Ecosystem services from rainwater harvesting in India

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Availability of a safe and reliable water supply is an issue in developing nations, including India. Rainwater harvesting (RWH) is a site-specific source control used to satisfy human, agricultural, and safety demands for water. This study analyzed the effects of capturing rainwater for a 12.5 year period (Jan 1999–Jun 2011) to provide three ecosystem services: water supplementation for indoor use, water supplementation for food production and groundwater recharge (GWR). A hydrologic analysis was completed using satellite rainfall data and a water balance approach. Two demand scenarios, indoor and outdoor, were considered, with water in excess of demand and storage directed to recharge groundwater. An economic analysis quantified RWH system net present value. The results indicated significant ecosystem services benefits were possible from RWH in India. RWH for the purpose of providing irrigation to a small garden and allowing overflow to a drywell for GWR was concluded to be an approach to maximize benefits. This scenario provided the greatest net present value (21,764–38,851 INR), fastest payback period (0.30–0.98 years), and recharge to groundwater of more than 40% of onsite rainfall. The benefit of the outdoor vegetable irrigation was determined and the results showed that the caloric demands of the typical Indian household (2.75 kg of tomatoes and 1.05 kg of lettuce) could be met with a 20 m² garden, and excess food could be sold to offset the capital cost of the system and later for economic gain.

Keywords: rainwater harvesting; ecosystem services; India

1. Introduction

India is in a water crisis. While 89% of the Indian population has access to improved water sources, it is generally intermittent with regional disparities in availability (UNICEF, 2008). In the early 1980s, residents of Bangalore had nearly twenty hours per day (hr/day) of access and Chennai had between 10–15 hr/day; however, these values dropped to 2.5 and 1.5 hr, respectively as of 2006 (World Bank, 2006). A widely accepted measure of water stability, the Falkenmark Indicator (Brown & Matlock, 2011), provides four levels of water scarcity, including: no stress, stress, scarcity and absolute scarcity. For India, which withdrew 627 m³/yr per person in 2010 (The Encyclopedia of Earth, 2012), the Falkenmark reveals a level of scarcity. This water supply crisis has been found to be autonomous of annual precipitation, as an investigation in Chennai revealed shortages despite an annual rainfall depth of 1300 mm (Jency, 2009).

Urbanization in India, as in other countries, has resulted in numerous water quality and quantity issues (Kumar, 2005; Lee & Heaney, 2003). Despite major investments in infrastructure over the past century, India’s existing water infrastructure cannot sufficiently provide sustainable or reliable water to its citizens, with the overall system capable of storing approximately 200 cubic meters per person (m³/person), far below the desired 1000 m³/person for countries with similar climate (Briscoe, 2006). For example, developed nations, like the United States, can store up to 5000 m³/person and middle income countries (e.g. Mexico and China) can store up to 1000 m³/person. The 200 m³/person in India is equivalent to approximately 30 days of rainfall, whereas major river basins in arid areas of developed nations can store up to 900 days of rainfall. To further complicate matters, precipitation in India is highly seasonal, with 90 percent occurring over the period of June–September (Briscoe, 2006).

Beyond supply, the rapid development of urban centers has further degraded water quality. One direct impact is the rise of endemic rates of diarrheal disease, which is not seasonally dependent (Dasgupta, 2004). For instance, citizens often resort to polluted sources of water when rations are insufficient during dry months. Alternatively, increased urban drainage (e.g. stormwater runoff, untreated urban domestic sewage, industrial effluent) during wetter months contributes to contamination of waterways and groundwater stores with fecal coliforms (Buecheler, 2005; Dasgupta, 2004). As such, citizens often resort to groundwater for personal consumptive uses. For example, to improve the reliability of existing water, homeowners are increasingly reliant upon personal tubewells (Shah & Patnaik, 2007). Such measures have
resulted in rapidly decreasing groundwater tables. A study by Rodell (2009) measured falling rates of 4 ± 1 cm/yr in northwest India over only six years (2002–2008). This resulted in a total volumetric loss of 109 million m$^3$ (Rodell, 2009).

