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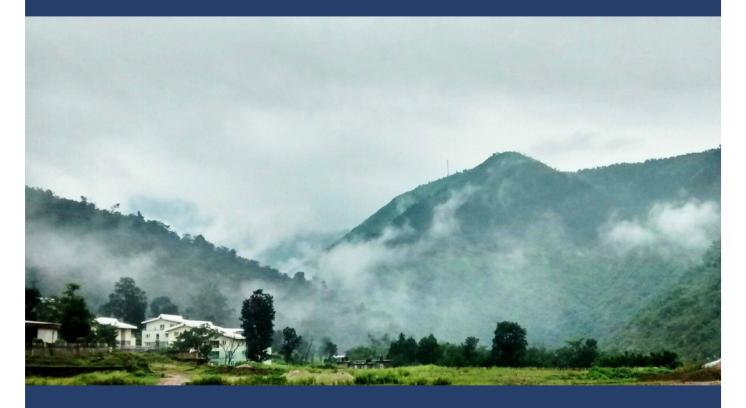
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Rainwater Harvesting in Mandi, India



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Rainwater Harvesting in Mandi, India

An Interactive Qualifying Project submitted to the Faculty of WORCESTER POLYTECHNIC INSTITUTE in partial fulfilment of the requirements for the degree of Bachelor of Science

by
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Abstract

Rainwater harvesting (RWH) was explored as a possible method to alleviate seasonal water scarcity in Himachal Pradesh. To investigate the feasibility of RWH, local residents were surveyed about their current water infrastructure and their perceptions of RWH. Based on analyzed data, models of RWH systems were designed for potential implementation on the IIT campus, Mandi town, and nearby villages. It was determined that RWH systems would be beneficial, but costs, lack of infrastructure, and misconceptions about RWH have impeded implementation.

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Authorship Page

Joseph Agresta: Primary editor for written work, created graphs and charts for presentations, contributed to all written work, conducted interviews, created final poster, took drone photography, contributed to final models.

Zachary Ericson: Primary writer for written work, contributor to presentations, conducted interviews, formulated interview data, created midterm movie, prototype creation and testing, formulated recommendations, contributed to final models.

Seth Norton: Primary data analysis and formulation of results leading to recommendations, secondary contributor to written work, contributor to presentation formatting, edited written work, conducted interviews, prototype design, simulation design.

Ankur Sadar: Conducted interviews and translation of information, interview data synthesis, created on campus implementation guide.

Alexa Stevens: Primary contributor for CAD modeling, primary contributor to final formatting of booklet, created SWOT analysis, contributed to written work, conducted interviews, contributed to cost analysis, case study research.

Rajat Valecha: Conducted interviews and translation of interviews, calculated regional rainfall data, created on campus implementation guide, contributed to on campus recommendations.

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An Opportunity for Rainwater Harvesting

In the northern Indian state of Himachal Pradesh, water crises occur on an annual basis (Singh, Sharma, Hassan, & Ahsan, 2010). Irrigation systems have been developed over the years, passed from family to family, and many towns have communal water reserves that supply their community. Pumping groundwater is often used to supplement reserves, however, even these solutions are not enough to keep up with demand. In areas of mountainous terrain, surface water is often lost to runoff, and groundwater is too far beneath the surface to sufficiently use pumps for water management.

Water scarcity in northern India is exacerbated by the difficulty of storing water beyond the rainy season. The monsoon brings around 80% of the region's annual rainfall in a three-month span while the rest of the year sees sporadic precipitation (Bloomberg, 2015). In addition to local rivers, natural subsurface aquifers store water from the rainy season



Figure 1: Bhiuli, an area facing water scarcity in Mandi, Himachal Pradesh which residents use for basic purposes. The water supply of underground aquifers, however, is not sufficient to meet the needs of residents, livestock, and agriculture (Himachal Pradesh Development Report, 2005, pp.342-343).

To meet the challenges of maintaining reliable, long-term water availability in Himachal Pradesh, this project assessed the economic costs and feasibility of rainwater harvesting (RWH) systems. Rainwater collection can provide self-supporting water supplies and reduce the challenges of pumping groundwater. In addition to supplying potable water, the collection of rainwater could help to reduce the soil erosion endemic in Himachal Pradesh by the implementation of surface runoff solutions. There is already ample roof space to theoretically implement high-yielding rainwater harvesting solutions. Therefore, to address water accessibility issues, we executed the following objectives:

- Conduct baseline assessment of existing rainwater harvesting opportunities and implementation constraints
- Evaluate properties of potential systems to develop a design-rubric to increase the efficiency of newly implemented systems
 - Construct proof of concept models and implementable designs

The information we gathered from these steps allowed us to implement a test system on the IIT Mandi Campus, create cohesive price quotes for further implementation, develop novel designs for areas that have no RWH, and support policy recommendations for the future.

Rooftop Catchment and Conveyance

The most commonly implemented rainwater harvesting systems are roof capture systems (Novak et al., 2014). Angled roof systems are ideal for many applications because they allow for a higher runoff coefficient and more efficient rainwater collection than flat roofs; a coefficient of around 0.8 for a sloped roof and 0.4 for a flat roof (Farreny et al., 2011). Sloped roofs also allow water to be gravity-fed into the conveyance component, which typically includes a gutter flowing into a downspout on the side of a house. Most downspouts then run into an underground storage tank or alternatively into aboveground tanks (see Figure 2 below).

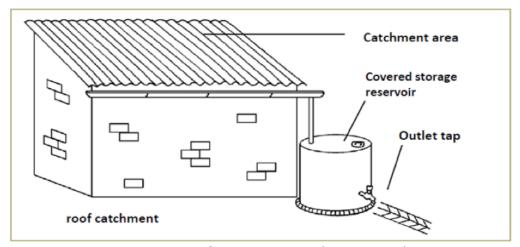


Figure 2: Roof capture system (UNEP, 1997)

The model in Figure 2 depicts a simple roof capture system where runoff is transported and captured using existing structures with the addition of a storage tank.

Filtration

Rainwater that has been harvested off of roofs can be contaminated before reaching storage and sometimes requires initial filtration. Screening using metal filters or sand can remove most sediment and debris that might have accumulated on rooftops or in pipes. These filters cannot remove bacteria, deposits from animals, or other contaminants. Technologies such as carbon filters and UV light treatments can be used to ensure that any stored water is potable (Novak et al., 2014). A simple way to do this is placing a transparent bottle of water in the sun so the sunlight kills the bacteria. Solar distillation and solar UV treatments, although effective, are time consuming. The fastest and most effective method of killing bacteria is simply boiling the water (Seneres et al., 2013, pg. 44). Both of these techniques can be a part of a rainwater harvesting system, although additional filtration is largely the decision of the user.

Storage

Storing rainwater captured in the rooftop systems is one of the greatest challenges of rainwater harvesting. First, the size of the tank must be determined by the needs of the

user and the potential amount of water that can be captured. Tank size can be limited by available space and structural constraints forcing many tanks to be constructed underground. Underground tanks have the disadvantages of challenging maintenance and susceptibility to contamination from sewage. The tank must also be sealed shut with the exception of openings for the water inlet and the overflow regulator.



