model to be completed as Phase II of this initiative.
3. Lay the groundwork for Phase II implementation, including by establishing relationships with individuals and organizations through whom communication and implementation goals will ultimately be achieved.

The report begins with a high-level overview of the connections among Yamuna River restoration efforts, GHG emissions, and the downstream benefits and co-benefits to people and of restoration and emission reductions. We then describe those relationships in greater detail for the principal domains of the YRP, namely wastewater treatment (or human waste management), green infrastructure (including riparian area restoration), and solid waste management. In these sections we also provide first

[1] These efforts include, but are not limited to implementation of the National Green Tribunal's recommendations for the restoration and conservation of the River Yamuna (Babu, Gosain, and Gopal, 2013). The YRP recognizes the prior and ongoing contribution of these efforts .

approximation estimates of GHG emissions associated with the domain under current conditions and describe the GHG benefits and co-benefits of actions in the domain are implemented.

Using the methods described it neh body of the report, we estimate total annual GHG emissions connected to the YRP, and net of sequestration by riparian vegetation, to be 1.14 million metric tons (Mg) per year (Table E-1). For comparison, this total is 0.03% of the estimated 2.8 billion Mg CO2E in GHG emissions for all of India in 2016 (World Resources Institute, “Greenhouse Gas Emissions Over 165 Years,” 2019).

Table E-1: Summary of Estimated Baseline Yamuna-River-Project-Related GHG Emissions, New Delhi NCT 2018.

Yamuna River Project Domain	CO2E Emitted (Mg/year)
Wastewater Treatment	19,221.6
Riparian Agriculture	8,448.4
Riparian Forest (sequestration)	-412,335.0
Municipal Solid Waste	1,524,970.0
Total:	**1,140,305.0**

The final section briefly describes a comprehensive system model that can be used by stakeholders, including governmental and other decisionmakers, to evaluate various scenarios or proposals for Yamuna River restoration.

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Terms and Abbreviations

CSE	Centre for Science and Environment
DJB	Delhi Jal (Water) Board, Delhi gov't agency
EPOD	Evidence for Policy Design, part of Harvard's Kennedy School
GHG	Greenhouse Gas(es)
IIC	International Innovation Corps, program of University of Chicago's Center in Delhi
I&FC	Irrigation and Flood Control, Delhi gov't agency
MSW	municipal solid waste
STP	sewage (or sewerage) treatment plant
WWTP	wastewater treatment plant, another name for STP
YBP	Yamuna Biodiversity Park
YRP	Yamuna River Project (University of Virginia's pan-University effort)

Overview of the Yamuna River, the Yamuna River Project, and the Climate Change Initiative

In a 2013 report to the National Green Tribunal, an Expert Committee headed by Dr. C.R. Babu (Delhi University) presented an assessment of the current status of the river, approaches to restoration of the river and its floodplain, and a detailed set of recommendations containing an institutional framework for river restoration. Babu, Gosain, & Gopal (2013) sum up the diagnosis and prescribed treatment as follows:

> "[the Delhi stretch of the Yamuna] of the river is also one of the most heavily polluted and degraded river stretches in the country.... The 52 km stretch of the river from Palla to Jaitpur in the NCT of Delhi has lost its potential for supporting life. The 22 km stretch from Wazirabad to Okhla is the most polluted segment of the river as it receives outfall from 22 drains which contribute 80% of the pollution load of the river. The vast floodplains, which serve as a floodway and help recharge groundwater, have also been gradually eliminated to a great extent and encroached upon by gradual reclamation by dumping solid wastes and construction of various buildings. This has reduced the flood carrying capacity, groundwater recharging capacity, and other biodiversity related ecological functions. The morphology of the river and wetland functions are also altered by embankments, bunds, roads, flyovers, guide bunds and spurs, several bridges and three barrages (p iii)."
>
> Restoration of a river to bring back its biophysical characteristics and ecological functions requires addressing the root causes of degradation. River Yamuna is severely affected by the elimination of its natural flow (except during the rainy season), destruction of its physical characteristics (elimination of floodplains by embankments and encroachments, and solid waste dumping and reclamation), habitat fragmentation (by barrages and guide bunds of bridges/flyovers), destruction of natural floodplain biodiversity, and excessive discharge of wastewaters (untreated or partly treated sewage, and stormwater). The Committee recognises that some of these changes are irreversible and it will not be possible to restore the river fully to its old glory, it is possible to rehabilitate the river for many of its functions, water quality and beauty (p 5)."

While several governmental and nongovernmental organizations are doing important work that will contribute to this rehabilitation. The Yamuna Biodiversity Park, for example, shows the type and degree of ecological restoration that is possible. Other organizations are thinking strategically about the effects, including feedback loops of such seemingly obvious measures like connecting more of Delhi's residents to municipal water supply and sewerage systems. As we have learned in the course of our preliminary research, however, progress has been slow, in part due to competing aims, visions, and approaches (natural science, communications, economics, engineering), and due to leadership changes that affect coordination and continuity. These are not uncommon challenges, however, and in the work that we outline here, we believe they can be addressed, if not overcome, by an approach that takes into account the multiple biophysical, economic, and human dimensions of the system whose function we seek to improve.

The University of Virginia's Yamuna River Project (YRP) seeks to do just that. A partnership with the Delhi Jal Board (DJB), YRP is an interdisciplinary research program whose objective is to advance ongoing river restoration efforts to revitalize the ecology of the Yamuna River in New Delhi and restore historical connections between India's capital city and its river. YRP sub-teams are supporting Indian-identified conservation strategies in several ways. Briefly, these include the following.

- In Architecture, project directors Pankaj Vir Gupta and Inaki Alday are heading an Urban Design study of the 58 km long Najafgarh Drain and the 7km long Supplementary Drain between Bhalswa landfill and the Yamuna. Architecture students have also designed green infrastructure and solid waste management strategies along the Yamuna's tributary drains. Key initiatives include zero-waste management strategy, which suggests scenarios to formalize and urbanize Delhi's waste management system to improve segregation process, recover the health of surrounding neighborhoods and provide more aesthetic public spaces.
- UVA environmental scientists and engineers are conducting water quality modeling in the Najafgarh Drain and the Yamuna River.
- UVA Environmental scientists are considering the potential for expanded restoration of riparian forest along the drains and the Yamuna's main stem. Matt Riedenbach and Mahesh Rao are working with the DJB on a Hydrological Model to map out untreated and treated flow that ends up in the river. They are investigating stormwater management, creating a drain model for the Yamuna Region and charting land use changes based on satellite and other remotely sensed data.

Finally, in a later addition to the YRP, the Yamuna River climate change initiative began with the idea that the overall YRP, if successful, should generate climate change benefits for the National Capital Region (NCR), for India as a whole, and for the entire planet. For example, changes in wastewater treatment may, by altering where and when and how human waste breaks down, change net greenhouse gas (GHG) emissions. Riparian corridor restoration should increase the rate of carbon sequestration. And changes in municipal solid waste management — more recycling, less hauling, more incineration and/or waste-to-energy conversion — will affect net GHG emissions as well. Therefore, one of our first challenges has been to estimate baseline GHG emissions from these interrelated systems.