With such a wide array of negative impacts of urban development, improvements to the sustainability of urban water resources should consider a broad range of factors and include the valuation of potential ecosystem services (Bolund & Hunhammar, 1999; Pataki et al., 2011). Ecosystem services, as defined by Costanza et al. (1997), include direct and indirect benefits derived by humans from ecosystem functions, including stormwater reduction, potable water demand supplementation, and food (e.g. crop) procurement. These services also carry both social and economic implications, including improved house prices, reduced household bills, ecological conservation with improved biodiversity of native species, and improved physical and mental well-being (Tratalos et al., 2007). Community gardens for example have been shown to directly improve the social, ecological, and economic sectors of urban areas (Barthel et al., 2010).

Increasing efforts are being made to harvest rainwater to combat water scarcity in India (Kumar et al., 2006). Tanks, or johads, are examples of common agricultural/rural runoff collection and storage practices employing earthen check dams or tanks in India (Kumar et al., 2006). For urban areas, where space is often limited, RWH offers a small footprint (i.e. high retrofit-ability) and relatively low cost solution to water supply and management issues. Direct ecosystem service benefits of RWH include (1) infiltration and recharge of the depleted groundwater (Sakthivadivel, 2007) and (2) provision of direct water supply for human needs (Grover, 2010). Additional ecosystem service benefits of urban RWH include stormwater runoff reduction, groundwater recharge (GWR), indoor demand supplementation, and irrigation for vegetation (e.g. small personal gardens). Small personal gardens also address the low consumption of vegetables (i.e. micronutrients) resulting from non-availability (NSSO, 2007). These benefits are in sync with the provisioning and regulating services highlighted in healthy urban ecosystems.

The widespread implementation of RWH has been shown to mitigate the catchment- and site-scale impacts of both stormwater runoff volumes (Steffen et al., 2013; Walsh et al., 2014) and pollution loading to both surface and groundwater sources (Kinkade-Levario, 2007). A study of RWH in Paris found that despite limited large event mitigation, prevention of sewer overflows for smaller, more frequent rainfall events can be improved (Petrucci, 2011). In a study looking at RWH in the Southeast US, it was found that increasing visibility and implementation of RWH also aids in educating the public about negative impacts from urbanization, resulting in smarter water use (Jones & Hunt, 2010).

When aquifer recharge rates are exceeded by groundwater pumping rates, RWH for GWR has been targeted, such as in a case study in Bangalore (Suresh, 2001). A vast majority of RWH studies in India target the benefits of GWR, since nearly 85 percent of drinking water is supplied by groundwater (World Bank, 2010). While RWH for GWR has had positive impacts on the subsurface, a direct benefit for immediate water supply does not exist (Jency, 2009). For instance, while Chennai was the first city to mandate RWH for new developments, GWR is the sole target, providing no benefit to piped water supply (Srinivasan, 2010).

Meanwhile, studies targeting the potential benefit of RWH for indoor uses found 77 percent of households surveyed were dissatisfied with the duration of city supplied water (Singh & Turkiya, 2013). However, 86 percent of these households were unaware of RWH technologies targeting the acquisition of water for potable uses (Singh & Turkiya, 2013). Another study found RWH for indoor use to be largely un-exploited (Grover, 2010), since RWH in India often refers to “enhanced aquifer recharge; rather than collection of rainwater in cisterns for (indoor use)” (Srinivasan, 2010). As such, exploration of other benefits stemming from RWH, including the ecosystem services of stormwater runoff mitigation, food production, and potable water supplementation, is warranted.

This study presents the potential for RWH to supplement indoor, recharge of groundwater, and garden irrigation demands throughout India. Six case study cities were established, representing the range of climatic and geographic characteristics, including Delhi, Hyderabad, Kolkata, Srinagar, Mumbai, and Bangalore. Hydrologic analysis was completed using processed satellite rainfall data, at three-hour temporal scales, for a total of twelve and a half years (Jan 1999–Jun 2011). Potential evapotranspiration rates established the irrigation demands, while growing seasons dictated the supply (i.e. in season or out of season) of water. The addition of long-term costs for purchasing, operation and maintenance (O&M), municipally-supplied water, and produce (i.e. vegetables) sales provided a net present value (NPV) for each regional scenario. Ultimately, the potential for water supply with RWH was translated into the following ecosystem services: (i) a reduction in monthly and annual water bills, (ii) a reduction in the stormwater runoff, and (iii) a caloric potential for a garden plot (i.e. one-to-one ratio of catchment area to irrigated plot area). The results provide a spatial and temporal analysis of the ecosystem services’ potential of RWH throughout India and suggest that RWH for the purpose of providing irrigation to a small garden and allowing overflow to flow to a drywell for GWR is the best option to maximize benefits.
2. Methodology