Figure 3: Rooftop water storage tanks in Mandi Town (Photo: J. Agresta)

The water flow regulator releases water if the tank is overfilled to ensure the pressure is maintained. The tank should be constructed with a non-porous material that is able to withstand the water pressure within it. Additionally, sunlight cannot enter the tank, as it could promote the growth of algae and other bacteria that would contaminate the water (Kinkade-Levario, 2007).

Surface Runoff

A second method of rainwater harvesting involves directing the flow of surface runoff from rainfall through passive rainwater collection (Kinkade-Levario, 2007). The goal in these systems is to recharge groundwater and to attempt to minimize soil erosion and flash floods caused when the top layer of soil is dry for long periods of time. These systems use nonporous surfaces such as clay, concrete, pavement, or other materials to direct water. The water that flows off the impermeable surfaces is then channeled into a gutter or well of increasing permeability. These distribution networks allow for gradual permeation of runoff to reduce erosion and recharge aquifers. Permeable roadway materials have also been discovered to prevent severe flooding and recharge groundwater instead. These materials are not widely utilized yet, so the extent of their benefits is unknown. (Jenkins, 2011).

Policy

The government of Himachal Pradesh currently requires that all new urban construction, including government buildings and schools, incorporate rainwater harvesting systems (Ministry of Water Resources, 2013). Requirements set forth by the Himachal Pradesh Town and Country Planning Department (2011) dictate that these

systems must include 20 liters of water storage for every square meter of roof area. For existing water delivery infrastructure, the Himachal Pradesh Irrigation and Public Health Department (IPH) and urban local bodies (ULBs) are recognized as the primary caretakers of drinking water systems (Himachal Pradesh State Water Policy, 2013). Due to budget limitations of municipal governments, Mandi, and all other towns with the exception of Shimla, are managed solely by the IPH and not by ULBs (Himachal Pradesh Development Report, 2005). As of 2015, it was also reported that 2,354 out of 3,571 planned rainwater storage tanks in Mandi District have been constructed under the Mahatma Gandhi National Rural Employment Guarantee Act (Tribune, 2015). RWH is garnering regional support through policy implementation, increasing the prevalence of these systems in Himachal Pradesh and the surrounding areas.

Methodology: Assessment and Design

The goal of this project was to assess the capacity and implications of rainwater harvesting in the Mandi area and to implement effective harvesting solutions on the IIT Mandi Campus. In order to accomplish this goal, we established several objectives:

- Conduct a baseline assessment of existing rainwater harvesting opportunities and implementation constraints
- Evaluate properties of potential systems to develop a design-rubric to increase the efficiency of newly implemented systems
- Construct proof of concept models and implementable designs Each of our objectives required multiple research strategies to complete (Figure 4).

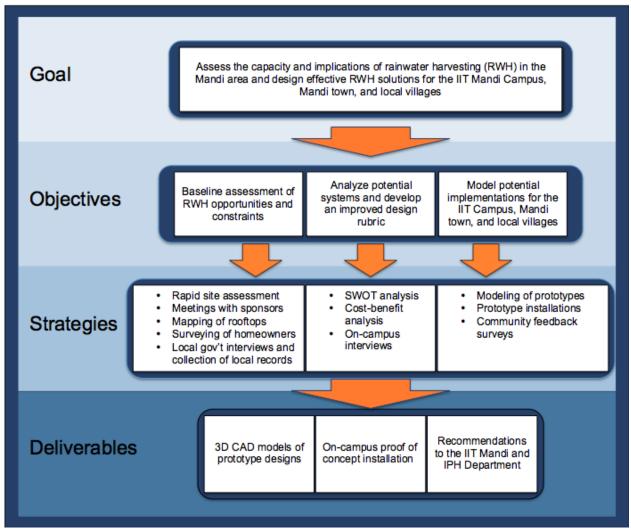


Figure 4: Project Overview

Our primary focus when first arriving in the region was to better understand the constraints and realities of the project site. Google Earth was used to map potential buildings in the study area; polygons were created for each building and the total rooftop area was calculated. Our team visited Mandi and conducted semistructured interviews with the residents of the mapped houses. We spoke to 73 of the 230 homeowners of flat-roofed buildings in the area, and catalogued them by the identification reference given to their homes. The interviews were conducted by one WPI student and one IIT student to integrate multiple perspectives and assist with communication.

After gathering the stakeholder data, we interviewed the local governing water authority, the Irrigation and Public Health Department (IPH), using a semi-structured format. We were looking for supplementary meteorological data for use in our calculations, in addition to information about the public water infrastructure. Once we had the rainfall data along with the rooftop areas and end user input, we conducted a SWOT analysis to examine the potential of rainwater harvesting solutions. In addition to the qualitative analysis listed above, we conducted a cost analysis based on local prices. From the information that was gathered and synthesized, we created a comprehensive design rubric in order to construct a system on the IIT Mandi Campus. Once the design rubric was

finalized, we conducted interviews of key stakeholders on campus (professors, students, staff) to ensure that all concerns were addressed. CAD modeling was then used to envision solutions to implement on the IIT campus and in Mandi.

After completing designs, we gathered materials from IIT and local suppliers to begin constructing a proof of concept model. Working in the IIT's machine shop, we fabricated the necessary parts to the specifications of our CAD model. The models were presented to the stakeholders and decision makers on campus. With the construction of the models completed, we tested the functionality and polled the campus for opinions. The result of our work on campus was a system that addressed the concerns held by residents affected by water scarcity.

Results and Discussion

Our fieldwork and interactions with stakeholders produced the following results.

Objective 1: Baseline assessment

Our team visited the Bhiuli region of Mandi Town and conducted interviews of 73 households in the area. Our goal was to examine the necessity for rainwater harvesting in the area and determine its effectiveness based on a variety of constraints. From the homeowner responses, we were able to gather that 63% of the residents in the area have faced some sort of water scarcity, meaning they sometimes did not have enough water to meet their daily demand. 55% of residents felt that rainwater harvesting could be useful for their families and lifestyles. Of those that faced water shortages, we found five (8%) that used rainwater harvesting in their homes. In two of the five houses, the owners were doctors, and had designed their own systems based on professional knowledge. One system was a rooftop system and another was a collection pond. Other systems were more improvised systems such as collecting rainwater in buckets or drums (See Figure 5).

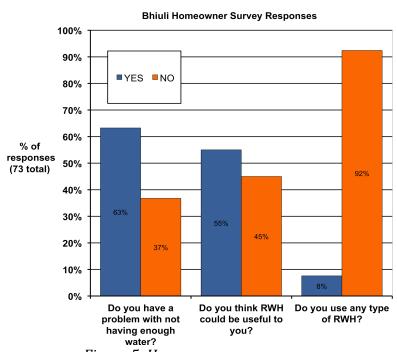


Figure 5: Homeowner survey responses

During a few interviews, homeowners speculated that houses far from water supplies faced increased water shortages while houses close to water sources received a more reliable supply of water. Discussion with homeowners showed that 95% purchase their water from the Irrigation and Public Health Department (IPH) and store the provided water on rooftop tanks. The other 5% rely on local sources such as river water, hand pumps, mountain springs, and village managed water supplies.