Second, and more importantly for the second phase of the initiative, we recognized early on that estimating the effect of the multiple facets of the overall YRP (and related restoration efforts) on GHG emissions would require a deeper understanding of the overall system that also involves effects on climate vulnerability, on multiple ecosystem services, and on human health and well-being that might not fit neatly under the heading of "changes in net GHG emissions". We have therefore designed this phase 1 effort as an exploration of the components and relationships in the overall Yamuna River system so that we can later construct a full, working "systems model" so that we can obtain estimates of the effects of the YRP on GHG emissions and other outcomes that is better grounded in the reality of the YRP system.

In addition, and given the added complexities presented by differences among stakeholders regarding what actions are most important, which agencies should be involved, and other more political-economic considerations, a systems modeling approach can facilitate deeper engagement and, perhaps, more concerted and coordinated action going forward. Our intention for Phase II is to build an interactive tool that enables residents, advocates, decisionmakers, other researchers, and stakeholders of all types to see how various combinations of policies, restoration actions, development scenarios, and management changes will affect not only GHG emissions but also other benefits and co-benefits of Yamuna River restoration in general and of the YRP in particular.

Geographic Scope

The Yamuna River Project itself has focused on the mainstem of the Yamuna River, the Najafgarh Drain, and the Supplemental Drain, and sewage treatment plants (STPs), certain agricultural, conservation, industrial, and residential facilities nearby, especially those in the floodplains. Like other research that is part of the project, including the hydrological modeling, our geographic scope is broader. The processes affecting GHG emissions and the people who would experience the benefits and co-benefits (and the costs) of actions that may reduce emissions are not confined to the immediate vicinity of the river and the drains. We therefore consider the entire National Capital Territory (NCT) and leave open the possibility of adding districts bordering the left bank of the Yamuna river in Uttar Pradesh for Phase II analysis.

Greenhouse Gas Emissions, Climate Change, and the Yamuna River System

It is well known that emissions resulting from human activities are substantially increasing concentrations of greenhouse gases such as carbon dioxide and methane in the atmosphere (IPCC Scientific Assessment, 1992). Greenhouse gases (GHGs), most importantly carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (NO), trap heat in the atmosphere, increase global temperatures, and contribute both directly and indirectly to negative environmental changes - including droughts, rising sea levels, ocean acidification, and environmental refugees (IPCC Fifth Assessment, 2013). Specifically in India, several studies have shown that climate change is likely to significantly impact freshwater resources and availability, susceptibility to extreme heat, rainfall patterns that create droughts and flooding, glacier melt and river flow, and sea-level rise (Mall, Gupta, Singh, Singh, & Rathore, 2006). Climate-related impacts on water resources may jeopardize India's food and energy security, as well as increased incidence of climate-related diseases and the lives and livelihoods of millions who depend on agriculture for income (Arcarnjo, 2019).

To the extent that actions taken as part of the YRP and other Yamuna River restoration efforts reduce net GHG emissions in the NCT, we would expect to see downstream improvements in people's lives. These improvements could include direct benefits like cooler and less volatile weather as the reduction in GHG emissions from the NCT helps mitigate climate change on a global scale. Realistically, GHG emission reductions in the NCT are unlikely to "move the needle" on global climate change by much. Moreover, continued inaction on climate change in other places may overwhelm any improvements made in the NCT itself. For these reasons, we would expect that the majority of discernable improvements in human welfare due to GHG mitigation in the NCT will come in the form of co-benefits or side effects of the actions taken to reduce GHG emissions.

For example, improving solid waste management in ways that limit methane emissions from the Bhalswa landfill is likely to also improve ground-level air quality, reduce the transmission of some diseases, promote new employment opportunities, and make portions of Delhi more aesthetically pleasing. Similarly, changes in wastewater treatment and/or promotion of other means of improving the disposal and treatment of human waste for the sake of reducing GHG emissions would also improve water and air quality, limit disease transmission, and provide other benefits. Finally, land use change in the floodplains, especially restoration of riparian forests, would sequester carbon and stabilize nitrogen that might otherwise contribute to GHG concentrations, while also creating wildlife habitat, enhancing protection from flooding, and reducing the urban heat island effect. Benefits such as these are, we believe, those most likely to be discernible from an analytical standpoint. More importantly, they are the effects that will be most immediate to Delhi stakeholders and, therefore, they are the effects most likely to induce or enhance support for the actions necessary to achieve the effects.

At the same time, most of the YRP actions would generate such benefits directly. Relative to those actions, one could consider GHG emission reductions as a co-benefit of wastewater treatment upgrades, of the creation of hill parks, and of enhanced recycling efforts. The systems modeling effort we outline here can therefore do double or perhaps triple duty by providing a way of assessing and communicating the already anticipated benefits of YRP actions, the co-benefits of those actions not anticipated (e.g. ecosystem services like protection from extreme events or wildlife habitat), and the benefit/co-benefit of GHG emission reductions.

Given the governance, political, and communications challenges surrounding Yamuna River restoration efforts summarized previously, we would anticipate that taking a systems approach and laying out the potential for all of these benefits will improve the chances of YRP implementation and, ultimately, successful restoration efforts overall. As outlined in our memo to the YRP team in February 2018, our initial scoping research and conversations revealed a lack of coordination among federal and state agencies, some mistrust among agencies and NGOs, and competing visions or objectives for the Yamuna and the NCT, all of which slow both research and on-the-ground implementation of restoration efforts. Along with skepticism that YRP could or would (or even should try to) make a difference in that on-the-ground reality, we heard clearly from multiple stakeholders that the systems approach would be very powerful for communicating the potential benefits of restoration and that such communication would be the basis for improved coordination and faster action to restore the Yamuna.

In short, while this effort began with a focus on climate change as an add-on to the Yamuna River Project, it will reach its full potential as an integral part of the Project's strategic research and communications efforts.

With that in mind, we turn to the components of the YRP and their connections to both GHG emissions and the various benefits and co-benefits, including GHG emission reduction, that would flow from Yamuna River restoration efforts.