2.1. Regional selection

Case study cities were selected based on geospatial characteristics, including differences in population, climatic patterns, and geographic location. Climatic zones were delineated using the Koppen classification system (Mapsof, 2012). A minimum population of one million was established for geographically-distinct climatic region cities. This resulted in a total of six cities, including Kolkata, Mumbai, Hyderabad, Delhi, Bangalore, and Srinagar as can be seen in Figure 1, which also provides the populations and average annual rainfall (Government of India, 2011). GIS datasets were obtained from Global Administrative Areas (http://www.gadm.org/).

2.2. Rainfall data source

Precipitation data was obtained from the publicly-available NASA Tropical Rainfall Measuring Mission (TRMM) (NASA, 2013). TRMM is a joint data-gathering mission between NASA and the Japanese Aerospace Exploration Agency. The benefit of TRMM data for RWH analysis in areas without easily accessible data is in its relatively fine temporal resolution and wide spatial distribution. This facilitates regional analysis of RWH and its effectiveness. This study used the three-hour temporal resolution precipitation intensity data, officially named “TRMM 3-Hourly 0.25 deg. TRMM and Other-GPI Calibration Rainfall Data,” with the short name “TRMM_3B42” (NASA, 2013). The period of analysis was 1 January 1999–30 June 2011. Quality assessment ensured the processed datasets were accurate by comparing with ground-based measurements at stations in the regions of analysis (Stout, 2013).

2.2.1. Rainfall distributions by city

An analysis of the continuous, long-term precipitation datasets found that the annual average precipitation event

![Figure 1. Republic of India, with study cities delineated. Population and average annual rainfall depths are indicated.](image-url)
intensities ranged from 2.9–10.4 mm/event (Srinagar to Kolkata). The annual average inter-event time ranged from 8 days to 30 days (Srinagar to Hyderabad). Average annual rainfall depths extracted from TRMM datasets totaled 492 mm (Srinagar), 658 mm (Delhi), 819 mm (Hyderabad), 991 mm (Bangalore), 1379 mm (Kolkata), and 1605 mm (Mumbai). Seasons were distinguished according to climate patterns following Rao et al. (2012), including winter (Jan–Feb), summer (Mar–May), southwest monsoon (June–Sept), and northeast monsoon (Oct–Dec). Results for seasonal average event intensity (Table 1) and inter-event duration (Table 2) highlight the regional differences in precipitation characteristics.

### 2.3. Household characteristics

Despite vast geographic differences, uniform application of a typical middle class housing unit was deemed acceptable. This is based on an analysis by Stout with the goal of providing the most widely applicable results, as the vast majority of the country’s residents live in such housing (2013). A typical middle class housing unit, in this case, was defined as a four storey (13.2 meters) apartment building housing two five-member families per storey (family unit floor plan area of 84-m²). Case study households were representative of a typical apartment layout, which are multi-unit dwellings. This information was obtained through conversations with Mr. Satish Kumar Vedulla, General Manager and founder of Harit Solutions (www.haritsolutions.com), a water engineering and consulting company headquartered in Visakhapatnam, India (Vedulla, 2013, personal communication) and checked using Google Earth. Using ArcGIS, a typical rooftop area for the multi-unit dwellings indicated by Mr. Vedulla was quantified (167-m²). This value was then subdivided by the number of apartment units, yielding a “typical Indian household” catchment area of 21-m². This approach yields applicable catchment areas for many parts of India according to analysis of Google Earth image files of the living situations in each of the cities of analysis and consultation with Mr. Vedulla. Background research on RWH capacities and catchment areas was completed by Stout (2013) and targeted the greatest efficiency for the typical family of five. The greatest efficiency was defined as matching most benefit (% water captured relative to demand) to lowest size cistern readily available in market (to keep material cost low). The analysis used precipitation patterns for each area, along with varying cistern sizes to compare the different benefits. At the point where the incremental increase in benefit relative to increasing cistern size began to decrease, the tank was considered most efficient. This resulted in the 757 L capacity providing the highest Water Saving Efficiency (WSE) for all cities except Mumbai, which maximized WSE with a 1893 L capacity (Stout, 2013).