Water storage tanks were found universally among households and the average total capacity of residential water storage tanks was approximately 2,560 liters per household. There was an average of 5.3 members per household giving a per capita storage capacity of 482 liters per resident. Figure 2 shows that most residential water storage ranged from 500 to 5,000 liters per household with 50% of homes with storage between 1,500 and 3,000 liters (see Figure 6).

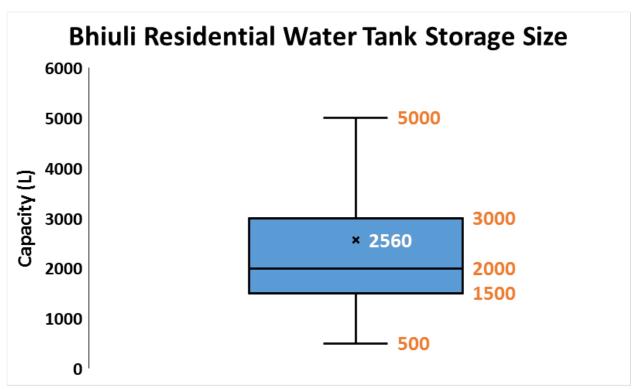


Figure 6: Water storage capacity based on survey results

Interviews proved that the residents were not always receiving the amount of water that they requested from the IPH; one resident reported only getting 400 liters out of the 1,200 their household needed per day. Almost all of the residents said that they had one or more metered IPH connections and that they only paid for water delivered, not water requested. When asked about clarifying the amount residents paid for water, officials at the IPH said they bill at the rate of 10.41 Rs/1,000L of water per month with a flat rate of 26 Rs/month per connection for families below the poverty line. The average water bill for all respondents was 236.2 Rs per month. Although the IPH treats the water they provide, 87% of residents still chose to filter drinking water before consumption, and the interviewed IPH officials also recommended additional filtration. Two residents reported receiving dirty water when it was pumped into their homes; the officials at the IPH attribute this to failing water supply pipes.

Our team questioned whether homeowners would be willing to share a RWH system with neighbors, and 65% of homeowners indicated they were open to using a shared system. Many of the respondents that did not wish to share a system stated that they wanted to avoid disputes with others and that they were concerned about how land would be allocated for water storage. Residents additionally expressed concerns that there would be no way to regulate individual water and that others would take more than their share. It was observed that the average age of homes in Bhiuli, based on homeowner response, was 21 years old. The average construction date in Bhiuli predates the 2009 government provision that requires RWH on any new construction. Many residents are looking forward to a new piped water scheme put in place by the IPH that is to come in effect within the next year.

We calculated the amount of rainwater that could be harvested from the rooftops of selected buildings on the IIT campus. As a point of comparison, the smallest rooftop on campus that was surveyed had an area of 227 square meters and an average annual rainfall catchment potential of 307,498 liters. The D2 mess hall had the largest roof area of 1459 meters squared, producing an average annual rainfall capacity of 1,972,698 liters. The total annual RWH potential of the nine selected buildings on campus totaled approximately 6,083,000 liters. Figure 7, below, illustrates potential by building.

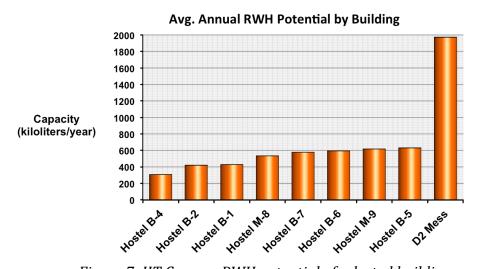


Figure 7: IIT Campus RWH potential of selected buildings

In Bhiuli, we calculated the rainfall collection potential of 262 homes with the smallest capable of collecting 5,683 liters and the largest capable of collecting 606,813 liters of water annually. The average rainwater collection potential per house in Bhiuli equaled approximately 128,875 liters per year. As shown in Figure 8, below, the middle 50% of rooftops were capable of producing between 68,903 and 161,512 liters of harvested rainwater per year.

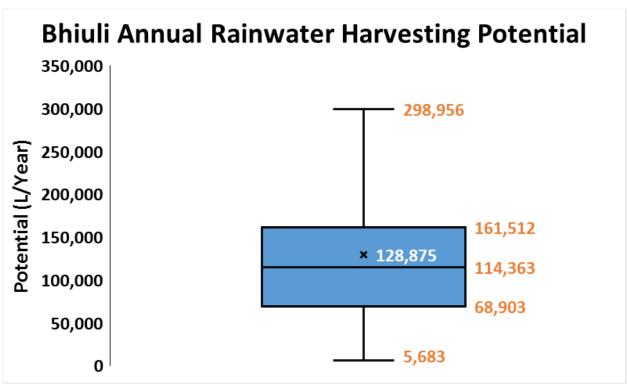


Figure 8: Distribution of annual RWH potential of rooftops in Bhiuli All the houses of Bhiuli combined were calculated to have an annual RWH potential of 33,765,000 liters.

Objective 2: Evaluate potential systems and create design rubric

After gathering the information from interviews with local homeowners and stakeholders on the IIT campus we created a design rubric featuring essential criteria derived from the responses.

RWH Design Rubric IIT Campus, Bhiuli Local M-8 Hostel Rooftops Villages Constraints: Constraints: Constraints: Cost: <10,000 Rs · Cost: as low as Cost: <5,000 Rs Readily available possible Readily available materials materials Readily available Minimal piping materials High runoff Gravity fed input Flexible to coefficient (0.8 -Minimal elevation various roof types 0.9)to pump water Highest runoff Wind and sun Easy access for coefficient resistant possible maintenance Minimal support Easy to maintain Filtration to structure remove large particles Social Implications: Social Implications: Aesthetically Aesthetically Social Implications: pleasing pleasing Aesthetically Non-Nonpleasing contaminating contaminating Multi-use space Allows for other (outdoor seating) uses of rooftop space

Figure 9: Design rubric of 3 possible implementations

Objective 3: Create designs and proof of concept

Before making recommendations for an implementation on the IIT campus, we surveyed faculty, students, and staff. After interviewing 10 students and 10 faculty and staff, we discovered that 90% had experienced some sort of water shortage on the IIT campus with 75% of them experiencing water shortages multiple times a year. Shortages were reported to have occurred in 13 different buildings across campus, and 79% of the respondents believed that the problem was due to the distribution system. When asked specifically about RWH, it was determined that 90% understand the concept of rainwater harvesting and do not believe that RWH currently exists on the IIT campus. Our survey additionally posed questions on RWH tank locations. In this case, 65% of respondents would prefer a tank location that would not be near a major walkway. To prompt reflection that could help us integrate tank design with campus deficits, 65% of our respondents indicated a shortage of outdoor seating on campus. Finally, in terms of usability, 35% think that harvested rainwater is not suitable for any use without filtration, with 60% suggesting that harvested rainwater could be used for anything but drinking without filtration.

To design a model for an affordable village rainwater system, we interviewed IIT guards that live in nearby villages to determine the need for supplemental water systems in these communities. Ten guards were surveyed, enabling us to collect data from seven different villages. From their responses we found that five of the villages facing regular water shortages. Of those that did not face a shortage, two respondents said that the water they did have was dirty. The villages mainly get water from natural sources and wells, but six respondents said that they store extra water because their water sources are unreliable.