Wastewater Treatment

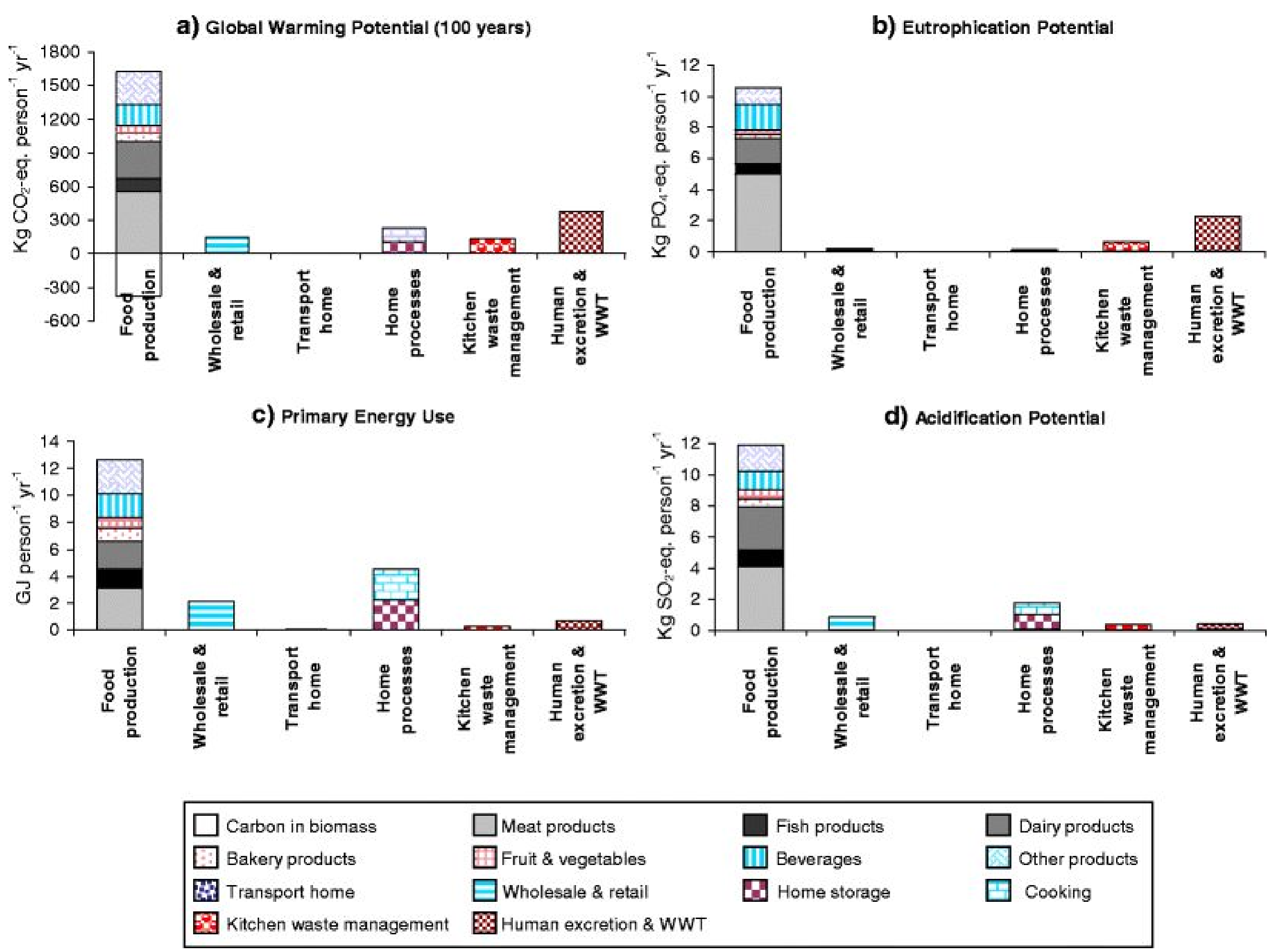
Human waste, whether treated in a wastewater treatment plant (WTP), through green infrastructure (e.g. natural or constructed wetlands), or simply left to decompose on dry land entails emission of CO2, nitrous oxides, and methane. The Intergovernmental Panel on Climate Change (IPCC) guidelines exclude CO2 emissions when tallying the GHG emissions from WWT plants, however, so only methane (CH4) and nitrous oxide (N20) emissions are counted (Magill, 2016, referencing Tseng et al., 2016). The rationale is that crops, whether fed to livestock or consumed by humans directly, take up as much CO2 as humans emit as waste.

Muñoz, Milà i Canals, and Fernández-Alba (2010) examined the diet of the Spanish population and discovered that human excretion and wastewater treatment has a negligible effect on net greenhouse gas emissions (the indicator in Figure 1, below, is global warming potential). The larger effects of human waste and wastewater treatment are in eutrophication potential — that is, in water quality degradation. In the context of the Yamuna modeling effort and relative to GHG emissions, therefore, changes in how human waste is managed and treated would have more co-benefits than benefits. Muñoz, Milà i Canals, and Fernández-Alba other results, however, do highlight the importance of food production as a source of GHG emissions, and those emissions — at least the local emissions as opposed to the full carbon footprint of food consumption by residents of the NCT — can be captured in the agriculture/land use part of the Yamuna River model.

For this phase of the project, however, we do want to provide some estimate of baseline GHG emissions from WTPs in the NCT. We initially hoped that these emissions could be calculated based on the volume and other characteristics of waste entering the WTPs. The data required, however, would be much more specific than that potentially available. Flow rates for plants, we learned from interviews, would come from various engineering studies as opposed to actual monitoring data. Plant capacity is known, but not necessarily utilization of that capacity, in other words. Moreover, one would need to pair temperature and other data with the flow rates (were they available), ideally on a daily basis, to make "realistic" calculations.

To overcome these data limitations, we use estimates of GHG emissions *per person*, combined with estimates of the number of persons served by sewerage connections to back out what we believe is a reasonable first approximation of total GHG emissions associated with WTPs in the NCT. To begin, we take an average of WTPs measured CH4 emissions per person served (Daelman, van Voorthuizen, van Dongen, Volcke, & van Loosdrecht, 2012). Excluding estimates for two plants with activated sludge (which results in much lower methane emissions per person) there are, on average 250.4 g CH4 emitted per year for each person served by a STP.

Figure 1: Global warming potential and other effects of the human diet.



Source: Muñoz, Milà i Canals, & Fernández-Alba (2010, p. 802).

To estimate the number of NCT residents served by a STP, we use data from the Socio-Economic Profile of Delhi, 2013-2014, which reports the percentage of number of households with a sewerage connection for three types of settlement: Urban Villages (95.6% of household connected); Regularized-Unauthorized Colonies (95.4%); and Resettlement Colonies (100%). Based on data from the Cities of Delhi Center for Policy Research, the sewerage connection data represent just 55.5% of the NCT population. We assume that the remaining 44.5% of the population live in settlements with no sewerage connection. Taking a weighted average of all the four types of settlement, we estimate that 56.6% of the population lives in a settlement where sewerage connections are available.

The final parameter for our estimate is the 13.5% of percentage of all GHG emissions from STPs that methane comprises (Daelman, van Voorthuizen, van Dongen, Volcke, & van Loosdrecht, 2013) .

Our calculation, then is as follows:

250.4 g CH4 person^{-1} year^{-1}

x 18.98 million persons

x 54.6% sewerage availability

= 2,596.5 Mg CH4 emitted per year

÷ 13.5% CH4 as a percentage of all GHG emissions from STPs

= 19,233.3 Mg

There is, a course, a range of possible estimates around each of these parameters, and in the Phase II systems model, users will be able to select scenarios in which, for example, more people are connected to sewerage, or different STP technologies are installed at the STPs where sewage it treated.

As noted, there are other ways of treating human waste. Natural and constructed wetlands, for example, can result in effluent that is as clean or cleaner than the effluent from STPs. Compared to sewerage and STPs, in which anaerobic decomposition produces methane, wetlands would have lower methane emissions. We do not know if there would be higher or lower N20 or C02 emissions, once uptake and sequestration of carbon and nitrogen by plants and soils in the wetlands are taken into account.

Similarly, and to the extent that the YRP and other restoration efforts include expanded use of waterless composting toilets or similar technology in areas not currently served by sewerage (and therefore not contributing to the GHG emissions from STPs) would change the level and mix of GHGs emitted by human waste. More composting toilets could mean more methane production, but if the methane is captured and used or even flared, net GHG emissions could be reduced relative to a scenario in which more households are simply connected to sewerage.