### 2.4. Hydrologic analysis components

#### 2.4.1. Storage volume calculation

Several methods exist for determining the volume stored in a rainwater cistern. For this analysis, the mass balance method was chosen. The mass balance method applies a water budget, accounting for the volume of the roof runoff (inflow), demand (outflow), and remaining water (storage) at each time step (Panu & Rebneris, 1997). The mass balance method produces the RWH volume necessary to supplement centralized water demand and allow for spillage at each time step. Inflow was calculated by multiplying the average catchment area by the rainfall volume and applying a runoff coefficient \((R_c)\) value of 0.9. The \(R_c\) of 0.9 represents a ten percent loss due to abstractions (e.g. evaporation, depression storage) and inefficiencies in collection.

#### 2.4.2. Storage and water demand

The volume of water stored was calculated based on the user-defined volume of the cistern, combined with the inflow volume and demand. Cistern spillage, equivalent to the overflow volume that occurs when storage capacity is met, can be estimated with either the yield before spillage (YBS) or yield after spillage (YAS) algorithms. This study chose YAS since it provides a more conservative estimate for supply (Schiller, 1987). Last, water demand (i.e.
outflow) was estimated based on survey data collected in the city of Visakhapatnam (i.e. population over 2.0 million persons), near Hyderabad. This survey found an average daily indoor water demand of 135 liters/person. This value fit within the range estimated by other studies (Falkenmark & Widstrand, 1992; Nandgaonkar, 2005; UNDP, 2006). Combined with the average household size of five persons (Census of India, 2001), the average daily household demand was estimated to be 675 liters.

Two different demand scenarios were analyzed to evaluate RWH’s effectiveness in meeting variable demands, including indoor potable and non-potable uses (IPnP) and outdoor vegetable irrigation (OVI). The volume of water available for GWR (cistern spillage) was also recorded for the long-term analysis (Jan 1999–Jun 2011) for each demand scenario. Constant indoor demands totaled 675 liters per day while irrigation demands varied seasonally as a function of evapotranspiration (ET) rates. The ET rates for each city were determined for four defined seasons by Rao et al. (2012) using the Penman-Monteith approach of the Food and Agriculture Organization of the United Nations described in Smith et al. (1991) (Table 3). The garden space being irrigated were assumed to have half of the area (10-m²) planted with lettuce and the other half (10-m²) planted with tomatoes, resulting in a 20 m² garden plot per household. Using a crop coefficient of 1.05 for both vegetables, the daily water demand was calculated. Two 4-month growing seasons were assumed for all cities except Kolkata, which was assumed to have three.

2.4.3. Water saving efficiency (WSE)

To determine the regional effectiveness of RWH in providing the household-scale ecosystem services of GWR, indoor demand supplementation, and irrigation potential, the Water Savings Efficiency (WSE) was calculated (Equation (1)).

\[ E_T = \frac{\sum T Y_i}{\sum T D_i} \times 100 \]

where \( Y_i \) is the yield (i.e. demand satisfied) and \( D_i \) is the household demand for a specified time period. This percentage, \( E_T \), is well-known throughout RWH literature and provides a useful tool to analyze the temporal distribution of the value of the harvesting system (Fewkes, 1999).

2.4.4. RWH performance metrics

A MATLAB code was written to analyze the performance of the different RWH configurations. The mass balance method described above was used to calculate the volume of water that was available for meeting the demand, the volume of water stored after the demand was subtracted and the overflow. The only inputs for the program were the discussed TRMM precipitation data and the cistern volume. The analysis was performed on a daily time step given the demand data acquired was on a daily basis, despite having finer scale precipitation data (3 hour). The TRMM data was downloaded on a 3-hour increment as the demand was anticipated having an hourly pattern. New precipitation data was not downloaded once the demand data returned on a daily basis, as the TRMM data download proved to be cumbersome, and the summed 3-hour data would provide the same level of accuracy as the daily. Comparison of values (volumetric reductions, WSE) was compiled at the annual scale for each city. A value of 0% signifies that none of the demand was met throughout the course of the year, while a value of 100% signifies full supplementation with RWH. The volumes available for GWR were divided by the total volume of precipitation for the year and multiplied by 100. For GWR results, a value of 0% signifies no GWR, while a value of 100% signifies all the rainfall was infiltrated via GWR.