Among the guards, RWH knowledge was widespread with all respondents reporting that they understand the concept. Three respondents additionally indicated that they have seen systems in place. The final questions asked were about the types of roofs that village residents have on their homes as well as water storage capacity. Seven said they had sloped roofs and six said they store water in some way.

Discussion

Our surveying process provided results that were both expected and unexpected. Based on the responses to questions about water scarcity and number of people in a household, we determined an average need for water in the area. We then calculated the potential that these homes and buildings have to collect rainfall by using our maps. The average monthly collection potential in Bhiuli was estimated at 10,700 liters per house. If a resident of Bhiuli used 70 liters of water per day, RWH on an average size rooftop could provide enough water to meet the entire monthly demand of 5 household members. With an average of 5.3 members per household, rainwater harvesting could come close to supplying the entire demand of households. Without solutions for long-term water storage, however, rainwater harvesting could serve as a supplemental water source rather than a sole water source, but RWH would still help to mitigate shortages and take stress off the current water distribution system.

Even with a majority of residents in support of rainwater harvesting and facing water shortages, there was still skepticism among homeowners about the feasibility of rainwater harvesting in Bhiuli. Doubts about RWH originated in perceptions that there is not enough space for sufficient rainwater collection, implementation costs would be too high, and other users may abuse shared systems by using too much water. With some households not affected by water shortages, interest in RWH as a solution was also uneven. Households without water shortages were less likely to support implementation of RWH, even if it was at little to no cost to them. In our initial interviews, one resident who was affected by lack of water, said that it would take a total crisis for everyone to get on board.

We have found implementation on the IIT campus to be a viable solution to the water shortage issues. After interviewing the faculty and students on campus, those that live with the IIT water supply, we were provided with important information about their experience with this system. The high number of respondents that indicated the presence of water shortages is indicative that the IIT water supply is not sufficient year round to sustain oncampus residents. On the south campus we determined that millions of liters could be harvested a year. Rainwater harvesting could also be implemented on the buildings being constructed on the north campus to meet the demand of the future increased population of the IIT Mandi. Additionally, there was overwhelmingly positive feedback about integrating the water tank as an outdoor feature such as a seating area. The multi-use aspect of this system is something that could improve social acceptability and encourage widespread implementation by the IIT. The cost of the tank for the proposed M8 Hostel implementation was higher than expected at 30,887 rupees. Although expensive, the storage tank will provide sufficient storage so that water is not wasted as overflow outside of the monsoon season. Monsoon rainfall would not need to be stored, and could instead be used to recharge groundwater, as most students and faculty are not on campus during the months of heaviest rainfall.

After speaking with the guards on campus to better understand the needs in small local village, it is clear that the surrounding communities also face water problems including scarcity and unclean water. Village water shortages could be partially mitigated with RWH, especially since a majority of homes have sloped roofs and already collect water. The largest challenge is implementing a cost effective solution that is easy for homeowners to install on their own. Knowledge of RWH is high, so informing residents about how they can construct low-cost implementations on their homes with available materials is key.

RWH System Designs and Implementation

Our team has prepared a ready-to-implement design for the IIT campus, a novel solution for the Bhiuli area, and a low cost design for village implementation. We used computer aided design (CAD) models to envision and plan rainwater harvesting systems based on our data analysis for the water-challenged Mandi region. Each design focused on meeting the needs of each target community.

Campus design

The goals of the system designed for the IIT campus were both to collect rainwater cost-effectively and to create a multipurpose space that would be socially acceptable on campus. The system developed for implementation on the IIT Mandi campus relied on the gutter and pipe system that was part of every hostel (dormitory) design. Hostel M8 was chosen for implementation because the building had existing aboveground gutter pipes that allowed for easy construction of a conveyance system. The elevation of the M8 Hostel also made it possible to gravity feed collected water into storage tanks that could be used by other hostels nearby (see Figure 10).



Figure 10: Immediate campus implementation

Pipes are attached to the ends of the drainpipes from the gutters, feeding into a first flush tank. The first flush system is used to eliminate the initial portion of water collected so that the majority of contaminants from the roof surface do not enter the storage tanks. Once the first flush tank is full, any additional water flows through the pipe into a multistage gravel and sand filter. The filtered water that passes the first flush filter system then fills into the storage tanks. The bottom of the first flush tank would be a mixture of gravel and sand to allow the water to slowly seep back into the ground. This dissipation would empty the tank automatically, only needing maintenance every other month to prevent buildup of organic material.

For storage, the tank size was calculated based on the area of the roof and the average calculated rainwater potential of the M8 Hostel. The tank is positioned downhill from the hostel, allowing it to be easily gravity-fed (See Figure 11).

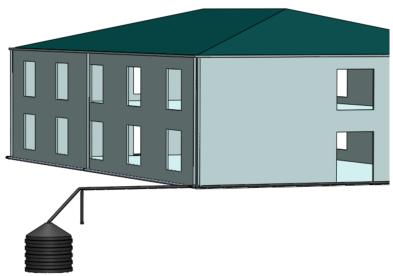


Figure 11: A CAD model of the initial prototype system

Overflow from the tank can also be directed to the well beside the D2 mess. The well can be gravity-fed from the tank, and the extra water will either be drawn up by the well pump or help recharge the groundwater.

From our interviews with students, we found that more outdoor gathering and working spaces were desired. From this requirement, we decided a large, half-buried concrete tank would be accepted by leaving the top half as a seating area. Comprehensive plans, including costs and multiple designs, have been developed and are ready for implementation in accordance with IIT building plans. Due to the time required to construct a concrete tank however, we installed a 5000-liter plastic tank as an initial prototype and recommend the concrete tank as a future, long-term solution. We also forwent the self-emptying first flush tank in favor of a quick, easy to implement first flush pipe that must be manually emptied after each rain event.

A RWH system for Mandi Town

The design devised for the town of Mandi, specifically Bhiuli village, was geared towards improving the efficiency of rooftop collection as well as making an affordable system that allows for multiple use rooftop space. A single slope canopy design was selected as a way to improve collection efficiency, allow for alternate uses of rooftops, and minimize construction material costs.

To improve the runoff coefficient of the flat rooftops, a sloped catchment area made from corriboard was proposed. Corriboard was tested and shown to transport over 90% of the water placed on it giving it a higher runoff coefficient than a sloped metal roof. The corriboard canopy was also designed with an origami technique to make the system removable and easily re-deployable.

The supports for the single slope canopy would consist of two sets of higher poles, and two sets of lower poles (see Figure 12) fixed to the roof with cement screws. The corriboard in the design is attached with simple hooks on each corner to create a sloped catchment. Rainwater would runoff the catchment into a pre-installed gutter system on the lower end. Harvested rainwater from the catchment is transported into rooftop tanks that would gravity supply water to residents living below. The novelty of this system is that it is

completely customizable (corriboard size, appearance, tank size) based on the home size and desired water collection. The use of existing rooftop storage tanks would also reduce space requirements and eliminate costs of purchasing dedicated RWH tanks.