Meanwhile, the type and level of co-benefits generated in each wastewater treatment scenario will vary, depending on the mix of technologies chosen to treat human waste. Adding constructed wetlands for wastewater treatment will support ecosystem services including local climate regulation, aesthetics, and recreational opportunities while limiting energy inputs relative to STP operations. Expanded use of composting toilets could produce energy for local use while reducing overall GHG emissions. And all measures that reduce exposure of people to bacteria, viruses, and chemicals in human waste and wastewater will increase human health.

Riparian Area Restoration

Within our geographic scope, the Yamuna River flows eastward through Delhi. The river enters Delhi at Palla Village to the north and exists at the Okhla Barrage, spanning approximately 35 km. It has approximately 97 km^2 of active floodplain bounded by embankments. Due to encroaching development, conversion to agricultural uses, and other land use changes over a period of decades, little of this floodplain is currently providing the type or level of ecosystem function that a natural riparian area would. It is impaired by water, air, and solid waste pollution, impoverished by the draining of wetlands, and watercourse themselves are choked by sediment carried from areas upstream.

Solid waste dumping, legal and illegal construction of embankments, roads, flyovers, and barrages, and other activities have gradually eliminated the riparian zone's capacity to serve as a floodway and to recharge groundwater (Babu, Gosain, & Gopal, 2013). In fact, "along the 55-kilometer (34-mile) long stretch of the Yamuna within the boundaries of Delhi, the floodplains have been reduced from their natural 5 to 10 kilometers width, to just a few hundred meters. Or in some places, next to nothing" (Deutsche Welle, 2017). Illegal construction in the floodplain has been well documented, and although construction was banned by the National Green Tribunal in 2015, activists report that the law is violated on a daily basis (Nath, The Hindu, 2018).

In their report to the National Green Tribunal, Babu, Gosain, & Gopal (2013) identify several areas of concern in the riparian areas.

- Biodiversity: In some places, the native floodplain forest and grassland areas are completely gone along with the capacity of the floodplain to provide wildlife habitat.
- Climate vulnerability: Loss of and changes in the composition of vegetation, encroaching development, and hardening of surfaces makes the river less capable of regulating the volume and energy of floodwaters, leaving the city exposed to flood risk during the monsoon.
- Water Quantity and Quality: As the authors put it, "the deterioration of the quality in the river is due to the complete withdrawal of fresh water for irrigation and drinking purposes and cumulative discharges of domestic, industrial and agricultural waste waters into the river, all of which transformed the river into an open sewer in Delhi-Agra stretch. This is adversely impacting riparian ecosystems and endangering public health of Inhabitants".
- Carbon Sequestration: Because the current land use and land cover in the floodplain provides less sequestration function than riparian forests, the floodplain is doing little to reduce net greenhouse gas emissions in the NCT.

To address these concerns, a combination of stopping further degradation and encroachment, and restoring natural riparian habitat — especially wetlands and floodplain forests — is prescribed and be built into the systems model in Phase II. Forest restoration will reduce net GHG emissions by replacing land uses or land cover types that function poorly for carbon sequestration with land cover that provides that function in abundance. As stated by Karky and Banskota (2006), "forests play a significant role in climate change as it emits as well as sequesters CO2. Trees absorb atmospheric CO2 for their growth and also increase the carbon content in the soil as well. Revitalizing degraded forest lands and soils in the global terrestrial ecosystem can sequester 50-70% of the historic losses. Forests play a profound role in reducing ambient CO2 levels as they sequester 20-100 times more carbon per unit area than croplands."

For this Phase, our task is to estimate GHG emissions from the Yamuna floodplain in it current, low-functioning land cover and land use. Our method is to estimate the area in major land use categories and then applying carbon emission and/or sequestration rates to those land uses. The two major GHG-relevant land uses are informal agriculture and other, more natural (though not necessarily native) vegetation. Together, these two land uses/land covers occupy 93.3 percent of the current active floodplain. (See Table 1.)

Table 1: Land cover breakdown in the riparian zone.

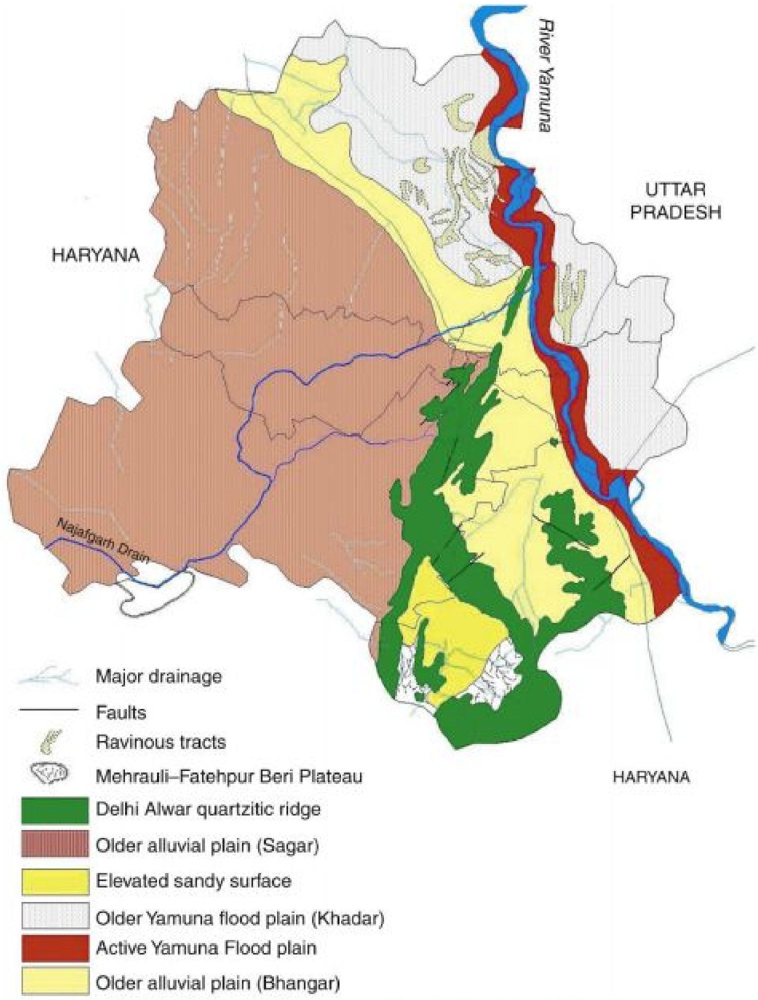
Land Use / Land Cover	Area, km^2	% Area
Forests & terrestrial vegetation	49.5	52.19%
Informal agriculture	38.3	40.10%
Lakes/ponds	4.2	4.34%
Settlements	3.29	3.36%
Total:	**94.8**	

Source: Tabusum et al., 2009

In an extensive study on the Yamuna riparian area vegetation, Tabasum, Bhat, Kumar, Fatma, & Trisal (2009) examined land use change over the period from 1994 through 2003. Forests occupied the largest area of the floodplain at approximately 52% of the total floodplain area. Figure 2 identifies the current active flood zone within the greater Delhi landscape. The main tree species in the forests were Acacia nilotica, Eucalyptus globulus, Pithocelobium dulce and Abutilon indicum.

Informal agriculture comprised the second largest floodplain land area, forming 40% of the total, with rice, wheat and vegetables being the primary crops grown. In total, at least 93.3 percent of the total active floodplain is composed of vegetation and informal agriculture (Table 1).