2.5. Cost analysis

A regional cost analysis for this study was based on individual municipal water costs for each city, the capital and operation and maintenance (O&M) costs for RWH systems, and the vegetation supplementation potential. Water rates (Table 4) were obtained through the respective agencies, including the Delhi Jal Board (DJB), Municipal Corporation of Greater Mumbai (MCGM), Bangalore Water Supply and Sewerage Board (BWSSB), Kolkata Municipal Corporation (KMC), and Hyderabad Metropolitan Water Supply and Sewerage Board (HMWSSB). For Srinagar, which resides in the state of Jammu and Kashmir, water usage charges could not be found and, therefore, were not included in the study.

These values were used in tandem with the demand supplied by municipal sources to calculate monthly cost savings for each typical apartment unit per region when RWH is implemented. To obtain the adjusted municipal...
volume supplied, the daily cumulative water supplementation was subtracted from the cumulative daily demand without RWH. Individual RWH tank costs were applied based on research of available plastic tanks in Hindustan, Jindal (1.8 INR/liter capacity) and Storex, Ganga (2.75 INR/liter capacity) (Rainwaterharvesting, 2014). These costs assumed inclusion of conveyance and basic filtration components. Recurring annual O&M costs were estimated to be 50 INR, accounting for filtration and conveyance cleaning and potential parts replacement. The eleven year net present value (NPV) was estimated with capital costs, O&M costs, and annual bill savings for each city assuming a five percent interest rate. Produce costs were estimated with regional data acquired from Numbeo (2014). Since tomatoes and lettuce were targeted for crop production, these vegetables were used to perform the RWH ecosystem services’ benefit analysis (Table 5).

### 2.6. Food yield and consumption

The food yield was determined based on the previous assumption of 20-m² gardens consisting of half lettuce and half tomatoes. Values for crop yield were assumed to be the same for each city, and were estimated based on information presented in Ackerman (2011). The yields used for lettuce and tomatoes were 2.44 kg/m² and 2.93 kg/m², respectively. These unit yields were multiplied by the irrigated area of 10-m² (for both lettuce and tomatoes) to produce the seasonal yields of 29.3 kg/season (tomato) and 24.4 kg/season (lettuce) for each garden.

Based on NSSO (2007) data, consumption patterns for targeted crops (i.e. tomato, lettuce) were extracted. This yielded a thirty day average per capita consumption of 0.55 kg and 0.21 kg for tomatoes and lettuce, respectively. For a family of five, this equated to a monthly household consumption of 2.75 kg of tomatoes and 1.05 kg of lettuce. These values established the monthly caloric needs per household and provided the basis upon which food yield would meet or exceed this demand.

### 3. Results and discussion

#### 3.1. Water savings efficiency for OVI and IPnP

**3.1.1. Annual results**

The annual WSE (recall WSE is water savings efficiency) was calculated and plotted in Figure 2. Both of the demand scenarios, IPnP (recall IPnP is indoor potable and non-potable uses) and OVI (recall OVI is outdoor vegetable irrigation), are shown to vary considerably. The OVI scenario showed a regional discrepancy in WSE, with less efficiency for Delhi, Hyderabad, and Kolkata (approximately 30–60%). Alternatively, the cities Bangalore, Mumbai, and Srinagar had the greatest WSE (approximately 60–90%). This is a function of the higher annual