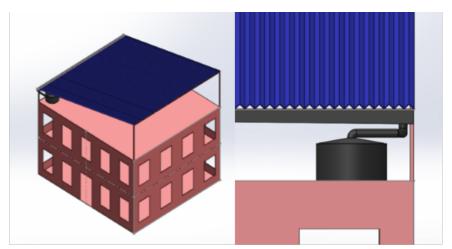


Figure 12: Mandi town model

We had considered other options including adding a solid permanent canopy to the roof (metal or plastic), adding material to create a sloped roof, and adding a permeable rooftop leading to a tank. During analysis the other options were ultimately rejected because they were more expensive, more difficult to implement, or more space consuming.

Village design

For villages in the district of Mandi, a model was created that featured recycled and inexpensive materials. The main constraint in this design was the cost of materials. In this design, we combined the two lowest cost ideas of a "rain chain" and of recycled plastic bottles as a conveyance system. The design consists of the chain running through the bottles that are connected end to end by removing the bottom end of each bottle (See Figure 13).



Figure 13: Village solution

Water then flows down the path of the chain and the bottles act as a splashguard to ensure the bulk of the liquid remains contained. Our findings found that most roofs in the surrounding villages had a roof gutter but no conveyance pipe to a storage container such as a bucket. This design alleviates that problem using readily available materials at low cost. This model was prototyped, but additional research and field testing was not included in the scope of this project.

Recommendations

Our first recommendation stems from cost concerns that we found while conducting our interviews with residents of Bhiuli. We believe that the IPH, or the Himachal Pradesh government, should offer a subsidy to offset the initial cost of rainwater harvesting systems. The subsidy will give the residents an opportunity to acquire a supplementary water supply, increasing the amount of water on hand while decreasing demand on the IPH public water distribution system. Although the IPH is increasing the amount of water in its system with additional sources, officials recognize that this is a 20-year solution at maximum. Instituting RWH systems will provide a secondary source of water that does not rely on piped water infrastructure or draw water from nearby rivers and groundwater.

Our second recommendation is to educate the people of Mandi about rainwater harvesting and its benefits. Most importantly, the education should focus on the idea that RWH can be done in densely populated areas, not just in large open expanses. Our interviews revealed that many residents weren't interested in the systems because they didn't think the space existed to implement them. This lack of knowledge is a mitigating barrier in advancing the rainwater harvesting movement. A future project could be implemented to increase the awareness and education of rainwater harvesting methods and techniques, including instruction on how people can make a simple system using what infrastructure already exists in their house. From our interactions with local homeowners,

we suggest a small working model on a demonstration site in addition to an informational campaign with graphics to overcome language discrepancies or misunderstandings.

Our third recommendation includes short and long-term plans for the IIT in regards to rainwater harvesting. The short-term plan involves the installation of a simple RWH system on the M8 Hostel as described above. For a long-term solution, we recommend creating a network of underground pipes running from multiple hostels and campus buildings to large underground storage tanks. Water should be collected from higher elevation buildings to supply lower buildings with minimal energy required to lift water to the rooftop tanks of each hostel. We also recommend the use of concrete tanks for largescale implementation because of the cost advantages over plastic tanks at large volume. One designs collects water from the D2 mess and directs it to recharge a borewell that is directly behind the building. The lack of recharge in the borewell has been a problem this past year and surely will be in the future if something isn't done. The overflow pipes from storage tanks should also be connected to the borewells to take advantage of excess water collected during the monsoon season. Even with students off campus during the monsoon season, extra collected water should still be used to recharge groundwater. The overall rainwater potential of campus is large enough to produce a significant percentage of water used on campus, but only if large-scale implementation is performed. We have provided the IIT with an implementation guide that details site locations, pricing, and timelines for construction.

Conclusion

In Mandi, India, unreliable piped water supplies and increased water demand from population growth have demonstrated a need for rainwater harvesting systems as a supplementary water source. In addition to meeting long-term demand and taking stress off of existing water supply infrastructure, the systems must meet the needs of the different implementation locations. These criteria include space conservative solutions for flat roofs in Mandi, low cost solutions for a village setting, and maximum water collection for the IIT campus.

Much of our research supports the idea that rainwater harvesting would be useful in Mandi, however, few examples of rainwater harvesting exist despite efforts by the IPH. Conversations with residents gave the impression that only a large-scale, extended water crisis would spur implementation. We have fulfilled our goals by demonstrating that rainwater harvesting is a viable mitigation technique for populations affected by water scarcity and by offering solutions that can be implemented for each location. Future projects could include researching ways to incentivize widespread implementation in Himachal Pradesh and resident education about the feasibility of rainwater harvesting for storage and groundwater recharge.

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Appendices Appendix A: Case S

Appendix A: Case Studies

Rainwater harvesting solutions provide variable quantities and qualities of water. In order to examine the benefits of rainwater harvesting-based water supply systems, we examined three case studies that focused on dimensions of rainwater harvesting which pertain to our site in Himachal Pradesh. We begin with a case study that examined the rainwater runoff output of different roof types in Spain.

1. Roof selection for rainwater harvesting: Quantity and quality assessments in Spain

In the roof selection case study conducted in Spain, roof slopes and materials were compared on their ability to produce runoff in an urban environment. Four rooftops of different materials were selected on the Autonomous University of Barcelona (UAB) campus, and the runoff output of each roof was compared to the total rainfall at each location. The roof materials included clay tiles, metal, polycarbonate plastic, and flat gravel. The output runoff from each system was additionally checked for levels of ammonium and carbonate contaminants (Farreny, Morales-Pinzon, Guisasola, Taya, Rieradevall, & Gabarrell, 2011).

Despite roofs having equally sized footprints, different roofs were shown to have varying output capacities due to the runoff coefficient of each roof material. The total potential output of a roof (in liters/year) is summarized in the rainwater potential equation below (Farreny et al., 2011):

RWH potential = P*A*RC

In the equation, P represents precipitation at a location (mm/year), A is the area of the roof (m²), and RC is the runoff coefficient. The runoff coefficient indicates the percentage of water that will become capturable runoff from a given amount of precipitation and roofs typically have a value between 0.7-0.95. The coefficient for a material was shown to be affected by factors such as roof slope, water retention rate, and roof roughness. Flat rough roofs (such as flat gravel) were shown to have lower runoff coefficients than smooth sloped roofs (metal), and rough roofs also retained more contaminants (Farreny et al., 2011). Most of the water losses in roofs occurred in what was known as the "initial abstraction" where water would adhere to rough areas and be lost to evaporation later (Farreny et al., 2011).

2. Conservation of groundwater through artificial recharge using rooftop rainwater in RV College of Engineering campus, Bangalore

Shipla Ramesh (2008) carried out the case study of design considerations of urban rainwater harvesting on the Rashtreeya Vidyalaya College of Engineering campus in Bangalore. The campus was relying on wells for their drinking water but due to rapid urbanization, the recharge rate of groundwater had dropped drastically. Roads, buildings, and other manmade structures that are not designed of permeable materials, redirect and impede rain from reaching the ground. In the study area, 32.8% of the ground was covered by impermeable construction which led to reductions in well yield and deterioration of water quality (Ramesh, 2008).

Instead of changing the existing drinking water systems from wells to rainwater collection and tank storage, Ramesh aimed to use rainwater to artificially recharge the aquifers that were already in use. A gravity head recharge settling tank was installed in order to recharge one of the wells used by the campus. In this system, rainwater from the rooftop is gravity fed into a tank that is divided by an overflow wall (see Figure 1).