Figure 2: Historical and current floodplains of the Yamuna River in the National Capital Territory



Source: Chaterjee et al. (2009)

We estimate total carbon assimilation or sequestration per year for each land cover by multiplying a representative rate of assimilation per hectare by the number of hectares in the land use. For forests, we draw that assimilation rate of 8.33 Mg/ha/year from Arora and Chaudhry (2017), who studied carbon sequestration capacity of Acacia nilotica planted under a social forestry scheme in Kurukshetra University, Kurukshetra (Haryana). This rate includes carbon stored above ground in woody biomass and below ground in roots and soil. The calculation and estimate are as follows:

Area in the floodplain in forest (ha)	49,500
x Average C assimilation (Mg/ha/year)	x 8.33
= Annual GHG sequestration (Mg/year)	412,335

While this method is solid, there are caveats that come with the estimate. First, this is a tree plantation, not a natural forest of the sort that could be restored in the Yamuna River floodplain. The density of trees and species composition could be different. Differences in water quality, temperature, seasonal flooding, and any other factor that makes Delhi different from the study site in Haryana mean that the actual results from riparian forest restoration could be quite different.

For agriculture, we return to the estimate from Tabasum et al. (2009) that 3,803 hectares of the floodplain are used for agricultural production. Because GHG emission varies by crop type, we augment this estimate with data from two studies that identify the specific crops grown in the floodplain and the emissions per hectare for as many of those specific crops as possible.

Cook et al. (2014) surveyed farmers operating in the floodplain and identified 19 different crops commonly grown there. For estimates of GHG emissions per hectare in agriculture, we turn to Vetter et al. (2017), which used the Cool Farm Tool (CFT) (Hiller et al., 2011) to estimate annual GHG emissions associated with the complete production of agricultural products, from planting to final sale. The tool takes into account soil, climate, fertilization, pesticide and herbicide use, residue management, and machinery and energy use. Of the Of the 19 crops identified in Cook et al., Vetter et. al. report GHG emission rates for just 8. Those eight, however, span the types of crops (grains or row crops, leafy vegetables, other vegetables) grown in the floodplain. (See Table 2.)

Based on these data, our first approximation of annual GHG emissions from informal agriculture in the active Yamuna floodplain, is 8,448 Mg CO2E per year, calculated as follows.

Area in the floodplain in informal agriculture (a)	3,803
x Average GHG emissions (Mg/ha/year) (b)	x 2.22
= Estimated GHG emissions per year	8,448

a. Crops represented include wheat*, rice*, gourds, eggplant, okra, corn*, pumpkins, cucumber, chilies*, black-eyed peas*, spinach*, leafy vegetables, cauliflower, mustard*, tomatoes*, melons, watermelons, carrots, radishes (Cook, et al. 2014).
b. Average of estimated total GHG emission for a subset of the crops identified in Cook et al. (2014) (Vetter et al., 2017). The subset is simply those crops included in both the Cook and Vetter studies. These are indicated by *s in note a. See also Table 2

Table 2: Informal Ag Cover GHG Emissions (X% Total Cover)

Crop	GHG Emission (kg CO2E ha−1 year-1)
Wheat	977.25
Rice	8,447.69
Gourds	
Eggplant	

Okra	
Corn	707.3
Pumpkins	
Cucumber	
Chilies	1,500.0
Black-eyed peas	540.1
Spinach	1,100.0
Leafy vegetables	
Cauliflower	
Mustard	1,500.0
Tomatoes	3,000.0
Melons	
Watermelons	
Carrots	
Radishes	
Average:	**2,221.5**

Sources: (Cook, Oviatt, Main, Kaur, & Brett, 2015;Vetter et al., 2017)

Beyond GHG emissions, formal and informal agriculture has other environmental impacts in and around the Yamuna River floodplain. Cook et al. (2013) found that farmers rely heavily on access to irrigation- but not directly from the river itself. The most common method were tube wells fueled by diesel pumps or manual handles. None of the farmers used river water directly, and farmers noted that the water made them sick. Despite their best efforts, groundwater is likely contaminated by the river and excessive chemical fertilizer and pesticide use. The farmers also reported that flooding was a chronic threat to their lifestyle, and they associate continuous flooding with productivity decreases. Repeated exposure to highly contaminated and polluted river waters can have very detrimental effects on human health outcomes and food supply. Residents endure poor sanitation and unsafe drinking water, and expire to hazardous syntactic chemicals in the air, food and water (McMichel, ny).

Net GHG Emissions on the Floodplain

To calculate *net* greenhouse gas emissions associated with the land cover currently in the Yamuna River Floodplain, we simply subtract the emissions from informal agriculture from the sequestration from forests. Because the sequestration by forested areas is greater than the emissions from the agricultural areas, we estimate that there is a net *sequestration* of 403,887 Mg CO2E per year.

Sequestration per year (Mg CO2E)	412,335
- Emissions per year(Mg CO2E)	- 8,448
= Net GHG emissions per year (Mg CO2E)	403,887

Beyond GHG emissions

It is likely that conversion of barren lands to riparian forests (aforestation) and/or the replacement of agricultural fields with forest land and other permanent vegetation will increase net GHG sequestration on the Yamuna River floodplain. It is also likely to produce a range of co-benefits, including greater soil stabilization, higher water quality, greater groundwater recharge, higher aesthetic and recreational value, and improved habitat for diverse wildlife species. Garrastazu et al. (2015) modeled the impact of more restrictive forest policies on carbon emissions in riparian areas in the Rio Do Peixe river basin in Southern Brazil. They found that the development of secondary forests and conversion of land into native forests led to significant gains in carbon sequestration capacity. Further, increased forest preservation was associated with gains in biodiversity in the same region. We anticipate that similar changes in the Yamuna riparian zone would greatly increase the region's ability to retain carbon and reduce overall emissions, as well as improve the region's biodiversity.

In meta-regression analysis on the economic importance of wetlands, Ghermandi et al conclude that flood control, water quality improvement and storm buffering are the most highly valued wetland services. All of these services have socio-economic impact. The government incurs the cost of preventable flood damage, and also allocates extensive resources towards water quality improvement. These yearly costs could be forgone with a one-time investment in wetland construction and restoration. Further, improving the aesthetic value of the land with increase usability of the space and potentially increase tourism, generating economic benefits as well.

Yamuna Biodiversity Park: A Case Study

A demonstration of the multiple ecological values of riparian forest and wetland restoration is playing out int Yamuna Biodiversity park. In this experimental effort to restore a portion of the floodplain, Faiyaz Khudsar, C.R. Babu, and their team have developed the Yamuna River Biodiversity Park to reintroduce native terrestrial and aquatic vegetation to the city and floodplain. The park was established in 2002 and has since reached over 457 acres on the flat alluvial floodplains of the Yamuna. Grasses, sedges, phragmites and salic have all appeared. To date, the park boasts biologically rich wetlands, grasslands, fruits and herbs - over 2000 plant and animal specifies living in 30 biotic communities, including native flora and fauna once considered virtually extinct.

The team is monitoring the ecological changes (species richness, soil fertility, water quality, etc.), and we expect to be able to apply these monitoring results in the systems model to simulate the effects of similar restoration in other parts of the floodplain.