### Table 4. Water usage charges relative to the cities analyzed (INR = Indian rupee).

<table>
<thead>
<tr>
<th>City</th>
<th>Municipality</th>
<th>Tier</th>
<th>Unit (kL) per month</th>
<th>Monthly Rate (INR) per Consumption (kL)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Delhi</td>
<td>DJB</td>
<td>1</td>
<td>0–10</td>
<td>2.66/kL</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>10–20</td>
<td>3.99/kL</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>20–30</td>
<td>19.97/kL</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4</td>
<td>&gt;30</td>
<td>33.28/kL</td>
</tr>
<tr>
<td>Mumbai</td>
<td>MCGM</td>
<td>1</td>
<td>0–22.5</td>
<td>50 (flat)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>22.5–30</td>
<td>4.75/kL, + 50 flat</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>&gt;30</td>
<td>29/kL, + 50 flat, +(4.75/kL for tier 2)</td>
</tr>
<tr>
<td>Bangalore</td>
<td>BWSSB</td>
<td>1</td>
<td>0–8</td>
<td>6/kL</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>8–25</td>
<td>9/kL</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>25–50</td>
<td>15/kL</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4</td>
<td>50–75</td>
<td>30/kL</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5</td>
<td>75–100</td>
<td>36/kL</td>
</tr>
<tr>
<td></td>
<td></td>
<td>6</td>
<td>&gt;100</td>
<td>36/kL</td>
</tr>
<tr>
<td>Kolkata</td>
<td>KMC</td>
<td>1</td>
<td>Domestic flat rate</td>
<td>12/kL</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Multi-store</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>2a</td>
<td>0–30</td>
<td>9/kL</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2b</td>
<td>&gt;30</td>
<td>12/kL</td>
</tr>
<tr>
<td>Hyderabad</td>
<td>HMWSSB</td>
<td>1</td>
<td>Multi-store flat rate</td>
<td>9/kL</td>
</tr>
<tr>
<td>Srinagar</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
</tbody>
</table>

### Table 5. Regional costs of targeted vegetables (INR/kg).

<table>
<thead>
<tr>
<th>Vegetable</th>
<th>Bangalore</th>
<th>Delhi</th>
<th>Hyderabad</th>
<th>Kolkata</th>
<th>Mumbai</th>
<th>Srinagar</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tomato</td>
<td>27</td>
<td>36</td>
<td>26</td>
<td>33</td>
<td>36</td>
<td>35</td>
</tr>
<tr>
<td>Lettuce</td>
<td>25</td>
<td>34</td>
<td>24</td>
<td>24</td>
<td>29</td>
<td>20</td>
</tr>
</tbody>
</table>
precipitation volumes characteristic of Bangalore and Mumbai’s climate, and the less seasonal (non-monsoonal) variance in Srinagar’s climate. Compared with OVI uses, IPnP has a much lower range of efficiency (4–12% across regions), this being a result of higher demands in IPnP than OVI. Kolkata and Mumbai possessed the highest IPnP WSE, ranging between 9–11% and 7–15%, respectively, while Srinagar provided the least (range 3–7%). Despite the regional dichotomy between WSE for OVI, the overall RWH efficiency outperformed that of IPnP for the long-term analysis. The efficiency of benefits result from the targeted demand, with smaller volumes (i.e., OVI) being realized in regions with annually reliable rainfall characteristics.

3.1.2. Seasonal results

The seasonal WSE was calculated from average supply and demand (Figure 3). As with the annual analysis, both of the demand scenarios, IPnP and OVI, are shown to vary considerably. It should be noted that 0% for OVI indicates no seasonal demand. This was due to poor growing conditions (i.e. out of season). All regions perform best during the southwest monsoon (maximized WSE of 63–97%), resulting from enhanced precipitation magnitude. Winter yields the least efficiency for all regions, resulting from poor precipitation magnitude. Similar to the annual results, IPnP efficiencies are lower than OVI across regions for the same reason of higher demands. Maximum IPnP efficiency is realized during the southwest monsoon (6–31%), though this is substantially lower than the OVI results (between 68% and 90% less). Similar to OVI, summer and northeast monsoon seasons have lower efficiencies for IPnP ranging from 1–7% and 0.6–7%, respectively. Winter values are all approximately 1%.

3.2. Groundwater recharge

3.2.1. Annual results

The percentage of total available precipitation (inflow) directed to GWR (recall GWR is groundwater recharge)
was calculated on an annual basis and plotted (Figure 2). Similar to the WSE results, the OVI scenario had much higher GWR potential compared with the IPnP scenario. GWR rates for IPnP ranged from 0–20% across all regions, with Srinagar simulating the least potential (0–8%) and Mumbai with the greatest potential (2–25%). This is a function of the annual precipitation volumes in Mumbai being the highest in the study and occurring almost exclusively during the monsoon, resulting in many times of cistern overflow; inversely Srinagar has the lowest annual precipitation volumes in the study, and fairly evenly distributed precipitation patterns across the year. OVI results could be separated into three categories of efficiency, based on regional results. The least efficient city was Srinagar (34–66%), the mid-efficient cities included Bangalore, Delhi, Hyderabad, and Kolkata (approximately 40–70%), and the most efficient city was Mumbai (75–88%). This hierarchy indicates the regions where the volume of GWR approaches the volume of precipitation (i.e. input). This highlights the potential for GWR to mimic the natural, pre-developed conditions (i.e. infiltration). Again, OVI outperformed IPnP for potential GWR rates for the long-term study due to the ability of captured rainfall to quickly satisfy OVI volumetric demands and, thus, supplement a greater proportion of the GWR demands.