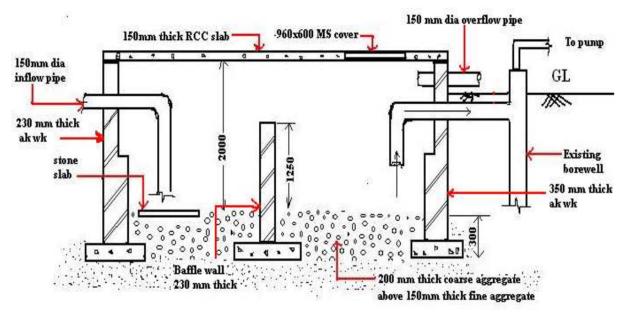


Figure 14: Recharge settling tank

As rain enters this system, any coarse particles that are mixed with the water will sink to the bottom and settle in the aggregate. As rain continues to enter the tank, some water will filter through the bottom, seep through the ground, and eventually reach the well after being filtered by the soil. The rest of the water will build, overflow the wall, and continue into the second half of the tank where particles will again settle out. Finally, the water drains directly into the well and recharges the aquifer. Any rainwater that enters this settling tank will add to the well, either by subsoil recharge or direct injection to the well (Ramesh, 2008).

The additional water collected and stored by this system was estimated to be worth 49,300 rupees if it were purchased. The cost of the project was only around 19,300 rupees meaning that the benefit to cost ratio was above 1.55. Based on these findings, the groundwater recharging systems were deemed economically feasible (Ramesh, 2008).

3. Sizing the first flush and its effect on the storage-reliability-yield behavior of rainwater harvesting in Rwanda

The first flush case study conducted in Rwanda (Doyle, 2008) analyzed and implemented the components necessary for a functioning first flush system for rainwater harvesting. A first flush system is a method of ensuring the water that enters a tank during rainwater harvesting is relatively free from contaminants from the roof which the rain is collected from. The amount of contaminants on each roof depends on the material and angle of the roof, the nearness of trees and other plant life, the type of pollutants in the air, and the amount of animals in the area (such as insects, lizards, and various rodents) (Doyle, 2008).

The level of contaminants is particularly important in determining the amount of water to divert during a first flush.

There are several different methods to divert water for a first flush. The most simple in design is a manual diverter where the water is physically redirected after the requisite amount of water has been washed from the roof.

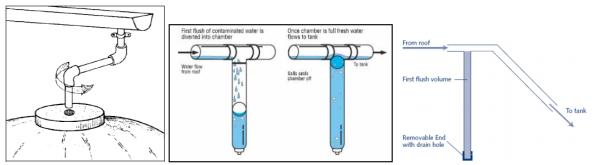


Figure 15 (L to R) Manual Diverter, Intensity-dependent diverter, and constant volume diverter

The manual method is the most time intensive version, and if the owner is not present during the rainfall, the system is completely useless. The next type is an intensity-dependent diverter, in which the strength of the rainfall determines how much water is flushed; the heavier the rain, the sooner the water will begin to fill up the clean tank. This system usually includes a flow restricting device that covers the emptying valve when the rainfall is heavy enough to have washed the contaminants from the roof. The intensity dependent model, however, has many small, independent parts that may fail, and is not recommended for places in which replacement may be difficult. The most common type of diverter, and the one implemented in the case study, is a constant volume setup, where water is directed into a separate chamber or pipe until full. Once the first flush chamber is full, the water passes over the opening and into the tank. The chambers or piping have a removable cap so that the contaminated water and debris can be drained out. This water can be used for other, non-potable purposes as to reduce wasted water (Doyle, 2008).Conclusions reached through case studies

The case studies we examined provided insight into design decisions that may influence our work in Himachal Pradesh. The first and second studies examined, were conducted in dense urban areas similar to Mandi and included analyses of roof types and groundwater recharge methods. The last study explored the newest methods of low-maintenance, high yield first-flush systems that eliminate manual operation by the user. By combining the lessons learned in each the case studies, we will be better able to establish design criteria for efficient and cost effective rainwater harvesting solutions.

Appendix B: Interview Questions and Responses

Questions for IPH Assistant and Executive Engineer, 4/4/16

- What infrastructure exists in Bhiuli?
- Where are the main water pipes/sources of water? Where can we find maps?
- Do they decide how many liters of water to pump to individual houses?
- What is the main source of water for IPH water supplies?
- Has there been analysis done to evaluate RWH capacity in Mandi?
- Are there complaints of water shortages? If so, in what areas?
- Is RWH encouraged or subsidized by the government?
- How is water billed, per liter, per month?
- How often does the government subsidize water?
- What are the causes of disruptions of service? How long do they typically take to fix?
- Do you know of existing RWH projects? Where could we find them?
- How much does the IPH spend to maintain water infrastructure?
- In existing RWH projects what challenges or barriers have been faced?
- How much does RWH cost?
- Is water treated before being sent out?

Interview Transcript - Rahul Abrol, IPH Assistant Engineer, 4/4/16

- Map of Bhiuli can be acquired from the Town & Country Planning Office
- There is no gov't subsidy for RWH
- On paper there is enough water in the system, but in practice it is not enough due to poor water distribution.
- There is a lack of water pressure in the system which makes it difficult for houses that are higher up and further away from the source to get ample water.
- There is 24 hour pipe replacement policy if there is a pipe break
- The IPH filters the water but still recommends that homeowners filter water on their own.
- The river is the primary source of water for the IPH system.
- If homeowners are BPL (below the poverty line) they pay a flat rate of 26 rupee/month
- Water distribution map of Bhiuli must be acquired from Sub-Division Mandi IPH Office at Trana location
- Rahul is going to try to get us data for water usage by house and total consumption in the area of Bhiuli (if possible)
- RWH costs of implementation per house- > depends on size of tank
- RWH collection capacity -> Approximately 8 MLD (million liters per day) ???
- Materials used -> concrete, reinforced concrete, cost of 6 Rs/L
- Residential bill rate: 10.41 Rs/1000L

- Commercial bill rate: 20.82 Rs/1000L
- Village rate: 26 Rs/month
- Mandi Town
 - Existing piped water capacity at Kanghidhar (spelling?) 6.15 MLD
 - Existing piped water capacity at Motipur 1-2 MLD
 - Proposed scheme for Mandi Town 15.15 MLD
- People to talk to:
 - IPH Sub-division R.K. Saini
 - O Town & Country Planning Mrs. Rita Mehendon

Stakeholder Ordered Interview Guide

House ID:

Interviewer Names:

- 1) Who is the owner of the house?
- 2) Are there any renters in the house?
 - a) Do renters pay the water bills separately or does the owner pay all the bills?
- 3) Do you know what rainwater harvesting is? (If NO, skip to question #9)
- 4) What do you think of rainwater harvesting?
- 5) Do you know anyone who uses rainwater harvesting?
- 6) Do you use any type of rainwater harvesting?
 - a) Do you have a rooftop system?
 - b) What has prevented you from installing a rainwater harvesting system so far?
- 7) What methods of rainwater harvesting do you, or someone you know, use?
- 8) Do you think rainwater could be, or is, useful to you?
- 9) Where do you get water from normally? Dry season vs. Monsoon season?
 - a) Do you have another water supply other than the municipal water supply?
- 10) Is your current water supply reliable?
- 11) Have you ever had a problem with not having enough water?
 - a) What do you need more water for?
- 12)Do you store water? How?
 - a) Do you have a water storage tank? How many?
- 13)Do you pay for water?
 - a) Is your water supply metered?
 - i) How many units per month?
- 14) What do you use water for in your day to day lives?
- 15) Do you filter water? How? (Boil, sand, UV/solar, reverse osmosis, other)
- 16) What type of roof do you have/what type of material is it made out of (flat, gable/slanted, other; metal, cement, shale, plastic, other)?
- 17) How many people live in your home?