In one future scenario that we could assess with the systems model is Khudsar's zonal restoration approach. In it, only 30-40% of the floodplain is developed by humans, and the majority is left "for the river." That majority of the floodplain would be reforested, planted in native grasses, or returned to wetlands (or new wetlands would be constructed), while some of the portion kept for human use would be developed as parks, trails, and greenways. (There is much overlap between this approach and work done by the YRP design teams.)

As an example illustration of how different strategies could be combined and jointly assessed using the systems model, wetlands constructed as part of riparian restoration could be designed to maximize their capacity for wastewater treatment.

The systems approach also allows consideration of potential social and economic costs that would accompany restoration. Conversion of land from informal agriculture to forests, and wetlands and other natural land covers will likely require the relocation of many farms and farmers. Positive benefits could come to farmers if new farming areas are safer, cleaner, and more suitable for habitation. However, floodplain restoration may destabilize communities in the short term. Direct economic costs will include the cost of relocation, and temporary losses in productivity as farmers get used to new surroundings and ways of farming. Crops may need to be transported farther to reach urban markets, and that will have a feedback effect of increasing the overall carbon footprint of food systems. In the long run, however, floodplain restoration could prevent even greater disasters, such as the monsoon flooding in Uttarakhand that killed over 600 people living illegally in the Ganges floodplain in 2013.

We do hope that this effort helps the Delhi government prepare for the costs and benefits of any action taken regarding floodplain restoration. Our aim is not to build a model to prove the superiority of one approach, but rather to build a model useful for exploring all of the consequences of actions taken to restore the health of the Yamuna River.

Solid Waste Management

Over the last twenty years, the city of Delhi has experienced rapid urbanization and economic growth. The absolute and per capita increase in waste generation has overwhelmed Delhi's solid waste management system, forcing municipalities to dump the majority of waste in unhygienic and exhausted landfills in the Yamuna River floodplain. We set out to quantify tonnes of greenhouse gas (measured in carbon dioxide equivalent) generated per day in the floodplain area to better understand how floodplain restoration and sustainable solid waste management practices could potentially affect associated emissions.

Delhi's three semi-controlled landfills (Okhla, Gazipur, and Bhalswa) were deemed dangerously over capacity in 2010 (Down to Earth, 2018). Despite the serious threat these landfills pose to both human and environmental health, the city continues to rely on them to dispose of the majority of its waste. While sanitary landfills contain 'leachate liners,' which prevent landfill leachate (runoff of toxic chemicals from decomposing garbage) from contaminating groundwater supply, Delhi landfills' 'leachate liners' are completely eroded, and landfill runoff is eventually deposited in the Yamuna River (Ghosh, 2015). Ghosh et. al (2015) tested the leachate from each of the landfill sites and found contaminants toxic enough to adversely affect human health if consumed in even trace amounts.

It has also been well-documented that landfills are also a point source of GHG emissions. As waste decomposes, a combination of chemical, thermal, and microbial reactions release gases (US Environmental Protection Agency, 1999). Landfill gas is a combination of methane and carbon dioxide in almost equal parts. The remaining 0.01–0.6 percent is composed of carcinogenic volatile organic compounds, such as benzene, toluene, xylenes, carbon tetrachloride, etc. (Residua, 2000). In India, emissions from waste are double the global average, due to a high proportion of biodegradables, and the warm, wet climate (Siddiqui, 2013). Landfills are the second largest source of methane in India after coal mining (CSE, 2016).

Open burning of solid wastes in dumps and spontaneous landfill fires also contribute to generating GHGs. In an evaluation of Indian waste management, Annepu (2012) estimated that an additional 22,000 tons of pollutants are generated per year from burning trash in Mumbai alone. These fires releasing carbon monoxide, particulate matter, dioxins, and furans into the atmosphere. Continuing to rely on landfills to dispose waste will exacerbate these issues in the long run.

The Yamuna River Project envisions a "Zero-waste" decentralized solid waste management system that will greatly reduce toxic runoff that reaches the river and associated landfill gas emissions. The model emphasizes the waste generator's responsibility to segregate at source into biodegradable (wet waste), non-biodegradable (dry waste), and domestic hazardous waste. Separating and safely processing hazardous waste protects wet and dry waste from contamination. Once waste is separated, it can be processed by type. YRP models imagine creative alternatives involving both local and central processes for biodegradable and recyclable waste, through composting systems, waste ‘hill’ parks, and forming formal partnerships with informal sector waste collectors.

Some of its tenets include:

- Enforcing collection fees to equip municipality to collect segregated waste: Municipalities levy fines on households and businesses that illegally dump wastes and charge user fees for waste management services to raise revenue. With these funds, the municipality equips collection vehicles (tippers, tricycles, tractors, trucks, etc.) with containers to keep biodegradable, recyclable, and hazardous waste separate.

- Installing community composting and municipality composting centers: Pending needs assessment, municipalities install composting pits or facilities and operating staff for processing biodegradable waste at the community and municipality level. At least one facility per municipality and 15 community pits per ward (approximately 2,000 households) are installed and maintained. In addition to anaerobic compost, municipalities could support mobile and fixed community and household biogas composting units. Biogas composting units capture emissions released from decay of compost, which can be used for cooking in households and businesses.

- Providing color coded bins to households and install bins at secondary storage units: To encourage separation, municipalities provide bins to households and commercial entities: green for wet (biodegradable) waste, blue for dry (recyclable) waste, and black for hazardous waste. For households and businesses without formal collection, the municipalities install bins at community-level waste units.

- Strengthening informal recycling cooperatives: Municipalities sign a Memorandum of Understanding (MOU) with existing recycling unions (for example, Safai Sena). The agreement could coordinate collection efforts, material recovery for each waste type, and establish compliance with waste segregation. The MOU could also allocate resources to existing recycling cooperatives to formalize their organizational capacity, strengthen their bargaining power, and enable them to provide workers access to health services. In addition to strengthening cooperatives, municipalities will uptake a rights-based approach by hiring recycling cooperatives to executive collection in underserved wards. The municipality will also train and hire informal workers to operate community composting facilities.

- Installing community inert and / or hazardous waste processing: The MCD collaborates with municipal hazardous waste processing centers to determine suitable locations for installing community-level centers to receive hazardous waste, and installs small landfills for non-compostable, non-recoverable waste.

- Launch awareness campaign for household compost: The plan will educate and sensitize waste generators to the importance of segregation at source, subsidies for composting equipment, and penalties for non-compliance. It will launch a Delhi-version of the India-wide mobile application “I Got Garbage” to inform citizens of collection schedules, source-separation guidelines, and fees.

GHG Emissions from Solid Waste

Methods

To understand how the zero-waste system may affect GHG generation, we have estimated a “baseline” of greenhouse gas generated within Delhi’s current solid waste management system. Table 3 reports that approximately 12,350 tonnes of waste generated in Delhi per day. Approximately 60 percent, or 7,340 tonnes, are informally dumped or landfilled, while 40 percent is sustainably processed via centralized channels (composting, Waste-to-Energy incineration) (Annepu, 2012; CSE, 2017).