3.2.2. Seasonal results

The percentage of the average available precipitation directed to GWR on a seasonal basis was calculated and plotted (Figure 3). Similar to the WSE results, the OVI scenario had a greater GWR potential compared with IPnP as a result of lower OVI demands being quickly satisfied and resulting in cistern overflow. The IPnP GWR rates...
were greatest during the southwest monsoon across all regions (2–18%) with Kolkata, Delhi and Mumbai having the highest results at 18%, 17% and 16%, respectively. IPnP GWR rates were high during the monsoon as a result of the high precipitation volumes in short periods of time, characteristic of monsoons, quickly filling the cistern and overflowing. Srinagar provided the lowest seasonal IPnP GWR rates as a result of non-monsoonal precipitation characteristics. Less GWR was experienced during the summer and northeast monsoon seasons, ranging between 5–12% and 2–19%, respectively. Again, winter values were less than 1% for all cities, except in Mumbai (21%) and Srinagar (5%), characteristic of months with very low precipitation. GWR rates when targeting OVI were appreciably higher, maximizing during the southwest monsoon (39–85%). All regions were capable of infiltrating over 50% of the precipitation, with the exception of Srinagar (39%), resulting from high precipitation volumes during the monsoon in all areas except Srinagar. Infiltration rates during the summer and northeast monsoon seasons were, again, less despite having reasonably high GWR values (20–48%). All cities, except Mumbai, infiltrated greater than 25% (11–68%). Winter infiltration ranged from 4–90%.

Comparison of monthly inter-event time (days) and precipitation event intensity (mm/event) (Figure 4) yielded a distinction in household IPnP reduction potential for months with values less than 30 days and greater than 5 mm, respectively. Similarly, seasonal plots (Figure 5) highlight a greater distinction in the reduction potential. Seasons exceeding the threshold values provide negligible IPnP benefits to the household. Srinagar is the only city in which this relationship does not hold true, which is a function of the precipitation trends (i.e. less intense, longer

![Figure 4](image-url)
3.3. Cost-benefit analysis

3.3.1. IPnP

Based on average daily consumption for a typical household of five, RWH was found to reduce annual water bills up to 1550 INR per year (Delhi), including annual O&M. No benefit was simulated for Mumbai, highlighting the importance of the water rate structure (due to usage less than 22.5 kL/mo being charged a flat rate). Monthly variations in IPnP reductions, represented as reductions in monthly bills, indicate the intra-annual periods when RWH is more beneficial both regionally and temporally (Figure 6).

Seasonal analysis of RWH effectiveness highlights the greatest reductions in bills occurring during the southwest monsoon, followed by the summer, northeast monsoon, and winter. The winter is least effective, due to the lack of precipitation. Figure 7 indicates the annual reductions as a

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Figure 5. Seasonal Average Inter-Event Time (days), X-Axis, versus Seasonal Average Precipitation Event Intensity (mm/event), Y-Axis. Size of points, Z-Axis, indicates the average seasonal volumetric reductions in household IPnP (indoor potable and non-potable) demand with the implementation of RWH.

Figure 6. Average monthly water bill reductions with RWH.
percent of the season, with inset values representing the total seasonal household bill reductions (INR).

The capital cost of each 757-liter RWH unit was 1363 INR, while the 1863-liter RWH unit for Mumbai was 2082 INR (e.g. based on 1.8 INR/L). Combined with the annual savings and O&M costs for the eleven years of analysis, the NPV for each city was calculated (Table 6). Table 6 also presents the regional average volumetric reductions for IPnP. Ranks indicate the best (value of one) locations, in terms of NPV and the long-term average volumetric reduction, for the implementation of RWH. These results highlight the difference between the seasonal and consistent annual potential of RWH for IPnP demand.