- a) Do they stay here or stay in some town and visit occasionally?
- 18) What times of the day are people in the house?
 - a) What is their occupation and duty hours?
- 19) Are you willing to share a water supply?
- 20) Are you willing to have a common water supply on your land?

Interview Data

This link directs to a Google Drive folder containing Excel spreadsheets of our interview results from surveys in Bhiuli as well as rainfall potential calculations. Supplementary maps are also included.

https://drive.google.com/folderview?id=0Bx11m_sl3kzHamZQdHNwMzFVQm8&usp=sharing

Appendix C: Project Video

https://www.youtube.com/watch?v=MfxRnACaU1c

Appendix D: CAD Model Images

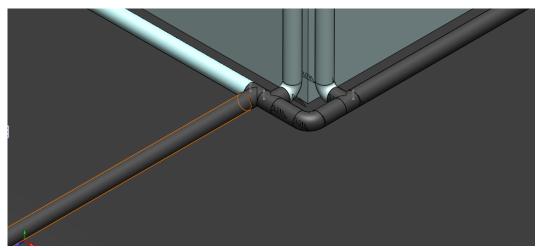


Figure 16: Campus model, corner piping

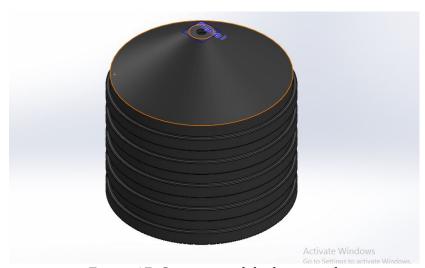


Figure 17: Campus model, plastic tank

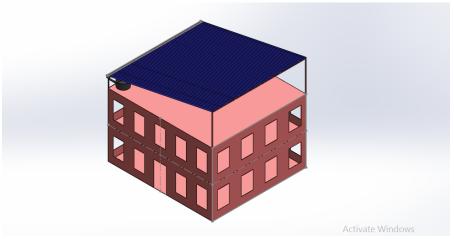


Figure 18: Town design

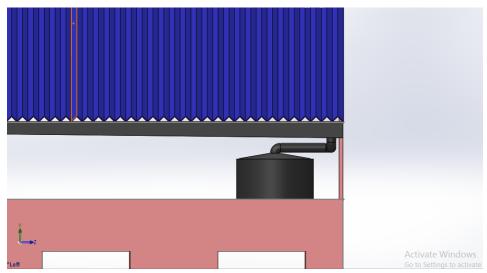


Figure 19: Town design, tank and gutter

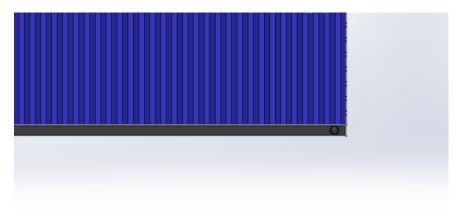


Figure 20: Town design, close up of roof and gutter from the top



Figure 21: Campus design

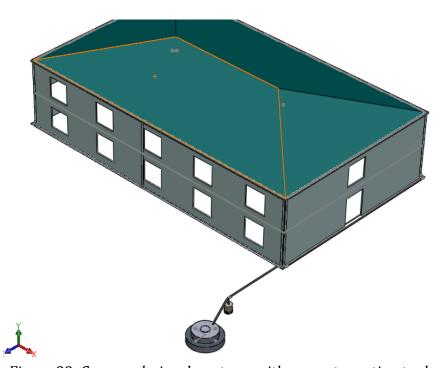


Figure 22: Campus design, long term with concrete seating tank

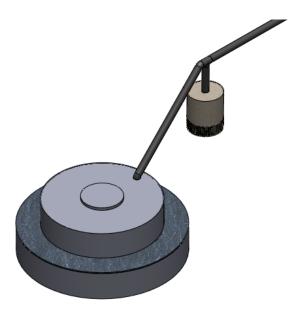


Figure 23: Campus design, concrete seating tank and first flush tank

Appendix E: Graphs, Charts, and Survey Pictures

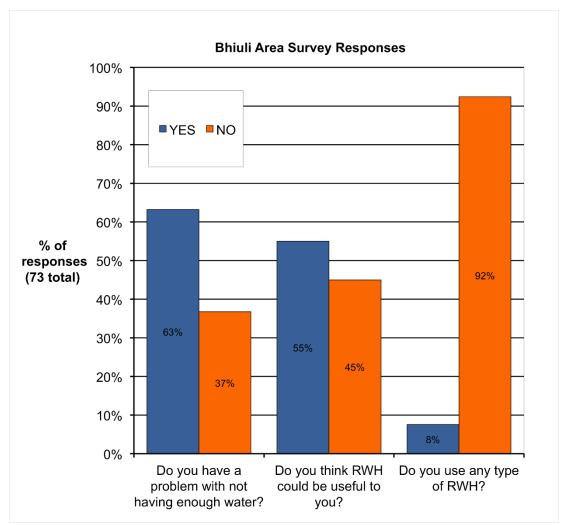


Figure 24: Homeowner survey responses

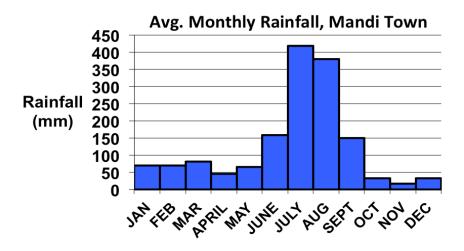


Figure 25: Average monthly rainfall

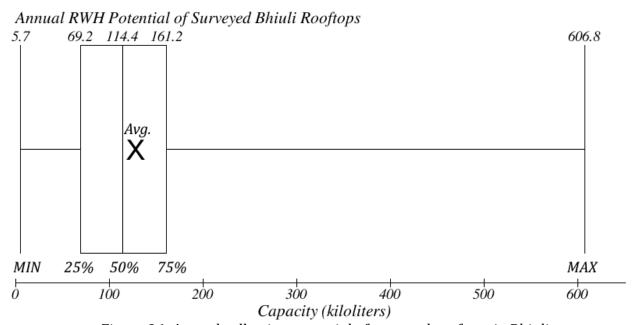


Figure 26: Annual collection potential of surveyed rooftops in Bhiuli

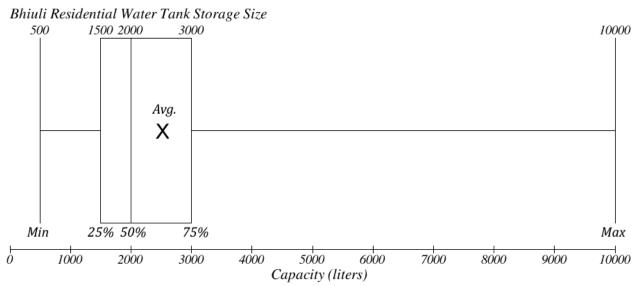


Figure 27: Water tank storage capacity in of surveyed houses in Bhiuli

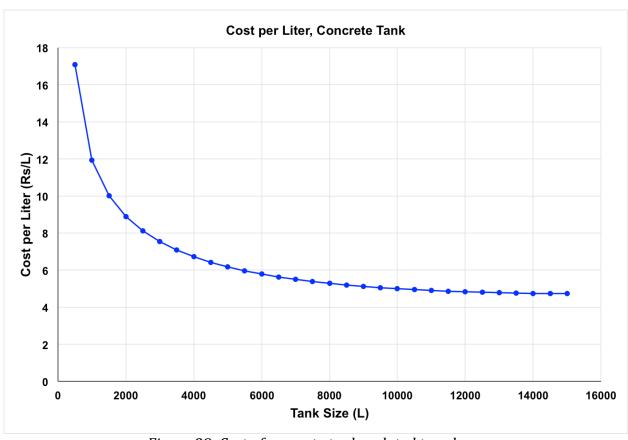


Figure 28: Cost of concrete tanks related to volume

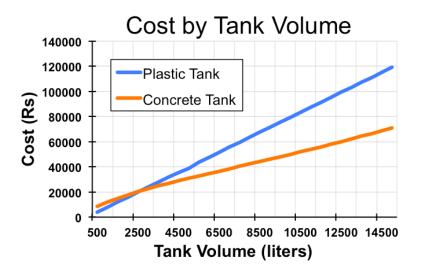


Figure 29: Cost of tanks based on volume