Table 3: MSW Generation, Collection, and Processing Per Day (2018), with 87% of Waste Collected

Waste Category	Weight (Mg per Day)	Total Waste Generated (%)
Total MSW sustainably processed	5,008.6	40
Total MSW dumped or landfilled	7,341.4	60
Total:	**12,350.0**	**100**

Using a model for Zero-waste management in Indian cities proposed by the Center for Science and the Environment (CSE) we estimate that if 90 percent of Delhi’s total waste generated is collected (an additional 3 percentage point increase in total waste collected relative to the status quo), the proportion of waste landfilled could decrease by upwards of 50 percent (Table 4).

<table>
<tr><th colspan="4">Table 4: MSW Generation, Collection, and Processing Per Day (2018), in Zero Waste Scenario</th></tr>
<tr><th></th><th>Waste Category</th><th>Weight (Mg per Day)</th><th>Total Waste Generated (%)</th></tr>
<tr><td rowspan="3">100% of Waste Collected</td><td>Total MSW sustainably processed</td><td>10,699.9</td><td>87</td></tr>
<tr><td>Total MSW dumped or landfilled</td><td>1,650.3</td><td>13</td></tr>
<tr><td>Total:</td><td>12,350.0</td><td>100</td></tr>
<tr><td></td><td></td><td></td><td></td></tr>
<tr><td rowspan="2">90% of Waste Collected</td><td>Total MSW sustainably processed</td><td>8,518.4</td><td>69</td></tr>
<tr><td>Total MSW dumped or landfilled</td><td>3,831.6</td><td>31</td></tr>
</table>

	Total:	**12,350.0**	**100**

Figures 3a and 3b, below compares the portions of wastes that are landfilled and sustainably processed in Delhi's current solid waste management system (3a) and a Zero-Waste, zero-landfill waste management system (3b).

Figure 3a. Status quo Sustainable Solid Waste Management, Delhi

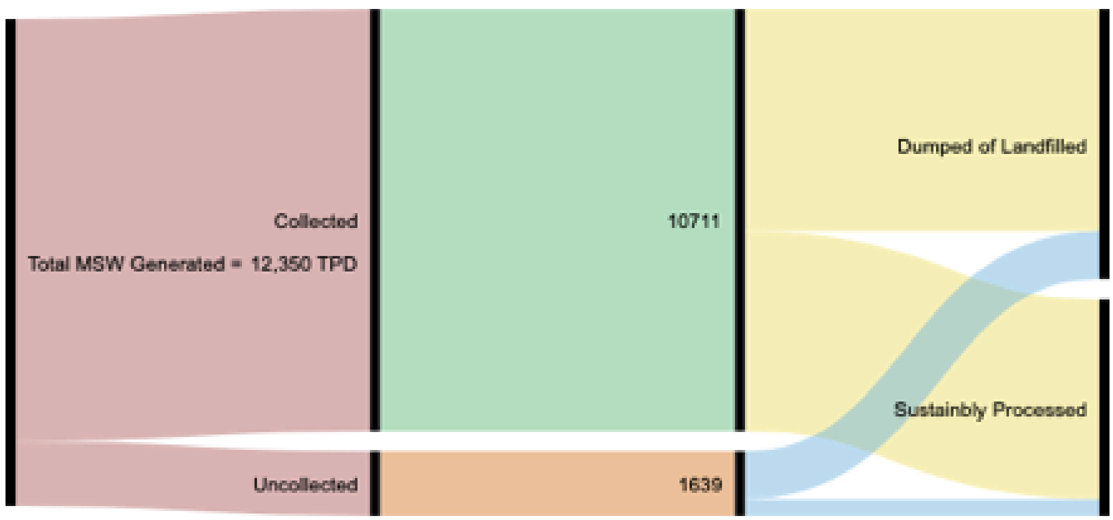
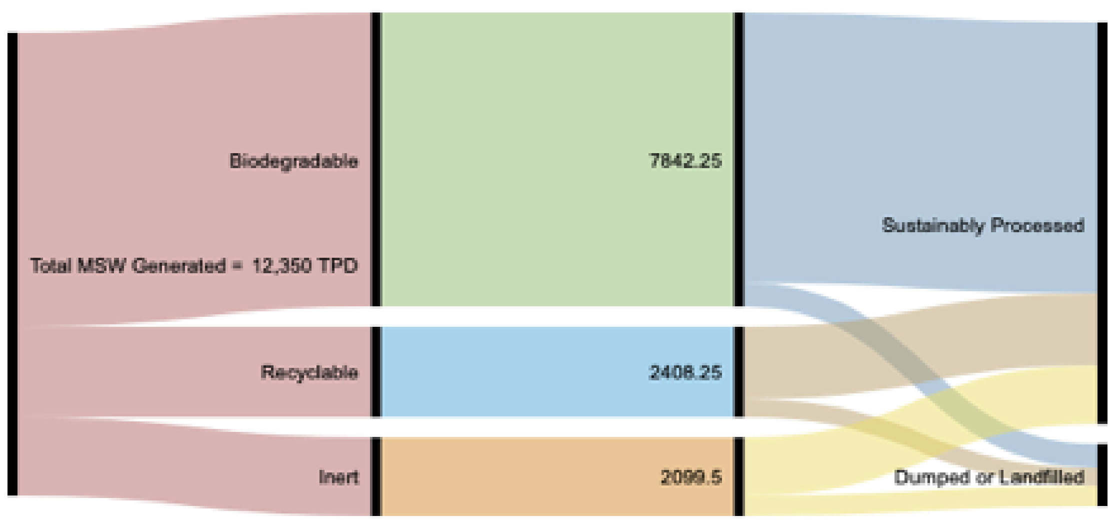


Figure 3a. Zero-Waste Solid Waste Management, Delhi



Source: Hammaker APP 2019, data from Annepu, 2012; MCD, 2017.

By segregating waste and increasing material recovery, the zero-waste solid waste management system reduces the volume of waste that is deposited in landfills, thereby reducing contamination of groundwater and GHG associated with waste decomposition and fires.

Baseline GHG Emissions and Potential Reductions

To calculate the net change in greenhouse gas emissions, we multiplied the weight of waste dumped by the carbon dioxide equivalent associated with the biodegradable content per ton of waste dumped.

According to Annepu (2012), within the current waste management structure approximately 0.57 tonnes of carbon dioxide equivalent are generated per ton of waste dumped or landfilled per day in India. Currently, the city dumps about 7,341 TPD of waste, which is associated with 4,178 tonnes of carbon dioxide equivalent generated per day from Delhi's three landfills.

Table 5: Estimated GHG Emissions from Solid Waste, Status Quo and Zero Waste

	MSW Dumped or Landfilled (MG/day)	CO2E (Mg/Mg MSW)	Emissions CO2E (Mg per day)
Status Quo	7,341.48	0.57	4,177.6
Zero-Waste Model	3,831.6	0.19	735.9

The findings reported in Table 5 suggest that in the Zero-waste model, a large portion of waste, and especially biodegradable waste, has the potential to be sustainably processed and diverted from Delhi's landfills. In the zero-waste option, nearly 82 percent of biodegradable waste is processed. Because biodegradable wastes are the primary source of GHG emissions in landfills, the increase in processing yields a lower estimate for carbon dioxide equivalent per tonne of waste dumped per day, from 0.57 to 0.19 CO2E equivalent per tonne of waste dumped or landfilled per day. By reducing waste landfilled or dumped to 3,831.6 TPD, the zero-waste model, generates approximately 735.9 tonnes of CO_2 equivalent. This is an 82 percent decrease in CO_2 equivalent production relative to the status quo.