Dividing the initial capital costs by the annual indoor water savings, which were adjusted for recurring O&M, the simple payback periods were estimated at: one (Delhi), six (Kolkata), ten (Hyderabad), and twelve (Bangalore) years. Mumbai never achieved payback due to the rate structure resulting in zero annual savings.

### 3.3.2. OVI and caloric potential

Cost-benefit analysis of OVI with RWH found a slight reduction in the average annual bill savings across regions. This was the result of supplementation from municipal sources to irrigate vegetation during growing seasons. The incorporation of vegetable consumption supplementation dramatically increased the NPV of all scenarios. The average annual production potential for tomatoes and lettuce was 58.6 kg and 48.8 kg, respectively, for all cities except Kolkata (87.9 kg, 73.2 kg). This exceeded the average annual household consumption of 33 kg and 12.6 kg for tomatoes and lettuce, resulting in the potential for profit by selling based on market prices (Table 5). Regarding annual consumption of vegetables, household savings ranged from 1172 INR to 1601 INR as a result of crop production. When leftover produce was sold, households profited between 1548 INR and 3261 INR annually. Total cost savings per region from targeting OVI ranged between 2605–4522 INR once capital costs were recouped after one year.

Normalizing total annual profits to the increase in annual bills, due to supplementation of OVI demands, yielded a long-term average annual savings between 6 INR (Delhi) and 82 INR (Bangalore). Significant improvements in RWH NPV were made by combining the potential profits with annual O&M, capital costs of purchasing, and bill reductions for all regional scenarios (21,764–38,851 INR). Thereby reducing all simple payback periods to within one year.

### 4. Conclusion

This study highlighted the potential for RWH as a decentralized method of reducing stormwater runoff, providing individual households with profits and caloric benefits, and recharging groundwater. The results provided a spatial and temporal analysis of the ecosystem services’ potential of RWH in India.

For vegetable irrigation, greater than 50% of the annual demand was supplemented by RWH across all geographic regions. Benefits were maximized during the southwest monsoon season. Supplementing outdoor demand with municipal water only reduced monthly bill savings by a small amount, but provided a significant increase in the net present value of the RWH project as a result of consumption supplementation and produce sales. When outdoor irrigation was targeted with captured rainwater, payback periods were reduced by 66% (Delhi, 0.3 years), 95% (Hyderabad, 0.5 years; Kolkata, 0.3 years), 96% (Bangalore, 0.5 years) and 100% (Mumbai, 1.0 years) compared with the indoor water demand scenario. This was driven by household profits stemming from consumptive supplementation and excess produce sales, which ranged from 2721 INR to 4647 INR.
regionally. Despite initial losses due to capital investment, results showed that households will quickly recoup costs through profits from vegetable sales.

Seasonal analysis of precipitation characteristics relative to indoor water demand supplementation highlighted the reduced efficiency of RWH for regions where less intense, more frequent very small events were analyzed (Srinagar). Cost-benefits were a function of the rate structure established by the municipality, where supplementation was maximized with Delhi’s rates and completely negated by Mumbai’s. This highlights the importance of water rates and public policy when indoor water demand supplementation benefits are targeted.

Less than 20% of the average annual indoor demand was met with RWH, though individual seasons (southwest monsoon, 6–26%) were shown to have improved supplementation. The southwest monsoon season yielded the greatest reductions in household water bills in India (average savings of 19–54 INR). Alternatively, RWH efficiencies were minimized during the winter (average savings of 1–5 INR). Seasonal reductions in household indoor water demand are greatest for all cities, except Srinagar, when inter-event dry time is less than 30 days and precipitation event intensities exceed 5 mm. For outdoor water use scenario, the overflow, or excess water not used for vegetation irrigation, was equivalent to greater than 40% of the annual precipitation (i.e. input) for all regions.

RWH for the purpose of providing irrigation to a small garden and allowing overflow to a drywell for groundwater recharge was found to be the most effective approach to maximize benefits. This scenario provided the greatest net present value (21,764–38,851 INR), fastest payback period (0.30–0.98 years), and an average annual groundwater recharge of 40% of onsite precipitation. This is important in the urbanized centers of developing nations, where density often restricts retrofitability for meeting such ecosystem services.

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