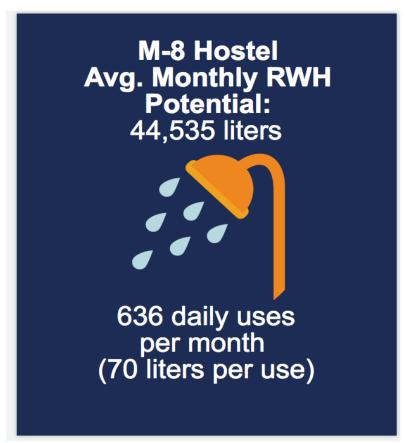


Figure 30: M-8 hostel monthly rainwater collection potential

Strengths

- Extra water to prevent shortages
- Decentralized water supply independent of IPH distribution system
- · Helps to prevent flooding
- Less susceptible to contamination
- Long-term profitability over lifted-water schemes
- Capitalizes on Monsoon rainfall

Weaknesses

- · Long-term storage
- · Initial investment costs
- · Lack of collection/storage space
- · Additional filtration
- Roof catchment angle
- · Long-term maintenance
- Clogging of system by debris
- · Disputes over shared systems
- Extra pumps and electricity usage
- First flush education

Opportunities

- · Improve the cost of the system
- Reduce maintenance and upkeep costs
- · Improve materials
- Make the system aesthetically pleasing and multi-purpose
- Fulfill government RWH mandate
- · Get government subsidies
- · Use recycled materials
- Make the system removable

Threats

- Lack of interest
- Perceptions RWH is unfeasible
- Cheap or subsidized IPH water
- Future IPH piped-water scheme in Mandi Town
- · Contamination from sewage
- Damage or contamination from animals (monkeys or birds)

Figure 31: S.W.O.T. chart

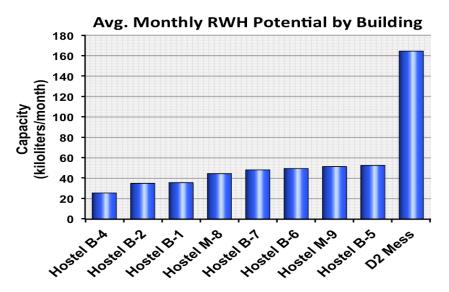


Figure 32: Monthly rainwater collection potential by building on the IIT Campus



Figure 33: Survey results

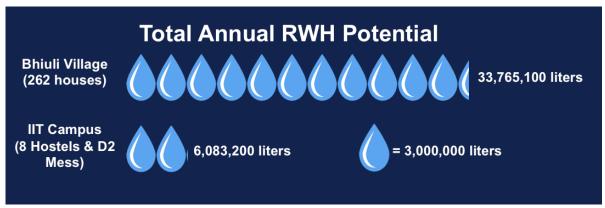


Figure 34: Rainwater collection potential from Bhiuli and IIT campus

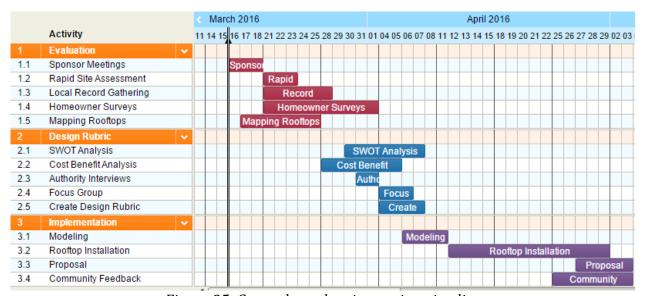


Figure 35: Gantt chart showing project timeline



Figure 36: IPH water meters on pipes in Bhiuli



Figure 37: Water storage tanks from Bhiuli area



Figure 38: Concrete IPH water tank, Bhiuli

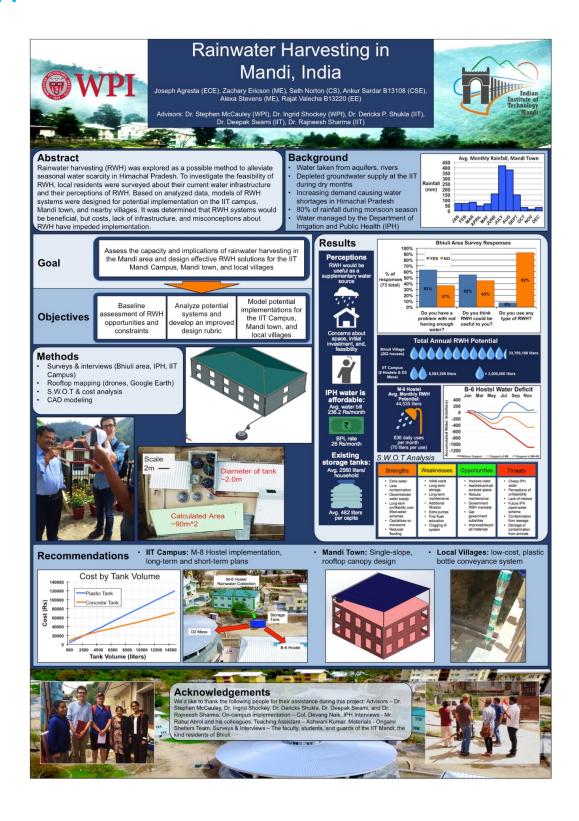


Figure 39: M-8 Hostel final implementation



Figure 40: M-8 Hostel RWH tank

Appendix F: Poster



Appendix G: References

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