Co-Benefits of reducing GHGs from Solid Waste

Human Health

Communities living in proximity of the unsanitary landfills are exposed to biological vectors such as flies, rodents, and insects. These biological vectors are associated with health conditions such as diarrhea, dysentery, worm infection, food poisoning, dengue fever, cholera, leptospirosis and bacterial infection (Pradyumna, 2013).

In addition to reducing disease, a Zero-waste system reduces harmful emissions generated by Delhi's WtE incineration plants. By enforcing waste segregation, municipalities will reduce the contamination of biodegradable waste that is burned in WtE incineration. This will reduce pollutants generated by emissions from WtE.

The model also encourages municipalities to set up formal partnerships with informal recycling unions. In a survey of informal workers, Annepu (2012) found that recyclists are more than seven times more likely to experience cardiovascular risk and more than three times as likely to experience lung infections than the general population. By investing in the informal sector, municipalities equip cooperatives to take additional health considerations to offset detrimental health outcomes. The model holds municipalities accountable for improving working conditions for informal workers by integrating them into the formal system, which could drastically improve health outcomes.

Proposed Phase II Modeling

As we have noted throughout this report, our goal for Phase I has been to gain an understanding of how Yamuna River restoration and the Yamuna River Project in particular may help meet climate change goals, and we have conducted the research for Phase I with greenhouse gas emissions as a central organizing issue or concept. We quickly discovered, however, that one cannot address just that one facet of the Yamuna River's degradation or that one benefit of its restoration. As Sierra Club founder John Muir said, "when you try to pick out one thing by itself, you find that it is hitched to everything else in the universe."

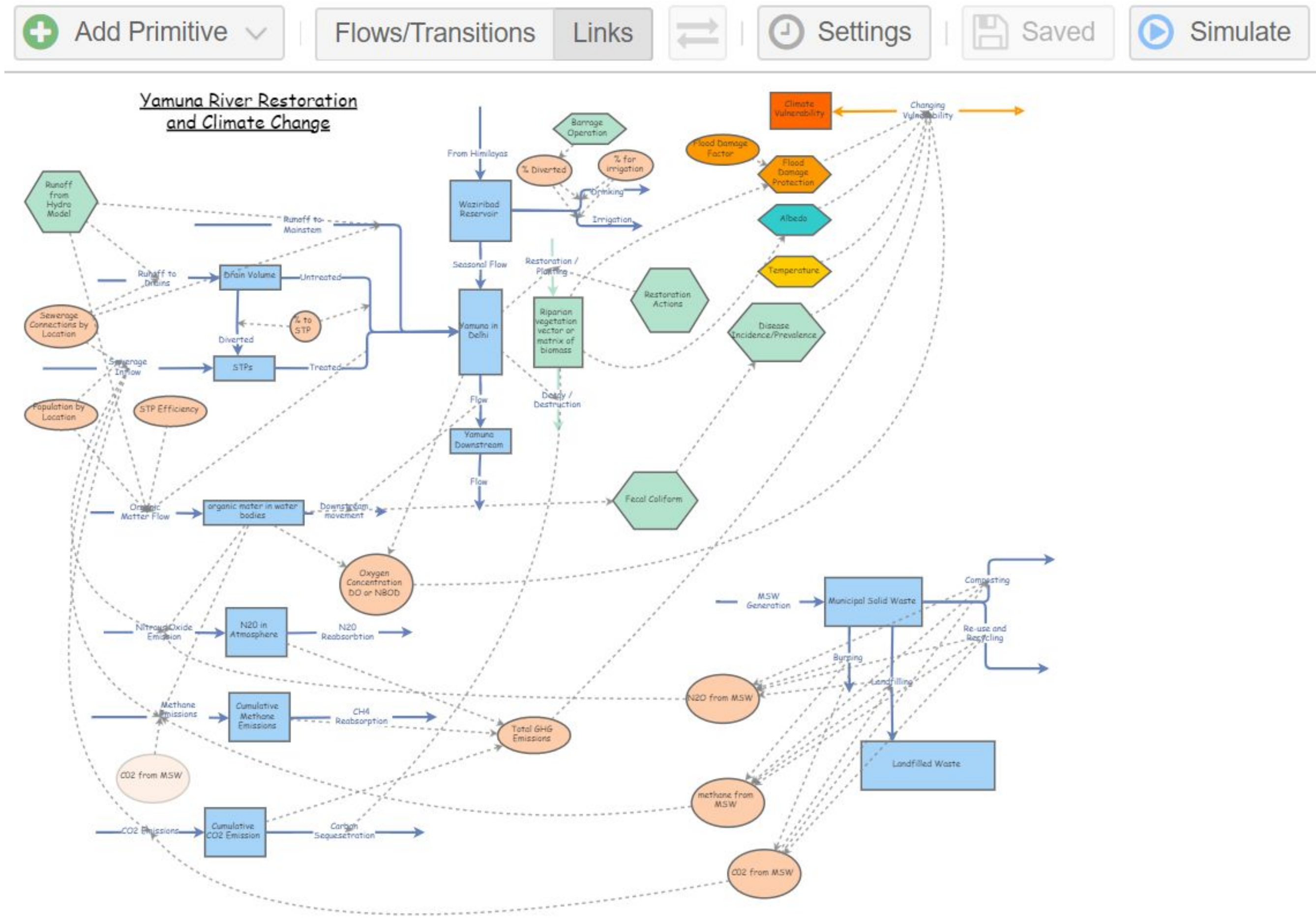
Our goal for Phase II, therefore, will be to build, test, and roll out a systems model of Yamuna River restoration that hitches together at least the most important pieces of the universe and allows stakeholders, decisionmakers, policy advocates, design teams, and researchers build their own understanding of how their interests connect with the interests of others. To lay the foundation for that effort, we have described important separate subsystems tied to key components of the YRP: wastewater treatment, green infrastructure (which we have expanded to a larger floodplain restoration), and improved solid waste management. And we have indicated some points of intersection among those components, such as restored wetlands in the floodplain serving as increased wastewater treatment capacity and, flowing the other way, improved wastewater treatment providing cleaner water for downstream uses, including recreation, and floodplain restoration.

We have also identified InsightMaker as the best platform for building and, importantly, sharing and collaborating on that model. The tool is cloud-based, runs in any internet browser, and is free to use. As in the early sketch of the model in Figure 4, below, the process entails drawing a fairly intuitive visual representation of the pieces of the universe to be modeled. The next step is to take each of the relationships (indicated by arrows) in the diagram and do the highly detailed work of writing equations, functions, and algorithms so that what happens in the model is a reasonable reflection of the real world.

As part of our Phase I research we have collected many studies that contain or can help us define the parameters to go into many of those equations. We have also identified sources of key data on initial stocks (rectangles in Figure 4), variables (ovals), converters (hexagons that operate like small input-output models), and other model needs. Finally, we have made some key contacts with researchers and practitioners on the ground in Delhi with whom we will consult as we move through the model building, testing, and rollout effort.

Our next step will be to develop a proposed plan of work for Phase II, including budget, timeline, and a more evolved picture of the model.

Figure 4: Sample InsightMaker Model (Conceptual), showing InsightMaker Controls



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